

ABS ADVISORY ON HYBRID ELECTRIC POWER SYSTEMS



TABLE OF CONTENTS

CONTENTS

Introduction.....	2
Energy Storage Technologies.....	5
Lithium-Ion Batteries.....	5
Introduction.....	5
Description and Operation.....	5
State of the Technology.....	10
Advantages.....	11
Challenges.....	13
Lessons Learned.....	14
Supercapacitors.....	15
Introduction.....	15
Description and Operation.....	16
Advantages.....	19
Challenges.....	19
Applications.....	20
Flywheel Energy Storage.....	21
Introduction.....	21
Description and Operation.....	22
State of the Technology.....	23
Advantages.....	23
Challenges.....	24
Applications.....	24
Energy Generation Technologies.....	25
Fuel Cells.....	25
Introduction.....	25
Description and Operation.....	25
State of the Technology.....	26
Advantages.....	27
Challenges.....	28
Applications.....	29
Wind and Solar Power.....	31
Introduction.....	31
Description and Operation.....	32
State of PV technology for marine applications.....	33
Vessels in operation with PV solar panels installed.....	33
Concepts for the future.....	34
Advantages.....	35
Challenges.....	35
Opportunities and Challenges For Hybrid Electric Power Systems.....	36
Opportunities.....	36
Challenges.....	37
ABS Role.....	37
Acronyms.....	39
References.....	40

INTRODUCTION

As technology evolves and regulatory complexities increase, the marine industry is faced with the reality of both complying with environmental requirements and meeting operational demands. To deal with these challenges, owners and operators are turning to more non-conventional sources of energy to power and propel vessels. As the industry moves ahead, hybrid electric power systems will play a key role in meeting the regulatory and operational demands placed on vessels.

Other industries, like electric utilities and aerospace, are already applying renewable energy technologies to their end products and finding innovative ways to reduce their environmental footprint while still maintaining their competitive edge. It is critical that lessons learned and experiences in the adaptation of hybrid electric power in other sectors are considered as the marine industry examines their various options. In developing this Advisory, ABS took a measured approach in evaluating the potential advantages and disadvantages, challenges and level of readiness for the primary hybrid electric power systems and components that are most suited for marine applications.

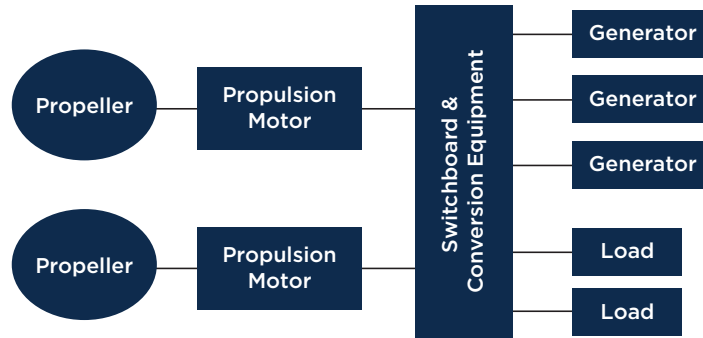
For over 60 years, the dominant form of ship propulsion consisted of diesel engines delivering thrust directly to the water via a shaft and propeller. Depending on the speed and power of the diesel engine, there may also be a gearbox between it and the propeller. Ships with this simple, reliable and familiar arrangement have been in use for many decades and are likely to continue to be built for the foreseeable future.

However, with current technological advances, there are an increasing number of options available which can better suit the specific needs of a vessel with a range of operational circumstances while meeting the current and foreseen environmental concerns. One alternative to the conventional mechanical propulsion arrangement is an electric propulsion system. An electric propulsion system allows for the propulsion capability of the vessel to be provided by electric propulsion motors. These propulsion motors are supplied by a common set of generators that also supply the vessel hotel loads.

The concept of electric propulsion is not new. Early implementation of electric propulsion systems date back to the 1800s. The concept has gained more popularity due to technological breakthroughs in power electronics which gives end users the ability to control electrical motors with variable speeds in a large power range with compact, reliable and cost competitive solutions. Figure 1 below compares a mechanical propulsion system and an electric propulsion system:



Mechanical Propulsion



Integrated Electric Propulsion

FIGURE 1: Comparison of Mechanical vs. Electric Propulsion Systems

One of the main benefits of electric propulsion systems is the ability to optimize the loading of the prime movers for the generators (diesel engines, gas turbines, etc.) so as to obtain maximum efficiency and reduce fuel consumption. This is especially beneficial in vessels with a diverse operational profile (such as DP vessels where a typical operational profile is divided between transit and station keeping operations). Generators and electric motors for propulsion offer greater flexibility in the utilization of on-board space than main engines.

Modern electric propulsion systems are being further enhanced by the incorporation of new technology. One example is the incorporation of alternative electrical power sources such as fuel cells, solar panels and wind turbines. Other designs employ one or more methods of energy storage such as batteries, super-capacitors and flywheels to supply and/or supplement the electrical power needs of the vessel. Vessels with such arrangements also incorporate power management systems that extend well beyond the standard electrical control systems. These types of systems are considered by ABS to fall under the new and developing category of hybrid electric power systems. For the context of this advisory, hybrid electrical power systems incorporate multiple sources of power, usually a combination of both non-traditional sources (batteries, capacitors, fuel cells, etc.) and traditional sources (diesel gensets). Examples of these types of systems are shown in Figure 2.

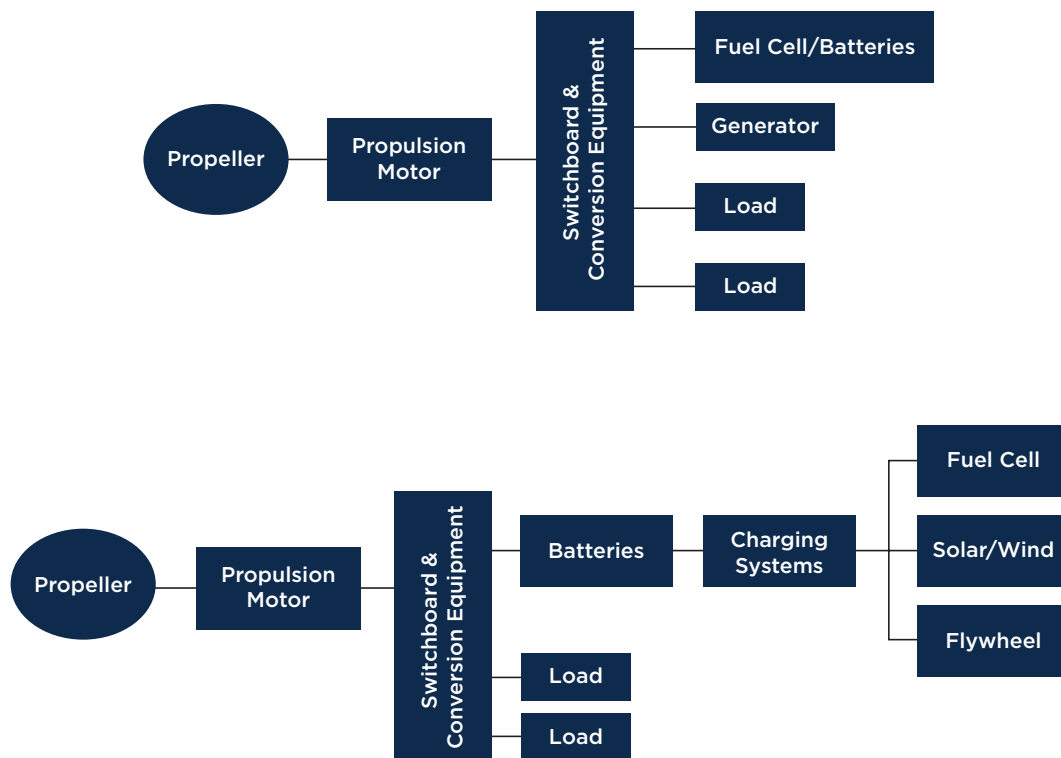


FIGURE 2: Examples of Hybrid Electric Power Systems

These hybrid electric power systems offer alternatives to traditional electrical plant configurations and allow vessel operators more options for optimizing the configuration to best serve the varied load profile during different modes of operation.

Hybrid electric power systems support compliance with the new stringent MARPOL Annex VI pollution regulations required in environmentally sensitive areas, while also assisting owners and operators in maximizing the efficiencies of their power plant and reducing operating costs. Hybrid electric power systems using stored energy as a backup for the main power source also allow vessel owners to enhance safety in response to emergency scenarios where all main power is lost, or in situations such as explosive natural gas buildups where use of internal combustion engines would not be considered safe.

This Advisory offers a high level overview on hybrid electric power systems, the current status of the component technologies, the advantages and challenges of each, along with some of the applications in the marine and offshore industry. The primary component technologies have been divided into two broad categories, namely energy storage technologies and energy generation technologies. The energy storage technologies covered include batteries (with a focus on Lithium-ion batteries), capacitors (with a focus on supercapacitors and hybrid capacitors) and flywheel energy storage. The energy generation technologies covered in this Advisory include fuel cells, solar and wind power.

ENERGY STORAGE TECHNOLOGIES

Energy storage technologies offer the opportunity to accumulate and store energy for use at a later time, possibly supplementing or replacing in some instances the onboard electrical power distribution system. This section provides information on alternative energy storage technologies, including lithium-ion batteries, supercapacitors and flywheel energy storage systems. Each of these technologies has its own advantages and challenges.

LITHIUM-ION BATTERIES

INTRODUCTION

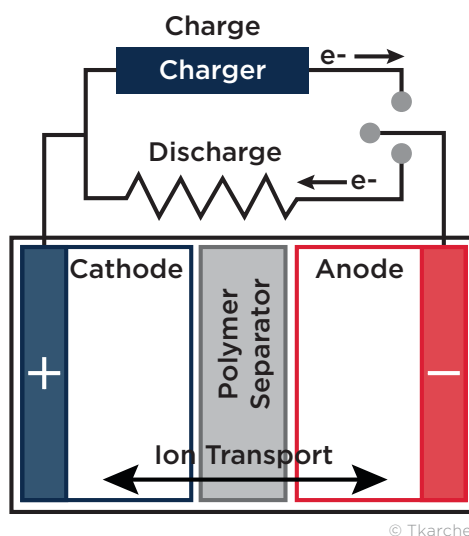
The first lithium-ion batteries were introduced in the mid-1990s. These batteries exhibited low internal resistance and low parasitic losses, and were used for low energy, low power and long life applications. However, advances in Li-ion chemistries have led to increased energy and power density along with a terminal voltage vs. state of charge that is superior to traditional battery chemistries such as Nickel Metal Hydride (NiMH), Nickel Cadmium (NiCd), lead acid, etc.

These favorable characteristics have facilitated the use of lithium-ion batteries in applications that were previously impractical for traditional battery chemistries. Large scalable lithium-ion battery packs have found applications in defense systems, electric vehicles, satellites and marine and offshore installations.

In spite of the many advantages, lithium-ion battery technology requires operation within defined parameters including specific charge/discharge rates, voltages, currents and temperatures. Operation outside these values can lead to premature failure, loss of performance and unsafe operation.

DESCRIPTION AND OPERATION

Lithium-ion batteries can be charged and discharged many times over their life. The fundamental element of a lithium-ion battery system is the lithium-ion cell, as shown in Figure 3. It is within the cell that the electrochemical reaction takes place to absorb energy when charging and releases stored energy when discharging. A lithium-ion cell consists of a negative electrode (called the anode) and a positive electrode (called the cathode), a conducting electrolyte, leads/terminals (external connection), pressure relief capability and a variety of ancillary components in an enclosure. The cell enclosure can be of different forms (cylindrical, pouch, etc.) to suit the application.



© Tkarcher

FIGURE 3: Lithium Ion Cell

When a lithium-ion cell is charging, lithium ions move through a separator from the positive electrode (cathode) to the negative electrode (anode). When the lithium-ion cell is discharging, this process is reversed.

In some applications, a single cell may be adequate to meet the energy and power needs of a load, while for others multiple cells may be needed to provide the necessary voltage, current or power. Consequently individual lithium-ion cells are grouped together in series and/or parallel combinations into battery modules, with ancillary devices that provide terminal arrangements, thermal (cooling or heating) monitoring, safety and control functions that make the module suitable for the intended use. See Figure 4 for an example.

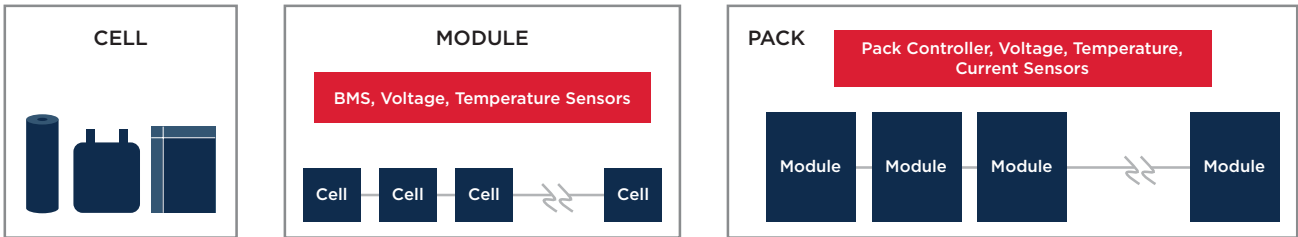


FIGURE 4: Battery Basic Figures

Modules may be further grouped together in series and/or parallel combinations to form a battery pack. The battery pack incorporates adequate housing for the battery modules and provides power terminal arrangements. The pack may also incorporate additional protective devices and circuits. Battery packs may also be grouped in series and/or parallel to form a battery system depending upon the expected loads. See Figure 5 for examples.

