

Entering a new era for electrical vessels on inland waterways

Entrando en una nueva era para los buques eléctricos en las vías navegables interiores

DOI: <https://doi.org/10.25043/19098642.230>

Jean Michel Chatelier ¹

Abstract

The shipping industry is moving towards quickly decarbonizing its assets. There is also a growing demand for new urban transportation (passengers, building materials, and equipment) with zero-emission propulsion. Zero-emission propulsion is available today for sustainable transport. The common size of inland navigation vessels offers the opportunity to implement innovative technologies earlier than seagoing ships. There is clearly a wide range of solutions available, with their own set of pros and cons. Batteries and fuel cells are part of a growing list of solutions to carbon-neutral or zero-emissions shipping. They become a strong choice and can be successfully combined with alternative fuels. As a result, electric and hybrid vessels are currently among the most important developments in the inland navigation sector. Bureau Veritas, as one of the major classification societies, proposes a brief review of state-of-the-art electrical solutions, considering available technologies, safety constraints and operational challenges, bringing to light its experience in electrical vessels, both in new constructions and conversions as well as in vessels in service. Although many parameters must be considered, the conclusion confirms that there are electrical solutions already suitable for a range of vessels and it is also possible to pencil the near future in association with new infrastructure and supply chain.

Key words: battery, fuel-cell, hybrid, safety, operations.

Resumen

La industria naviera se está moviendo rápidamente hacia la descarbonización de sus activos. También existe una creciente demanda de nuevos medios de transporte urbano (pasajeros, materiales de construcción y equipos) con propulsión de cero emisiones. La propulsión de cero emisiones está disponible hoy en día para el transporte sostenible. El tamaño común de las embarcaciones de navegación en aguas poco profundas ofrece la oportunidad de implementar tecnologías innovadoras de forma más práctica que en los buques oceánicos. Claramente, hay una amplia gama de soluciones disponibles, cada una con sus propias ventajas y desventajas. Las baterías y las celdas de combustible forman parte de una lista creciente de soluciones para la navegación neutra en carbono o de cero emisiones. Se convierten en una elección sólida y se pueden combinar con éxito con combustibles alternativos. Como resultado, los buques eléctricos e híbridos son actualmente uno de los desarrollos más importantes en el sector de la navegación en aguas poco profundas. Bureau Veritas, como una de las principales sociedades de clasificación, propone una breve revisión de las soluciones eléctricas de vanguardia, teniendo en cuenta las tecnologías disponibles, las limitaciones de seguridad y los desafíos operativos, destacando su experiencia en buques eléctricos, tanto en nuevas construcciones como en conversiones, así como en buques en servicio. Aunque se deben considerar muchos parámetros, la conclusión confirma que ya existen soluciones eléctricas adecuadas para una variedad de buques, y también es posible vislumbrar el futuro cercano en asociación con nuevas infraestructuras y cadenas de suministro.

Palabras claves: batería, celda de combustible, híbrido, seguridad, operaciones.

Date Received: November 21st, 2022 - *Fecha de recepción: 21 de noviembre de 2022*

Date Accepted: January 15th, 2023 - *Fecha de aceptación: 15 de enero de 2023*

¹ BUREAU VERITAS – Marine & Offshore Division. Antwerpen, Belgium. Email: jean-michel.chatelier@bureauveritas.com

Introduction

The need to decarbonise transport is already a priority for international institutions and the shipping industry is moving towards quickly decarbonizing its assets to reduce, or eliminate, greenhouse gas (GHG) emissions from ship operations. Many ferry operators have taken steps toward zero emissions by ordering partial or fully electric ships¹. Also, there is growing demand for new urban transportation, embracing passengers, goods, materials and even waste, with low air and water emissions.

Zero-emission propulsion is available today for sustainable transport. Potential alternative solutions over the long run embrace thermal engines and fuel cells and batteries, including hybrid installations. There is clearly a broad range of solutions available when it comes to achieving the environmental goals and compliance with future regulation, and each carries its own set of pros and cons.

The common size of inland navigation vessels offers the opportunity to implement innovative technologies earlier than seagoing ships. Batteries and fuel cells are part of a growing list of solutions to carbon-neutral or zero-emissions shipping. They become a strong choice and can be successfully combined with alternative fuels. Batteries may be used alone on board, or in parallel with existing generators (hybrid solution). As a result, electric and hybrid ships are currently among the most important developments in the maritime and inland navigation industries as part of efforts to limit GHG emissions and advance the energy transition.

Fuel cell technology is another expanding application to decarbonize shipping, competing in two weight classes: alternative fuels and clean electricity. Also, supply of electricity to vessels in port (Shore-to-Ship power) has become a key issue in the fight to reduce exhaust emissions in densely populated areas.

