

# Consideration of Hybrid Technology & Associated Machinery

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Abstract:

The technological advances in energy storage devices and distribution systems have seen further uptake in hybrid propulsion and powering solutions across a widening variety of marine applications. In this paper the authors provide details of some of the challenges for this technology and the approaches made by Lloyd's Register to provide the required level of industry assurance. Focus is made on the offshore and towage segment covering aspects such as propulsion systems and bollard pull certification

## INTRODUCTION

In the last years, the industry innovations have been driven to the hybridization and electrification in a number of transportation sectors. In particular the automotive industry (passenger vehicles, commercial and construction vehicles), has had a strong boost in the direction to electrification but also the water and air transportation systems are moving on the same road to hybrid and electric. This innovation change was a result of a mixture of environmental and market driven objectives as high fuel economy, pollution and limited resources of fossil combustibles. The new technologies in the vehicles industry have increased the design complexity as the hybrid and electric solutions offer a number of systems configurations becoming a challenge for the original equipment manufacturers (OEMs) in finding the highest optimisation of design and systems operation profiles.

Among the objectives that increase the interest for the hybrid electric vehicles (HEV), the reduction of the CO<sub>2</sub> emissions is the most attractive. The use of alternative sources of energy that have a lower impact in terms of CO<sub>2</sub> emissions leads directly to a reduction of air pollution. In the automotive industry the Toyota Prius was launched for the Japanese

market in 1997. This innovative car is based on the hybrid electric technology being powered by a combination of electric motors and a conventional petrol engine. A rechargeable battery plays the role of the source of energy for the electric motors and the propulsion power is optimised by managing both electric motors and engine to provide power to wheels. Following that innovative technology other car manufacturers released hybrid passenger's cars. Nowadays hybrids are offered by Ford, General Motors, Honda, Nissan, GM, Daimler Chrysler, Peugeot, Citroen, Mercedes-Benz, Hyundai and others and full electric cars (Tesla in front) are starting to increase their market in a number of countries where incentives from government make very attractive such innovative green technology.

The hybrid electric concepts have entered other transportation markets as hybrid commercial vehicles (buses, construction machineries, boats or aircrafts).

In the marine industry there are triggers to replace the consolidated conventional diesel mechanical drives by new concepts. Not only is there the ever increasing but also continuously and unpredictably variable price of fossil fuels, but, also the need to reduce

emissions in specific areas - Sulphur Emission Control Areas (SECA) or Emission Control Areas (ECAs). These are sea areas in which stricter controls were established to minimize airborne emissions from ships as defined by Annex VI of the 1997 MARPOL Protocol (1). Starting from 1 January 2015, in those areas only fuels having a sulphur content generating SOx emission of 0.1% or less will be allowed in many coastal regions.

Within the emerging culture and needs of a higher respect to the environment and the issues with the use of fossil fuels, new concepts have been introduced and are nowadays consolidated as follows:

**Energy Efficiency**, as stated by the International Energy Agency (IEA) (2), is the key to ensuring a safe, reliable, affordable and sustainable energy system for the future. It is the one energy resource that every country possesses in abundance and is the quickest and least costly way of addressing energy security, environmental and economic challenges.

**Renewable Sources of Energy.** Unlike fossil fuels, which are finite, renewable energy sources regenerate. There are five commonly used renewable energy sources:

- Biomass—includes: Wood and wood waste, Municipal solid waste, Landfill gas and biogas, Ethanol, Biodiesel,
- Hydropower
- Geothermal
- Wind
- Solar

Renewable energy is at the centre of the transition to a less carbon-intensive and more sustainable energy system. Renewables have grown rapidly in recent years, accompanied by sharp cost reductions for solar photovoltaics and wind power in particular

Some countries have initiatives that support industry and consumers to the use of 'zero emission' vehicles and craft only and a huge

number of ports are thinking in the near future of having close to zero emissions. This is starting to be achieved by use of renewable energy to electrify ports piers in order to shut down ship's engines when in port, but also reducing trucks and tugs emissions.

The high 'energy efficiency' and the capacity to use energy stored from renewable sources that are typical characteristics of the hybrid electric systems, have attracted the harbour tug sector as Port Authorities are looking for cuts in emissions in 'port cities' where the impact of tug emissions can be very important.

## **AN OVERVIEW OF HYBRID POWER SYSTEMS AND INTEGRATED POWER SYSTEMS**

In general the hybrid concept has different definitions. In the transportation industry a system is considered hybrid when two sources of power contribute to the propulsion of one vehicle with one or more possible configurations. In the automotive industry it is, typically, assumed that a car is hybrid when, in addition to the conventional internal combustion engine, a battery of accumulators provide a source of energy for the electric motors that concur to power the car. An Energy Management System (EMS) is needed to manage the status of charge (SOC) of the battery and optimize the power to the wheels according to various operating profiles and power demand.

From a technology perspective the biggest difference in the use of hybrid electric propulsion on ships compared to similar concepts systems in automotive is the recovery of braking energy. The lack of direct adhesion between the propeller and the water makes it difficult to recover energy during braking for ships. These results in smaller savings through the use of hybrid drive concepts compared to road vehicles.