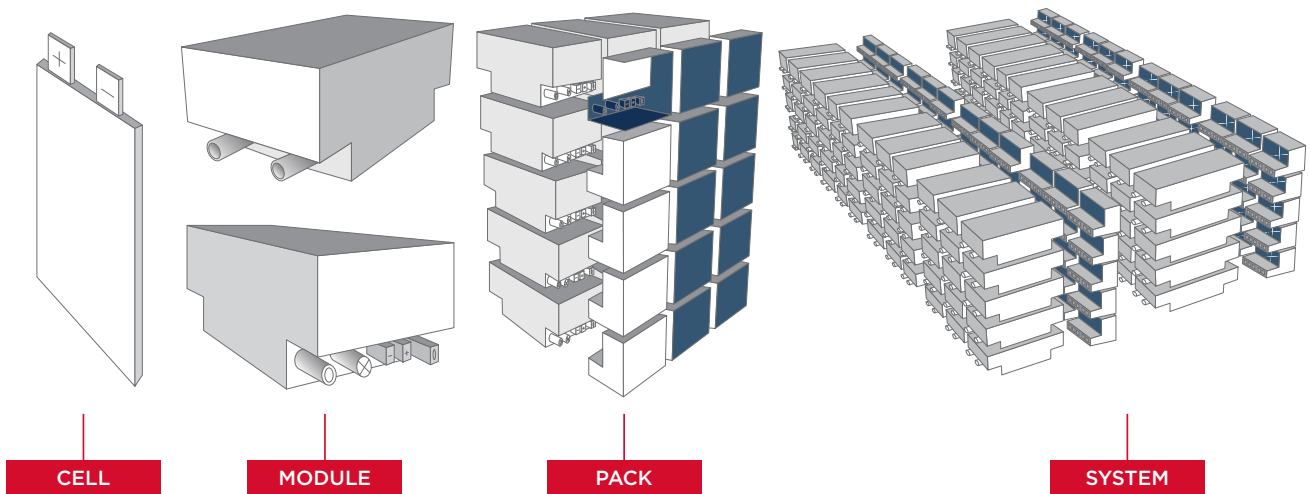


FIGURE 5: Energy Storage System

Safety assurance, risk management and operational performance of lithium ion battery systems must be designed in at the most basic level, starting from the constituent elements from which the cell is built including all the ancillary components upon which the system is constructed. See Figure 6 below for the typical layers of protection from the basic cell to the system level.

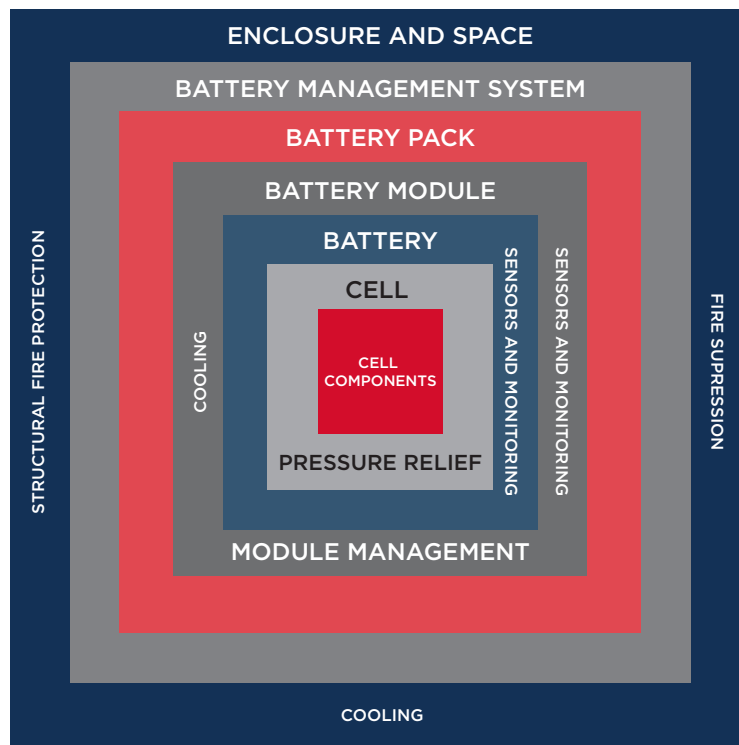


FIGURE 6: Layers of Protection

The operational performance and safety of a lithium-ion battery as a whole is accomplished by a control device commonly called the Battery Management System (BMS). A typical BMS is divided between components installed in individual battery modules and other components installed in battery packs.

The BMS can control the thermal management system to regulate the temperature of the battery modules. Control of the cell temperature maximizes the performance of energy storage/delivery, cycle and calendar life. The BMS and the thermal management system may operate at the module level, supplying liquid media or air to individual battery modules; alternately it may control the environmental temperature (the temperature within an enclosure) and/or the ambient temperature (the temperature external to an enclosure).

A battery system typically has a BMS that works with a battery charger/converter to provide operational control and monitoring as well as safety functions. Operational control includes control of charging, discharging, cell balancing, etc. Safety functions will disconnect either portions of or the entire battery system in the event of over/under temperature, voltage, current, etc. See Figure 7 below for an example.

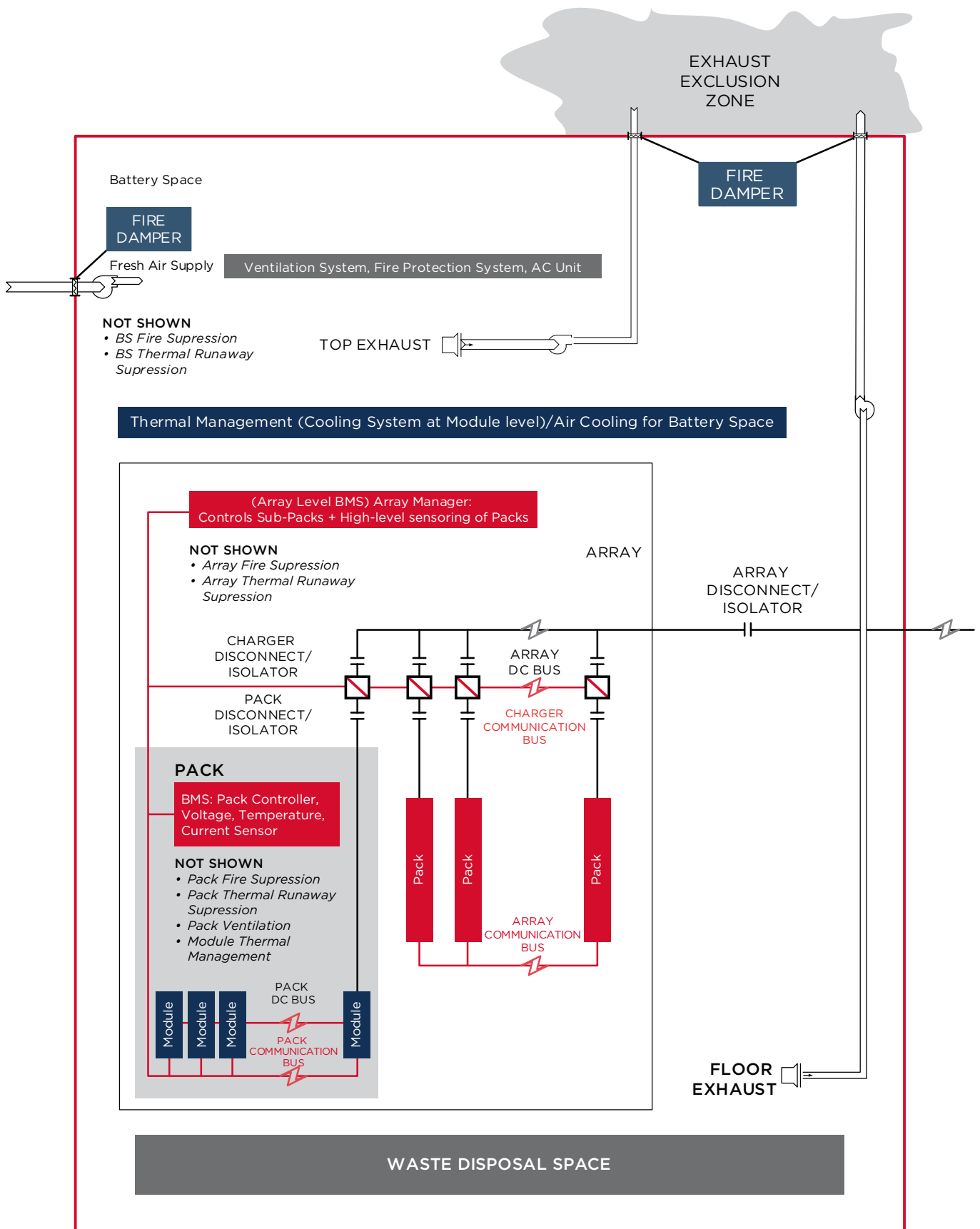


FIGURE 7: Battery System

The various chemistries of lithium-ion batteries provide different operational and safety characteristics. Selection of a specific chemistry is dependent upon the application. Some of these characteristics are:

- Energy required to be stored
- Rate of energy delivery (power)
- Duty cycle
- Operational voltage range
- Maximum current, charging time, discharging time
- Heat flux, temperature control
- Cooling needs
- Control capabilities
- Expected service life (storage/standby/cycle)

Figures 8 and 9 provide comparisons on the energy and power density of different battery chemistries in addition to other types of energy storage and generation technologies. It is apparent that lithium-ion batteries have a higher energy density on a mass basis as well as a volumetric basis than do other battery types.

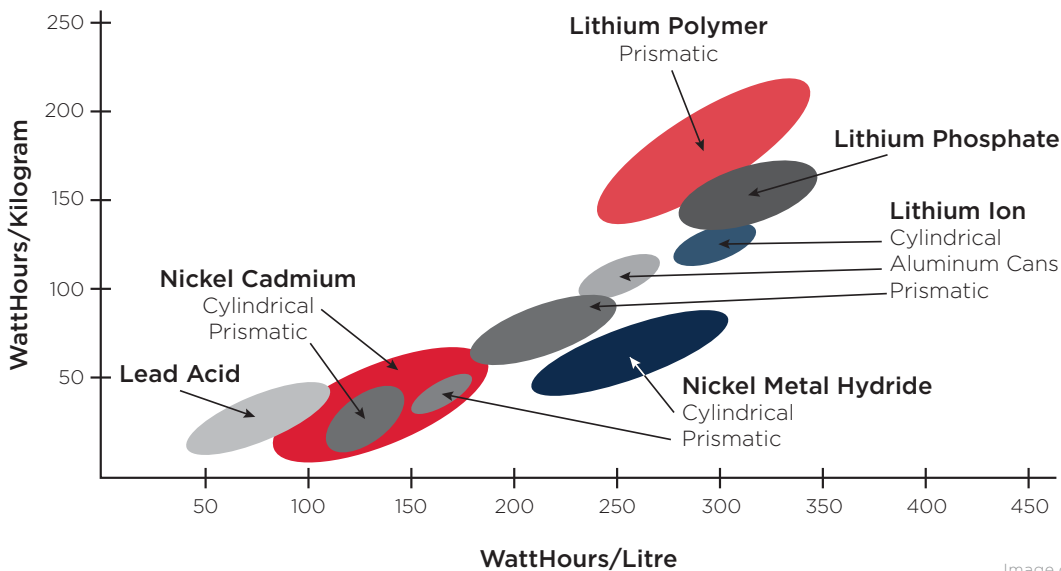


Image courtesy of Woodbank

FIGURE 8: Energy Density Comparisons

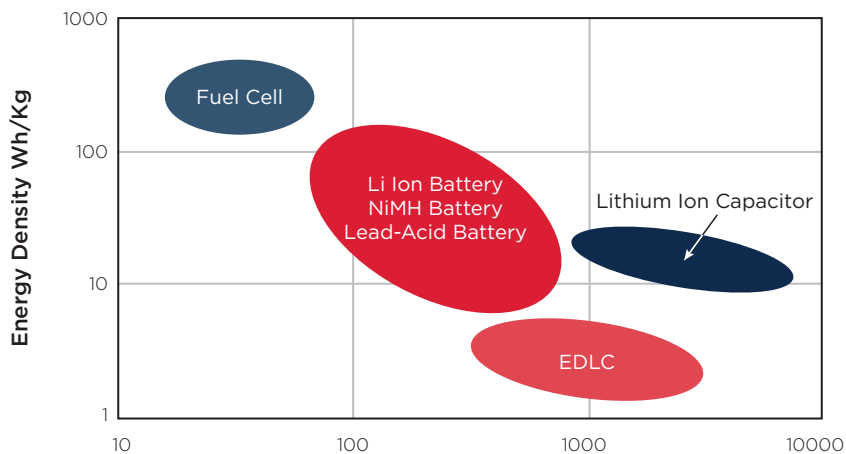


FIGURE 9: Energy vs. Power Density

The most commonly used types of lithium-ion chemistries include:

- Lithium Cobalt Oxide (LiCoO₂)
- Lithium Manganese Oxide (LiMn₂O₄)
- Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO₂ or NMC)
- Lithium Iron Phosphate (LiFePO₄)
- Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO₂)
- Lithium Titanate (Li₄Ti₅O₁₂)

The Table below provides the differences in characteristics between these lithium-ion chemistries. The relative merit of various chemistries is provided with a value from zero to four with zero representing the lowest level of performance and four representing the highest level of performance for individual characteristics.

Chemistry	Lithium Cobalt Oxide (LiCoO ₂)	Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO ₂)	Lithium Manganese Oxide (LiMnO ₄)	Lithium Iron Phosphate (LiFePO ₄)	Lithium Titanate (Li ₄ Ti ₅ O ₁₂)	Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO ₂)
Specific Energy (wh/l)	4	4	3	2	2	4
Specific Power (w/l)	2	3	3	3	3	4
Safety Low (1) -> High (4)	2	2	3	4	4	2
Performance	3	3	2	3	4	3
Life Span	2	2	2	4	4	4
Cost Low (4) -> High (1)	3	2	2	2	4	3

STATE OF THE TECHNOLOGY

The development of lithium-ion batteries for large energy applications is still relatively new, especially in the marine and offshore industry. It is an evolving technology with substantial amounts of ongoing research world-wide to further increase the energy capabilities to reduce the size and cost, and increase reliability and safety.

Even though standards such as IEC 62619, IEC 62620 and UL 1642 address requirements for lithium-ion cell construction and testing requirements for use in industrial applications, the standards guiding their use in marine and offshore applications are not yet fully mature.

ADVANTAGES

Lithium-ion batteries offer advantages over other traditional battery chemistries such as lead acid, NiCd and NiMH.

- **Specific Energy (watt-hours/kg):** Lithium-ion batteries offer a much higher specific energy and capacity compared to other traditional batteries. Their low internal resistance makes a lithium-ion battery more suitable for high power applications.

