

Acceptability of Decarbonization Technologies available for Offshore Support Vessels

^[1]Gireesh Mukundan, ^[2]K Sivaprasad, ^[3]Satheesh Babu P K

^[1]Ph.D Student, Department. of Ship Technology, Cochin University of Science and Technology, Cochin, India

^[2]Professor, Department of Ship Technology, Cochin University of Science and Technology, Cochin, India

^[3]Head of the Department, Associate Professor, Department of Ship Technology, Cochin University of Science and Technology, Cochin, India

Abstract: - Offshore support vessels (OSV) and similar vessels utilized in supporting offshore oil & gas activities have an operational profile, that is different to that of seagoing cargo ships. Energy efficiency technologies that are suitable for commercial ships engaged in long voyages are non-viable for OSVs. However, the highly fluctuating load characteristics of the OSVs makes them highly suitable for certain other technologies like Variable frequency drives and shore side electricity, along with other solutions utilizing Biofuels, hydrogen fuel, methanol-based solutions and so on. This paper shortlists the technologies that contribute to decarbonizing the OSV sector based on their techno-commercial viability for use on OSVs. The criteria based on which the various stakeholders in the industry select the suitable technology on their ship are identified and defined. A survey is conducted among industry stake holders to assess the importance that they give to the criteria. Acceptance of these technologies in the industry is assessed by formulating an Acceptability index (AX) based on the survey conducted. A.X thus arrived at, can be used by the industry as a reference for selecting suitable options.

Keywords: decarbonisation, efficiency, OSV.

1. Introduction

Trade between nations is largely dependent on transportation of goods from their source of production to the consumers. Sea transportation plays a major role in facilitating trade. When compared to other modes of transport, sea transportation of goods requires the lowest fuel consumption. As technology conquers new frontiers shipping is venturing into more hostile parts of the oceans, to greater depths to extract resources and enable world economic growth.

Transporting cargo using ships is the main way to do it with least amount of pollution. Yet pollution caused by ships is significant. Ships release nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon dioxide and particulate matter (PM) into the atmosphere. [1]. According to the Fourth IMO Green House Gas Study of 2020, the greenhouse gas (GHG) emissions — including carbon dioxide (CO₂), methane (CH₄) and Nitrous Oxide (N₂O), expressed in CO₂e of total shipping increased from 977 million tonnes in 2012 to 1,076 million tonnes in 2018. The share of emissions from shipping has increased from 2.76% in 2012 to 2.89% in 2018. [1]. Ships also emit significant volumes of air pollutants such as Volatile Organic Compounds (VOCs), Carbon Monoxide (CO), and Particulate Matter (PM). In addition, the marine environment is also polluted due to release of chemicals from antifouling paints, oil spills, and leakages during routine ship operations.

1.1. Regulatory Actions for mitigation

In the recent decade, the shipping industry has started making concerted efforts to mitigate the increasing environmental regulations imposed by IMO through the implementation of operational strategies and the development of technologies. These technological efforts have indeed facilitated reductions in fuel consumption and consequently the pollutant emissions on a capacity basis (tonne-mile). However, the expectations from the global community have become much more intense, specifically on the shipping industry also.

The Paris Agreement, an international legal agreement on climate change was ratified by 196 parties at the United Nations Climate Change Conference (COP21) held in Paris, France, in 2015. The Convention entered into force on 4 November 2016 aiming for global average temperature” of 2°C below pre-industrial levels” and efforts to “limit temperature rise to 1.5°C above pre-industrial levels”. [2]

Coopting the shipping industry to the broad climate goals has been the foremost concern for international organizations. IMO and the European Union has initiated the decarbonization process by IMO defining their initial greenhouse gas strategy and ambitions and the EU defining the FuelEU Maritime, to decarbonize ships travelling within, to and from the EU [3]

The MEPC 80 session of IMO that concluded in July 2023, adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships. Further enhanced targets were finalized to reduce emissions. This revised strategy adopted an enhanced ambition to reach net-zero GHG emissions from international shipping close to 2050, a commitment to ensure an uptake of alternative zero and near-zero GHG fuels by 2030, as well as indicative checkpoints for 2030 and 2040. [4].

The MEPC session also discussed a basket of candidate mid-term GHG reduction measures, and adopted Life cycle GHG assessment guidelines allowing for a Well-to-Wake calculation, including Well-to-Tank and Tank-to-Wake emission factors, of total GHG emissions related to the production and use of marine fuels. An interim guidance on the use of biofuels was also released. [4]

1.2. Emissions from OSVs

Within the maritime industry, approximatively 90% of CO₂ emissions were transport-related in 2012, while non-transport service vessels such as tugs (2.7% of shipping emissions) or offshore vessels (2.9%) represent a limited share. [5]