In the marine industry the diesel-electric propulsion (a simplified concept is shown in

Figure 1) is well consolidated and the benefits of such system are well known and widely applied. On ships the concept of hybrid propulsion (or Hybrid/electric propulsion) is generally associated to those propulsion systems where the propeller is driven by a conventional internal combustion engine and/or an electric motor powered by the ship's electric system. In these cases the hybrid configuration is referred to the combination of a main propulsion engine and a diesel-electric propulsion system as in Figure 2.

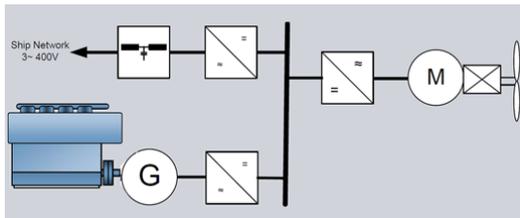


Figure 1 conventional diesel electric (courtesy of Siemens)

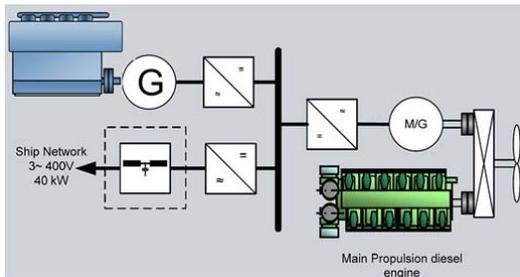


Figure 2 Hybrid/electric propulsion system (courtesy of Siemens)

There are a number of possible configurations and integration of machinery and equipment available to design a hybrid/electric system and Figure 3 shows an option where the electric power is generated and distributed by Alternate Current (AC) and the electric rotating machine providing both propulsion motor (M) and shaft generator (SG) is driven by a converter AC/DC-DC/AC using the typical DC link concept.

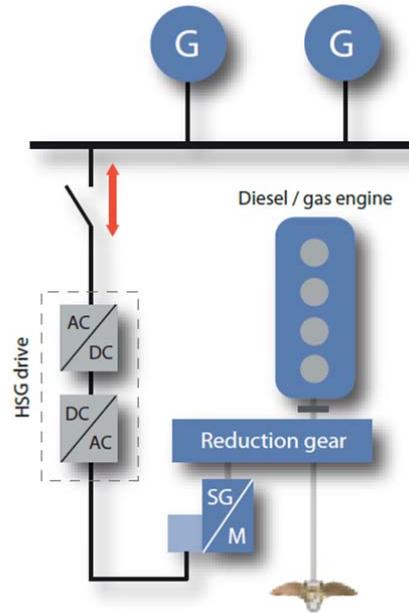


Figure 3 Hybrid Shaft Generator (courtesy of Rolls-Royce)

Other options of diesel electric propulsion systems are based on generation and distribution by Direct Current (DC) as shown in Figure 4. Here the propulsion system is a pure diesel-electric but the innovation is given by the use of the DC generation and distribution.

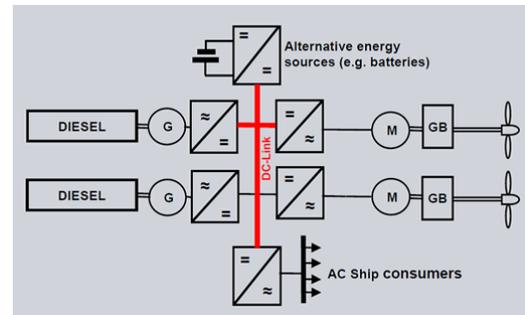


Figure 4 Diesel-electric system in DC (courtesy of Siemens)

In Figure 4b, a similar DC system is the main characteristic of a hybrid propulsion system as having the propulsion power made by a hybrid diesel-direct and diesel-electric.

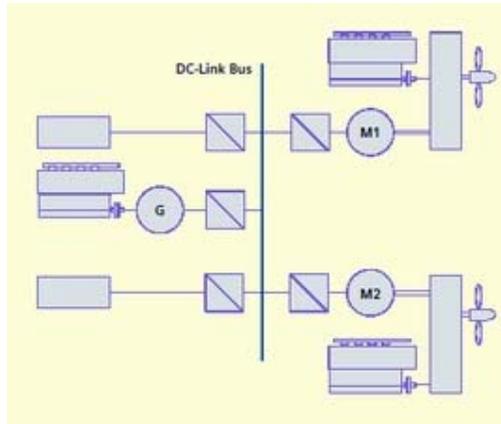


Figure 4b Hybrid diesel-direct and diesel electric with DC distribution system (courtesy of Siemens Siship Ecoprop system)

In all cases the DC-link offers the chance to provide an additional DC source of power in the form of a stored energy that will contribute to the propulsion power and potentially could provide the power needed for low speed and short time navigation.