The paper proposes a brief review of state-of-the-

art electrical solutions, considering technologies, safety and operational challenges, bringing to light the experience of Bureau Veritas², as one of the major classification societies, in electrical vessels, in both new constructions and conversions as well as in vessels in service.

Technical Aspects

Battery

Batteries are the central part of the electric system which store the energy and release it according to the needs of the vessel. The main interest in batteries is to provide high power with optimized energy production, distribution, and consumption. (see Fig. 1).

From lead to lithium-ion batteries

Lead batteries have been the traditional batteries used to provide back-up power to ships. They are subject to longstanding rules for installation and maintenance and require low CAPEX investments. Lead batteries are dependable and recyclable, but they have relatively low energy density, they are rather heavy and bulky and there is no option of fast charging.

Battery technology is developing fast, especially Lithium-ion batteries, and it is widely used in current projects. Although they are commonly used as backup power, however they can enable ships to run in zero emissions mode, when batteries temporarily function as the only source of electricity, enabling ships to comply with strict port requirements and travel in environmentally controlled areas (ECA). Additionally, batteries can be used for “peak shaving”, taking over from onboard generator sets to deliver the peak load of energy.

Li-ion batteries design and characteristics depend on need for power or energy. They can be designed to meet demands for high energy/ low current/long discharge applications to those operating with very high-power pulse output, where they can match the performance of supercapacitors. Lithium-ion

¹ <https://www.electrichybridmarinetechology.com/online-magazines>

² <https://marine-offshore.bureauveritas.com/>

batteries are the best energy density on the market (200Wh/kg, five times lead acid and twice nickel cadmium) with low self-discharge.

Risk of uncontrollable thermal runaway exists, therefore an internal electronic control for thermal protection is needed. The battery management system (BMS) is an electronic system associated with a battery pack which monitors and manages in a safe manner its electric and thermal state by controlling its environment, and which provides communication between the battery system and other macro-system controllers, such as a power management system (PMS). The BMS is to be provided to monitor the modules, sub-packs, packs (voltage, temperature) and to control proper connection / disconnection of battery packs and sub-packs when in critical state.

There are several types of lithium batteries technologies, with various characteristics. Some technologies are known as safe, such as Lithium iron phosphate (LFP) and Lithium titanium oxide (LTO). LFP has high power density (W output / kg) and safety, medium cost and lifecycle, but lower energy density (Wh/kg). LTO presents high safety, long lifecycle, medium power density, but lower energy density and higher cost.

Charging

Energy is required to produce electricity used

for battery charging; therefore, the assessment of environmental footprint depends on how the electricity is produced.

C Rate is the current which described how fast the cell is charging or discharging, e.g., in theory, 1C means the cell can charge/discharge within one hour, 0.5C means charge/discharge within two hours. It is of importance to specify the C rate at design stage to suit the operational constraints.

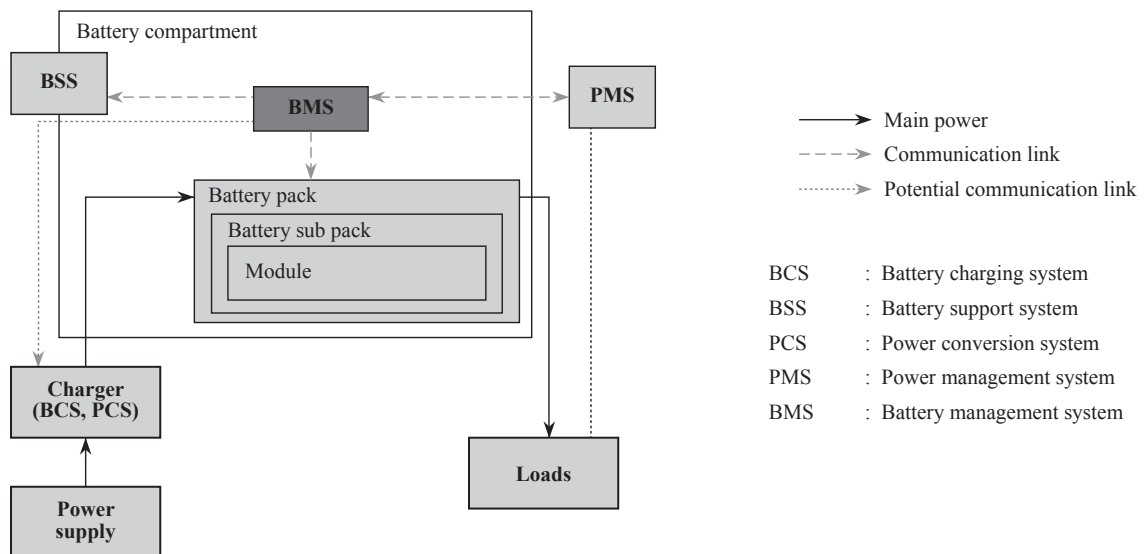
Fuel Cells

Principle

Fuel cells is a device which convert chemical energy from hydrogen (H₂) into electrical energy to create a direct current through the electrochemical reaction between hydrogen and oxygen from air with efficiency range between 35 and 55%. No energy is stored in the fuel cell but rather in the associated hydrogen container. Fuel cells offer one of the best efficiency-pollutant ratios. It emits only heat and water. If the fuel cell operates at a sufficiently high temperature, its waste heat may also be recovered in onboard heating systems.