Offshore trade is characterized by specialized supply chains. Offshore units range from shallow water jackups to semisubmersible drilling rigs or production rigs installed on the seabed. What they have in common is the need for logistics services, both to serve onboard staff and the production or exploration process. This complex supply chain is supported by Platform Supply Vessels (PSVs) that are used to transport the cargo or personnel between shore supply bases and the offshore installations. During exploration phases, mobile rigs and their multiple anchors need to be moved between oil or gas fields. For such purposes, specialized PSVs like the Anchor Handling Tug Supply (AHTS) vessel is used. Although the main power demand in PSVs is for their main propulsion, they also have major requirements for thrusters in station keeping during off-loading at the platforms, for bollard pull requirements, use of cranes etc. [6]

The most common intensity measure for GHG emissions currently being used in the shipping industry measures the emissions per ton-kilometers. The weight carried and the distance travelled are the main factors that drive the measurement of the emissions. [7] However while these may be applicable for cargo transport ships, their applications to the OSV sector would not be apt, considering the operational profiles of the vessels in this sector. Due to the variety of uses that a typical OSV is put into service for, identifying the right emission reduction measure requires a careful study of operators' requirements and vessel capabilities.

1.3. Objectives

This paper aims to identify decarbonization technologies that are suitable for OSVs considering their unique operating characteristics as mentioned above. Once that is accomplished, various criteria that form the basis of acceptance of these technologies are established. Each of the technology shortlisted are assessed on their effectiveness for each of these criteria. The importance attached to each of these criteria by the industry, is concluded based on a survey conducted among experience professionals. This forms the basis of generating an acceptability index of the decarbonization technologies studied herein.

2. Methodology

Transition and decarbonization of the energy sector require the utilization of new technologies and a mix of energy sources. Most of the alternative fuels that are considered for future applications are already known chemicals or products, nowadays used for other purposes. However, when used on ships, different fuels pose different challenges to address before it could be considered techno commercially viable to be used as a marine fuel. The safety, toxicity, fire hazard, storage, handling, infrastructure, distribution network, demand and supply are a few of the aspects that must be addressed.

Selection of a suitable decarbonization technology or the apt fuel for the OSV is a challenge faced by the owner or operator of the OSV. The decision making based on the below criteria is assessed as part of this paper.

In this paper, the decision-making criteria are defined separately for installation of Energy Efficient Technologies (EETs) on the vessels. The defined criteria take into consideration various aspects that could come into play in a stakeholder deciding to adopt the particular technology, like the technological maturity of the solution, the cost of implementation, the Green House Gas (GHG) reduction potential of the solution, the ease of installation and long term maintenance requirements after the installation.

In the case of adoption of alternate fuels for operating the vessels, the defined criteria for decision making have been selected as the Technological maturity of the fuel concerned, the availability of storage and distribution network for the fuel, its ability to be produced from renewable resources, the cost, the GHG reduction potential and the energy density of the fuel concerned.

2.1. Technological maturity

Selecting technologies with a focus on their technological maturity is one of the important criteria for effective CO₂ emissions reduction. This criterion hinges on the readiness, reliability, and proven performance of the technology under consideration. Mature technologies bring about Reliability and Performance Assurance and will be less prone to unexpected failures or performance hiccups. They will have undergone Real-world Validation: A mature technology has likely been deployed, allowing for comprehensive testing and validation. Emerging or experimental technologies often carry higher levels of uncertainty. Adopting a mature technology, reduces the risk associated with their adoption. Another important factor in adopting this criterion is regulatory Compliance and Public Acceptance. Mature technologies are more likely to have established regulatory frameworks governing their use. This provides clarity for all stakeholders' confidence in their deployment.

2.2. Availability of storage and distribution network

Availability of a mature storage and distribution network is another criterion chosen. This criterion revolves around the infrastructure readiness and accessibility of a given fuel. Here are several compelling reasons why prioritizing the availability of storage and distribution networks is of paramount importance. An extensive storage and distribution network indicates that the infrastructure for a particular alternative fuel is already in place. This eliminates the need for development of new facilities, which can be a significant barrier to the adoption of emerging fuels. A well-developed storage and distribution network ensures that the chosen alternative fuel is readily accessible to the consumers. Furthermore, an established storage and distribution network is designed to ensure a consistent and reliable supply of the alternative fuel for uninterrupted access minimizing the risk of supply chain disruptions.

2.3. Cost of implementation

Prioritizing the cost of implementing a solution is a crucial criterion for all stakeholders when studying technologies for reducing CO₂ emissions. This financial consideration plays a pivotal role in determining the feasibility, scalability, and overall impact of an emissions reduction strategy. Budgetary Constraints plays a significant role in decision-making, especially when confronted with multiple solutions at differing maturity of advancements and effectiveness. Keeping an eye on the costs, allow for the implementation of a broader range of strategies. Cost-effective solutions are more likely to be competitive in the marketplace. The economic viability of emissions reduction technologies is essential for long-term sustainability. Cost-effective emissions reduction technologies offer a quicker and more tangible return on investment, making them an attractive option for stakeholders. Implementing expensive emissions reduction technologies can potentially lead to economic disruption. Thus, prioritizing the cost of implementing emissions reduction solutions is a strategic and practical approach as it combines the benefits of affordability, impact maximization, market competitiveness, and economic viability.