This concept can be extended from the diesel electric propulsion system to the hybrid/electric propulsion system and Figure 5 shows how a hybrid/electric propulsion system (combination of conventional propulsion engine and diesel electric propulsion) integrates a large battery installation (2000kW) that can provide power to both the propulsion motor and the vessel loads. Figure 5 shows the operation mode where both main propulsion engine and diesel generators are off. In this mode, the batteries generate the energy needed for both the propulsion and for the vessel's consumers. As the main diesel engine and the diesel generators are off, gas emissions and noise generation are eliminated. Some OEM names such a mode as the 'green mode'.

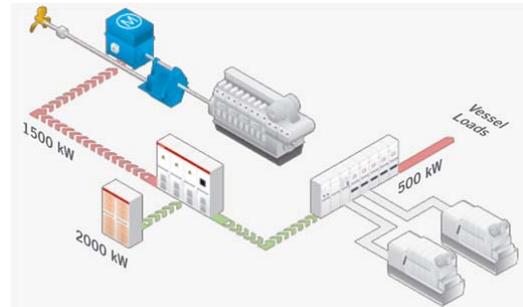


Figure 5 Hybrid/electric propulsion with battery (courtesy of Ingeteam)

Other alternative sources of Energy that could be integrated in such a hybrid/electric propulsion system can be supercapacitors, fuel cells, solar arrays and other Electrical Energy Storage (EES) but a number of them are still at a research study level.

Though the battery technology is proven and consolidated in a number of applications and, at the present level of technology, it offers a number of advantages that put them as the most chosen option for an alternative source of power.

Additionally the battery offers the possibility to be charged in port by appropriate shore connections and this is satisfying the trend of port's policies to enhance electrification based on renewable sources of energy, Figure 6. Ships can benefit by electrification of ports by shutting down onboard diesel generators and contributing to a better clean atmosphere, whilst hybrid/electric propelled ships and tugs can benefit from electrification by charging the battery when moored in port.

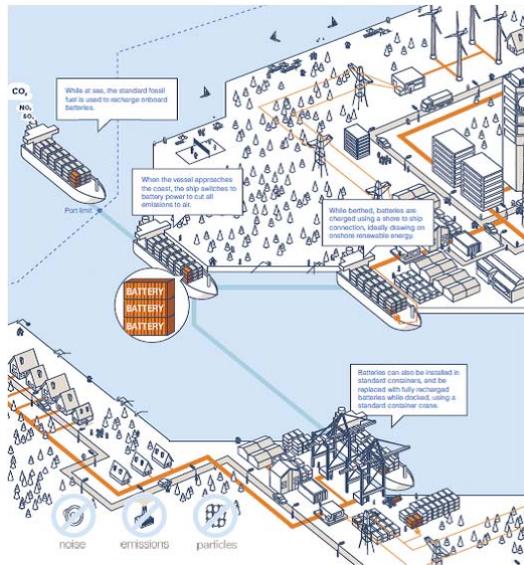


Figure 6 Zero emission Port Call (courtesy of ABB)

## ELECTRICAL ENERGY STORAGE IN A SHIP'S POWER SYSTEM

The Electrical Energy Storage (EES) technologies are in rapid development in the last years as they are responding to a number of issues coming from worldwide needs to keep energy more efficient and reduce emissions and greenhouse gases. The hourly variations in demand and price of electric energy on the land based grids and the needs to use more renewable sources of energy make a trigger to the EES technologies that play the following basic roles in an electric power system:

- Reduce electric power costs by storing energy when the price is lower (off-peak time) and use it when the price is higher (peak time),
- Respond to the power fluctuations in both consumers and producers (in particular when power is generated by photovoltaic arrays or windmills that do not have a continuous power generation profile)
- Reduce emissions caused by vehicles that use electric power for propulsion, electric power coming from renewable sources,

- Maintain power continuity for critical services (hospitals and other critical infrastructures) in case of power supply failure (black out conditions).

Similar to the land based applications, the present and future EES technologies give opportunities to improve ship power systems and optimize their functionality and performances responding to the same issues as above and others.

The EES technologies can be considered of the following type (3):

- Mechanical (e.g. compressed air and flywheels)
- Electrochemical (e.g. batteries)
- Chemical (e.g. Fuel Cells)
- Electrical (e.g. Double Layer Capacitors DLC better known as supercapacitors, superconducting magnetic coils)
- Thermal (e.g. sensible heat storage)

Because of their characteristics the most attractive EES technologies for the ship's industry applications are at present only a few of the above.

The mechanical storage of energy at the flywheel has a limit given by the quantity of energy that can be stored through the mass/inertia of the flywheel. This makes the attraction to such EES technology in vehicle and ship applications as limited to their use in short time power peak shaving. However, as stated, where a high energy capacity should be needed for other uses, then the flywheels become inconvenient and this is the main reason why at present there are no known applications of this technology.

At the present stage of industry advances, the most attractive EES technologies for the ship's application and where the shipping industry is investing in terms of research are the Battery, the Fuel Cells, and the Supercapacitors.

Within the battery technologies (Electrochemical Energy Storage) there are a number of chemistry offerings in the market, but, the most popular in various applications is the Lithium Ion (Li-Ion) type. In respect of other well consolidated technologies as Lead Acid, Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH) the Lithium Ion type has the following characteristics that – even if costs per Wh are greater than other types – make them the most used Energy Storage Systems onboard ships in recent years.