Specifications	Lithium-Ion			Lead Acid	NiCd	NiMH
	Cobalt	Manganese	Phosphate			
Specific Energy (wh/kg)	150-250	100-150	90-120	30-50	45-80	60-120

- **Light Weight:** Lithium-ion batteries are one-third of the weight of lead acid batteries, and are smaller in size than other rechargeable batteries of similar capacity. Lithium-ion batteries are practical in applications in which physical specifications such as space, weight and total energy storage are considered important.
- **Faster Charging:** The lower internal resistance of the lithium-ion chemistries when compared to that of traditional batteries allows for charging with lower losses and heat gain. This advantage can result in faster overall charging times for batteries of comparable capacity, however a variety of factors influence the ultimate result. Some lithium-ion chemistries have symmetrical charge and discharge rates while others are asymmetrical with the discharge current several times that of the allowable charge current.
- **Self-discharge:** All batteries are subject to losses in the form of self-discharge, which can be an important issue for batteries where longer term energy storage is required. The self-discharge rate for lithium-ion batteries is typically lower than that for other battery types and for other energy storage technologies.
- **Low Memory Effect:** Memory effect is a phenomenon observed in rechargeable batteries in which they lose their maximum energy capacity when repeatedly recharged after being only partially discharged. This memory effect is common in rechargeable batteries such as NiCd and NiMH. Lithium-ion batteries have little or no memory effect.
- **Low Maintenance:** Lithium-ion batteries typically require little maintenance, whereas lead acid batteries require maintenance every 3-6 months, and NiCd and NiMH batteries require a full discharge periodically so that they do not exhibit a memory effect. A process known as cell balancing is important to the deployment and efficient utilization of lithium-ion battery technologies. Although cell balancing is incorporated into the BMS and typically does not require operator intervention or supervision, it may potentially impact the availability of the battery system as cells must be off line during the rebalancing process. This loss of capacity may be an important factor depending upon the service involved.
- **Cycle Life:** The cycle life is much higher for lithium-ion batteries when compared with other traditional batteries. For lithium-ion batteries, the cycle life is impacted by the depth of discharge (DoD). A shallow DoD prolongs cycle life. The below table shows the cycle life at 80% DoD, the values may change based on the DoD.

Specifications	Lithium-Ion			Lead Acid	NiCd	NiMH
	Cobalt	Manganese	Phosphate			
Cycle Life (80% DoD)	500-1000	500-1000	1000-2000	200-300	1000	300-500

- **Cell Voltage:** Lithium-ion cells have a chemistry that results in a higher open circuit voltage than traditional cells. See the table below for a comparison.

Specifications	Lithium-Ion			Lead Acid	NiCd	NiMH
	Cobalt	Manganese	Phosphate			
Cell Voltage (nominal)	3.6V	3.7V	3.2-3.3V	2V	1.2V	1.2V

- **Flat Discharge:** Lithium-ion chemistries have a relatively flat discharge curve as shown in Figure 10, consequently they are capable of delivering constant power at a relatively constant current for a large portion of their discharge curve.

Typical Li-ion Discharge Voltage Curve

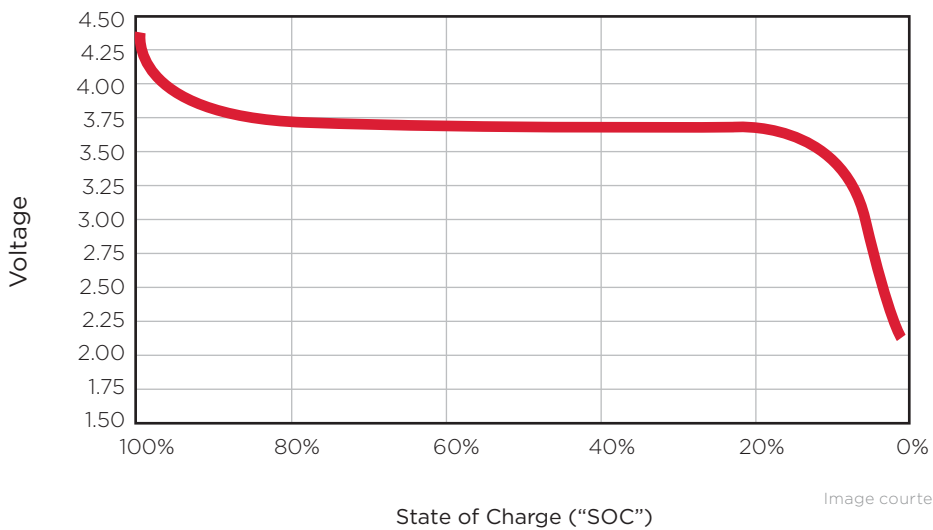


Image courtesy of Silicon Lightworks

FIGURE 10: Lithium-Ion Battery Discharge Curve

- **Toxicity:** Lithium-ion batteries when disposed of are environmentally friendly compared to traditional batteries. The toxicity limits for lithium-ion batteries are low. See the table below for a comparison.

Specifications	Lithium-ion	Lead Acid	NiCd	NiMH
Toxicity	Low	Very High	Very High	Low

CHALLENGES

While there are many advantages with lithium-ion batteries, there are also challenges.

- **Complicated monitoring and protection circuits:** Lithium-ion battery chemistries are not as stable as other rechargeable batteries. They require monitoring and protection from conditions such as over charge, over discharge, high and low cell temperatures.
- **Aging:** Like all batteries, lithium-ion batteries suffer from aging. The aging process is not only time/calendar dependent, but also on the number of charge/discharge cycles of the battery and the cell (battery) temperature. When lithium-ion batteries are stored they need to be partially charged around 40-50 % and kept in a cool storage area. The charge and the storage temperatures may vary for different lithium chemistries.
- **Temperature sensitivity:** Lithium-ion batteries must be operated in a fairly narrow temperature window. Operation outside this window can decrease battery performance, reduce cycle life, calendar and storage life. High temperatures increase the rate of self-discharge. Further, exposure to extremely high temperatures can cause a cell to go into thermal runaway.
- **Increased Cost:** Lithium-ion batteries are more expensive to manufacture than other rechargeable batteries. The initial cost of lithium-ion batteries is around 40% higher than nickel-metal hydride batteries. The monitoring and protection circuitry also makes the lithium-ion battery system more expensive compared with other traditional batteries. See the table below for a comparison of the cost of different batteries per cycle.

Specifications	Lead Acid	NiCd	NiMH	Lithium-ion	Lithium-polymers
Cost per cycle (US\$)	\$0.10	\$0.04	\$0.12	\$0.14	\$0.29

The cycle life of a lithium-ion battery is many times that of a lead acid battery and is several times

- **Transportation:** There are several restrictions and limitations for the carriage of lithium-ion batteries, especially via air travel. Proper care must be taken when carrying in bulk and they must be protected against external short circuits with protective covers on the battery terminals.
- **Thermal runaway:** Thermal runaway is considered to be the most significant disadvantage of lithium-ion batteries. Thermal runaway is an uncontrolled self-sustaining and accelerating chemical reaction that occurs at the cell level and results in the catastrophic and/or destructive failure of the cell. Damage and destruction may not be confined to a single cell but may propagate to adjacent cells and to ancillary components and equipment within the module. In certain circumstances, thermal runaway may not be contained within a battery module and will impact adjacent modules and the ambient environment. Battery chemistry and the BMS play an important role in the prevention of thermal runaway.

The build up to thermal runaway goes through several stages and each stage results in progressively more damage to the cell. Several events could lead to thermal runaway such as an external short circuit, internal short circuit, overcharging, high ambient operating temperatures, overheating from external sources, mechanical damage and a BMS failure. Therefore, special safe guards must be incorporated to protect against thermal runaway and the possibility of resulting fires.

LESSONS LEARNED

There have been maritime incidents resulting in fires on ferries and tugboats. One example is a hybrid tugboat with lithium-ion batteries installed in the engine room that caught fire. The incident was traced to the rupturing of a lithium-ion battery module, caused by numerous repeated overcharging events.

Some of the key factors which contributed to the rupture of the lithium-ion batteries were:

- A failure triggered by a series of overcharging events.
- Alarms that may have been ignored or overridden, allowing long-term overcharging of the battery.
- A software error in the controller which prevented the contactors from operating.
- A glitch that led to a series of overcharge cycles eventually causing the lithium-ion polymer cells in the battery to fail.

An abbreviated sequence of events includes:

- The battery cell overheated due to repeated overcharging.
- The battery cell pouch burst due to gas generation inside the cell.
- The pressure inside the battery module increased to the point of lifting the battery enclosure lid.
- Hot gasses released into the battery compartment.
- Ducting melted due to high temperatures from the fire and hot gasses.
- Failure of the vent ducting allowing hot gases to escape the engine room.
- The fire was eventually extinguished with release of a fixed gas firefighting system.

These lessons learned are being used to refine existing requirements and develop new ones for lithium-ion batteries which are discussed further under the ABS Role in Applications.

Applications

Applications for lithium-ion batteries include:

- When used for load levelling/peak-shaving batteries act as a buffer to supply/absorb energy allowing for generator sets to be operated at a near constant load. Use of these batteries can reduce maintenance on engines due to optimal loading and reduced engine running hours. With optimal loading, higher average load can be maintained resulting in a smoother and more stable operation of engines.
- A vessel can run an electrical motor at low speed (using batteries) in port or during transit or in zero emission areas and transition to a diesel engine or a gas turbine for medium or high speed for its voyage.
- Batteries may be used in some instances as an additional power source in case of generator shutdown.
- Using batteries as a standby power source may mean fewer generators need to be in operation.
- Batteries may be used for blackout prevention, fault ride thru and blackout recovery in some instances.
- Batteries may be used as an emergency source of power for essential and emergency services in some instances.

ABS Role:

ABS has been involved in various efforts by battery manufacturers as well as owners, designers and operators. ABS has developed internal documentation regarding the installation of lithium-ion batteries and is now in the process of finalizing a guide for publication. In the interim, ABS offers consideration of hybrid battery installation through the approach outlined in the *ABS Guidance Notes on Review and Approval of Novel Concepts* that can be found on-line at www.eagle.org with additional information provided in the 'Opportunities and Challenges for Systems Incorporating Energy Storage and/or Generation Technologies' section.

ABS has worked with different battery vendors such as Corvus Energy and Valence Technology to perform a Product Design Assessment as part of the ABS Type Approval Process (<http://ww2.eagle.org/en/what-we-offer/type-approval.html>) of specific models for marine and offshore use. Due to the nature of the technology and limited industrial experience, additional documentation will be requested from these vendors during a project-specific engineering review. ABS has also classed vessels with lithium-ion battery installations. One such example is the *Bhagwan Dryden* which is a twin screw diesel propulsion dive support vessel wherein each shaft line is fitted with an auxiliary electrical propulsion motor driven by a 65 kWh battery system. In an emergency where the diesel propulsion plant has shut down, each shaft line has the ability to be supplied for approximately 15 minutes in an all-electric mode.



FIGURE 11: ABS Classed Vessel Bhagwan Dryden with Corvus Energy Batteries

SUPERCAPACITORS

INTRODUCTION

Traditional capacitors in AC power systems have been used for power factor correction, motor starting and harmonic filtering. Capacitors have also been used for low frequency filtering in power supplies and for high frequency filtering in radio circuits.

The commercial use of capacitors for energy storage is a relatively new concept made possible by the development of the Electric Double Layer Capacitor (EDLC). The EDLC is an electrochemical capacitor and is commonly referred to as a super or ultra-capacitor. Another type of capacitor that is often associated with the supercapacitor is the lithium-ion capacitor (LIC).

Capacitors store energy in an electric field. The amount of stored charge and consequently stored energy is related to the materials selected as well as their construction and arrangement.

The charging and discharging of a battery involves a temperature dependent electrochemical reaction between the electrodes and the electrolyte. An EDLC distinguishes itself from a battery in that the charging and discharging process does not involve a chemical reaction and is largely independent of temperature. Capacitors typically do not have the same energy storage density as do batteries but are capable of delivering stored energy more quickly than batteries.

DESCRIPTION AND OPERATION

Supercapacitors/EDLC

An EDLC is constructed of two electrodes surrounded by a common electrolyte as shown in Figure 12 below. Essentially the EDLC consists of two capacitors in series separated by an ion-permeable membrane, where each of the capacitors is constructed of a polarized electrode and opposite-polarity ions in electrolyte. As is often the case, both electrodes are constructed of the same material and consequently, the EDLC is known as a symmetrical capacitor.

Lithium-Ion Capacitor

A LIC is constructed of two electrodes surrounded by a common electrolyte as shown in Figure 13 below. The LIC is a hybrid electrical energy storage device, which combines the EDLC's cathode and a lithium-ion battery's anode. The LIC keeps the EDLC's advantages in conjunction with lithium-ion battery's features, e.g. high energy density. In the case of a LIC, the two electrodes differ in material and construction. A LIC is also known as an asymmetrical capacitor.

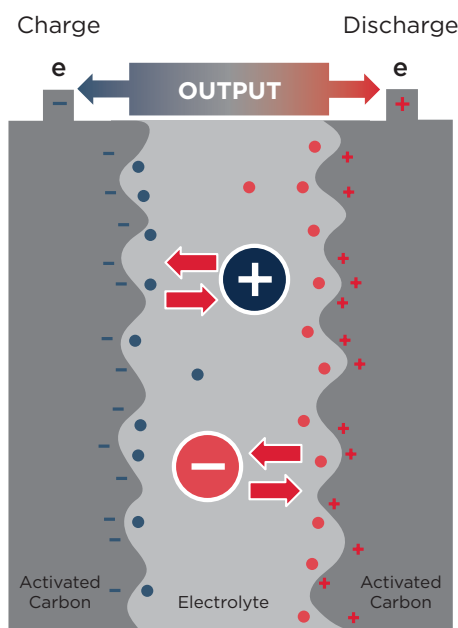


Image courtesy of JSR Micro, Inc.