2.4. Efficiency of CO₂ emission reduction potential

The efficiency of CO₂ emission reduction potential is a critical criterion when evaluating technologies for mitigating climate change. This criterion assesses the effectiveness and output of the technology of fuel in question, in relation to its input, ensuring that resources are optimally utilized in the pursuit of greenhouse gas

reduction. Technologies with high efficiency in CO₂ reduction make the most effective use of available resources, ensuring that investments yield maximum environmental benefits. Efficiency often correlates with scalability, enabling the widespread adoption of the technology. Highly efficient technologies typically have a smaller environmental footprint compared to less efficient alternatives. This is particularly crucial when considering the full life cycle of a technology.

2.5. Ease of installation

Ease of installation or implementation of the technology is a crucial criterion when evaluating technologies for emissions reduction. This criterion focuses on the practicality and simplicity of deploying a given solution, ensuring that it can be adopted efficiently and effectively. It enables rapid deployment and can be put into action promptly, allowing for more immediate reductions in CO₂ emissions. Complex and time-consuming installations can disrupt existing vessel operations. Prioritizing technologies that are easy to implement helps to minimize the downtimes. Furthermore, complex installations may require specialized technical expertise, which can be a limiting factor. Technologies that are easy to install or implement are often more flexible in terms of scale. This adaptability is crucial for addressing emissions reduction. It combines the benefits of rapid deployment, reduced disruption, cost-effectiveness, and accessibility.

2.6. Maintenance requirements

Long term Maintenance requirements is a crucial criterion when evaluating technologies for CO₂ emissions reduction. This criterion focuses on the sustainability and durability of a solution over an extended period. Technologies that have low maintenance requirements are more likely to be sustainable and reliable. This ensures that the emissions reduction solution can continue to operate effectively on a longer term. Generally solutions with lower long-term maintenance requirements typically incur fewer costs over their operational lifespan. Complex and high-maintenance technologies may require extended periods of downtime for repairs or servicing. Prioritizing solutions with low long-term maintenance needs helps to minimize these disruptions, ensuring a more consistent and reliable emissions reduction strategy. Technologies with low maintenance requirements are more likely to operate at peak efficiency throughout their lifespan. This leads to higher overall performance and a more effective approach to reducing CO₂ emissions. High-maintenance technologies may require a significant amount of resources for repairs, replacements, or upgrades. Technologies with low long-term maintenance requirements help to conserve resources, aligning with sustainability goals.

2.7. Availability from renewable resources

Prioritizing the availability of alternate fuels from renewable resources and exploring the the potential for entirely renewable production is a pivotal criterion when evaluating options for reducing CO₂ emissions. A fuel sourced from renewable resources and produced using entirely renewable energy creates a positive impact on sustainability. It addresses both the environmental aspect of resource availability and the energy production process, contributing to a more comprehensive approach to emissions reduction. Fuels produced from renewable resources and utilizing entirely renewable energy sources have the potential to be carbon-neutral or even carbon-negative. Thus, the carbon emissions associated with their production and use can be fully offset by the carbon sequestration or avoidance, leading to a net reduction in CO₂ emissions.

2.8. Energy density

Energy density of alternate fuels, particularly when compared to fuel oil, is a crucial criterion when evaluating options for reducing CO₂ emissions. Energy density refers to the amount of energy that can be extracted from a given volume or mass of a fuel. Fuels with higher energy density contain more energy in a smaller volume or mass. This is particularly important in applications where space is limited, such as in ships and specifically for OSVs. This aspect is also critical in extending the range of the vessels and avoid frequent call at ports for refueling.

Fuels with higher energy density require less storage space. This can lead to cost savings, as it reduces the need for larger fuel tanks, especially where space is at a premium. Furthermore, most existing vessels are designed to handle fuel oils and alternate fuels with comparable energy densities will minimize the need for

extensive retrofitting. Thus prioritizing energy density, especially when compared to fuel oil, is a strategic and practical approach as it combines the benefits of space efficiency, extended range, and cost savings.

3. Decarbonization technologies and solutions for OSV sector

The below main Energy Efficiency Technologies (EETs) and alternate fuels available for implementation in the OSV sector are assessed in this paper.

Eight different technologies considered are retrofit of Variable Frequency Drives (VFDs), Cold Ironing, implementation of data driven decarbonization, using ultrasonic antifouling technology, installing energy storage solutions and hybrid retrofits, usage of additives and alternate fuel injection, installation of LED (Light Emitting Diode) lights and application of low friction paints

Five alternate fuels considered for vessel operations are LNG (Liquified Natural Gas), Methanol, Biofuel, Ammonia and Hydrogen

3.1. Retrofit of Variable Frequency Drives (VFDs)

There are many onboard ship systems which do not operate continuously. Many systems also do not require to be operated at full capacity most of the time. Examples would be cooling water pumps or ventilation fans. Electric motors of such systems consume more power when operated at lower speeds.