First of all the Li-Ion cells have a high voltage (up to 3.7V) that is about 3 times the nominal voltage of a NiCd battery (1.2V). To have a battery system voltage at the level required by the system there is a less need of connections and electronics.

Secondly, a high energy density. Figure 7 shows a Ragone Plot where specific energy is on the x-axis and specific power is on the y-axis. This plot captures how much energy the battery can provide at a certain level of power. The ratio of energy to power is the time of discharge of the battery and is given by the diagonal lines.

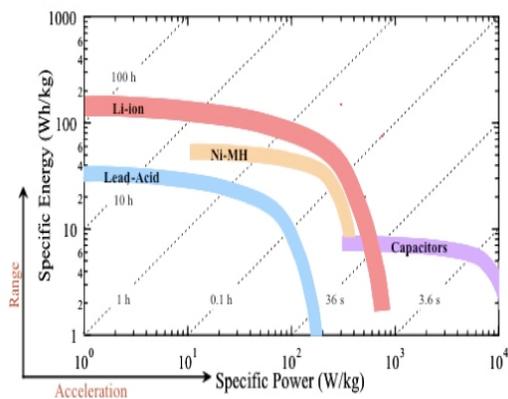


Figure 7 Ragone Plot

The plot clearly shows the Li-Ion specific energy as higher than other chemistry but also as compared to capacitors to have another electro technical reference.

Nevertheless the Li-Ion battery has safety issues. Most of the Li-Ion battery metal oxide electrodes are thermally unstable and can decompose at high temperatures ending to a thermal runaway (a high energy rapid reaction delivering very high quantity of heat). To mitigate the risk of such behavior the latest technologies of Li-Ion batteries include monitoring systems preventing over- and under- discharging and other abnormal conditions that can lead to thermal runaway.

A mention is needed to be made to the Metal Air (Me-Air) battery that at present is still not a mature technology, but, being under consideration for its theoretical specific energy of about 11.14kWh/kg being about 100 times more than other battery types and even greater than petrol specific energy (10.15 kWh/kg).

There is a continuous development of other electrochemical energy storage technologies. The Sodium Sulphur Battery (NaS) consist of liquid (molten) sulphur at the positive electrode and liquid (molten) sodium at the negative electrode; the active materials are separated by a solid beta alumina ceramic electrolyte and the battery is kept between 300°C and 350°C to keep the electrode molten. The Sodium Nickel Chloride (NaNiCl) battery, better known as the ZEBRA (Zero Emission Battery Research) battery, is – like the NaS battery – a high-temperature (HT) battery. Its operating temperature is around 270 °C, and it uses nickel chloride instead of sulphur for the positive electrode. NaNiCl batteries can withstand limited overcharge and discharge and have potentially better safety characteristics and a higher cell voltage than NaS batteries.

The ZEBRA technology has been successfully implemented in several electric vehicle designs (Think City, Smart EV) and is an interesting opportunity for ships' applications.

The Fuel Cells can be used for combined generation of electricity and heat as the chemical reaction that takes place is the

reverse of water splitting into hydrogen and oxygen. The electrolysis reaction is exothermic, i.e. releasing heat and takes place in the fuel cell that contains an electrolyser. The overall efficiency of the hydrogen as energy storage is low compared to storage technologies such as Li-ion battery, but the chemical energy storage is the only concept which allows storage of large amounts of energy, up to the TWh range, in reason of the hydrogen storage tank capacity. The hydrogen storage technologies are developing fast either in the direction of a gas under high pressure, as liquid at very low temperature, adsorbed on metal hydrides or chemically bonded in complex hydrides.

Of high interest is the application of chemical energy storage within a renewable power station in Prenzlau (Brandenburg, Germany), Figure 8 (4), where a hybrid power plant generates 220kV electric power from 3 x 2MW wind energy mills, distributing into the European power grid and to a 500kW pressure electrolyser that generates oxygen and hydrogen. This last gas is stored and made available as fuel in F-Cells cars filling stations and as a fuel for fuel cells that generate electricity and heat.

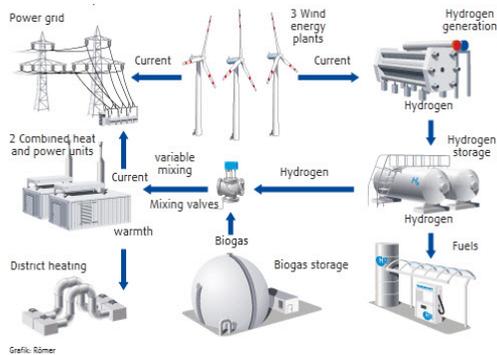


Figure 8 Prenzlau Hybrid power station (courtesy of ENERTRAG)

**APPLICATION OF HYBRID POWER SYSTEMS TO THE HARBOUR TUGS**

Responding to the needs of Energy Efficiency, Green Ships and Environmentally Friendly solutions, the concept of full electric ships, e.g. a ship where the source of power is solely a battery of accumulators with the appropriate technical facilities to provide charging operations when moored on port, is the solution most likely to be adopted.

