An Overview of Hybrid Power Systems and their Architecture

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This Paper offers an overview of hybrid power systems and their Architecture, the advantages and challenges/disadvantages of each, along with their applications in the marine Industry. The primary component technologies have been divided into two broad categories, namely Energy Generation Technologies and Energy Storage Technologies. The Energy Generation technologies covered include fuel cells, solar and wind power. The Energy Storage technologies detailed in this Paper are batteries (Lithium-ion batteries), capacitors (super capacitors) and flywheel energy storage.

Sun ship: The solar-powered Turanor, with some of its solar panels retracted, docks at Fan Pier in Boston.(source: technology review.com)

KEY WORDS

Fuel cell, Solar Energy, Wind Energy, Super Capacitor, Flywheels and Architecture.

INTRODUCTION

The propulsion and power generation plants for future ships have to reduce fuel consumption and emissions over the coming years. IMO has adopted mandatory energy-efficiency measures to reduce emissions of greenh*ouse* gases from international shipping, under Annex VI of IMO's pollution prevention treaty (MARPOL).

The IMO Marpol regulations have set targets for reducing the Energy Efficiency Design Index (EEDI) for new ships. This EEDI is a measure of the amount of CO_2 emissions that a ship produces per tonne of goods transported per nautical mile. From 1 January 2013, following an initial two year phase zero when new ship design needed to meet the reference level for their ship type, the level is to be made stringent incrementally in 4 phases (Phase 0,1,2,3) every five years. Currently we are in phase 1.

Phase	Period	Reduction % relative to the EEDI Reference line
Phase 0	1 Jan 2013 – 31 Dec 2014	0 %
Phase 1	1 Jan 2015 – 31 Dec 2019	10 %
Phase 2	1 Jan 2020 – 31 Dec 2024	20 %
Phase 3	1 Jan 2025 and onwards	30 %

In Pursuance of IMO's strategy to limit and reduce GHG emissions from International shipping and reduce fuel consumption, a technological option like installation of Hybrid Power Systems onboard Ships to reduce fuel consumption, and the CO2 emissions which are projected to increase 50–250% by 2050, is explored.

Advances in power and energy management improvements, however, can significantly contribute to reducing both CO2 and NOx emissions. Modern electric propulsion systems are being 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 to fall under the new and developing category of hybrid power systems.

For the context of this paper, hybrid power systems incorporate multiple sources of power, usually a combination of both non-traditional sources (batteries, capacitors, fuel cells, etc.) and traditional sources (diesel gen sets).

ENERGY GENERATION TECNOLOGIES

Fuel Cells

Fuel cells, like a battery, produce energy from an electro-chemical process rather than combustion. Fuel cells have no moving parts but do require additional support plant such as pumps, fans and humidifiers. Two reactants, typically hydrogen and oxygen, combine within the fuel cell to produce water, releasing both electrical energy and some thermal energy in the process. Unlike a conventional battery in which the reactants consumed in the energy conversion process are stored internally and eventually depleted, the reactants consumed by the fuel cell are stored externally and are supplied to the fuel cell in an analogous way to a conventional diesel engine. Hence a fuel cell has the potential to produce power as long as it has a supply of reactants. Many values are quoted for the efficiency of a fuel cell and all should be treated with caution and considered in context. The fuel types, storage conditions, inclusion of a reformer and type of output power must all be considered.

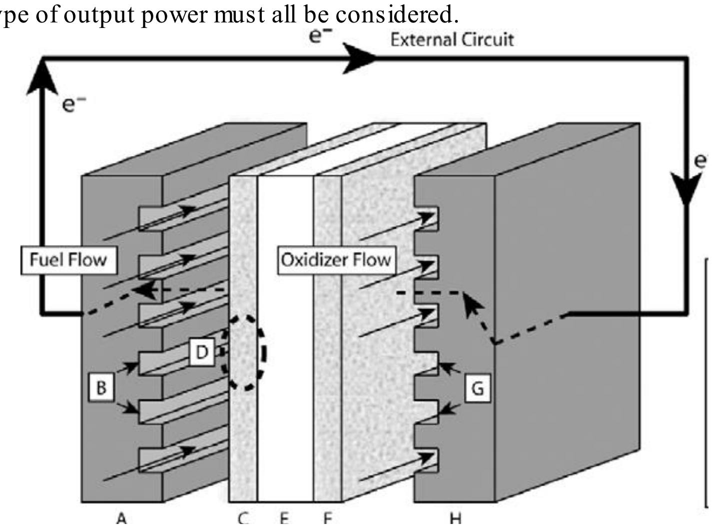


Figure 1 Schematic of an individual generic fuel cells (Source: Mench, 2008)