The electric motors when fitted with Variable frequency drives (VFD) helps it to operate more efficiently while in partial loads. This is applicable when the vessel is operating at slower sailing speeds or with having lower ventilation requirements. While requiring low demand, the motor runs slowly and the power consumed reduces in proportion. The reduction of pump speed will affect the electric power consumption to the power of three. For example, a reduction in the pump speed of 10% will save 27% of the consumed power.

Installation of VFDs for motors in ships is a technology that had been developed during 1960s, and the technology has since evolved to maturity. It has relatively low cost of installation. The installation of the system will result in low maintenance of equipment thereby reducing overall maintenance cost as well. It is highly effective for vessels having varying operational profiles like offshore support vessels. Savings can reach figures up to 20% for non-optimized vessels. It is relatively easy to install comparing many other EETs. Sometimes replacement of certain components are needed to suit the VFD drive. Fairly good knowledge on the process and system is needed in performing installation and maintenance. Normal visual inspections, regular cleaning and connection checks would be needed.

3.2. Cold Ironing

Cold ironing is the technology by which a ship berthed at a port can shut down or minimize the use of its generators, by utilizing power generation unit in the Port or from power plant that supplies to the port itself.

It is also called Alternative Maritime Power (AMP). Installation of the AMP, enables connection of the ship's power system with onshore supply grid. The electricity for onboard operations while at port is provided from external sources, enabling the diesel generators onboard to be shut off. AMP provides power for reefer containers, lights, refrigerators, air-conditioners, and other equipment on berthed ships. This directly reduces fuel consumption while at port, thus cutting off exhaust emissions and noise.

If the port avails its power supply from alternate energy sources, it offers a completely green energy solution to the ship while berthed at ports. Installation of AMP onboard ships generally involves installation of Cable Reels, Transformers, modifications to Main switch boards, Control panels for AMP etc.

The technology of installing cold ironing facility onboard ships is mature. However, until very recently, the facility to provide shore power has been available in very few ports. New regulatory forces that are in place, will push ports worldwide to implement the technology sooner or later. The installation cost is relatively high although lower than installing hybrid/Battery technology onboard the vessel. The technology demands heavy cost investment both on ship and shore. The GHG reduction potential for the concerned ship is less considering the investment made. Only hotel and port loading / unloading loads could be addressed with cold ironing. This will however be advantageous in reducing the CII, for applicable vessels. Individual components like the cable reels are big in size and need space optimization, especially for retrofits. The system reduces the operational hours of generators, thereby reducing overall maintenance to generators as well.

3.3. Data driven decarbonization

Data Driven Decarbonization is a term that is given to the process of analyzing an historical data of the vessel in order to reduce fuel consumption and emission. This involves installation of software and appropriate sensors onboard a vessel to enable data collection and digital management. For each vessel, a unique baseline can be created. This can be based on the vessel's historic performance, for every activity of the specific vessel. Since the software is able to analyze the performance of the vessel in a realtime, it is an important tool that helps owners and managers with effective energy management onboard.

A most important aspect of data driven decarbonization measures is to collect accurate data from onboard. This can be made possible through precise sensors and meters that can measure the required information. Once this is done, a software capable of combining the available data from the vessels with relevant baseline data sets is required to provide insight on the trends and suggest how to reduce fuel and emissions. Using this method, it is easy to analyze the effect of individual energy saving initiatives, or whole programs while also making fleet wide comparisons. Effective utilisation of the data driven decarbonization measures can reduce fleet fuel consumption by around 5-12 % [8]

The tremendous developments in the field of software technologies, data analysis and collection in recent years have made this technology well accepted within the maritime industry also. With Artificial Intelligence features, softwares and sensors will improve further in the coming years. It is a low-cost installation, mostly with an initial CAPEX and further periodical subscriptions from software providers. It is highly effective for vessels having varying operational profiles like OSVs. Savings can reach figures up to 20% for non-optimized vessels. It is very easy to install overall. Integration is needed with the vessel's existing data sources. Additional sensors / data sources could be implemented for customized requirements. Upgrades on software will be needed from time to time, that shall generally be part of the subscription.

3.4. Ultrasonic antifouling technology

Hull fouling increases viscous resistance and degraded hull hydrodynamic increases fuel consumption and leads to increase in emissions. In this technology, High frequency sound or Ultrasound probes are mounted at various locations on hull. The ultrasound prevents fouling and marine growth on hull. The base component of any underwater ecosystem are single cell organisms like algae. Microscopic bubbles are created due to the high intensity of ultrasound, which implode due to positive pressure due to cavitation. destroying the algae and stopping further growth. Clean hull increases the efficiency of the vessel. The technology consists of transducer fitted into hull, propeller and other appendages which will generate the ultrasound. The installation of ultrasonic antifouling technology can yield a fuel consumption reduction of 5-7%. [9]

Being a recently developed technology especially for commercial vessels, the technology is still undergoing developments. However, since hull fouling is a major contributor to inefficiency on ships, it has high potential for greater efficiencies. The cost of installation is low and relatively has better potential in reducing GHG compared to LED lighting and VFD. It is relatively easy to install as dry docking of the vessel is not needed. It is necessary to clean the hull before the installation, the system will not work on already fouled hull. The system gives protection to difficult to access areas like sea chest. It is very efficient and considered relatively maintenance free. Visual inspections need to be done on a regular basis, which is normal for any such systems.