However such a concept can be considered as applicable to a limited number of cases within the shipping industry, namely short voyage ferries having a simple operating profile based on continuous voyage-manoeuving-docking-maneuvering. In such an operating profile, the power request for voyage and maneuvering propulsion and services can be provided by an Electric Energy Storage system (as battery) and the energy needed can be stored during the docking time by appropriate charging facilities. The typical example of such application is the MV Tycho Brahe and MV Aurora, two Scandlines train and car ferries recently converted that have 4x4160 kWh batteries providing the sole source of power (diesel engines are still onboard as a backup source of power). The ferries operate on the Helsingør-Helsingborg route taking approximately 20 minutes. The docking time is about 5,5 minutes in Helsingør and 9 minutes in Helsingborg and in these short times the batteries need to be charged by approximately 1,200kWh, that is the energy needed for the 20 minutes voyage and manoeuvring.

Other kinds of ships' operating profiles are difficult to consider as appropriate for a full electric power system. In particular, Harbour Tugs have a typical operating profile that needs big power availability for short periods of time and a flexibility of power available that is not matching the functionality and performance of a full electric system.

A harbour tug's typical yearly operating profile is such that its request for propulsion power during operational hours can be summarized by Figure 9.

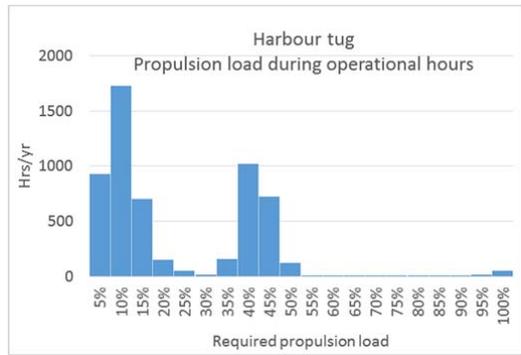


Figure 9 Harbour Tug propulsion load during operational hours (courtesy of HyPS)

Typically a harbour tug having 60 tonnes of bollard pull will comprise twin propulsion lines of about 2000 kW each. The operational profile in a year for such a harbour tug shows that 30% of time is spent as berthed. During operation the tug has a long time at low load operations (station keeping, running idle) mixed with medium load transit (free sailing) and towing along with very short periods of bollard pull. The propulsion system on a conventional harbour tug is designed to provide bollard pull, thus, at the low load operations (the majority of the operational time) it works at very poor levels of (Specific Fuel Oil Consumption (SFOC) and very high levels of emissions. In fact, under low load, diesel engines run inefficiently, pollute internally and externally to the environment, requiring more maintenance and age much more quickly.

Based on such a typical harbour tug operational profile, the combination of two main engines with two electric rotating machines acting as Power Take Off and Power Take In (PTO/PTI) as shown in Figure 5, is considered as an optimal solution to the above mentioned issues concerning the conventional propulsion system. The rotating electric machines can act as motors (PTI) when supplied by the main source of electrical power. When this is supported at its available DC link by a battery system as shown in

Figure 5, then there can be an enhancement in the operational modes of the power system.

This is basically a combination of diesel-direct and diesel-electric propulsion system with the addition of an Energy Storage System (the battery).

The appropriate use of the available combinations of power sources in such a hybrid system allows shut down of the main propulsion engines at low propulsion loads demand time resolving the issues of poor SFOC and high emissions and noise. This leads to lower fuel consumption, reduction of exhausts emissions, less internal engine pollution increasing the maintenance intervals and the engine lifetime expectancy.

The battery pack if appropriately designed can provide enough power during station keeping and free sailing at low speed (4-5 knots) giving the chance to shut down all the engines (both main and auxiliary)

The configuration considered in the above examples (a combination of diesel-direct and diesel-electric propulsion together with an EES at the most convenient point of the DC power) provides the availability of different operating modes that are optimized by an appropriate power and energy management system. The operator from the bridge can select the most appropriate mode within the following typical modes.

**Green mode or Stand-by mode.** All diesel engines (main and auxiliary) are shut down but in stand-by (i.e. ready to start) and the battery pack feeds the normal electric system and the electric propulsion motor (acting as PTI). This mode is also called discharging or 'green mode' as the battery pack is the sole source of power and the tug is at zero-emissions. Where the battery pack has enough power, the stand-by mode can be used for station keeping, manoeuvring and free sailing at low speeds.

**Sailing mode.** The auxiliary generator(s) is(are) on and supply the electric propulsion motors (in PTI mode) and the other electric loads of the tug. The main engines are off and the battery pack can be either contributing to the electric power or as load peak shaving or being charged respecting the Energy Management System setting parameters for the charging/discharging operations. The free sailing mode can be used for station keeping, maneuvering and free sailing at speeds higher than those available in the stand-by mode.