To date, fuel cells have seen limited application in the marine industry, and installations and components have still to be adapted for the marine environment and approved for use on vessels to power propulsion or auxiliary power systems.

Fig. 1. Typical battery system.



In view of challenging storage and carriage of hydrogen, Liquid Organic Hydrogen Carriers (LOHC) provide significant advantages in terms of availability, recharging, and safety.

Types of fuel cell

Depending on the fuel and electrolyte, fuel cell technology covers a range of cells such as AFC (Alkaline Fuel Cell), PEMFC (Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Membrane), SOFC (Solid Oxide Fuel Cell) and DMFC (Direct Methanol Fuel Cell). The choice between these technologies will depend on parameters such as starting time, operating temperature, power, and lifetime.

PEMFC is the most used, but it uses only pure hydrogen and requires platinum as a catalyst. It is compact and runs at 80°C. For the time being, PEMFC appears to be the most used option for small applications. The axis of improvement would increase the temperature (up to 200°C) for better efficiency, while the lifetime could be increased.

SOFC is suitable for heavier power requirements. It is operated at high temperatures (800 – 1,000 °C) and requires a significant start-up time. It stands out with the advantageous feature of fuel flexibility since it is not limited to pure hydrogen.

Several possible hydrogen carriers (LOHC)

Methanol (MeOH) can be stored and handled easily at ambient conditions, and it can be produced from various sources such as low-cost biomass on a large scale. Using a mixture with 60% methanol and 40% water is less flammable than pure methanol and it can be converted into a hydrogen rich gas using a reformer that is a device that contains a catalyst and heat-exchanging surfaces for process heat transfer. Methanol reforming takes place typically at 220-300°C, it is an endothermic process, it needs additional thermal energy to drive the process. Also, advantage is that methanol has a much higher volumetric energy density than hydrogen and therefore permits fuel tanks of more compact dimensions.

Ammonia (NH₃) has a long-term track-record of successful handling and distribution, worldwide.

Liquid ammonia can be stored in large tanks at room temperature. Compared to hydrogen, ammonia is easier to be transported. It is much more energy efficient and much lower cost to produce and store. It can be directly used as fuel in SOFC where it is cracked into hydrogen and nitrogen in the anode. The decomposition of ammonia into nitrogen and hydrogen increases with increasing temperature. Already from 400 °C, this decomposition is nearly complete. LNG can be also an option, but it would be suitable to LNG tankers.

Combination of batteries and fuel cells

Usually, fuel cells are not installed alone on board, and a normal main source of power is installed, usually batteries. To date, fuel cell is not able to supply a sizeable ship alone. The dynamic of the fuel cell is not enough and, due to its intrinsically characteristics, it is not able to face the load impact coming from the starting / stopping of large auxiliaries (voltage variation, frequency variation in AC- Alternating current -). In combination of fuel cells and batteries, the high discharge rate of batteries can compensate for the low dynamic of the fuel cell discharge current, the fuel cells deliver a continuous current used to supply the vessel and charge the batteries.

Hybrid solutions

By definition, “hybrid” is of mixed character, a composition of different elements, where each of it can commonly serve propulsion and services.

Apart from common diesel-electric system, there are two main types of electrical hybrid, hybrid propulsion and hybrid production.

Hybrid propulsion

- Parallel hybrid concept: the electrical motor is fitted in parallel of the propeller shaft. Either the thermal engine or the electrical motor can be used (or both), depending on the needs (e.g., urban operation, manoeuvre).
- The serial electrical hybrid: the electrical motor is fitted in series of the propeller shaft, avoiding mechanical loss due to reduction

gear. The vessel can operate at low speed on electric mode only.

Hybrid production

Batteries are associated, wired in parallel with generator. There are three power management modes:

- Load smoothing mode, where the energy storage system (ESS) is charged and discharged all the time to compensate for the network load variations. This will result in limited load fluctuations of the main generating sets, allowing optimized fuel consumptions and reduced exhaust gas emissions.
- Peak shaving mode is dedicated to instant power demand. The purpose is to supply peaks of a highly variable load (e.g., during manoeuvring) and to avoid the connection of an additional main generating set.
- Enhanced dynamic mode is mainly relating to gas fuel or dual fuel generator sets. In case of sudden load increase, the ESS instantaneously supplies the corresponding power demand, thus enhancing the generator dynamic performance, and, for dual fuel engines, preventing the possible switch-over to fuel oil due to ramping-up.