3.5. Energy storage solutions and hybrid retrofits

Hybrid power technology is one of the most suited options for reducing emissions for OSVs. It refers to installing an Electric battery capacity to the conventional power setup of a vessel.

When power demand for the vessel is low, the battery-based energy storage system stores energy. When the demand increases, it delivers it back. The flow of energy is controlled by Energy Storage Control System. This feature ensures operation in several modes as required by the vessel, improving the fuel consumption efficiency. While at quay side, energy from the battery can be used to reduce the requirement of running one of the main engines. Running on batteries also provides a quiet and vibration free environment for the comfort of the crew.

Some of the functionalities of energy storage that are deemed useful in offshore applications include generator load peak shaving to optimize the loading of the generator sets and to prevent starting or stopping of the

diesel engines during load changes. When energy storage is integrated in the power and propulsion system, it can support DP operation while reducing the number of gensets in operation. The engine load during DP operations is typically low, commonly in the range of 30% – 40%. [10]. With a reduced number of running gensets and using energy storage as “spinning reserve,” the loading of each engine is increased, hence improving the fuel efficiency. The system reliability and redundancy are also not compromised. For OSV sector, utilization of Hybrid power technology could result in fuel savings of 10 to 40%. [11]

The energy storage system through batteries is a relatively mature technology, although adaptation to ships is a challenge due to requirement of optimization on battery volume and weight necessary for the ship’s requirements has to happen in due course. It has a very high cost of installation. Batteries are highly priced, and the control and integration components are costly. It has very high GHG reduction potential. of installation. Very tough to install. Space planning is a must before installation. Integration and control systems are complex. It is highly maintenance intensive system. Hybrid propulsion system will generate more heat compared to conventional propulsion system, and hence efficient cooling system is needed.

3.6. Additives and alternate fuel injection

The additives and alternative fuels injection works on various principles to achieve overall GHG reduction, viz. increasing combustion efficiency, reduction in temperature of combustion leading to a reduction NO_x, soot formation, enhancing soot burnout by increasing the concentration of oxidation elements, improving atomization, and mixing of air fuel mixture. Some of the methods employed in this sector are water-in-fuel emulsions, direct injection of additives to the combustion chamber, fumigating into the engine intake air, metal-based additives, methanol injection etc. There are various commercial institutions that provide effective solutions to the marine industry. 10-15% fuel savings are claimed by various solutions providers. [12]

The technology of mixing additives in fuel for better combustion efficiency is not fully mature. Since it involves making modifications to the fuel supply to main engines, it had a relatively high cost of installation although lower than hybrid/Battery technology. It has a moderate GHG reduction potential. Generally, 5-15 % reduction in CO₂ emissions could be achieved. Individual components are big in size and need space allocation in the engine room, especially for retrofits. The additive mixing and injection process happens outside the engine, modification to engine as such is not needed. The additives will improve the smoothness of operation of the engine, thereby generally reducing engine maintenance requirements.

3.7. Installation of LED Lights

Many of the existing OSVs use conventional lighting equipment that consume more power and are not efficiently used. Installation of energy efficient light fittings like LED (Light Emitting Diode) along with implementation of electronically controlled systems for reducing intensity, automatic shut off, etc. on vessels can considerably improve the power consumption onboard. LED technology has been used extensively for availing maximum illumination power with higher energy efficiency, they are also ones with longer lifespans and hence economically attractive.

Although nowadays widely adopted for new builds, it can be made use of in older vessels also. Although it makes a higher impact on passenger vessels, the emission reduction potential is estimated from the total auxiliary engine consumption on normal commercial ships is assessed to be in the range of 0.25% to 5% [13]

3.8. Low Friction Paints

A ship’s performance greatly depends on the roughness of the hull surface that is in contact with water. An increase of roughness of around 10 to 20 microns, causes a 1% increase to the total hull resistance. [14]. This increases the requirement of engine power and consequently the fuel consumption and emissions. Therefore, reducing friction is an effective way to reduce CO₂ emissions during ship operation.

The major contributors towards hull roughness are physical corrosion and biological fouling. Advanced low friction coatings contain components that allow water to fill within the imperfections to reduce friction. Fouling is a major issue. It has a major economic impact on the operation of ships. A moderate fouling could bring down the speed of the vessel by 15 to 18%. Therefore, the presence of good anti-fouling paint is essential for good

ship performance. 3-5% fuel savings have been recorded on vessels that have been coated with advanced antifouling paints. [15]

Antifouling paints work on different principles, Water solubility of paint, smoothness of coating etc. However, the key to good performing anti-fouling coatings will be the roughness. The advantage of low roughness is not only its contribution in reducing the friction coefficient and in turn reduce the fuel consumption, is because low roughness will offer better antifouling performance as well. It is therefore important to reduce the initial roughness to below 40 or 50 microns to obtain a better performing hull.