**Towing mode or Power boost.** Main engines are on and deliver the propulsion power and the auxiliary generator sets supply the electric power system. The electric propulsion motor can operate either as PTI in case of propulsion power needs as a booster, or as PTO contributing to the electric power supply to both the electric loads and the battery charging. The battery can operate either as boosting power to the propulsion system or as peak shaving the electric load or as being charged respecting the energy management system setting parameters. The towing mode is used during push/pull operations and free sailing at the maximum speed.

There could be a number of additional modes based on the availability of battery energy. Examples are the use of battery for the starting of the engines and the charging of the battery in port by using appropriate shore connection facilities.

The Hybrid Power System as described, needs a complex power and energy management system that monitors and controls different machinery (main and auxiliary engines), equipment (main switchboard either AC or DC, propulsion converters, the battery or whatever the Energy Storage system is.

## **LLOYD'S REGISTER APPROACH TO THE HYBRID AND INTEGRATED POWER SYSTEMS ON TUGS**

The development of Integrated Power Systems in the shipping industry has strong interest in the application of DC grids for a number of reasons (5). Medium Voltage DC systems (MVDC) optimize efficiency by reduction of impedance and, by having no losses due to reactive current; the prime movers can run at the optimised speed in respect of the power demand, thereby increasing fuel efficiency. In a DC system the fault currents can be reduced by power electronics. Although, AC systems need much simpler circuit breaking technology than AC systems as electrical arcs clear at zero-crossing of the current, there is general reduction in weight and space in DC system equipment.

The existing Rules and Regulations for Ships (6) are, however, designed around the conventional AC systems and considerations to the operational and safety issues associated to the DC technology need to be taken into account in addition and complementary to the prescriptive Rules.

In general, the existing Lloyd's Register Rules and Regulations for Classification of Ships incorporate requirements driven by safety operation concepts and, from this perspective, there are prescriptive requirements identified for equipment and components. Nevertheless the integration of systems has always introduced additional risks associated to how consolidated and known equipment interact when integrated and due to this the Lloyd's Register approach to complex and integrated systems is to use a Risk Based Design approach (7) for a better comprehensive assessment of safety issues.

In recent years a number of full electric and hybrid ships has been classed by LR and the classification process has been conducted on the base of the above concept to combine existing prescriptive applicable Rules to Risk Based Design approach. In the Marine Industry the Risk Assessment approach is considered mainly in three ways:

a) where an existing prescriptive Requirement is deviated from, there is the need to consider an alternative design meeting the intent of the deviated requirements, but, it must provide an equivalent level of safety;

b) where a new technology is not covered by existing requirements, it needs to be evaluated as providing the same level of safety as the existing technology; and

c) where the proposed arrangement combines established technologies in complex integrated systems that could provide additional risks not covered by subsystems' existing requirements.

For this purpose the fully electric powered ship (where power is purely provided by a rechargeable battery) is considered by LR as not being covered by existing requirements for ships. Similarly, the hybrid ships where a large battery can provide main source of power, are again not covered by the existing prescriptive Rules as these are based on the concept of the main source of power being rotating machines (generators) driven by an internal combustion machine as prime mover.

The Lloyd's Register Risk Based Design process is simplified in Figure 10.

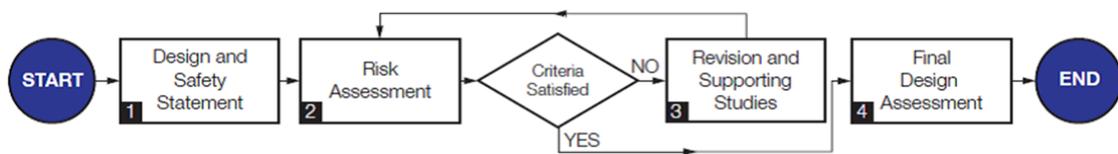


Figure 10 Generic Process for Risk Based Design.

Such process needs a definition of the Assessment Team, comprising involvement of the equipment and the system integrator and designer, the builder, the National Administration, the prospective ship Owner and ship Operator and the Classification Society. When the Design reaches a sufficient level of maturity, the Team provides a Risk Assessment basing such exercise on the Risk Assessment Techniques as detailed in the ISO31010 Standard (8). The outcome from the Risk Assessment provides the body of recommendations to the designer, builder and operator to mitigate the risks identified and needed to be controlled.

From the experience gained in a number of Risk Assessment processes, it has been noted that the majority of the risks within full electric and hybrid/electric ships relate to the battery during normal and abnormal operating conditions. A simplified process to address the risks associated to battery is shown in the flowchart of Figure 11.