Commonly, hybrid systems are based on diesel-electric system coupled with battery system. To reduce gas emission, diesel engines would be replaced by alternative fuel engine, notably LNG (or CNG) or biofuels, same as vessels fitted with conventional thermal engine propulsion systems.

Safety Aspects

Battery

The challenge of thermal runaway

The primary safety challenge for battery-powered vessels is the issue known as “thermal runaway”. Thermal runaway occurs in situations where an increase in temperature changes the conditions, either from a high current discharge rate or proximity to external heat sources. This can cause a chain reaction, creating a large-scale conflagration

that can damage vessels and threaten passengers and crew.

The three major possible consequences in case of thermal runaway:

- Flammable/toxic gas emission, possibly with bursting generating mechanical hazards.
- Flame ignition, and possible flame propagation in the cells or batteries casing and packaging.
- Heat emission and thermal runaway propagation from cell to cell or battery to battery, in absence of flames.

Those specific risks must be mitigated and there are some additional safety measures such as appropriate ventilation (especially when hazardous areas may be created), protection against water ingress and leakage in battery compartment, protection against electrostatic hazard, gas detections, fire protection and fire-extinguishing system suitable to the battery type.

Regulations

To mitigate risk, specific rules and standards are used to test batteries, such as IEC 62619 and 62620, while additional safety measures can be applied, such as Battery Management Systems (BMS). BMS monitors the voltage, current and temperature of battery modules, packs and sub-packs, and controls the proper connection and disconnection of battery packs and sub-packs.

Beyond providing critical safety information, BMS also enable ship operators to optimize energy use and availability, and to increase battery lifetime.

The major IACS³ classification societies have developed several rules related to battery systems which reflect the latest technical and safety developments in order to limit risk, both for the battery itself and onboard integration.

Manufacturers must carry out a risk analysis, including risk evaluation for sensor failure, internal and external short-circuiting, thermal runaway, fluid leakage, and possibility of gas release (toxic

³ <https://iacs.org.uk/>

or explosive). Shipyards must also perform comprehensive risk analysis, assessing ventilation systems, hazardous areas, and energy storage system spaces, to reduce risk and demonstrate that battery-powered ships are safe.

Bureau Veritas currently offers the notation “Battery System” for battery-powered vessels, covering safe installation and use of batteries, by providing safety testing and risk analysis before integration onboard, and offering a standardized approach to risk management. This notation is mandatory when the ship is relying only on batteries for propulsion or electrical power supply for main sources. Battery cells and battery packs must be type-approved with prototype tests conforming to a national or international standard. The type of approval must cover both the battery pack and the BMS. The Rules book NR320 “Certification Scheme of Materials and Equipment for the Classification of Marine Units” must be applied.

The fire-extinguishing system must be suitable for the battery type. There are also specific requirements for ventilation when using large-vented batteries.

When size of compartment permits, floodable battery compartment, in case of fire, would allow to stop the overheating escalation process. Stability calculation relating to the flooded condition would be required.

Hydrogen fuel cells

Hydrogen has one of the widest explosive/ignition mix ranges with air, falling at the extreme end as low as 4%. Special care is required when handling hydrogen as it is flammable, explosive, and prone to leak. Hydrogen application in shipping entails specific procedures in terms of transportation, bunkering, storage at high pressures or very low temperatures, and use.

Maritime stakeholders developing and using fuel cells must carefully assess the risks associated with their design, construction, installation, and operation. Specific safety requirements must be met to receive certification for fuel cell systems, and a range of risk assessments are required in

order to limit the risk of explosion, fire outbreaks, and the spread of toxic chemicals.

As with batteries, specific rules and standards are used to test the fuel cells, and a risk analysis of installation must be performed to assess the ventilation systems, hazardous areas, and fluid leakage. This risk analysis must cover installation, but also gas storage and supply piping.

Bureau Veritas has developed the Rule book NR547, “Ships using Fuel Cells”, to cover fuel cell technologies which are adapted to multiple alternative fuel types, each with their own risk profile.

NR547 focuses on the fuel cell system and is to be used in conjunction with several other Rule Notes for alternative hydrogen carriers, including methanol (NR670), LNG (NR529), and ammonia (NR671).

An extensive range of risk assessments must be carried out to be granted the “fuel cell” notation, including HAZID (hazard identification) study of fuel cell spaces, HAZOP (Hazard and Operability) study of fuel cell power system, and FMECA (Failure Mode, Effects & Criticality Analysis) analysis of fuel cell power installation when used for essential services.

The functional requirements are based on fail-safe design principles (minimize hazardous areas and ignition sources, arrangements to sustain or restore operation, shutdown arrangement, fire detection, fire protection, etc.).

Electrical hybrid

Hybrid design allows multiple solutions where the alternative fuels and technologies can be combined. The regulations and the classification Rules applicable to each part of the complete system would be superimposed to cover the risks generated by each fuel or technology.