FIGURE 12: EDLC Construction

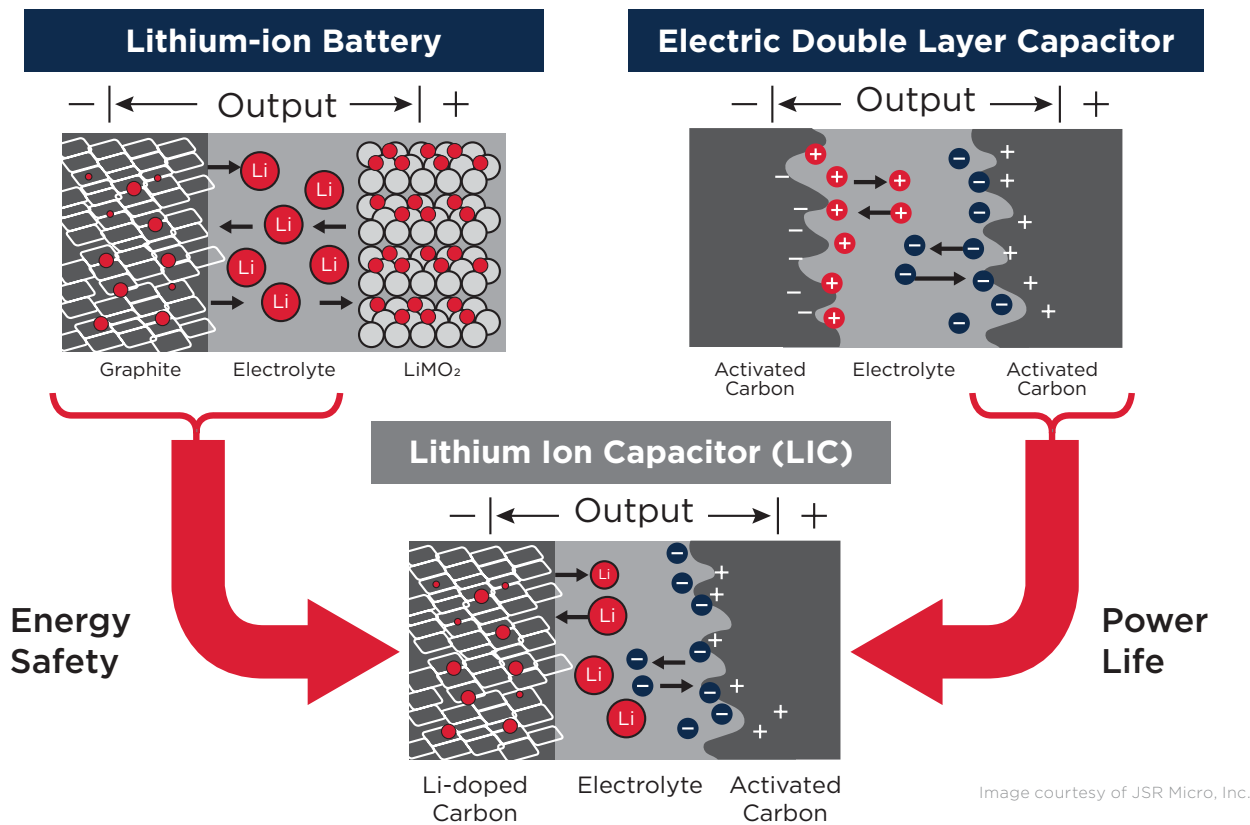


FIGURE 13: Lithium-Ion Capacitor Construction

Capacitor elements

Capacitor elements are the basic components inside of a capacitor-type energy storage system. Several capacitor elements can be connected in series and/or parallel to achieve a specified terminal voltage, terminal current and energy storage capacity. Typically, capacitor elements require the addition of ancillary devices to create a useable system.



Supercapacitor



Lithium Ion Capacitor

FIGURE 14: Capacitive Element Examples

Capacitor modules

The combination of capacitor elements and the addition of ancillary devices within an enclosure forms a functional unit known as a capacitor module. It is the capacitor module that may be safely operated when connected to a capacitor management system, a capacitor charger/converter and a load. In small installations, a module based capacitor management system may be one of the ancillary devices installed within each capacitor module.



Image courtesy of Maxwell, Inc.

Supercapacitor Module



Image courtesy of JSR Micro, Inc.

Lithium Ion Module

FIGURE 15: Capacitor Modules

Capacitor packs

Capacitor modules can be connected together to form capacitor packs/groups/banks/systems with connections in series or parallel to achieve desired terminal voltage and current characteristics.

Capacitor characteristics

Capacitive elements possess a trade-off between energy storage and voltage rating. The stored energy is directly proportional to the capacitance and the square of the applied voltage. The capacitance is directly proportional to the area of the electrodes and inversely proportional to the thickness of the dielectric. The voltage rating of the capacitor is related to the thickness of the dielectric. Keeping other parameters fixed, as the thickness of the dielectric layer decreases the capacitance increases and the voltage rating of the capacitor decreases. In power applications where there is a need for energy storage at higher voltages, individual capacitive elements can be combined in series to achieve the required terminal voltage and strings of capacitive elements can be combined in parallel to achieve the required energy storage and string current requirements.

Capacitors are often thought of as lossless circuit elements. They do however have a very small internal electrical resistance (fractional milliohms) and there is a power loss associated with this resistance and the capacitor current. This power loss manifests itself as heat which must be dissipated. The amount of internal heat generated is dependent upon the magnitude of the capacitor current and is independent of direction (charge or discharge). The continuous capacitor current derived due to charging from, or discharging to, the network is limited by the total allowable temperature range and the establishment of thermal equilibrium between the capacitor, any thermal management system (cooling system) and its surroundings.

Capacitor short circuit current is driven by the internal capacitor element voltage. The fractional milliohms of resistance allows for short circuit currents at the capacitor terminals that can be in the range of tens of kilo-amperes.

EDLC capacitors operate from 0 V to their rated voltage. At 50% rated voltage, the EDLC can store only 25% of its rated energy. LICs are not capable of operating down to 0 V. Instead, LICs have a minimum cutoff voltage similar to that of a lithium-ion battery. Operation of the LIC below this cutoff voltage will result in damage to the capacitor. The existence of the cutoff voltage of the LIC is a result of the carbon material of the anode which is pre-doped with lithium ions. The doping of the anode lowers the anode potential and results in a higher output voltage for the LIC. A typical value for the cutoff voltage of the LIC is in the range of 2.2 volts. A LIC may be operated from its rated voltage down to the cutoff voltage without damage to the capacitor.

Capacitor element and module balancing

Capacitor element and module balancing is a mechanism utilized by the capacitor manufacturer to create the ability for the capacitor element and module to have identical voltages. The capacitor elements can be arranged to support a single capacitor element, a parallel grouping of capacitor elements or a series grouping of capacitor elements.

The capacitor elements need to be balanced in order for the unit to deliver its full capacity, and is usually performed at the time of charging. Capacitor element balancing is achieved by means of a balancing circuit. One or more capacitor elements (as a result of aging differently over their lifetime) may become under-charged or overcharged, as compared to other capacitor elements within the capacitor module and/or system. Capacitor element unbalance may prevent the capacitor system from working at full capacity.

Thermal runaway

Neither an EDLC nor a LIC is subject to a thermal runaway reaction as is possible with a lithium-ion battery. Both the EDLC and LIC capacitor cathodes are constructed of a carbon material with minimal bound oxygen. During heating of the LIC cathode, oxygen is not released to initiate or sustain combustion of the LIC electrolyte even if the electrolyte is flammable and above its ignition temperature. If the electrolyte comes in contact with atmospheric oxygen or some other oxidizer, a combustion reaction can occur. However, it is not a self-sustaining uncontrolled exothermic thermal runaway reaction that can occur with a lithium-ion battery.

ADVANTAGES

- **Excellent cycle life:** Capacitors for energy storage can be cycled millions of times.
- **High specific power (in KW/MW level):** A capacitors' low internal resistance enables high discharge current.
- **Fast charging and discharging rate:** Capacitors for energy storage can be charged and discharged within a few minutes for LIC or even seconds for EDLC.
- **Easy charging without overcharge protection:** Capacitors are not subject to overcharge/over-discharge due to stabilized ion reactions and fractional milliohms of internal resistance. It is not necessary for capacitors to have an end-of-charge termination mechanism.
- **Safety:** Neither EDLC or LIC have a risk of thermal runaway because of their carbon-based cathode material with minimal bound oxygen. In addition a pressure-relief valve on each capacitor will reduce the internal pressure due to internal short circuit.
- **Outstanding low-temperature charge and discharge performance:** The operating temperature range of an EDLC is from -40°C to 65°C . The operating temperature range of an LIC is from -20°C to 70°C .
- **Reduced load variations:** When capacitors are used as an energy buffer they can reduce load variations due to sudden external disturbances.
- **Improved system stability:** When capacitors are used as an energy buffer it increases the average loading with fewer running generators.
- **More fuel-efficient operations:** When capacitors are used as an energy buffer it allows for more fuel-efficient operation of available generators resulting in lower fuel consumption and maintenance.

CHALLENGES

- **Low energy density:** Supercapacitors have a lower energy density of approximately 5wh/kg compared to lithium-ion batteries.
- **High self-discharge rate:** Supercapacitors have a higher self-discharge rate than lithium-ion batteries. Self-Discharge is a phenomenon whereby the open circuit voltage on the terminal of a charged capacitor/battery drops after a set period of time without being connected to any load. Self-discharge can lead to a capacitor having less than full charge when connected to a network.
- **Low voltage per capacitor:** Capacitors have a low voltage per basic element (typically 2.7V for EDLC) which requires multiple capacitors to be connected in series in order to meet the system voltage requirement (e.g. a typical crane operation needs about 900V).
- **Limitation to use full stored energy:** The linear discharge voltage of supercapacitors prevents using the full stored energy.

APPLICATIONS

Supercapacitors and LICs are suitable for applications where there is a need to quickly deliver energy to a load. Applications such as these are often referred to as pulsed power applications. Similar to pulsed power applications are applications where there is a need for rapid and repeated bi-directional exchange of energy between an electrical network and a load. In pulsed power applications capacitors are charged as quickly as possible, limited only by the capabilities of the electrical network and can quickly deliver the stored energy in a high power pulse. Charging times could be seconds or minutes while discharge times could be micro or Nano seconds.

In bidirectional energy exchange applications, capacitors may be initially charged to some fraction of their energy storage capacity and then float on the electrical network, delivering stored energy when needed and absorbing excess or regenerative energy when available. Another application of capacitors is the delivery of stored energy to an electrical network when normal sources of power are not available. Although capacitors do not store as much energy as do batteries, they may be capable of delivering enough energy between an electrical network and a load to allow it to ride through a temporary interruption of normal electrical power until such time as another source of electrical power may come on line to assume the load.

Although the technology associated with supercapacitors and LICs is still maturing, they are presently considered a viable energy storage solution that may be confidently deployed in the right application.

Currently, supercapacitors and LICs are a leading energy storage choice in applications where a fast rate of charge or discharge is required or where the required cycle life is high. Supercapacitors and LICs have excellent performance capabilities allowing for management of peak power and average power demands of power grids or acting as backups for primary energy supplies such as diesel generators, gas turbine generators or fuel cells.

Supercapacitors or LICs can also be installed with batteries as a combination which can protect the batteries from extreme peak loads, extending battery life and taking advantage of the batteries' higher energy storage capacity. The following are two examples of supercapacitors utilized in offshore applications.

Heavy-Lifting Equipment

In the offshore and subsea industry heavy-lifting capability affects all project phases including design, installation, commissioning, maintenance and decommissioning. Heavy-lifting equipment includes cranes and winches on marine and offshore installations. The power supply for the heavy-lifting equipment plays a vital role in realizing its functionalities. Supercapacitors used in heavy-lifting equipment can improve energy efficiency during peak loading demands and can capture and reuse the energy when the load is lowered through regeneration systems.



FIGURE 16: Examples of Heavy Lifting Equipment

Renewable Energy Storage

The sporadic nature of renewable energy like solar and wind can be offset by the use of supercapacitors during periods of low load power where they can absorb excess energy; functioning as an energy reservoir to smooth the integration of intermittent renewable energy sources into the electrical network.



FIGURE 17: Wind Farm

Future Potential for Marine and Offshore Applications

With the supercapacitors' characteristics of a nearly unlimited cycle life, immunity to thermal runaway, symmetrical and rapid charging/discharging rates their use is likely to increase on vessels that experience rapid changes in electrical load such as on vessels with dynamic positioning systems, cranes, active heave compensation, drilling, mining and cargo pumping.

FLYWHEEL ENERGY STORAGE

INTRODUCTION

Flywheels have been used to store energy for many years. The use of flywheel energy storage was boosted in the 1960s and 1970s when NASA sponsored programs that proposed energy storage flywheels as possible sources of power for space missions. In the 1980s, trends like miniaturization of power electronics, use of magnetic bearing systems and high power density motor-generators led to the increased consideration of flywheel energy storage.

A basic Flywheel Energy Storage System (FESS) consists of a rotating assembly that consists of an energy storage unit (the flywheel) and a mechanical/magneto-electric energy converter. Energy is stored in the rotating assembly as rotational kinetic energy; the stored energy is proportional to the mass moment of inertia and the square of the angular velocity of the rotating assembly. Energy is added to the FESS by accelerating the rotating assembly and removed by decelerating the FESS. High speed flywheels where windage losses would be significant are typically mounted inside of a vacuum enclosure.

Flywheel energy storage systems offer the ability to optimize both energy storage capabilities and energy rate (power) capabilities independently of each other. The rotating assembly is readily designed to store the required amount of energy and the mechanical/magnetic converter is independently sized to deliver the power required.

Over the years, different industrial flywheel manufacturers have deployed units which have demonstrated flywheel energy storage systems as a viable energy storage option technically suited for reliable and cost-effective use in various applications. Proven power quality compensation applications

range from low-power telecommunications equipment support (low kW, for hours) to high-power industrial equipment support (hundreds of kW, for seconds). Although both of these applications are possible in the marine and offshore environment, it is the second application where instantaneous high power is required that flywheels are of great interest.

DESCRIPTION AND OPERATION

A basic block diagram of a FESS is as shown and described below:

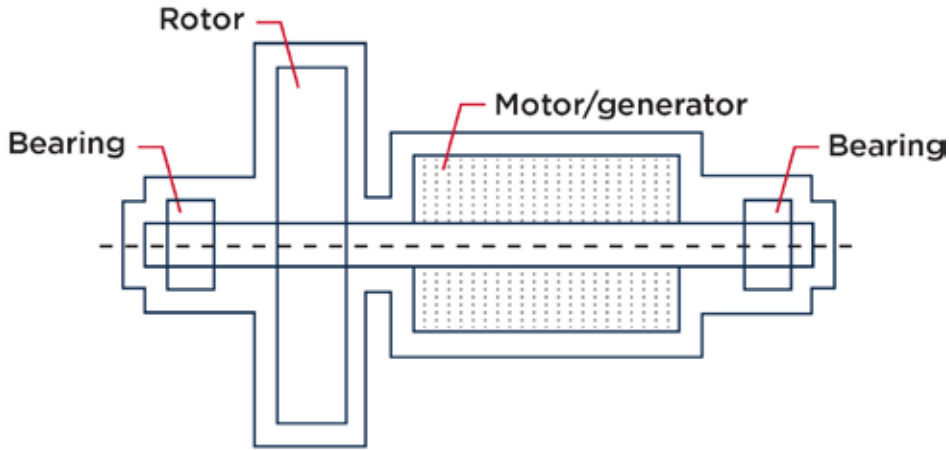


FIGURE 18: Block Diagram of FESS

The rotor is connected to a motor/generator unit, which in turn is connected to a power distribution system through a power converter. The flywheel is charged by extracting electrical energy from the grid and powering the motor/generator unit in the motor mode. By increasing the speed of the rotor, additional kinetic energy is added to the flywheel. When the energy stored in the flywheel is needed, the motor/generator unit is switched to the generator mode and is driven by the inertia of the flywheel. The speed of the flywheel gradually slows as the kinetic energy in the flywheel is consumed driving the generator.