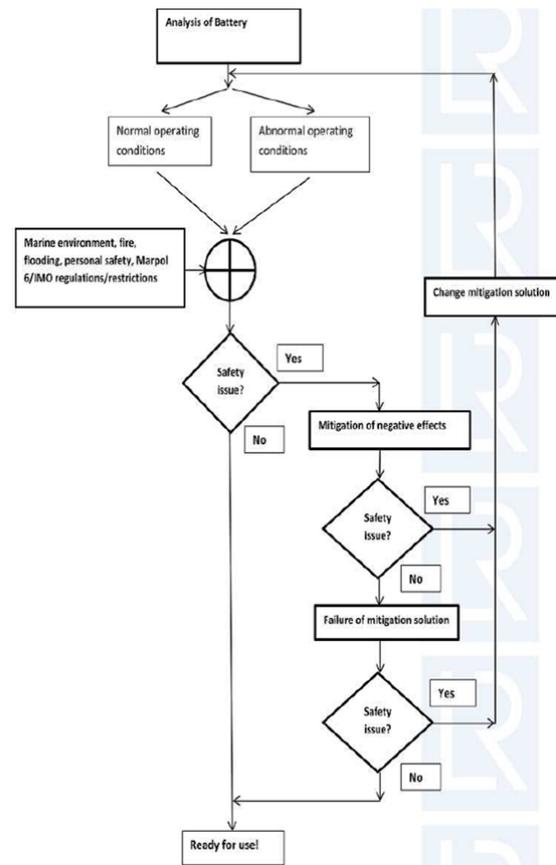


Figure 11 Battery Risk Analysis flowchart

Typical hazards associated with the battery result from mechanical failure, thermal runaway, internal overpressure, wrong energy management and are, in general, mitigated by battery construction characteristics, whilst risks associated to fire are treated with the choice of appropriate fire-fighting systems specifically designed to the battery chemistry characteristics.

The full electric and hybrid/electric ships have in some configurations extended direct current (DC) power systems. Also these are not covered by the existing Rules. Specific functional, performance and verification requirements have been issued by Lloyd's Register in a set of Provisional Rules for Direct Current Distribution Systems (9) where, however, a Risk Assessment is required to be carried out by suitably qualified and experienced individuals to a recognised Standard (e.g. ISO31010). Such Risk Assessment needs to take into consideration all normal and reasonably foreseeable abnormal operating conditions, such as start-up, normal shutdown, non-use, and protection, short circuit, earth fault, fire, flooding, cooling failure, operation outside of the designed parameters and profile and system electrical protection philosophy. The functional requirements then need to be derived from the Risk Assessment outcome.

After having gained a consolidated experience in hybrid/electric applications LR considers that Hybrid Power Systems and Integrated Power Systems are nowadays mature technologies and it has been recognised that a set of dedicated Rules would better address the needs and clearly guide designers and builders to a commonly recognised safety governance.

The Risk Assessment approach has given evidence of typical risks associated to the hybrid and integrated power systems and this gives the base to develop prescriptive

requirements having the intent to mitigate such typical risks.

Within the framework of a set of new Rules for Hybrid and Integrated Power Systems Lloyd's Register is going to include specific requirements for

- AC network architectures
- DC network architectures
- Mixed AC & DC architectures
- Power management
- Personal safety
- Protection and discrimination
- Reliability, availability and maintainability
- Batteries
- Fuel Cells
- Photovoltaic arrays
- Super Capacitors

In addition to the above, the configuration of those hybrid power systems where the power to the shaft has contribution from both main propulsion engine and the PTI electric motor, either directly or via a geared system, needs a review of the requirements for dimensioning which are not based solely on maximum engine output power.

### **BOLLARD PULL CERTIFICATION FOR HYBRID PROPULSION TUGS AND TOWING VESSELS**

A hybrid and integrated power systems as considered for a harbour tug, shows that the available propulsion power is no longer simply related to the main propulsion engines. There is a significant contribution from the electric motors (PTI) when they are supplied from the diesel electric system and such a contribution needs to refer to the battery or whatever EES is integrated into the tug power system.

The above can affect the propulsion performance and the bollard pull.

While full scale bollard pull certification is neither a Statutory nor Classification

requirement, a true figure of the bollard pull capability is often required. In particular Class Rules require for escort operation performance numeral and trials (10) and a Bollard Pull Test to be carried out.

The “Bollard Pull Certification Procedures Guidance Information” was published in October 1992 (11) and was based on the consolidated tugs and towing vessels conventional propulsion systems having oil engine(s) powering the propellers. Such guidelines provide definitions of the different bollard pulls as follows:

**Maximum Bollard Pull (MBP)** – Equal to the maximum average of recorded tension in the towing wire over a period of one minute during testing at an approved installation. MBP is normally associated with the maximum engine output and optimum propeller pitch;

**Steady Bollard Pull (SBP)** – This bollard pull should be achievable over a period of not less than five minutes. It represents the continuously maintained tension in the towing wire. Where peculiarities of a particular testing site are such that sustained five minute pull is difficult to achieve, bollard pull readings could be made at the times when the tug’s pull and direction are steady;

**Effective Bollard Pull (EBP)** – The bollard pull which a tug can develop in an open seaway. EBP is not normally established during testing at approved establishments and in most cases represents a fraction of the SBP. This fraction is often taken to be about 0.75 x SBP after making due allowance for weather;

Among various details the main objective of the Guidance is to provide a standardised procedure including testing environment, being to facilitate comparison with results obtained at different testing establishments

The final Certification includes a full report on completion of the testing containing all of the

relevant information concerning the tug, environmental data, propeller, machinery, instrumentation and all trial records.