Technology is still in the process of adapting. Better products are under development, which gives a more prolonged periods of protection. Cost of implementation is moderate, and has good GHG reduction. Low friction paint is easy to install. This can be applied above existing paint, however it requires a high degree of maintenance keep the efficiency of the paint.

3.9. LNG

LNG is the most well-known and widely accepted alternative fuel in the shipping industry. The primary advantage of LNG is that it produces no sulphur oxide or particulate matter emissions. Compared with traditional fuel oil, the nitrogen oxide emissions and GHG emissions are also lower. The Engine technology and logistics for LNG as fuel is now technologically fully matured and fast developing and hence the fuel is considered as the most favored one for the transition stage towards zero carbon fuels.

Despite these advantages, LNG is still a fossil fuel. An additional challenge is the issue of methane slip. Due to incomplete combustion of LNG fuel inside the engine, methane is emitted along with the exhaust gas. Methane is a potent Green House Gas (GHG). Considering the wide acceptance of LNG as fuel, the infrastructure for storage and supply network has been fast developing. Hence it is a widely accepted choice as fuel in the OSV industry also. Green LNG, is achieved either by reducing carbon emissions or by GHG offsets using carbon credits. The cost of fuel is lesser compared to other alternate fuels.

The GHG reduction potential of LNG is higher than fuel oil, however lower compared to other alternate fuels. The carbon factor considering tank to wake is 2.75 t CO₂/t fuel. Due to its high global warming potential, release during production, boil off and methane slip, the carbon factor is likely to be more while taking the well to wake aspect. Energy density of LNG is higher than fuel oil with a calorific value of 46300 kJ/kg

3.10. Methanol

The use of Methanol as a fuel for ship propulsion has been more recent than LNG. The technology can be considered as proven. Sulphur Oxide and Particulate matter emissions can be eliminated by use of Methanol as fuel. It is easier to handle than LNG. Methanol is a widely used substance there exists a well matured terminal network across the world. However, it is still not widely used as a fuel on ships and hence the bunkering facilities available are still limited. Methanol is flammable in nature, and needs to be handled carefully. It has significantly lower energy density than fuel oil and hence ships fuelled with methanol have to be designed specifically with larger bunkering tanks. At present the fuel costs are higher when compared with LNG.

Considering the deepening interest of the industry in using methanol as fuel, IMO has adopted interim guidelines for ships using it as fuel. A complete regulatory framework is available considering applicability of the IGF Code and Methanol Ready class notations. Methanol can be produced from renewable sources. Renewable methanol cuts CO₂ emissions by up to 95%, reduces nitrogen oxide emissions by up to 80%, and eliminates sulphur oxide and particulate matter emissions. [16]

Methanol is a low-cost fuel. However, the cost of renewable methanol is however high currently due to its production process and low quantity of availability. This will come down with process optimization, scaling up of production and adoption of state renewable policies. The GHG reduction potential of Methanol is higher than most fuels. The carbon factor considering tank to wake is 1.375 T CO₂/T fuel. However its Energy density of methanol is relatively low, with a calorific value of 19900 kJ/kg.

3.11. Biofuels

Biofuels are produced by converting biomass or their residues into liquid or gaseous fuels. – are a possible solution to decarbonize the shipping sector. The main advantage of using biofuels in shipping industry is

that it can replace the current fuel oils with very few modifications to the vessel systems. The engines, tanks and fuel oil lines presently installed are compatible with Biofuels also, resulting in significant cost savings from a conversion. [17]

Currently, most biofuels used in shipping are types of biodiesel: fatty acid methyl esters (FAME) or hydro-treated vegetable oils (HVO). Both primarily use plant oil feedstocks such as rapeseed, soybean and palm oil, but it is possible to use waste and residue fats as well.

It is either used in blends with traditional petroleum fuels or as 100% biofuel. Although the tank to wake CO₂ emissions for biofuels is considered as zero, the non-renewable energy consumed during production of the biofuel will contribute towards the lifecycle carbon dioxide content of the fuel. [18]

Biofuels is a technologically mature fuel in its utilization for marine engines, and burns like convention marine fuels. No modifications are required on the engine to use biofuel. Supply chain network for 100% biofuel need further investments and development. However, sharing of infrastructure facilities of petroleum based fuels, and blending it with conventional fuels is possible. The fuel is in liquid state at normal atmospheric pressure and temperature; therefore storage is quite easy. They are available from renewable sources. Biomass is considered as renewable source of energy, although non renewable energy sources will be needed for the process to convert it into biofuels. Biofuels are highly priced currently. Energy density is relatively low, but higher than methanol with a calorific value of 26800 kJ/kg

3.12. Ammonia

Anhydrous ammonia (NH₃) has been identified as a potential long-term fuel that could offer a zero-carbon solution on a tank-to-wake basis. If produced with renewable power source, it can be termed as a zero-carbon fuel on a well-to-wake basis also. Engine technologies catering to Ammonia as fuel is still under development. There exists extensive land-based experience with production and use of ammonia for other industries like petrochemicals and fertilizers. The shipping industry has had adequate experience in carriage of ammonia as cargo in liquefied-gas carriers with rules and regulations for transportation being specified in the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)

The challenges in using Ammonia as fuel onboard relates to the toxicity of the chemical presents challenges when compared to other fuels in consideration. Using ammonia in an onboard fuel-cell system would reduce emissions even more than when using 2 or 4-stroke engines as no combustion products are formed during the process. Yet, this technology is still not mature.