At Bureau Veritas, all the requirements for assignment and maintenance of each class notation are given in the Rule book NR467 (“Rules for the classification of steel ships”).

Thermal engine and batteries

The notation “Electric Hybrid” caters for vessels using a combination of diesel engines and batteries used to supply the electric propulsion and/or the main electrical power distribution system of the vessel.

With “Electric hybrid” notation, the ESS is not considered as forming part of the main source of electrical power and it remains independent of the emergency source or transitional source of power. A Failure Mode and Effects Analysis (FMEA) demonstrates the availability of ship propulsion and main electrical source of power in case of failure of the ESS.

The notation “Electric Hybrid” must be completed with either:

- “PM” for Power Management mode (load smoothing mode, peak shaving mode, enhanced dynamic mode).
- “PB” for Power Back up mode where the ESS is permanently connected to the main electrical power distribution system of the ship and is able to deliver power immediately in case of failure of one main generating set.
- “ZE” for Zero Emission mode where the ESS is temporarily the only source of power connected to electrical network. The ZE mode, unlike the PB mode, is activated intentionally.

Thermal engine and electrical engine

The notation “Hybrid Mechanical Propulsion” may be assigned to vessels provided with a propulsion plant which combines diesel mechanical system and electric system. It provides requirements for remote and local control of both propulsion and switch over from one propulsion type mode to another one. The notation does not require battery.

The additional notation AVM is relevant to systems enabling the ship to carry on limited operations when single failure affects propulsion or auxiliary machinery or when an external event such as fire or flooding involving machinery spaces affects the availability of the machinery. The notation is complete with the system (*i.e.*, Alternative propulsion, Duplicated propulsion or Independent propulsion).

Operational Aspects

Battery

Lithium-ion battery

Shipowners and operators anticipated lower prices thanks to improved technology and increased competition among manufacturers. Indeed, the average cost of lithium-ion batteries has declined by 89% since 2010, falling to just \$132/kWh in 2021⁴. It was estimated that the average price for battery packs would fall to \$92/kWh by 2024. Presently, that forecast seem increasingly unlikely. The cathode needs lithium, nickel, and cobalt, which prices skyrocketed beginning in late 2021. Some experts expect about a 10% rise in 2022, even a jump of 20% year over year⁵.

Ships need to recharge their batteries by connecting to the electrical grid in port. This means ports must have the suitable installations and electrical capacities, coming from renewable sources. Batteries can also be charged using onboard generator sets, using decarbonized fuels.

Li-ion batteries are preferred but they suffer from ageing and there are additional safety concerns. One of the challenges is to increase the energy density and to manage the risk of thermal runaway and explosion. There is also the question of sustainable recycling.

Beyond providing critical safety information, BMS also enables ship operators to optimize energy use and availability and increase battery lifetime.

There are other factors that contribute to the cost of lithium-ion systems. The cells make up only 40-50% of overall battery pack cost. BMS is significantly expensive because it requires more flexibility and mechanism to shift energy to and from the battery frequently and in a wide range of operating conditions. These factors increase the specific cost of the battery pack. Large power systems level up in BMS design. For instance, a 1200V system could be monitoring 320 cells

⁴ Source: Full Stack Economics Dec.13, 2021 & BloombergNEF report 2021.

⁵ Source: Emerging Tech Brew April 13, 2022.

with multiple stacks in parallel plus an overall management system to aggregate all the stacks into a single system representation. A BMS can cost round \$10,000 depending on the nominal voltage of the battery stack and quantity of parallel stacks⁶.

Swappable containerized batteries

The swappable containerized batteries system, where the electrical output is either AC voltage or DC voltage, may help accelerate electrification of inland waterway traffic with a lower investment for shipowners and operators. It is notably interesting when operation constraints do not give enough time for recharging.

Roughly, considering the volume of a 20' container, 1 MWh of batteries - with DC voltage supply - or 3 MWh of batteries - with AC Voltage - can be installed.

A 3 MWh containerized battery pack can be integrated on board within minutes when using a swap-and-carry concept.

A battery container needs to fulfil all regulatory requirements from structural and fire integrity aspects.

The distance between swaps is the key point. There is a necessity to build a network of stations along the route and pay the associated cost for the system. For instance, a battery container with a capacity of 2 MWh could be a solution for an electric vessel that need power about 500-1,000 kW, provided the route allows for 2-4 hours of work between swaps.

Fuel cells

Hydrogen is increasingly viewed as a contender among alternative fuel solutions, receiving increased investment. It has gained momentum in recent years as technology matures, and the price gap with conventional technologies narrows.

The main advantage of fuel cells is the high energy density of hydrogen. In electrical terms, the energy density of hydrogen is equal to 33.6 kWh of usable

energy per kg, versus diesel which only holds about 12–14 kWh per kg.