Furthermore bollard pull may be certified for more than one engine setting. This certification may cover a range of bollard pulls from idling to full speed and may be of interest for tugs engaged in regular harbour service and the SBP and MBP may be obtained for the engine overload conditions.

As far as can be ascertained, the only reference to bollard pulls in Statutory documentation are IMO advisory Guidelines (21) that provide minimum requirements for the organisation, planning and execution of ocean towages and the design of associated equipment. They are applicable to international towing operations, but, may also be used for any other ocean tow, principally related to salvage.

Referencing the needs to reconsider bollard pull in light of the hybrid power systems technologies, it is highlighted that the named IMO Guidelines provide the following:

*During testing of continuous bollard pull (BP) the main engine(s) should be run at the manufacturer’s recommended maximum torque according to maximum continuous rating. Verification of the actual output should be requested during the test.*

*During testing of overload pull, the main engine(s) should be run at the manufacturer’s recommended maximum rating that can be maintained for minimum 30 minutes. The overload test may be omitted.*

*The figure certified as the vessel’s continuous bollard pull shall be the towing force recorded as being maintained without any tendency to decline for a duration of not less than 10 minutes.*

*Certification of bollard pull figures recorded when running the engine(s) at overload, reduced RPM or with a reduced number of*

*main engines or propellers operating can be given and noted on the certificate.*

Further information is provided by the European Tugowners Association (13) and the Shipowners' Club (14) and consideration are given to the effects of ageing on engines performance. The Shipowners' Club state that "It is not unexpected that as the tug gets older, the efficiency of the main engines and equipment will decrease the BP. It is generally accepted that if the BP certificate is less than 10 years old the BP rating is as stated on the certificate". And that "If the BP certificate is older than 10 years, the accepted BP rating should be reduced by 1% per year of age greater than 10 years i.e. a tug with a 20 year old BP certificate of 50 tonnes will effectively have a BP rating of 50 tonnes less  $10 \times 1\% = 45$  tonnes".

The effects of the tug age need to be further considered where the propulsion system is hybrid and the output power to the shaftline is given by contribution from both the engine and the electric motor supplied by battery.

The battery depletion due to ageing affects the battery performance and where the BP has been tested considering the contribution from the battery in powering the e-motor, then this value could need to be amended once the installation has some years of service.

As a general discussion it is evident that there is a lack of consistency within the industry in the manner in which the towline force as a function of time is used during the bollard pull testing to define the certified value.

The provisions for bollard pull certification at more than one engine setting, including the overload condition, appears ideally suited for accommodating the requirements of the hybrid powered tug in which the diesel and battery power will be significantly greater than the diesel only power, but will be more transient in nature. A possible approach to the needs to include the e-motor contribution to the tug

propulsion power when battery supplies it is to define two different Bollard Pulls as follows:

**Diesel Only Bollard Pull.** This will use just the diesel engine(s) running at the manufacturer's recommended maximum continuous rating and at which the bollard pull test will be carried out. Lloyd's Register's present definition of Steady and Maximum Bollard Pulls and the conduct of the bollard pull trials will be applied as per the 1992 Guidance Information. The term 'Diesel Only' may need refinement based on the individual application as, for example, the propulsion system may be Diesel-Electric in the case of propulsors;

**Hybrid Bollard Pull.** This will use the Diesel/Diesel-Electric power plus that available from the Batteries. It is proposed that the steady and maximum pulls as per Lloyd's Register's 1992 Guidance can be used and be recorded on the certificate as the Steady Hybrid Bollard Pull and Maximum Hybrid Bollard Pull. Clearly, this will be a time limited and the duration for which the Hybrid mode can be usefully applied shall also be stated on the certificate.

In order to accommodate the potentially differing hybrid operating modes, bollard pull testing throughout hybrid operation may be required with an entry on the certificate of the Steady Hybrid Bollard Pull and Maximum Hybrid Bollard Pull – as defined in LR's Guidance – at the start and conclusion.

It is important that the Hybrid Bollard Pull is not seen as such a marketing exercise. The optimal way to achieve this will be through physical demonstration by testing and appropriate entries on the tug's bollard pull certificate.

## **CONCLUSIONS**

There are a number of reasons attracting the harbour tugs design to the latest energy efficient technologies adopting integration of machinery and electrical equipment. In

particular the Electrical Energy Storage technologies that are quickly developing in a number of vehicle applications give the chances for more efficient propulsion systems and this can be exploited to reduce emissions in ports. Even if the concept of hybrid and integrated power systems and the use of new EES technologies introduce additional risks that are not covered by existing Rules and Regulations, the industry is considered mature as a number of real applications have been already delivered and are in operation for many years. The experience gained with such real applications can then be used to identify technical issues and develop prescriptive Rules and Regulations that simplify the process to certify systems and class vessels. Interesting scenarios are also open to the consideration of how power performances of tugs are enhanced and how to standardise the certification and the evidence of such improved performance. Industry and stakeholders have big opportunities in promoting Joint Industry Projects to address such challenging scenarios.

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