A: Anode current collector
B: Anode flow channels
C: Anode catalyst layer (CL)
D: Close-up of anode CL
E: Electrolyte
F: Cathode catalyst layer
G: Cathode flow channels
H: Cathode current collector

Basic physical structure of generic fuel cells is shown in Figure 1. It shows that fuel cells consist of a negative electrode and a positive electrode which are sandwiched around an electrolyte. Fuel is fed to the negative electrode and oxygen is fed to the positive electrode. Activated by a catalyst, hydrogen atoms separate into protons and electrons. Electrons go through the external circuit creating electricity flow. Protons migrate through electrolytes to the cathode. Protons then reunite with oxygen and the electrons to produce water and heat.

The high temperature fuel cells have the potential to achieve efficiencies similar to if not better than those of large marine diesel engines, especially if they are combined with a steam plant to make use of their thermal output.

While extensive literature is available on the development of fuel cells, commercial application of electrochemical power supply in the maritime environment is limited. Application of series production fuel cells on board has been limited to air independent propulsion on submarines, as the storage of the hydrogen fuel limits the amount of energy that can be produced without refueling. Research now is focused on more compact storage of hydrogen, fuel cells with or without reformers that can use other fuels such as methanol, LNG or even diesel oil, and fuel cells combined with diesel engines or gas turbines to achieve high efficiencies while using more energy dense fuels.

A major issue for fuel cells is their fuels: oxygen can be obtained from air but hydrogen is more of a challenge. One option is a direct supply of hydrogen, but at present bulk storage is problematic and the infrastructure is lacking. The external reformation of diesel is an alternative and is seen as a viable alternative for vessels which uses high distillate fuel. However, it is more challenging to reform the low-cost, heavy fuel oil commonly used by the merchant marine. A more realistic shorter term scenario for marine fuel cell power generation would be operation by natural gas. A number of high temperature fuel cells are capable of operating directly on natural gas by converting methane into hydrogen within the fuel cell itself; termed internal reformation. The disadvantage is that carbon in the fuel is converted into CO_2.

Indeed, green hydrogen, generated using renewable energy ashore and consumed in hydrogen fueled fuel cells onboard ships, may offer a solution. In such an ideal operating environment, the benefits of fuel cell technology could be fully exploited.

Some potential advantages and disadvantages of the technology:

Advantages

- Fuel cell technology has a potential for ship propulsion in the medium to long term.
- At the present, encouraging experience is being gained through auxiliary, hybrid and low power propulsion machinery.
- For marine propulsion, the high temperature solid oxide and molten carbonate fuel cells show most promise. For lower powers, the low temperature proton exchange membrane fuel cells are better suited.
- Methanol is a possible alternative fuel.
- Fuel cells produce a DC electrical output and are, therefore, suited to ships with electrical transmissions.
- Fuel cells have no moving parts and consequently are quieter than conventional machinery
- If fueled with hydrogen, they emit no carbon dioxide from the ship.
- They require clean fuels and so do not emit SOX, but also they are low temperature devices and emit no NOX.

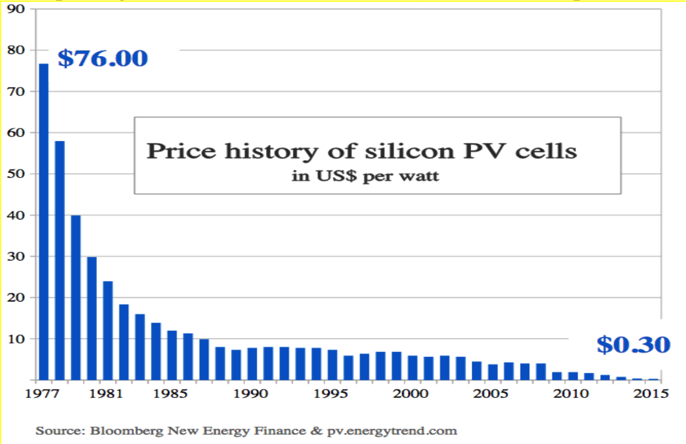
Disadvantages

- Although hydrogen is the easiest fuel to use this would require a worldwide marine infrastructure to be developed for supply to ships: perhaps adjacent to an automotive sector.
- The use of more conventional marine fuels in fuel cells would present problems and necessitate complex onboard preprocessing to take place. They would in this case be a significantly more expensive way of generating electricity than conventional methods.
- Fuel cells produce DC electrical output and, hence, are not so suited to ships with mechanical transmission systems.
- Fuel cells have lower specific powers and power densities than diesel engines.