The amount of energy that can be stored in a FESS is primarily dependent upon the mass of the flywheel and its rotational speed. The stresses in the assembly increase dramatically as the rotational speed increases, and the peak energy storage for a given flywheel is limited by the maximum allowable stress in the material from which the flywheel assembly is constructed.

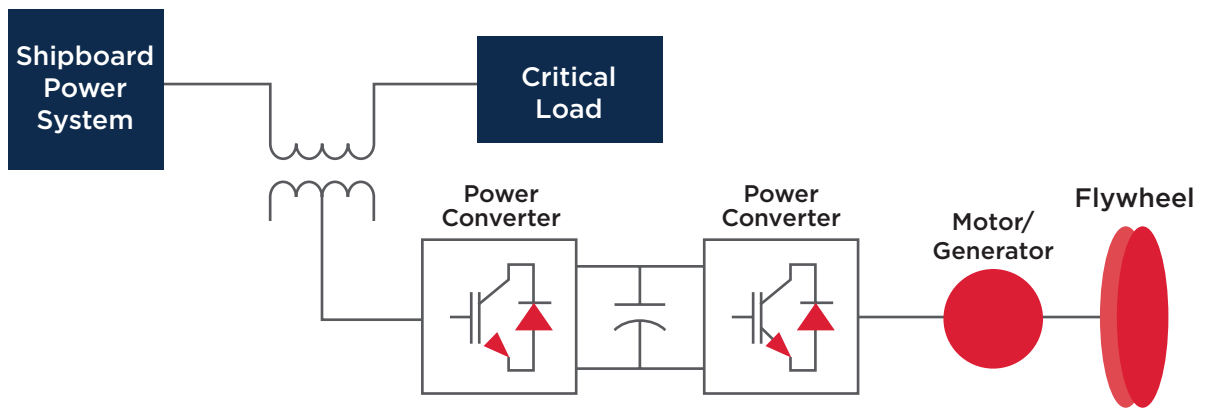


FIGURE 19: Basic Circuit of a FESS

Flywheel technologies can be broadly divided into two classes: low-speed flywheels (less than 10,000 rpm) and high-speed flywheels (more than 10,000 rpm). Low-speed flywheels often use steel rotors with conventional bearings and they can achieve energy densities of 5-30 Wh/kg. High-speed flywheels use composite rotors with low friction bearings (e.g. magnetic or foil bearings). Composite rotors are lighter and much stronger than steel, so they can be used with extremely high rotational speeds and achieve a high energy density up to or in excess of 100 Wh/kg. The amount of energy stored in a flywheel is directly proportional to the mass moment of inertia and the square of the rotational speed, making high-speed flywheels desirable for energy/mass ratio optimization. Shown below is the pictorial representation of a typical flywheel.

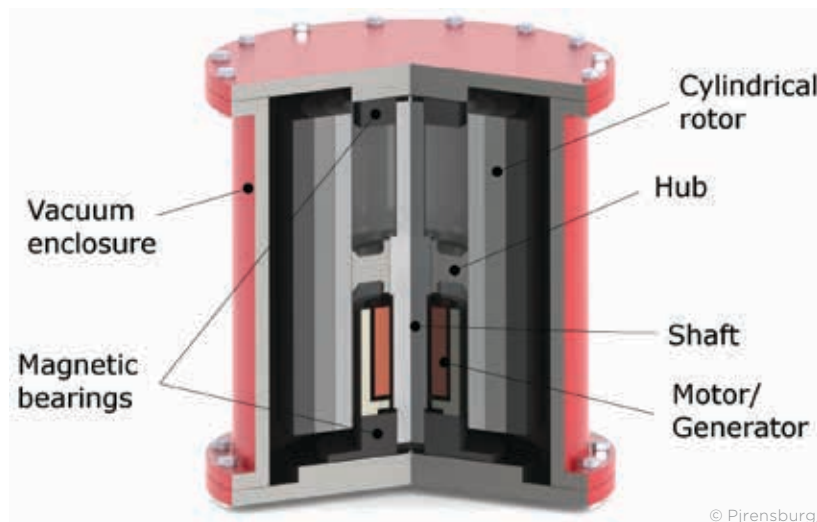


FIGURE 20: Cross-Section of a Typical Flywheel Enclosure

STATE OF THE TECHNOLOGY

FESS technology has been used successfully for applications in the space industry and on land. However, in the marine and offshore industry, it is still considered an emerging technology as the viability of its operation in the dynamic environment of marine and offshore installations is yet to be validated.

ADVANTAGES

Some of the main advantages of using a FESS are:

- **Long design life:** A FESS can have a much longer design life (~ 20 years) that exceeds the life of electro-chemical energy storage systems such as batteries and when combined with the higher cyclic life can result in a reduced life-cycle cost.
- **Modular architecture:** Flywheels can be scaled and configured accordingly to meet different power or stored energy requirements.
- **High cyclic life:** A FESS is capable of hundreds of thousands of cycles, and performance does not degrade due to depth, rate or frequency of charge/discharge cycles.
- **Temperature tolerant:** Unlike batteries whose performance degrades at temperature extremes, flywheels exhibit no change in capacity based on environmental conditions.
- **Increased system availability:** Since flywheels are capable of charging at a rate equal to or greater than their discharge rate, they are comparatively more available than sources such as batteries.
- **Increased predictability:** Since the state of charge of a flywheel is known precisely at all times as a function of speed (rpm), flywheels are more predictable than batteries.
- **Environmentally friendly:** Compared to batteries, there are no additional costs associated with hazardous chemical transport, installation and disposal.

CHALLENGES

Some of the major challenges associated with implementation of FESS on board ships and offshore units are as follows:

- **Design issues related to a dynamic shipboard environment:** The shipboard environment poses some additional design challenges to a FESS installation such as pitch and roll rates which may require the flywheel to be mounted in a specific manner. The bearing assembly must be sized accordingly to accommodate the forces resulting from the expected rotational and translational motions of the marine environment.
- **High self-discharge rates:** A FESS can suffer from high self-discharge rates. These high discharge rates arise from frictional losses that can amount to as much as 100% of the energy stored per day. This is less of a problem in modern flywheels using magnetic bearings, where the losses due to friction and windage are very minimal.
- **Challenging economics:** Flywheels often require the use of advanced materials (such as composites) to achieve the high rotational speeds and energy density. This use of advanced materials, combined with limited mass production, may make flywheels economically unviable.

APPLICATIONS

Flywheel energy storage for stationary applications

There are examples of flywheel energy storage use on land, most notably for power grid frequency regulation purposes. One such example is that of a 5 MWh (20MW over 15 minutes) flywheel energy storage farm in Stephentown, NY that is connected to the New York ISO power grid.

Flywheel energy storage for mobile applications

Another commercial application of FESS is for load leveling and energy recovery for diesel electric locomotives. An accelerating diesel electric locomotive requires great power; however emissions controls on locomotive engines designed to reduce particulate and other emissions tend to reduce the overall power rating. A flywheel energy storage system is capable of delivering energy to the locomotive traction motors during the acceleration period, reducing the load on the diesel. At running speed when the diesel is not fully loaded the flywheels may be recharged. In addition, when braking, regeneration is possible further charging the flywheel system with energy that otherwise would be lost as heat in a resistor braking system or in a rail friction braking system. One such FESS was developed by University of Texas at Austin to store 130KWh of energy at a peak design of 15,000 rpm for use on high speed passenger trains.

Installations of flywheel energy storage on marine/offshore units

There is no known commercial marine vessel or offshore unit currently with an installed flywheel energy storage system. The US Navy has studied different methods, including FESS to maximize the survivability of its combat ships. In 2009, the company Beacon Power Corporation received funding for a contract from the US Naval Sea Systems Command (NAVSEA) to evaluate the use of flywheel-based energy storage technology for multiple shipboard applications, but there is no public information available as to the final results of this study.

There has also been interest shown by international Navies in exploring how FESS technology can be used to store energy and deliver it at the required rate for high-energy weapons. The British military is evaluating the use of flywheel energy storage to power a laser weapon system that is planned to be deployed on a naval vessel by 2020. This new laser weapon system is expected to have a much lower cost-per-shot when compared to conventional ammunition.

Potential future applications

A promising potential future application of FESS is in the heave compensation systems on drilling units. One such effort is being undertaken by Maersk Drilling in association with its partners. The FESS technology, which will be used for load leveling, is expected to help stabilize the power system by reducing the heavy power fluctuations that occur during drilling operations when the draw-works and the associated electric winches raise and lower the risers, blow out preventer and drill pipes in and out of the well. By performing load leveling, the average load on the generator prime-movers can potentially be increased, thus contributing to energy savings.

ENERGY GENERATION TECHNOLOGIES

With the increased regulatory and commercial interest in emissions reduction and energy efficiency, energy generation technologies such as fuel cells, solar and wind have continued to gain attention in the marine and offshore industries. The following sections provide a more in-depth look at fuel cells, solar and wind power energy generation technologies providing the industry with information needed to determine what solutions exist and which may be best for their application.

FUEL CELLS

INTRODUCTION

A fuel cell is an electrochemical device that continuously converts chemical energy from a fuel (hydrogen, methane, etc.) into electricity and water through an electrochemical reaction with oxygen. The main distinction among fuel cell types is the electrolyte, and thus they are classified by such.

Fuel cells can be traced back to the 1830s. Sir William Robert Grove is credited with developing the first fuel cell (referred to as a gas voltaic battery). The first significant use of fuel cells came during the NASA space program in the 1960s. Development and refinement of fuel cell technology continues to this day.

Fuel cells have a variety of applications such as a means of electrical power in remote areas as well as for industrial, residential and commercial buildings. Fuel cells can be used to power vehicles, vessels and submarines.

DESCRIPTION AND OPERATION

As depicted in the figure below, a fuel cell consists of a negative electrode (anode) and a positive electrode (cathode), an electrolyte, a fuel and oxygen (air) system, electrical terminals and ancillary devices. A fuel such as hydrogen is fed to the anode and air is fed to the cathode. A catalyst at the anode separates hydrogen molecules into protons and electrons, which take different paths to the cathode. The electrons go through an external electric circuit to power a load. The protons journey through the electrolyte to the cathode, where they unite with oxygen (from the air) and electrons to produce heat and water.

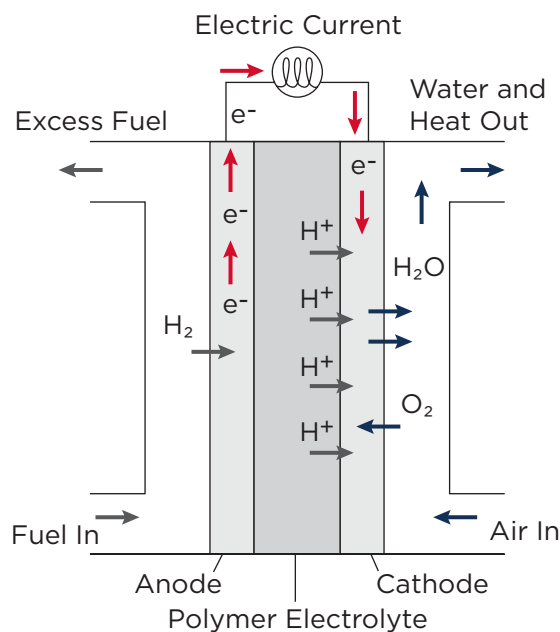


Image Courtesy of Woodbank

FIGURE 21: Typical PEM Fuel Cell

Fuel Cell Types

The main difference among fuel cell types is the electrolyte. Therefore, fuel cells are generally classified by the type of electrolyte utilized. Some of the key types of fuel cells available today include Proton Exchange Membrane, Alkaline, Phosphoric Acid, Molten Carbonate and Solid Oxide fuel cells.

Proton Exchange Membrane (PEM) Fuel Cells

PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum or platinum alloy catalyst. They need only hydrogen, oxygen from the air, and water to operate. They are typically fueled with pure hydrogen supplied from storage tanks or reformers (a device that extracts pure hydrogen from hydrocarbon or alcohol fuels). PEM fuel cells operate at relatively low temperatures, typically less than 120°C (248°F) and typically use a noble-metal catalyst (platinum) to separate the hydrogens electrons and protons.

Alkaline fuel cell (AFC)

AFCs use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. AFCs operate at temperatures between 100°C and 250°C (211°F and 482°F). The fuel supplied to an AFC must be pure hydrogen as carbon dioxide (CO₂) can negatively affect an AFC reducing fuel cell performance.

Phosphoric acid fuel cell (PAFC)

PAFCs use liquid phosphoric acid as an electrolyte which is contained in a teflon-bonded silicon carbide matrix and porous carbon electrodes containing a platinum catalyst. PAFCs operate at temperatures between 150°C and 220°C (302°F and 428°F). PAFCs are more tolerant of impurities in fossil fuels that have been reformed into hydrogen than other fuel cell types.

Molten carbonate fuel cell (MCFC)

MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix; non-precious metals can be used as catalysts at the anode and cathode. An MCFC operates at 600°C to 700°C (1112°F and 1292°F). MCFCs do not require an external reformer to convert fuels such as natural gas and biogas to hydrogen. At the high temperatures at which MCFCs operate, methane and other light hydrocarbons in these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming.

Solid oxide fuel cell (SOFC)

SOFCs use a hard, non-porous ceramic compound as the electrolyte. SOFCs operate at 650°C to 1000°C (1202°F to 1,830°F). High-temperature operations remove the need for a precious-metal catalyst such as platinum. SOFCs reform fuels internally, which enables the use of a variety of fuels such as natural gas, biogas, and gases made from coal.

STATE OF THE TECHNOLOGY

Hydrogen fuel cells have been successfully deployed for naval submarine service. German Type 212 Class submarines have a liquid hydrogen and/or oxygen fuel cell system. At least ten of these submarines have been completed.

From an electrical perspective, the use of a fuel cell is sufficiently advanced to be readily deployed; power electronic converters are readily available to connect the fuel cell to both AC or DC electrical networks and are able to be programmed to provide required voltage and frequency regulation as well as load sharing. Power generation by fuel cells range from kilowatt to multiple megawatts in output. Fuel cells can also be integrated to provide higher power outputs. ABS participated in a recent study by Sandia National Laboratories on the use of fuel cells in ferries. The specified power output was nearly 5 MW by using 40 plus fuel cell racks.