Meanwhile, creating hydrogen by splitting water by electrolysis is a costly process. Approximately, 50 kWh of electricity is needed to produce 1 kg of hydrogen that subsequently yields only 33 kWh of energy⁷.

There is a high initial cost of hydrogen installation, and storage and transport are complex due to hydrogen's low energy density by volume and special pressure/temperature requirements (storage under high pressure, 350 bar even 700 bar, or cryogenic, -253°C).

Green hydrogen produced with renewable resources costs between about \$3/kg and \$6.55/kg, according to the European Commission's July 2020 hydrogen strategy⁸, while the cost of blue hydrogen, which pairs carbon capture with steam methane reformation of natural gas, is estimated at about \$2.40/kg⁹. Projections show that renewable hydrogen production costs could decline to \$1.4 to \$2.3 /kg by 2030¹⁰. At-scale, international distribution could arrive by 2030 at total costs of \$2-3/kg (excluding cost of production).

One must consider the fuel cell system cost and the hydrogen fuel cost. Manufacturers of fuel cell system estimate a current price of € 1,800/kW with a price reduction down to € 1,000/kW towards 2025¹¹. The storage tank itself would cost about 400 €/kg in 2024 and 300 €/kg in 2030¹² but in addition to the hydrogen tank, there are costs related to valves and piping, bunkering interface, instrumentation, fire insulation, detectors and firefighting systems. It is assumed

⁷ Source: Prof. Werner Antweiler, University of British Columbia - Sep.18, 2020.

⁸ Source: Briefing towards climate neutrality, European Parliament – April 2021 [https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689332/EPRS_BRI\(2021\)689332_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689332/EPRS_BRI(2021)689332_EN.pdf).

⁹ Source: Reglobal.co, “The Risks of Investing in Blue Hydrogen for Europe” – May 25, 2022.

¹⁰ Source: Hydrogen Insights Report 2021 - Hydrogen Council, McKinsey & Company.

¹¹ Source: “Energy and cost analysis of a hydrogen driven high speed passenger ferry” Aarskog Fredrik G., Danebergs Janisa, Strømgren Trondb, Ulleberg Øysteina – July 8, 2020.

¹² Source: Clean Hydrogen Joint Undertaking (EU) - Strategic Research and Innovation - Agenda 2021 – 2027.

⁶ Source: EDN (<https://www.edn.com/>)

that the additional costs are in the same order as the tank itself.

Most of the time, the fuel cells are not maritized yet since they come from the car industry where proven equipment have been developed. Equipment approval and installation on board must be adapted to meet the class requirements.

Once fuel cells are integrated onboard, ship operators must safeguard crew and ensure appropriate training for proper handling of fuel cell equipment.

Hybridization with batteries is expected to increase the lifetime of the fuel cell system significantly.

If one of the LOHC is used instead of pure hydrogen, the technology and equipment must be suitable for the fuel, and the specific regulation must be complied with. Investment depends on the type of equipment corresponding to the fuel, including safety aspects, and operational costs are dependent on availability of bunker stations.

Some manufacturers think also about using a hydrogen version of swappable containers.

Hybrid solutions

There is a multitude of solutions, each of them with its own advantages and disadvantages, depending on the technology and fuel. From an environmental point of view, the efficiency of the solution would imply using biofuel – made from sustainable source – or natural gas.

Electrical hybrid solution may save on fuel, however the expected reduction in consumption depends on the engine load. It would be more significant during manoeuvres (*e.g.*, ferries).

Power in port

Increasingly, ships are connecting to a green energy grid in port, thereby completely eliminating exhaust gas emissions. Power installations at berth are technically sophisticated and must provide enough power to supply several vessels simultaneously.

Distribution systems and power receptors must also be harmonized so that a ship can connect in each port with its own onboard equipment, while the installation must also cater for many different types of vessels.

In order to guarantee the effective safety and functionality of installations, there are appropriate technical standards, depending on the nominal power of the shore installation, *e.g.*, European Norms EN15869-1: 2019, EN15869-3, EN16840, as well as Bureau Veritas' Rules. The additional class notation "HVSC" (High-voltage shore connection systems) may be assigned to ships fitted with electrical and control engineering arrangements allowing operation of services by connection to an external high-voltage electrical power supply in port. The requirements for the assignment of this notation are given in NR557 "High-Voltage Shore Connection Systems".

Conclusions

There currently exists no single substitute to the diesel engine. There is obviously a large panel of solutions to go toward the environmental goals and to comply with the related regulations to come, if not already in force. Operators must make their choice depending on vessel type and operational constraints, while also anticipating future fuel alternatives, availability and pricing, and managing challenges of safety and regulatory requirements.