Solar Energy

Photovoltaic (it is a process by which voltage and current are created in material on exposure to sunlight) methods offer an approach for limited amounts of power generation onboard ships and trials have demonstrated that some benefit is available for auxiliary power requirements. However, the maximum contribution is small when compared with the power required to drive the ship. The average raw power of sunshine is a variable depending upon the latitude and the angle at which the photovoltaic cell is positioned relative to the sun. Throughout the world the variation in power availability under average cloud cover is minimum of 87 W/m2 to a maximum of 273 W/m2. However, the effect of cloud cover is significant in terms of the energy that can be derived from the sun using this technology. Consequently, weather conditions and position on the planet are significant influencing factors in developing the potential of solar power. However, the principal constraint is the ability to find a large deck surface area on the ship which does not interfere with cargo handling or other purposes for which the ship was designed and coupled with a maximum attainable specific power from the sun at given global locations and the generally limited available deck area suggest that the power attainable would only be sufficient to augment the auxiliary power demands.

The costs of producing photovoltaic cells have dropped recently due to the vehement push towards renewable energy adoption across the world, and also due to technological developments as well as Quantum of PV cells produced. The below chart shows the pricing trend for PV cells (USD Price per watt):



It is pertinent to mention that:

- with the decreasing trend of PV Cells price.
- for more than 100m2 PV area available
- with input solar energy density along the (e.g.,) Indian coast being 5.5-6.0 KWh/m2/Day (GHI).

  It would be feasible to go in for Solar Energy for Auxiliary power requirements onboard vessels operating along Indian Coast with additional resultant annual savings on recurring basis.

Wind Energy

Methods that use the wind to provide energy to drive ships include a variety of techniques. Typically these embrace Flettner rotors, kites or spinnakers, soft sails, wing sails and wind turbines.

In the case of wind turbines mounted on ships for the generation of electric power, an adequate differential wind speed over the turbine rotor is required. For small ships and leisure boats gyroscopic couples from a wind turbine also need to be taken into account to prevent stability issues in a seaway.

Some potential advantages and disadvantages of the Solar and Wind Energy technology:

Advantages

- Power derived from the wind is free from exhaust pollutants.
- Partial propulsion benefits can be achieved through wind-based methods.
- Solar power has been demonstrated to augment auxiliary power.

Disadvantages

- Wind power systems rely on the wind strength to be effective.
- The use of some wind-based systems rely upon adequate control system technology being installed on board the ship.
- Applications involving power derived from the wind are limited to the augmentation of propulsion unless a full return to sail is contemplated for specific applications.
- Solar power availability is global position dependent.
- Solar energy is feasible as an augment to auxiliary power but photovoltaic processes are inherently of low effectiveness, even under the best of conditions, and require a significant deck or structural area upon which to place an array of cells.

ENERGY STORAGE TECHNOLOGIES

Batteries

Lithium-ion uses a positive electrode, a negative electrode and electrolyte as conductor. The positive electrode is metal oxide and the negative electrode consists of porous carbon. During discharge, the ions flow from the negative electrode to the positive electrode through the electrolyte and separator; charge reverses the direction and the ions flow from the positive electrode to the negative electrode. Figure 2 illustrates the process.

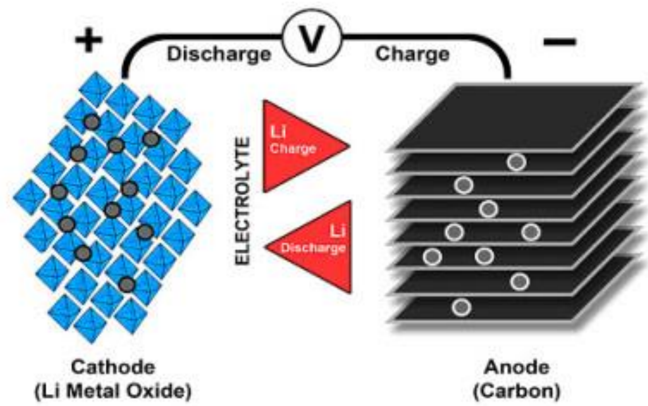


Figure2: (source: Battery University.com)

When the cell charges and discharges, ions shuttles between the positive electrode and negative electrode, on discharge negative electrode undergoes oxidation, or loss of electrons and positive electrode sees a gain of Electrons. Charge reverses the movement.