There are no established maritime regulations currently providing prescriptive requirements for fuel cell installations. Safety issues such as hydrogen, methane and some other gaseous fuels being lighter than air while propane being heavier than air need special ventilation arrangements to prevent the formation of hazardous areas. For many fuel cells, the non-hydrogen supply is externally reformed to

hydrogen and other byproducts prior to introduction into the fuel cell. The hydrogen portion of the fuel system from the reformer to the fuel cell therefore needs special consideration. An additional challenge, is understanding the requirement for intake and exhaust for fuel cells including required airflow and allowable backpressure.

Reviews of fuel cell installations for marine and offshore installation are primarily a risk-based study in combination with IMO regulations, IACS requirements, relevant industrial standards and existing Rules or Guides based on the particular design and configuration of the fuel cell system. The International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels known as the IGF Code is currently being revised to address requirements for fuel cell systems.

ADVANTAGES

- **Energy Efficient:** Fuel cells generate electrical energy through an electrochemical process. They do not burn the fuel and are more efficient than combustion systems. Also, waste heat is generated by the fuel cells and can be captured for Combined Heat and Power (CHP) known as cogeneration which can reduce energy costs up to 40%. Using this waste heat can bring the system efficiency up to 85% compared with other types of electrical generating devices. Please see the table below for a comparison of the energy efficiency of various electrical generating devices.

Electrical Generating Device	Conversion Type	Energy Efficiency
Gas turbine	Chemical to electrical	Up to 40% (primary)
Gas turbine plus steam turbine (combined cycle)	Chemical/thermal to electrical	Up to 60% (combined)
Wind turbine	Kinetic to electrical	Up to 59% (primary, theoretical limit)
Solar cell	Radiative to electrical	6-40% (primary, technology-dependent, 15-20% most often, 85-90% theoretical limit)
Fuel cell	Chemical to electrical	40-60% (primary), up to 85% (combined (CHP))

- **Low to Zero Emissions:** When fuel cells use pure hydrogen as a fuel, the system can operate with zero emissions with the only by-products being heat and water. When run on hydrogen-rich reformat gas mixtures, harmful emissions can result. These harmful emissions can be less than those emitted by an internal combustion engine.
- **Refueling vs Recharging:** Fuel cell systems do not require recharging like a battery would. However, fuel cell systems must be refueled, which can be faster than charging a battery installation and can provide a greater range of operation depending on the size of storage for the fuel.
- **Reduced Noise:** Fuel cells do not rely on combustion, have few if any moving parts and run quiet at around 60 decibels, making them less obtrusive wherever they are located.

Specific fuel cell type advantages:

PEM Fuel Cell Advantages:

- Smaller footprint - low weight and volume compared with other fuel cell types.
- Low temperature - at typically less than 120°C (248°F).
- Quick start up time - (seconds) with less wear on system components, resulting in better durability.

AFC Advantages:

- Material cost - wider range of stable materials allow lower cost components.
- Low temperature - between 100°C and 250°C (211°F and 482°F).
- Quick start up time - (seconds) with less wear on system components, resulting in better durability.

PAFC Advantages:

- Tolerant - to fuel impurities.
- Low temperature - between 150°C and 220°C (302°F and 428°F).

MCFC Advantages:

- Reduced cost - non-precious metals can be used as catalysts at the anode and cathode.
- Reduced cost - MCFCs do not require an external reformer to convert fuels such as natural gas and biogas to hydrogen.

SOFC Advantages:

- Reduced cost - non-precious metals can be used as catalysts.
- Reduced cost - SOFCs do not require an external reformer to convert fuels to hydrogen.
- Fuel flexibility - SOFCs can use natural gas, biogas and gases made from coal.

CHALLENGES

The following identifies some of the common challenges for all fuel cell types:

- **Increased cost:** Fuel cells are usually hand assembled one at a time which contributes to the increased cost in addition to expensive catalysts such as platinum. Fuel cells can be up to ten times more expensive than internal combustion engines. However, fuel cells that are designed to be mass produced on automated equipment for a lower cost are becoming available in addition to the use of less expensive catalysts.
- **Increased weight:** The combined weight of the fuel cells, support systems and fuel storage is presently greater than that of a comparable combustion engine system. However, fuel cell systems are generally lighter than comparable battery systems.
- **Increased complexity:** Fuel cells require complex support and control systems. Support systems can consist of vaporizers, reformers, fuel purifiers, pumps, heat exchangers and power conversion equipment. Unfamiliarity with non-traditional fuels combined with concerns about safety, volatility and hazardous area zones increase the complexity. Adding additional complexity, fuel cells have a relatively slow dynamic response. This may require energy storage integration to provide for large dynamic load changes.
- **Hydrogen manufacturing and storage:** Current manufacturing processes are expensive and energy intensive for hydrogen fuel and will likely be developed with the use of fossil fuels. Gaseous hydrogen storage systems can be large and heavy to accommodate based on the low volumetric energy density of hydrogen. Liquid hydrogen storage systems are smaller and lighter compared to gaseous hydrogen and must operate at cryogenic temperatures (approximately -150°C or lower).
- **Bunkering availability:** Bunkering stations (refueling) for fuel types such as gaseous and liquid hydrogen are currently limited and such fuels often need to be transported onsite.

Specific fuel cell type challenges:

PEM Fuel Cell Challenges:

- Increased cost - PEMs typically require a noble-metal catalyst (such as platinum) to separate the hydrogen's electrons and protons.
- Fuel purity - the platinum catalyst is sensitive to carbon monoxide poisoning which can reduce efficiency and power output. This requires a reactor to reduce carbon monoxide in the fuel gas if the hydrogen is derived from a hydrocarbon fuel.

AFC Challenges:

- Fuel and air purity - AFCs are susceptible to poisoning by carbon dioxide (CO₂). A small amount of CO₂ in the air and or fuel can affect fuel cell performance and durability due to carbonate formation resulting in reduced efficiency and power output for these fuel cells.

PAFC Challenges:

- Increased cost - PAFCs require the use of more platinum catalysts than other types of fuel cells do.
- Increased weight - PAFCs are less powerful than other fuel cells, given the same weight and volume, causing these fuel cells to be large and heavy.
- Start-up time - increased start-up times in minutes as opposed to seconds for other types of fuel cells.

MCFC Challenges:

- Durability - the high temperatures at which MCFCs operate and the corrosive electrolyte used accelerate component breakdown which decrease the lifespan.
- Start-up time - increased start-up times in minutes as opposed to seconds for other types of fuel cells.
- High temperatures - MCFCs operate at 600°C to 700°C (1112°F and 1292°F).

SOFC Challenges:

- Durability - the high temperatures at which SOFCs operate can accelerate component breakdown decreasing the life.
- Start-up time - increased start-up times in minutes as opposed to seconds for other types of fuel cells.
- High temperatures - SOFCs operate at 650°C to 1000°C (1202°F to 1,830°F).

APPLICATIONS

Fuel cell systems in the maritime realm have been primarily installed or considered for installation on military submarines, commercial ferries, offshore support vessels and yachts, although there is interest in developing the use of fuel cells for other applications.

ABS Role

ABS has been involved with fuel cell projects including an effort to develop a prototype hydrogen fuel cell unit to power onboard refrigerated containers. This fuel cell unit fits into a standard twenty foot container to replace diesel generators which power refrigerated containers both in port and while being transported by barges.



FIGURE 22: Hydrogen Fuel Cell Container

ABS is also involved with the San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE) concept project which aims to study the feasibility of designing a high-speed passenger ferry powered by hydrogen fueled PEM fuel cells for operation in the San Francisco Bay area.



FIGURE 23: SF BREEZE Concept

Future Growth

As the requirements for emission reductions and increased energy efficiency become more stringent driven in large part by MARPOL 73/78 Annex VI, a move towards the use of fuel cells with zero or reduced emissions is one possible solution. The use of fuel cells is expected to grow on smaller vessels such as ferries and as costs continue to be reduced for fuel cells and quality, reliability, efficiencies and power output improves, a move towards larger vessels.

It is expected where fuels other than hydrogen are used, the fuel will be converted to hydrogen within the fuel cell itself or external to it by reforming. Fuels such as LNG and methanol are expected to be primarily used with future consideration towards pure hydrogen to remove all possible emissions as new methods are found that can provide a renewable sustainable source for hydrogen.

WIND AND SOLAR POWER

INTRODUCTION

The use of what is now referred to as renewable energy has a long tradition in the marine industry, sails were the predominant form of ship propulsion for hundreds of years being eclipsed in the late 19th century by steam ships and eventually motor ships. In our time, with interest in a traditional source of renewable energy, wind has re-emerged for propulsion. In addition solar technologies are being seriously looked at as sources for electrical energy.

Wind energy may be utilized directly for propulsion with both traditional cloth and flexible sails as well as with more modern rigid sails, Figure 24 shows such an example.



Image courtesy of Bluebird

FIGURE 24: Wind Energy via Sails

Wind energy has also been utilized for production of electrical energy utilizing wind turbines as shown for the Hornblower Hybrid in Figure 25. The Hornblower Hybrid with vertical wind turbine generators was built by Alcatraz Cruises in 2008. It uses a combination of solar, wind and diesel power to operate.



© Dale Frost

FIGURE 25: Wind Energy via Turbines

Solar photovoltaic energy systems have been utilized to capture solar energy for direct conversion to electrical energy on ships like the M/V Emerald Ace, which is a car carrier.

DESCRIPTION AND OPERATION

Photovoltaic (PV) cells typically consist of one or two layers of a semi conducting material, usually silicon. When light is projected on the cell, an electric field is created across the layers that produces a measurable DC voltage at the solar panel terminals. The greater the intensity of the light, the greater the DC voltage that is available. PV cells are often referred to in terms of the amount of energy they convert in full sunlight conditions, this is known as kilowatt peak or kWp.

The solar cell is the basic building block of Solar PV technology. Cells are wired together to form a module (PV Solar Panel). PV Modules can be joined together to form a PV Solar Panel system. See Figure 26. A power electronic converter is often interposed between the solar panel and the load to stabilize the voltage delivered from the PV Modules to the load. In some cases the power electronic converter will perform a DC/DC conversion, in other cases the power electronic converter will be an inverter, a specialized converter that can convert this DC power into alternating current (AC power).

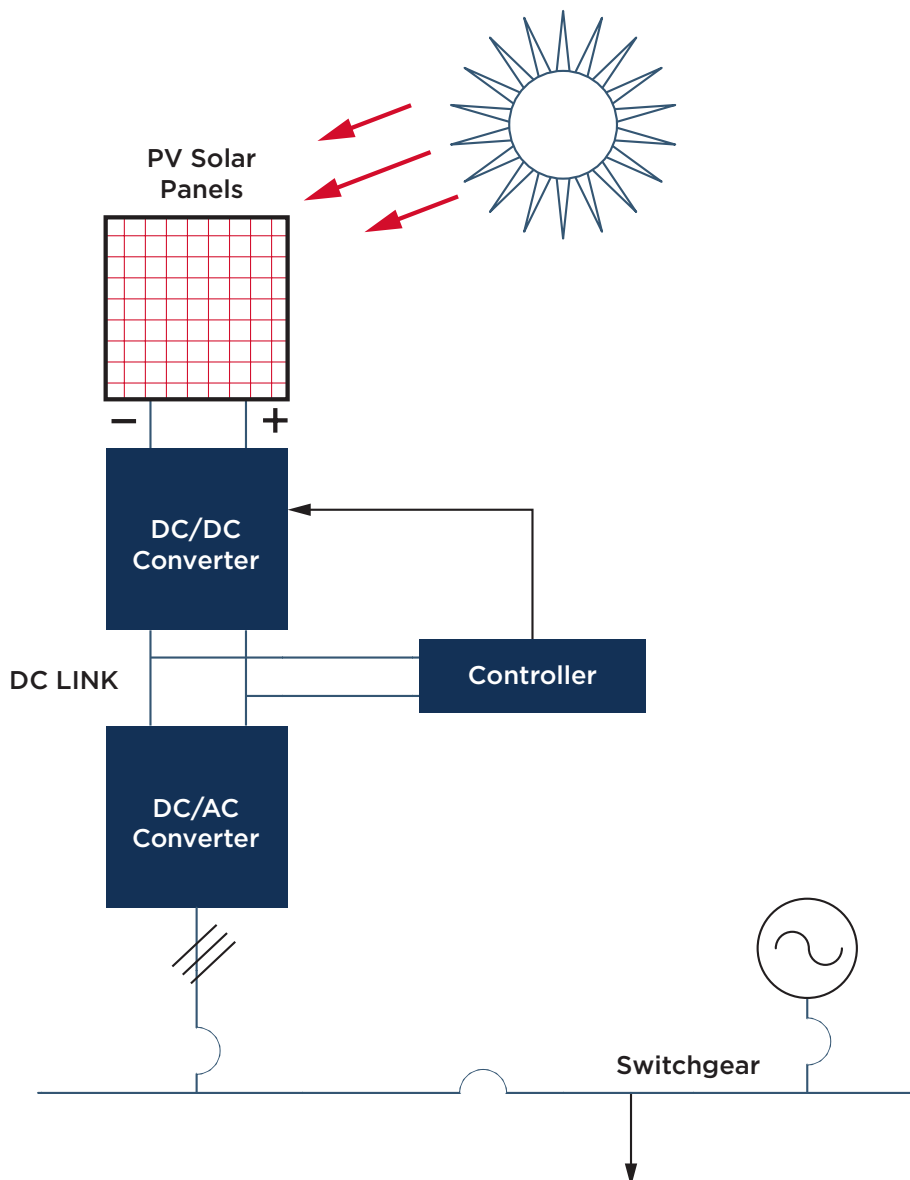


FIGURE 26: Solar Energy Operation

Types of PV Solar panels

There are several types of PV Solar panels available in today's market for land, marine and offshore applications.

Mono-crystalline solar panels

The mono-crystalline solar cells owe their name to their almost perfect single-crystal silicon structure. They are constructed according to a specific process (called the Czochralski process) in which the polysilicon starting material is melted, specially cooled to monocrystal semi-round or square bars and cut into wafers.

Polycrystalline solar panels

Unlike monocrystalline based solar panels, polycrystalline solar panels do not require the Czochralski process. Raw silicon is melted and poured into a square mold, which is then cooled and cut into perfectly square wafers. The polycrystalline cells therefore consist of crystal grids with different orientations.

String Ribbon Solar Cells

These solar cells are manufactured using a manufacturing technology named "String Ribbon" which produces a form of polycrystalline silicon. Temperature resistant wires are pulled through molten silicon, which results in very thin silicon ribbons.

Thin-Film Solar Cells (TFSC)

In contrast to crystalline solar cells, thin film solar cells have no crystalline structure. They are constructed by applying thin layers of photoactive semiconductors on low cost substrate (usually glass).