Electrical propulsion is increasingly emerging as an alternative solution. Battery systems, fuel cells, and hybrid are solutions which can be adopted in combination with other technologies and alternative fuels to achieve crucial reductions in pollution, noise, maintenance costs and fuel consumption. Those solutions are set to play an important role in the shift to sustainable shipping, especially on those vessels transiting waterways and estuaries, travelling short and fixed distances, such as ferries and vessels engaged in harbour operations, but also those sailing on waterways benefiting from suitable infrastructure and designed for fast recharging or swappable battery containers.

Battery

The battery market is now nearly mature, and regulations are well established, with both IEC standards and classification rules. The market for battery systems of lithium-type is increasing, with a growing number of vessels in operation or under construction (round 40 vessels have been approved by Bureau Veritas the last two years).

For small-to-medium sized ships on short-haul voyages with multiple port calls – such as passenger ferries, tugs, and specialized vessels – using batteries to store energy may be a viable option.

As progress is made and economies of scale are triggered by the uptake of the technology by terrestrial transportation, the cost of batteries will become more favourable. However, extra cost would remain about safety construction and equipment as well as for battery management.

The positive effect on the environment will depend on how electricity used for charging batteries is produced, either from shore grid or generator on board.

The swappable container solution could be an interesting option, with few adaptations of the deck arrangement, mainly for vessels operating short distances, but it would require an extensive network of stations for vessels sailing long haul.

Fuel cells

Hydrogen fuel cells are also developing quickly, and they could also be serious contenders for vessels that require limited autonomy. So far, the adoption of fuel cells has been hindered by their short service life and price.

Also, the majority of these cells are not adapted yet for marine and the climate for type approval remains challenging. PEMFC seems to offer a better proven time of experience. For the moment, some innovations were approved considering the fuel cells as “non-essential service” and it has been focused on the safety aspect only (risk of gas leakage, explosion). It provides experience in service, and it

gives the opportunity to the various manufacturers to prepare for Type Approval Certificate which is the final target.

When it comes to hydrogen, storage remains a technical obstacle that will be expensive to solve in the short term. Currently, there is almost no infrastructure in place for hydrogen bunkering and operations made to date have used custom-made truck bunkering. Cost of green hydrogen would decrease when more production installations are developed.

There are other hydrogen carriers, each of them with their specific safety challenges and regulations. Also, the choice would depend on availability of bunkering stations and price, which is a key parameter that operators have to consider when investigating a fuel to evaluate a vessel's future OPEX.

While fuel cells are not able to withstand the load impact of activating/deactivating large power consumers and may generate excessive onboard voltage and frequency variations (when AC current is used), the batteries instead can deliver a high current in short time. A combination of batteries and fuel cells may offer great flexibility, with the fuel cells delivering a continuous current which is used to supply the vessel, if maximum power output is needed, or to charge the batteries. This combination also reduces charging time at port.

Hybrid solutions

Electrical hybrid solution may be a valuable investment in conversion of existing vessels by saving on fuel, however the expected reduction in consumption depends on the engine load. It would be more significant during manoeuvres, therefore choice for electrical solution must integrate the manoeuvring time among the operations.

Combination with batteries can provides flexibility and possibility to operate with zero emission in harbour and urban areas.

Availability and cost of alternative fuels, to reach the low emissions goal, remain the key point.

Shore connection

It is developing increasingly fast in many harbours and urban areas, following state policy and decision of major municipalities to eliminate easily gas emissions in densely populated zones.

Table 1 is a simplified synoptic summary of the main electrical solutions together with the capabilities offered by the various options and the associated difficulties that generate the challenges to be taken into account when considering a new construction or a conversion.

Table 1. Summary of electrical solutions on inland waterways.