Advantages

- High specific energy and high load capabilities with Power Cells
- Long cycle and extend shelf-life
- High capacity, Low self-discharge (less than half that of NiCd and NiMH) low internal resistance, good coulombic efficiency

- Simple charge algorithm and reasonably short charge times

Limitations

- Requires protection circuit to prevent thermal runaway if stressed
- Degrades at high temperature and when stored at high voltage
- No rapid charge possible at freezing temperatures (<0°C, <32°F)
- Transportation regulation required when shipping larger quantities.

Super Capacitor

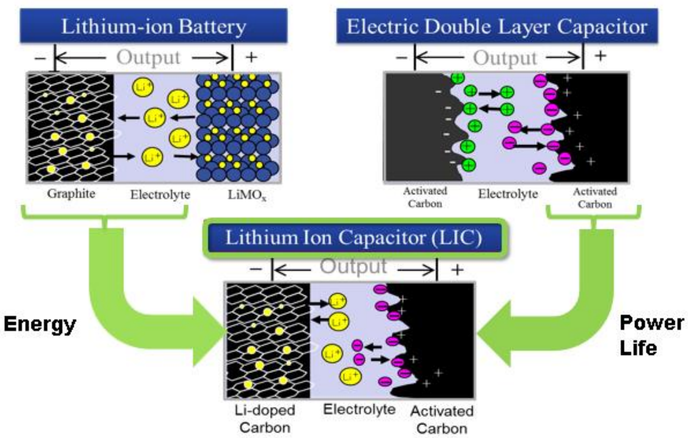


Fig 3 Working Principle of Super Capacitor (Source: jsr micro inc)

A lithium ion capacitor cell is composed of a pre-doped Carbon anode, similar to a lithium ion battery negative electrode. The positive electrode consists out of Activated Carbon, like electric double layer capacitor cathodes.

Pre-doping negative electrodes with lithium ions, it is possible to have next-generation electricity storage devices that achieve a combination between high power density and high energy density, are safe in use and exhibit superior life characteristics.

Supercapacitors are ideal when a quick charge is needed to fill a short-term power need; whereas batteries are chosen to provide long-term energy.

Supercapacitors are most effective to bridge power gaps lasting from a few seconds to a few minutes and can be recharged quickly. Its broad temperature range and long life offers an advantage over the battery. Supercapacitors are expensive in terms of cost per watt.

Advantages

- Virtually unlimited Cycle life; can be cycled millions of time.
- High specific power: low resistance enables high load currents.
- Charges in seconds; no end-of-charge termination required
- Simple charging; draws only what it needs; not subject to overcharge
- Safe;
- Excellent low-temperature charge and discharge performance.

Limitations

- Low specific energy; holds a fraction of a regular battery.

Flywheel Energy Storage (FES) System

Structure and Principle of FES Systems

Typical FES system mainly consists of flywheel, dual mode motor/generator (M/G), power electronics system, bearings system, controllers and containment structure. When the machine works as a motor, it converts electricity through power conversion system and exerts a torque to the flywheel rotor. Depending on the torque/rotor inertia ratio, the flywheel rotor increases its speed at a certain rate up to the maximum velocity, storing the desired kinetic energy. Then, the kinetic energy is maintained in the standby mode.

However, FES systems still encounter some challenges in the considered applicative scenario. Firstly, flywheels must compete with batteries and ultra-capacitors on the basis of costs. Most of the FES systems have an ability of some minutes only, and they tend to be more useful for very short duration applications

The FES systems available today have a maximum speed around to 100,000 rpm. In future, to increase the speed of FES systems the adoption of ultrahigh speed machines, such as induction machines (e.g. 120,000 rpm) and permanent magnet synchronous ones (e.g. 1,000,000 rpm), could be investigated.

HYBRID POWER SYSTEMS ARCHITECTURE

Electrical Propulsion with Hybrid Power Supply

In electrical propulsion with hybrid power supply, a combination of two or more types of power source can provide electrical power. It is proposed to classify power sources into:

- Combustion power supply, from diesel engines (1), gas turbines or steam turbines;
- Electrochemical power supply from fuel cells; or

- Stored power supply from energy storage systems (2) such as batteries, flywheels or super capacitors.

The development of stored power supply for automotive and power system application is an extensive research area. However, purely stored power supply on ships is limited, due to its limited range. During the period, When the Flywheel's Energy Storage is required, the Generator mode will be changed to "ON" and will be driven by the Inertia of the Flywheel.