Although ammonia is looked as one of the future zero emission fuels, it has not completely matured as a technology that could be adopted in a commercial scale. Its toxicity, corrosivity, and safety for use as a marine fuel is to be addressed and proven. The supply chain is not developed. Ammonia from completely renewable sources is not available for the moment. Blue ammonia, that is prepared from fossil fuels with carbon capture is available. Several players are focusing efforts towards refining the technology, production and certification of green Ammonia. It is highly priced and the energy density is relatively low, with a calorific value of 22500 kJ/kg

3.13. Hydrogen

Hydrogen is a clean fuel, since it can be generated from renewable energy through electrolysis. Presently prevalent means for producing hydrogen mainly rely on the use of fossil fuels. However, it is however possible to use water and renewable energy to produce hydrogen. For using hydrogen as an on-board fuel, two means are being widely explored - using hydrogen fuel cells or using combustion engines capable of running on hydrogen as fuel. The most crucial constraint in using hydrogen as a fuel is the storage and handling. Although by weight, hydrogen is an excellent energy carrier with a lower heating value (LHV), it has a very low volumetric energy content at atmospheric conditions. In order to make storage more efficient, techniques like compression, liquefaction and storage in physical or chemical "carrier substances" are used. The energy density of liquid hydrogen is around 8.5 MJ L⁻¹, compared to the value for diesel fuels of 36.3 MJ L⁻¹, roughly 4.5 times lesser than diesel.

Considering the above factors and the prospect of large-scale production of Hydrogen from renewable sources, it is a highly valuable fuel of the future along with ammonia.

The technology to produce hydrogen from renewable electricity sources is under development. A commercial scale production by this technology can revolutionize the zero-carbon fuel sector. Hydrogen is highly priced. Energy density of hydrogen is high, with a calorific value of 120000 kJ/kg. However, the density of hydrogen is too low even when it is in liquid state, reducing its energy content per unit volume.

4. Selection of the decarbonization solutions

Transition and decarbonization of the energy sector require the utilization of new technologies and a mix of energy sources. Most of the alternative fuels that are considered for future applications are already known chemicals or products, nowadays used for other purposes. However, when used on ships, different fuels pose different challenges to address before it could be considered techno commercially viable to be used as a marine fuel. The safety, toxicity, fire hazard, storage, handling, infrastructure, distribution network, demand and supply are a few of the aspects that must be addressed.

Selection of a suitable decarbonization technology or the apt fuel for the OSV is a challenge faced by the owner or operator of the OSV. The decision making based on the below criteria is assessed as part of this paper.

4.1. Survey methodology

A survey was conducted among 25 experts who have significant experience on working in the sector. Each of them was asked about the importance of each of the above criteria to their decision making to choose the right EET for their vessel.

The experts who participated in the survey were chosen for their experience in working in the OSV industry. A cross section of individuals having 15 to 36 years of experience in the industry were surveyed. This included engineers, captains, consultants, management personnel, technical superintendents and operations managers. These experts who undertook the survey were required to answer a questionnaire about the importance they would assign to the decision-making criteria as above for installation of the chosen decarbonization technologies or the chosen alternate fuels. The survey was conducted between July 25, 2023 and August 10, 2023.

Decision making for Alternate Fuels

Based on the survey responses received, a weightage (W_j) given to each criterion, calculated as per below, j being one of the criteria. If n is the number of experts who responded to the survey, $i = 1$ to n

$TM_{avg} = \frac{\sum TM_i}{n}$ where TM_i is the score assigned by the expert for the criterion “Technological Maturity”

$C_{avg} = \frac{\sum C_i}{n}$ where C_i is the score assigned by the expert for the criterion “Cost”

$R_{avg} = \frac{\sum R_i}{n}$ where R_i is the score assigned by the expert for the criterion “GHG reduction potential”

$IN_{avg} = \frac{\sum IN_i}{n}$ where IN_i is the score assigned by the expert for the criterion “Ease of Installation”

$M_{avg} = \frac{\sum M_i}{n}$ where M_i is the score assigned by the expert for the criterion “Maintenance requirement”

If $Q =$ sum of the averages of all criteria as above $= TM_{avg} + C_{avg} + R_{avg} + IN_{avg} + M_{avg}$

Weightage factor for each criterion shall be calculated as below.