Summary of electrical solutions on inland waterways							
Technology	Capabilities			Status	Difficulties		
	Environmental impact	Technical	Operational		Technical	Safety	Operational
Battery	<ul style="list-style-type: none"> Depend on the charging mode Zero emission mode 	<ul style="list-style-type: none"> Best energy density Low self discharge Various C-Rate Swappable containers 	<ul style="list-style-type: none"> Small-to-medium sized ships Mainly for vessels operating short distances 	<ul style="list-style-type: none"> Nearly mature Cost would decrease Increase the energy density Manage the risk of thermal runaway Growing number of vessels Charging network or swap stations 	Suffer from ageing	<ul style="list-style-type: none"> Thermal runaway: Specific safety measures Risk analysis Floodable compartment 	<ul style="list-style-type: none"> Cost (battery + BMS + extra safety equipment) Electrical grid in port Container: Adaptation of the deck arrangement & distance between swaps
Fuel Cells	Best efficiency-pollutant ratio	<ul style="list-style-type: none"> High energy density of hydrogen Fuel flexibility: LOHC (SOFC) - Methanol, Ammonia - and possible mixture (water) 	<ul style="list-style-type: none"> Small applications Vessels that require limited autonomy Waste heat can be recovered Combination with batteries 	<ul style="list-style-type: none"> Adaptation to maritime environment Technology is maturing Improvement: temperature (PEMFC) Price would decrease Hydrogen storage remains a technical obstacle Cost of green hydrogen would decrease Swappable containers under study 	<ul style="list-style-type: none"> Limited power Hydrogen: 50 kWh of electricity to produce 33 kWh 	<ul style="list-style-type: none"> Hydrogen is flammable, explosive, and prone to leak. Risk analysis regarding installation, gas storage and supply piping 	<ul style="list-style-type: none"> Hydrogen transportation and storage Additional safety measures Limited ability to load impact High Capex Short service life Infrastructure for bunkering Start-up time (SOFC)
Hybrid solutions	<ul style="list-style-type: none"> Reduction in consumption depends on the engine load Depends on fuel (bio-fuel or natural gas) Reduced exhaust gas emissions Possibility to operate with zero emission 	<ul style="list-style-type: none"> Hybrid propulsion / hybrid production Allows multiple solutions where the alternative fuels and technologies can be combined Solutions with no battery 	<ul style="list-style-type: none"> Flexibility Batteries may take over from generators 	<ul style="list-style-type: none"> Mature Alternative fuels under development 	<ul style="list-style-type: none"> Diesel engines would be replaced by alternative fuel engines (e.g., LNG, CNG or biofuels) 	<ul style="list-style-type: none"> Depend on fuel Failure Mode and Effects Analysis (FMEA) 	Availability & cost of alternative fuels
Shore connection	No exhaust gas emissions in port	Supply power needs	No energy production	Developing increasingly fast in many harbours and urban areas	<ul style="list-style-type: none"> Must be harmonized so that: ship can connect in each port Port installation can cater for all vessels. 	High voltage	Standardized connections

Bibliography

Bureau Veritas Rules and Guidelines (available at: <https://marine-offshore.bureauveritas.com/rule-notes-and-guidance-notes>):

- Rules for the classification of inland navigation vessels, NR217, Jun 2021.
- Rules for the classification of steel ships, NR467, Jan 2023.
- Certification scheme of materials and equipment for the classification of marine units, NR320, Jul 2022.
- Gas-fuelled ships, NR529, Jul 2022.
- Ships using Fuel Cells, NR547, Jan 2022
- High-voltage shore connection system, NR557, Jan 2010.
- Methanol & ethanol fuelled ships, NR670, Aug 2022.
- Ammonia-fuelled ships, NR671, Jul 2022
- Requirements for survey of materials and

equipment for the classification of inland waters-operated vessels / units, NR544, Nov 2021.

- VNF, Voies navigables de France, Direction du Développement, 62408 Béthune, France: “Les cahiers techniques de BATELIA“ (Bureau d’Assistance Technique et Logistique pour les Industriels et Artisans), including:
 - CAHIER TECHNIQUE N°1, Propulsion hybride pour bateaux fluviaux » - Édition avril 2018.
 - CAHIER TECHNIQUE N°2, Propulsion hydrogène pour bateaux fluviaux » - Édition janvier 2020.
- “Hydrogen Insights - A perspective on hydrogen investment, market development and cost competitiveness” - Hydrogen Council, McKinsey & Company - February 2021.
- “What role does hydrogen have in the future of electric mobility?”, Prof. Werner

Antweiler, Ph.D., University of British Columbia – Sep.28, 2020.

- Electric & hybrid marine technology international at: <https://www.electrichybridmarinetechology.com/>
- "Creating a rule framework for the green revolution in shipping industry" Internal & territorial waters, Ship Science & Technology, vol.15, nr.19 (page 71) – July 2021 - Jean Michel Y. Chatelier.
- "Shaping a better maritime world", Matthieu de Tugny, President Bureau Veritas Marine & Offshore – 2022.
- "Alternative fuels outlook for shipping", White paper, Bureau Veritas – Sept. 2022.
- "Inland waterways fast-track green transport", Bureau Veritas magazine – Oct.11, 2022.
- "Fuel cells – tailor-made for inland waterways?", Bureau Veritas magazine – July 12, 2022.
- "Decarbonizing ports for the 21st century", Bureau Veritas magazine – June 2, 2022.
- "What well-to-wake decarbonization means for shipowners", Bureau Veritas.
- "Power in port", Bureau Veritas magazine – April 1, 2022.
- "Regulating hydrogen fuel for inland navigation vessels", Bureau Veritas magazine, Dec. 22, 2021.
- "What sustainability means for inland navigation vessels", Bureau Veritas magazine, May 10, 2021.
- "Client corner: battery-powered ships FAQ", Bureau Veritas magazine, Feb.24, 2021.
- "Entering a new era for battery-powered ships", Bureau Veritas insight, June 22, 2021.
- "Future marine fuels: pathways to decarbonization", Bureau Veritas insight, Oct. 7, 2019.