Research into energy storage technology on board ships is significantly more limited and primarily focused on the use of battery technologies. Specifically for handling pulsed loads on naval vessels, hybrid energy storage technology is required to supply up to 10 GW during microseconds bursts to high energy weapons. This hybrid energy storage combines high power density of ultra-capacitors with high energy density of batteries.

A typical architecture of an electrical propulsion plant with hybrid power supply is shown in Fig. 4. In this case, energy storage (2) is connected to the main distribution bus.

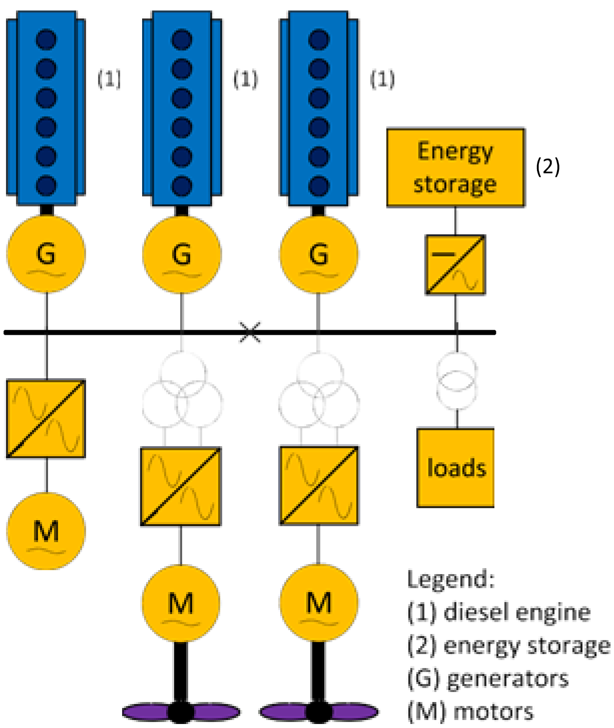


Fig. 4. Typical electrical propulsion system with hybrid power supply (Source: Applied energy 194(2017)30-54)

The benefits of applying stored and hybrid power supply in ship power and propulsion plants can be diverse:

- Saves fuel, reduces emissions, and reduces noise, increases comfort and enable temporarily sailing without emissions, noise and vibrations from the engines.
- The battery can enable load levelling, by handling the power fluctuation. This configuration could achieve significant savings in fuel consumption, CO_2 and NO_x emissions.
- The battery can enable peak shaving; the battery delivers power during periods where high power is required and recharges when less power is required. This strategy can run engines more efficiently and reduce installed power.
- When the battery is recharged from the grid alongside, this can reduce fuel consumption and local emissions, although this power might be generated from renewable energy sources.
- This can eliminate the need for running extra diesel engines as spinning reserve and can potentially reduce the installed power on vessels with a requirement for a high availability of propulsion, for example DP vessels. The battery in a hybrid power supply runs in parallel with generators.

This leads to the following challenges:

- The control strategy needs to maximize the reduction in fuel consumption and emissions, by charging and discharging the battery at the right time.
- Load fluctuation on diesel engines increases fuel cost, emissions and maintenance load. Thus the control strategy should ideally share dynamic load between the battery and the diesel engine in such a way that the fuel cost, emissions and maintenance load of all power suppliers are minimized.
- The increase in purchase cost due to the installation of batteries needs to be minimized or offset by reduced installed power.

Hybrid Propulsion with Hybrid power supply

Hybrid propulsion with hybrid power supply utilizes the maximum efficiency of direct mechanical drive (1) and the flexibility of a combination of combustion power from prime mover(s) (2) and stored power from energy storage (3) for electrical supply. At low propulsive power an electric drive (4) is available to propel the ship and switch off the main engine (1). The machine providing electric drive can also be used as a generator. A typical architecture is illustrated in Fig. 5.