STATE OF PV TECHNOLOGY FOR MARINE APPLICATIONS

Some of the most recent PV panels developed and available in the market are those made using mono-crystalline cells, with polymers of high strength.

These PV solar panels are specified to withstand harsh conditions at sea, and they have been used in small vessels (e.g. pleasure craft) and in larger vessels such as ocean-going passenger ferries and cargo ships (e.g. M/V Auriga Leader, further examples are provided below).

VESSELS IN OPERATION WITH PV SOLAR PANELS INSTALLED

M/V Auriga Leader

A slightly less complex application involves the car carrier *M/V Auriga Leader* (Figure 27) owned by Nippon Yusen Kabushiki Kaisha (NYK Line). Completed in 2008, the 200 meter (m) vessel contains 328 solar panels. This smaller arrangement accounts for 10% of the ship's power while in port. It can also operate in all weather conditions. What makes this ship unique is that when it was originally built, the power generated by the solar panels was fed directly into the ship's electrical system. This arrangement proved to be too unpredictable and batteries were installed to provide a controlled power delivery. This system utilizes nickel hydrogen batteries.



FIGURE 27: *M/V Auriga Leader*

M/V Emerald Ace

The *M/V Emerald Ace* is a hybrid car carrier owned by Mitsui O.S.K. Lines, Ltd. Launched in 2012, the *M/V Emerald Ace* has 768 Panasonic solar panels on its main deck, for a total rated power output of 160 kilowatts (kW). The panels generate Direct Current (DC) power which is then stored in batteries or converted to Alternating Current (AC) and dispersed throughout the ship. The ship contains 52 lithium-ion battery modules/units with a total capacity of 2.2 megawatt hours (MWh). The *M/V Emerald Ace* is unique since it is able to operate without emissions while in port. It is able to completely shut off the diesel generators and operate solely off of power provided by the solar panel system. This cuts the total emissions of the vessel by 4.5%.

Motor Ship (MS) Tûranor

A novel design that has been already built and put in service in 2010 is the *Motor Ship (MS) Tûranor PlanetSolar*, which has a deck covered by 512 m² of solar panels. These panels charge six blocks of lithium ion batteries which weigh 8.5 tons and supply power for 72 hours in darkness. This catamaran runs at an average of 5 knots and has a maximum speed of 14 knots. It cost several million dollars to build but has no fuel costs associated with its operation.

CONCEPTS FOR THE FUTURE

The following are examples of some of the future concepts being developed:

STX EOSeas

The *STX EOSeas* is a 305 m long passenger ship integrating a novel concept using wind power via sails in combination conventional propulsion developed by STX France and partners.

The Hexifloat

The *Hexifloat* is a floating platform designed by Hann-Ocean Technology that integrates solar, wind, wave and tidal energy with solar leading the way. It is considered an attractive concept for countries with limited land area for these types of technologies.

Aquarius MRE System

Another concept is the *Aquarius MRE System* that was developed by Eco Marine Power as show in Figure 28. The system, which is a patented design, is claimed to be “an advanced integrated system of rigid sails, solar panels, energy storage modules and marine computers that will enable ships to tap into renewable energy by harnessing the power provided by the wind and the sun.”

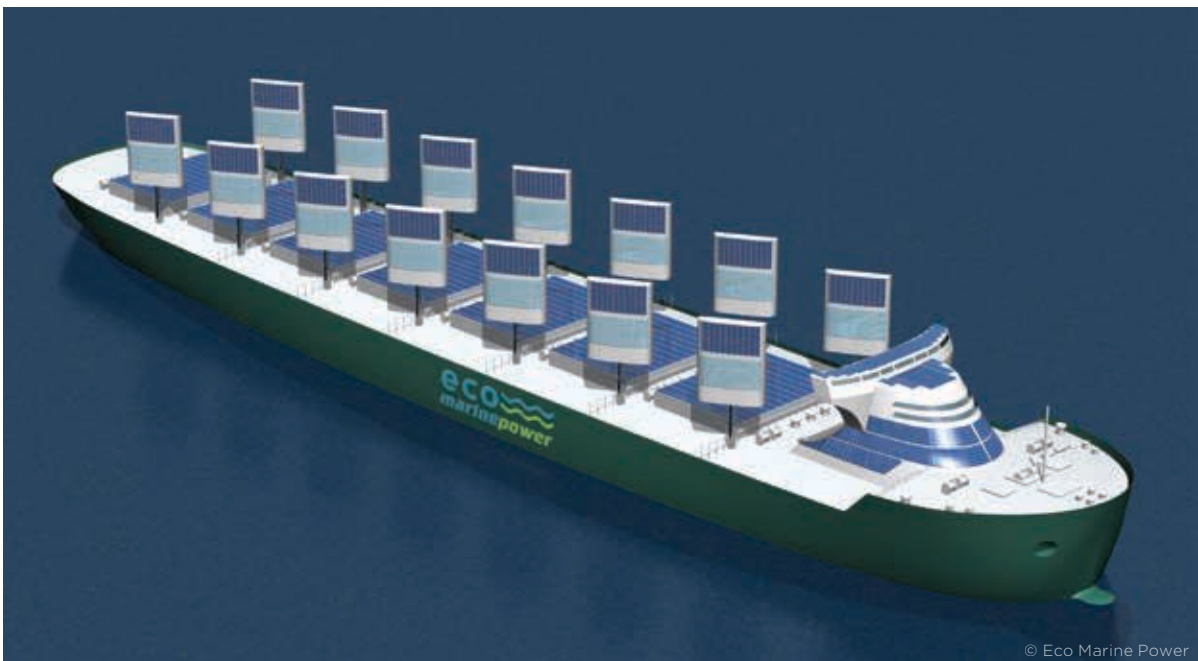


FIGURE 28: *Aquarius MRE System*

ADVANTAGES

Solar Power

Advancements in solar panel efficiencies along with advancements in energy storage technology can provide a feasible option for emissions reduction and fuel savings on ships. The use of alternative energies, such as the installations of the PV cells, presents these advantages:

- Gas emissions reduction: The use of Solar PV panels on ships will reduce gas emissions.
- PV cells low costs: Since the PV cells can be mass produced this makes them relatively inexpensive.
- Good power-to-size ratio: Some types of PV cells can give relatively good power-to-size ratio (e.g. efficiencies within ranges of 135-170 watts/ m²).
- Good life spans: Some types of PV cells have a good life span (e.g. mono-crystalline type being advertised for 25 years).

Wind Energy

- Gas emissions reduction: the use of rigid sails on ships will reduce gas emissions.
- Lower maintenance times and costs: A decrease in gen-sets installed in these ships will reduce maintenance plans on rotating machinery.
- Development of new international guidance and rules: The use of these novel concepts will help the marine and offshore industry to develop new and better guidance related to safety.

CHALLENGES

Solar Power

Vessels with installed PV cells and wind sails as one alternative arrangement for a renewable source of power have encountered the following issues:

- Adverse Environmental conditions: Humidity, shading, corrosion problems, and wind are some of the issues faced by current PV system technology.
- Limited area for PV arrangement: Areas on the vessels to install the PV are limited; therefore, the aggregate power output by this type of source is low.
- Technology limited to small vessels: Lack of sufficient deployment space on board for the PV panel makes this technology relevant to small vessels.
- Lower power output contribution to the whole system: Due to the low power output, the installation of PV cells has been on relatively small ships. The use of energy storage systems is needed in these installations.

Wind Energy

- Technology still evolving: For ships, the design process for wind-generator technologies is more complicated and multi-dimensional than those technologies already proven for land applications. Since wind-powered ship technology is emerging, prototypes to fully developed products will take time to evolve.
- Loading and unloading operations concerns: Safety concerns related to loading and unloading operations in ships are issues to overcome (due to sizes of sails, etc.).
- Obstructions: Obstructions during transits under bridges are concerns yet to be overcome.

OPPORTUNITIES AND CHALLENGES FOR HYBRID ELECTRIC POWER SYSTEMS

OPPORTUNITIES

Vessels and offshore installations require electrical power for everything from communications and navigation systems to crew comfort and reliable propulsion systems. These requirements offer a great potential for savings by using hybrid electric power systems.

The opportunities offered by hybrid electric power systems are summarized as follows:

- **Integrate multiple energy generation and storage technologies thereby increasing operational flexibility, reliability and safety**

Hybrid electric power systems provide opportunities to utilize different energy storage and generation technologies. Lithium-ion batteries, supercapacitors, flywheel energy storage, fuel cells, solar and wind can be used to supplement or in some instances replace traditional gen-sets during a vessel's different operational scenarios such as at sea, during maneuvering, and docking. This diversity of available electric power sources helps improve operational flexibility and reliability by allowing for a minimum number of generators to be run where previously multiple generators were operated with less than ideal loading.

An example of this is in vessels engaged in long, low power transits such as a river or a canal passage where multiple generators are normally run for electrical plant reliability purposes alone. The use of the appropriate energy storage system can decrease generator use with the energy storage providing ride through power to prevent a blackout until the time it takes for the stand-by generator to come online. Energy storage technologies can serve a similar function in vessels during dynamic positioning operations, cable/pipe laying, etc. Other uses of energy storage are load leveling such as active heave compensation of drilling derricks and crane systems.

- **Optimize generator capacities and appropriately meet power consumption needs**

The inclusion of alternate energy generation and storage technologies in the vessel electrical plant allows for a minimum number of generators to be run, thereby offering the opportunity to optimize the number and the operating point of generators for different operating scenarios. Maintenance costs can be cut by reducing running hours on equipment as well as operating generators at or close to the point of maximum efficiency, as alternate sources are available to supply the required power needs of occasional and starting loads instead of a lightly loaded generator. This optimization leads to less air-pollution and environmental impact, an important aspect when vessels operate in environmentally sensitive or coastal areas.

- **Minimize environmental impact**

As discussed above, the integration of multiple energy storage and energy generation technologies can result in reduced the environmental impact by a vessel. Many port states and individual ports have designated areas along their coast as emission control areas. Similarly, many flag states have elected to impose emission limits on vessels as part of national and international policies. The utilization of hybrid electric power systems can greatly assist with reaching these goals.

CHALLENGES

The growing availability of alternative energy storage and generation technologies provides more options and benefits to designers of vessels and offshore installations. These options can be combined in different and imaginative ways, and this has led to the advent of more complex electrical systems. This in turn has influenced the entire vessel design concept. The proper selection of the most appropriate combination of technologies is crucial and can have an important impact on the desired benefits such as reduction of capital expenditures (CAPEX), operational expenditures (OPEX), the environmental footprint and increased safety.

It is also important to understand that these factors may also compete against each other. New, more complex designs are more difficult and impractical to assess using traditional discrete electrical design tools such as a load analysis, short circuit analysis, coordination study and harmonic analysis. Limiting common mode voltages and currents must also be considered in contrast to traditional alternating current power.

As technology progresses, the means of addressing this increased complexity is being developed with the advent of new modeling and simulation tools and techniques. The more these simulation techniques are used to assess the electrical aspects of the design (including newer considerations such as power quality, stability, loading/rejection and energy storage needs/performance), the more the designer is able to consider other variables, including non-technical considerations such as CAPEX, OPEX and specific regulatory requirements.

When a preliminary decision is made on a design, it can then be reviewed for practical aspects such as layout, Failure Modes and Effects Analysis (FMEA), response in a blackout, operator and maintenance aspects. It can also be reviewed for compliance with Class Rules, other regulatory aspects and owner requirements. Modeling and simulation efforts should ideally be performed in an environment that supports model exchange between simulation engines. One such environment is the Functional Mockup Interface (FMI) Standard.

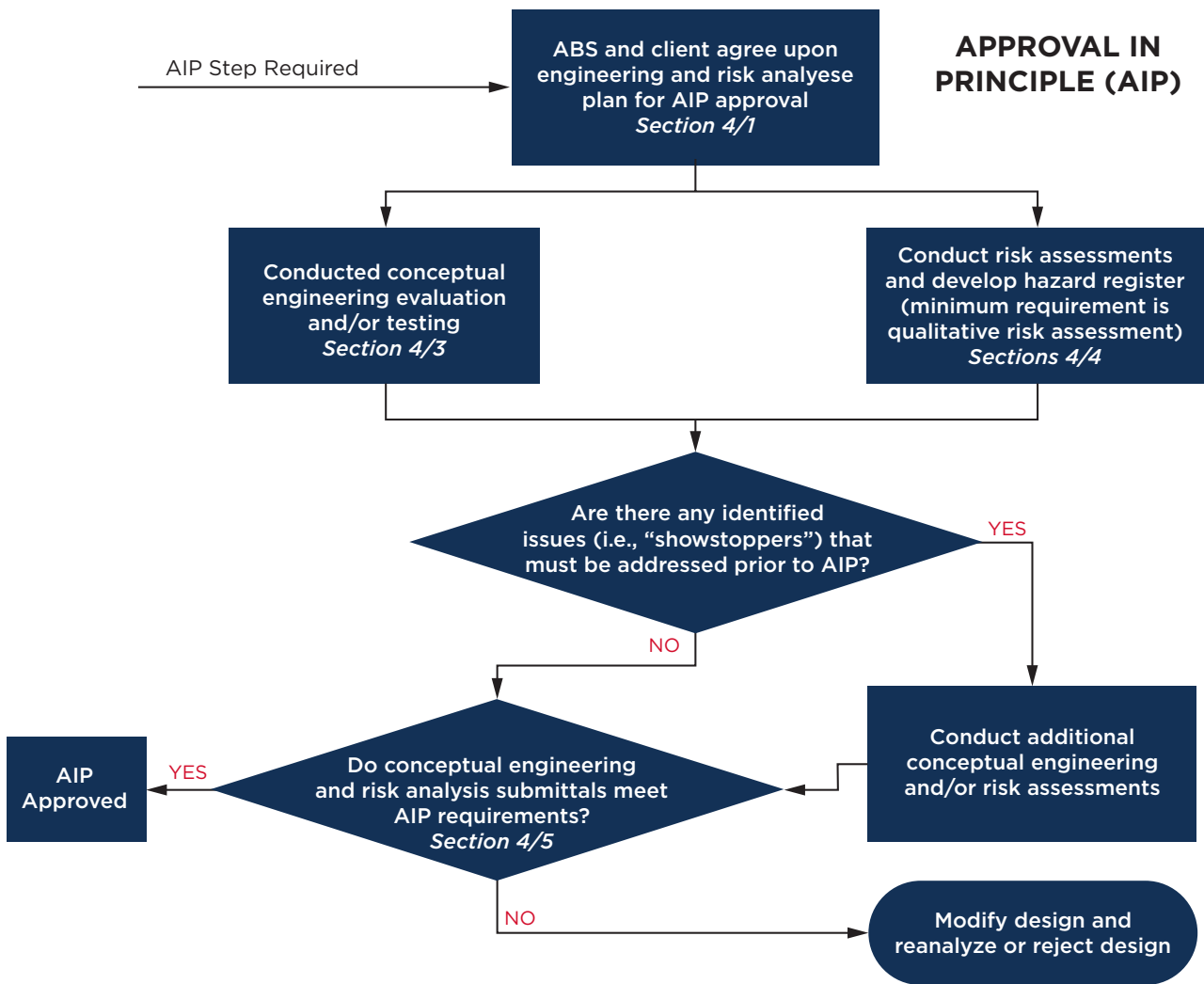
ABS ROLE

Another challenge is that existing classification requirements and international regulations may not be current for evolving energy storage and generation technologies. To address the above challenge, ABS offers an Approval in Principle (AIP) of Novel Concepts that verify new technologies and their applications to marine and offshore assets.

The AIP program is outlined in the ABS “Guidance Notes on Review and Approval of Novel Concepts” and can be found on-line at www.eagle.org (publication #116). The Guidance Notes are for an application with a high degree of novelty, which is defined as an application or process that has no previous experience in the environment for which it is being proposed. The approach in the guidance notes can be used for all novel or unique concepts as well as for arrangements not adequately addressed in the current Rules.

With the AIP approach, ABS works closely with the Client to develop an Engineering and Risk Analysis Plan that can allow for designers and manufacturers to help identify applicable Class and regulatory requirements that can be applied to new or novel arrangements. The AIP process also allows exploration of issues that are outside of the scope of the existing Rules and identification and resolution of issues and concerns that may not be adequately addressed. ABS also works with the stake holders involved in identifying how to best address safety concerns as well as assists in the development of a roadmap to move the effort forward and obtain classification approval. At the conclusion of the AIP process, clients gain an understanding of the requirements for project-specific engineering reviews and surveys that will be required during an actual project.

A general outline of the AIP procedure is provided below.



Utilizing the AIP process also delivers a value to both organizations during plan approval as well as in the execution of future projects because the engineers and surveyors in ABS and the client company have a better understanding of the system, which improves the efficiency of their work and consequently streamlines the approval and survey processes.

Once granted an AIP, the client will then most likely advance into the next phases of the project, the detailed design and also the advanced risk assessment and testing which may have been identified in the conceptual phase. This will aid the client and ABS in gaining certainty in their design as the level and accuracy of the risk assessment and engineering evaluation increases. This phase of the project will involve traditional Class participation in the form of design review and survey with the ultimate goal of Class approval.

ACRONYMS

ABS:	American Bureau of Shipping
AC:	Alternating Current
AFC:	Alkaline Fuel Cell
AIP:	Approval in Principle
BMS:	Battery Management System
BS:	Battery System
CAPEX:	Capital Expenditures
CHP:	Combined Heat and Power
CO ₂ :	Carbon Dioxide
DC:	Direct Current
DoD:	Depth of Discharge
DP:	Dynamic Positioning
EDLC:	Electric Double Layer Capacitor
FESS:	Flywheel Energy Storage System
FMEA:	Failure Modes and Effects Analysis
FMI:	Functional Mockup Interface
IACS:	International Association of Classification Societies
IEC:	International Electrotechnical Commission
IGF Code:	The International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
IMO:	International Maritime Organization
ISO:	Independent System Operator
kW:	Kilo-watt
kWh:	Kilo-watt Hour
kWp:	Kilowatt peak
Li ion:	Lithium Ion
Li ₄ Ti ₅ O ₁₂ :	Lithium Titanate
LIC:	Lithium-ion Capacitor
LiCoO ₂ :	Lithium Cobalt Oxide
LiFePO ₄ :	Lithium Iron Phosphate
LiMn ₂ O ₄ :	Lithium Manganese Oxide
LiNiCoAlO ₂ :	Lithium Nickel Cobalt Aluminum Oxide
LiNiMnCoO ₂ :	Lithium Nickel Manganese Cobalt Oxide
LNG:	Liquefied Natural Gas
MARPOL:	Marine Pollution (International Convention for the Prevention of Pollution from Ships)
MCFC:	Molten Carbonate Fuel Cell
MS:	Motor Ship
MW:	Mega-watt
MWh:	Mega-watt Hour
NASA:	National Aeronautics and Space Administration
NAVSEA:	Naval Sea Systems Command
NiCd:	Nickel Cadmium
NiMH:	Nickel Metal Hydride
NYK:	Nippon Yusen Kabushiki Kaisha
OPEX:	Operational Expenditures
PAFC:	Phosphoric Acid Fuel Cell
PEM:	Proton Exchange Membrane
PV:	Photovoltaic
RPM:	Revolutions per Minute
SF-BREEZE:	San Francisco Bay Renewable Energy Electric vessel with Zero Emissions
SOC:	State of Charge
SOFC:	Solid Oxide Fuel Cell
TFSC:	Thin-Film Solar Cells
UL:	Underwriters Laboratories
W/l:	Watt/liter
Wh/kg:	Watt-hour/kilogram
Wh/l:	Watt-hour/liter

REFERENCES

Introduction:

1. Comparison of Conventional vs. Diesel Electric Propulsion System. Reference: 'Electrical Propulsion System in Ships'. Credits: yanmar.com
<http://www.marineinsight.com/marine-electrical/electrical-propulsion-system-in-ships/>

Lithium-Ion Batteries:

1. IEC 62619: Secondary cells and batteries containing alkaline or other non -acid electrolytes - Safety requirements for secondary lithium cells and batteries for use in industrial applications, 2014, Committee Draft
2. IEC 62620: Secondary cells and batteries containing alkaline or other non -acid electrolytes - Secondary lithium cells and batteries for use in industrial applications, 2014
3. UL 1642: Standard for Safety of Lithium Ion Batteries, 2012
4. Battery University: <http://batteryuniversity.com>
5. Performance of Various Lithium-Ion chemistries. Reference: 'BU-205: Types of Lithium-ion'. Credits: Cadex and Boston Consulting Group. http://www.batteryuniversity.com/learn/article/types_of_lithium_ion
6. <https://www.marad.dot.gov/wp-content/uploads/pdf/FOSSFINALREPORTONBATTERYRE-INSTALLATION.pdf>

Supercapacitors:

1. Alternative Energy - Ultracapacitors http://www.altenergy.org/new_energy/ultracapacitors.html
2. 125 Volt Transportation Module
<http://www.maxwell.com/products/ultracapacitors/125v-tran-modules>
3. The New K2 3.0V/3000F Cell Documents
<http://www.maxwell.com/products/ultracapacitors/k2-3-series/documents#>
4. BU-209: How does a Supercapacitor Work?
http://batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor
5. The concept of Lithium Ion Capacitor
<http://www.jsrmicro.be/emerging-technologies/lithium-ion-capacitor/concept-lithium-ion-capacitor>
6. Renewable Energy and Electricity
<http://www.world-nuclear.org/information-library/energy-and-the-environment/renewable-energy-and-electricity.aspx>
7. Electrochemical Supercapacitor, Scientific Fundamentals and Technological Applications, B.E. Conway, 1999
8. Supercapacitor Market - Global Industry Analysis, Trend, Size, Share and Forecast 2015 - 2023
<http://www.transparencymarketresearch.com/supercapacitor-market.html>
9. IEC 62576 Electric double-layer capacitors for use in hybrid electric vehicles -test methods for electrical characteristics
10. IEC-TC 40/PT 62956 Hybrid electric double layer capacitors for use in electric and electronic equipment
11. IEC 62813 Lithium ion capacitors for use in electric and electronic equipment - test methods for electrical characteristics
12. IEC 62391 Fixed electric double-layer capacitors for use in electric and electronic equipment - Part 1: Generic specification
13. UN 3508 Capacitor, asymmetric, electric double layer (with an energy storage capacity greater than 0.3 Wh)
14. UN 3499 Capacitor, electric double layer (with an energy storage capacity greater than 0.3 Wh)

Flywheel Energy Storage:

1. Beacon Power – Carbon Fiber Flywheels <http://beaconpower.com/carbon-fiber-flywheels/>
2. BEACON POWER SIGNS CONTRACT WITH U.S. NAVY VALUED AT UP TO \$3 MILLION http://www.sec.gov/Archives/edgar/data/1103345/000110465909006058/a09-4596_1ex99d1.htm
3. 20 MW Flywheel Energy Storage Plant http://www.sandia.gov/ess/docs/pr_conferences/2014/Thursday/Session7/02_Areseneaux_Jim_20MW_Flywheel_Energy_Storage_Plant_140918.pdf
4. Beacon Power's Bankruptcy Autopsy <http://www.greentechmedia.com/articles/read/beacon-powers-bankruptcy-autopsy>
5. "Flywheel Energy Storage System for Electric Start and an All-Electric Ships", J. McGroarty, Naval Surface Warfare Center ; J. Schmeller ; R. Hockney ; M. Polimeno, 2005 IEEE Electric Ship Technologies Symposium
6. UK funding combat lasers on Navy ships by 2020 and will use formula 1 flywheel technology to store energy for laser shots, <http://nextbigfuture.com/2015/09/uk-looks-to-put-combat-lasers-on-navy.html>
7. SPIN COMMISSIONING AND DROP TESTS OF A 130 kW-hr COMPOSITE FLYWHEEL https://repositories.lib.utexas.edu/bitstream/handle/2152/30671/PR_365.pdf?sequence=1
8. "Flywheel Technology: Past, Present and 21st Century Projections", J.G. Bitterly, 1997 Energy Conversion Engineering Conference.

Fuel Cells:

1. ABS Presentation "Fuel Cells at Sea", Rich Delpizzo, ABS Washington DC, December 2015
2. Fuel Cells | Department of Energy, <http://energy.gov/eere/fuelcells/fuelcells>
3. Energy and Fuels in Society: Analysis of Bills and Media Reports," by L.R. Radovic, Textbook online, www.ems.psu.edu/~radovic/matsc101.html
5. Feasibility of the SF-Breeze: a Zero Emission, Hydrogen Fuel Cell High Speed Passenger Ferry, J.W. Pratt and L.E. Klebanoff, Sandia National Laboratories, 2016
6. Module 4: Fuel Cell Technology, College of the Desert, Revision 0, December 2001. http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm04r0.pdf
7. Fuel Cells 2000 Benefits <http://www.fuelcells.org/base.cgim?template=benefits>
8. Fuel cells, what is a fuel cell, disadvantages, benefits http://www.altenergy.org/renewables/fuel_cells.html
9. Energy & Climate, Secure & Sustainable Energy Future <http://energy.sandia.gov/transportationenergy/hydrogen/markettransformation/maritimefuelcells/>
10. Red and White Fleet eyes fuel cell powered ferry, Marine Log, http://www.marinelog.com/index.php?option=com_k2&view=item&id=9500:redandwhitefleeteyesfuelcellpoweredferry&Itemid=230

Wind and Solar Power:

1. ASTM E1597-10: Standard Test Method for Saltwater Pressure Immersion and Temperature Testing of Photovoltaic Modules for Marine Environments
2. IEC 62670-1, Concentrator photovoltaic (CPV) module and assembly performance testing and energy rating
3. IEC 62124, 2004 Ed 1, Photovoltaic (PV) standalone systems – Design verification
4. M/V Emerald Ace PDF Presentation – MOL Mitsui O.S.K. Lines
5. <http://sunboat.com/history/history.html>
6. “Solar Energy Helps to Power Huge Ship at Port of Long Beach”. Ronald D. White. Los Angeles Times. July 2009.
7. World’s First Solar Power Assisted Vessel Further Developed. NYK Line News Release. May 2011.
8. MS Tûranor Planet Solar Project, <http://www.planetsolar.org/>
9. We Got the Power! – Wind Turbines: A Buyer’s Guide. Practical Boat Owner. March 2013.
10. “Study Finds Wind Speeds On the Rise”. Carl Holm. ABC. March 2011.
11. USA Solar & Wind Inc - 200kW Wind Turbine Technical Specification, <http://www.usasolarwind.com/200kw%20wind%20turbine%20Technical%20specifications.pdf>
12. Eco Marine Power – Aquarius Eco Ship, <http://www.ecomarinepower.com/aquarius-eco-ship>
13. Wind and Sun Power One-Legged Platform. Innovation at Shell, <http://www.shell.com/global/future-energy/innovation/inspiring-stories/monotower.html>
14. Solar for Offshore Oil Platform. GreenTEC Renewable Energy Solutions LLC., http://www.greensolgroup.com/greentec/off_shore_spv_system.php
15. Research Article. PV Systems Installed in Marine Vessels: Technologies and Specifications
16. Global Marine Technology Trends 2030 Commercial Shipping: LR, QinetiQ, University of Southampton, <http://www.stxeurope.com/UK/stxfrance-ecorizon-0-ecorizon.awp>
17. <http://www.statoil.com/en/TechnologyInnovation/NewEnergy/RenewablePowerProduction/Offshore/HywindScotland/Pages/default.aspx>
18. <http://www.hann-ocean.com/products/hexifloat-renewable-energy-platform/introduction/>
19. http://www.bluebird-electric.net/wind_powered_ships_marine_renewable_energy_research.htm

CONTACT INFORMATION

ABS WORLD HEADQUARTERS

ABS Plaza
16855 Northchase Drive
Houston, TX 77060 USA
Tel: 1-281-877-5800
Fax: 1-281-877-5803
Email: ABS-WorldHQ@eagle.org

ABS AMERICAS DIVISION

ABS Plaza
16855 Northchase Drive
Houston, TX 77060 USA
Tel: 1-281-877-6000
Fax: 1-281-877-6001
Email: ABS-Amer@eagle.org

ABS EUROPE DIVISION

ABS House
No. 1 Frying Pan Alley
London E1 7HR, UK
Tel: 44-20-7247-3255
Fax: 44-20-7377-2453
Email: ABS-Eur@eagle.org

ABS GREATER CHINA DIVISION

5th Floor, Silver Tower
No. 85 Taoyuan Road
Huang Pu District
Shanghai, 200021 P.R. China
Tel: 86-21-2327-0888
Fax: 86-21-6322-9649
Email: ABS-GreaterChina@eagle.org

ABS PACIFIC DIVISION

438 Alexandra Road #10-00
Alexandra Point
Singapore 119958
Republic of Singapore
Tel: 65-6276-8700
Fax: 65-6276-8711
Email: ABS-Pac@eagle.org

www.eagle.org

© 2017 American Bureau of Shipping.
All rights reserved.