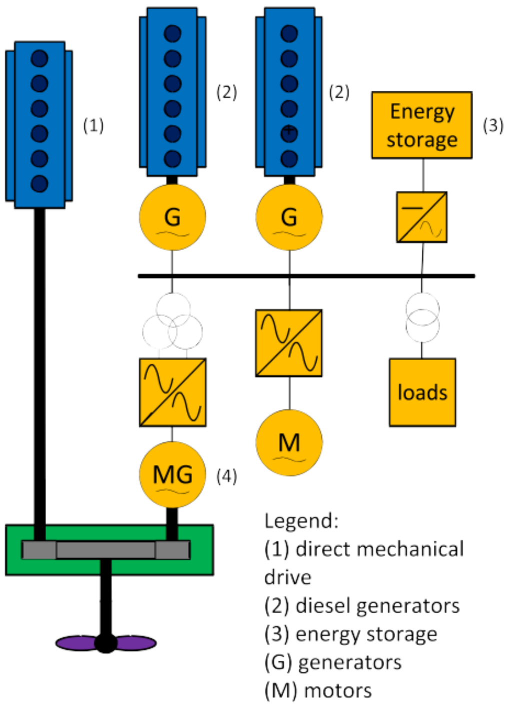


Fig. 5. Typical hybrid propulsion system with hybrid power supply. (Source: Applied energy 194(2017)30-54)

Electrical Propulsion with DC Hybrid power supply

Historically, DC systems have been applied in specific applications such as submarines. However, fault protection and power system stability issues have limited their application. The continued development of power electronics and intelligent schemes to protect against faults and ensure power system stability have enabled more widespread application of DC systems. The most important reasons for applying DC systems are increased fuel efficiency when running generators in part load and reduced power conversion losses. A typical architecture of electrical propulsion with DC hybrid power supply is presented in Fig 6.

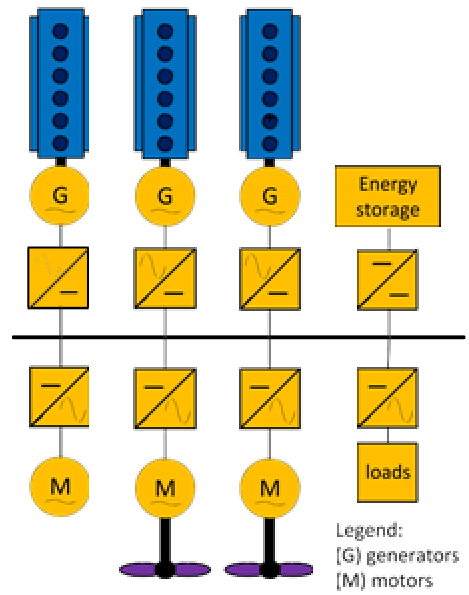


Fig. 6. Electrical propulsion with DC hybrid power supply. (Source: Applied energy 194(2017)30-54)

Benefits of DC hybrid power supply

The benefits of applying hybrid DC power supply to ships with electric propulsion are as follows:

- DC architectures are resilient to faults, because power electronics allow instantaneous control of electrical variables and electrical faults do not spread across the electrical network and disturb network voltage and frequency.
- The amount and size of switchgear potentially reduces when the power electronics in the system perform fault protection .Although DC architectures can provide significant benefits, the following challenge needs to be resolved:
- A coordinated control strategy is required to resolve stability issues.

CONCLUSION

This paper has reviewed current and future Hybrid Power systems constituents and their architectures along with the respective advantages & disadvantages/Challenges. The variety and complexity of these architectures poses an increasing amount of design choices to the ship. In order to determine the optimal architecture, knowing the operational profile is essential. Hybrid power systems is beneficial when the total electrical load has a great spread over time and can improve availability and reduce noise. Further the use of energy storage system and better arrangement would achieve lower pollutants emissions and a lower fuel consumption. Finally, DC power systems potentially reduces fuel consumption and associated emissions with up to 20%. It is pertinent to mentioned that Renewable energy sources are free from exhaust pollutants like CO2, NOX, SOX, volatile organic and particulate emissions points of view since none occur during operation.

Considering existing technology developments, for the short term, fuel cells application could be promoted to be adopted in vessels which take advantage of power generation with less noise and vibration, and also for less emission in harbors and inland waters, such as small passenger vessels, research vessels, tugs and cruise vessels.

Strength & Opportunities of Hybrid Power Systems

Environmental

- Low Emission
- Low Noise
- Low Vibration

Regulation

- Guidelines
- Safety Rules
- High Policy Support

Technical

- Technical Development
- Considerable Efficiency
- Technological Dissemination

Weakness & Challenges of Hybrid Power System

Environmental

- Full life cycle Environmental Impact
- Use of Renewable Hydrogen

Technical

- Hydrogen Safety
- Fuel & Infrastructure
- Reliability
- Ship Integration
- Power Density
- Volumetric Size

Economic

- High initial cost
- Cost Effectiveness in operation
- Life time perspective

Disclaimer:

The views expressed in the above paper is the author's own view and is not the view of Indian Register of Shipping.

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