$$W_{TM} = \frac{TM_{avg}}{Q}, \quad W_C = \frac{C_{avg}}{Q}, \quad W_R = \frac{R_{avg}}{Q}, \quad W_{IN} = \frac{IN_{avg}}{Q}, \quad W_M = \frac{M_{avg}}{Q}$$

In the next step, scores are assigned to each fuel and EET relating to their performance against each criterion on a scale graduated zero to ten (0–10), summary of which is presented in the paragraphs above for each

fuel. If S_{TM-VFD} is the score assigned to Technological Maturity of the EET “VFD installation”, S_{C-VFD} the score assigned for Cost of the installation of VFD and so on, an Acceptability index (AX) can be calculated for the VFD (AX_{VFD}) based on the formula below

$$AX_{VFD} = S_{TM-VFD} \cdot W_{TM} + S_{C-VFD} \cdot W_C + S_{R-VFD} \cdot W_R + S_{IN-VFD} \cdot W_{IN} + S_{M-VFD} \cdot W_M$$

Similarly AX is calculated for Data driven decarbonization AX_{Data} , Low Friction Paints AX_{Paint} , Fuel cells AX_{FC} , Energy storage and Hybrid AX_{Hybrid} , Installation of LED lights AX_{LED} , Cold ironing AX_{CI} , Ultrasonic Antifouling AX_{AF} ,

Decision making for Alternate Fuels

Based on the survey responses received, a weightage (W_j) given to each criterion, as per below, j being one of the criteria. If n is the number of experts who responded to the survey, $i = 1$ to n

$TM_{avg} = \frac{\sum TM_i}{n}$ where TM_i is the score assigned by the expert for the criterion “Technological Maturity”

$C_{avg} = \frac{\sum C_i}{n}$ where C_i is the score assigned by the expert for the criterion “Cost”

$R_{avg} = \frac{\sum R_i}{n}$ where R_i is the score assigned by the expert for the criterion “GHG reduction potential”

$D_{avg} = \frac{\sum D_i}{n}$ where D_i is the score assigned by the expert for the criterion “Storage and Distribution network”

$A_{avg} = \frac{\sum A_i}{n}$ where A_i is the score assigned by the expert for the criterion “Availability from renewable sources”

$E_{avg} = \frac{\sum E_i}{n}$ where E_i is the score assigned by the expert for the criterion “Energy Density”

If $Q = \text{sum of the averages of all criteria as above} = TM_{avg} + C_{avg} + R_{avg} + D_{avg} + A_{avg} + E_{avg}$

Weightage factor for each criterion shall be calculated as below.

$$W_{TM} = \frac{TM_{avg}}{Q}, \quad W_C = \frac{C_{avg}}{Q}, \quad W_R = \frac{R_{avg}}{Q}, \quad W_D = \frac{D_{avg}}{Q}, \quad W_A = \frac{A_{avg}}{Q}, \quad W_E = \frac{E_{avg}}{Q}$$

In the next step, scores are assigned to each fuel relating to their performance against each criterion on a scale graduated zero to ten (0–10), summary of which is presented in the paragraphs above for each fuel.

If S_{TM-FO} is the score assigned to Technological Maturity of the fuel “Fuel Oil”, S_{C-FO} the score for Cost of the fuel and so on, an Acceptability index (AX) can be calculated for the fuel oil (AX_{FO}) based on the formula below

$$AX_{FO} = S_{TM-FO} \cdot W_{TM} + S_{C-FO} \cdot W_C + S_{R-FO} \cdot W_R + S_{D-FO} \cdot W_D + S_{A-FO} \cdot W_A + S_{E-FO} \cdot W_E$$

Similarly, AX is calculated for all alternate fuels studied here viz Methanol ($AX_{Methanol}$), Hydrogen ($AX_{Hydrogen}$), Biofuels ($AX_{Biofuel}$), Ammonia ($AX_{Ammonia}$), LNG (AX_{LNG}),

Table 1 : Comparative study of various Alternate fuels with fuel oil based on multiple decision making criteria

	Technological Maturity (TM)	Cost (C)	GHG reduction potential (R)	Storage and distribution network	Availability from renewable sources (A)	Energy Density (E)	Benefits	Challenges	Acceptability Index (AX)
Weightage Factor w_j	0.176	0.180	0.154	0.176	0.151	0.163			
Fuel Oil	10	8	0	10	0	10	High energy density Low cost Matured technology Established supply chain Easy availability	High GHG emissions Dwindling long term availability Non-renewable energy source	6.59
LNG	8	7	3	8	2	8	High energy density Low cost compared to alternate fuels Matured technology Established supply chain Easy availability	Better on GHG emissions than Fuel Oil Non renewable energy source	6.15
Methanol	5	8	6	8	3	5	Existing production technologies E-methanol and Bio methanol produced using renewable energy sources	High cost of production if using renewable sources	5.92
Biofuels	7	3	6	8	3	5	Easy to integrate with fuel oil infrastructure	Commercial usage can impact food security	5.37
Ammonia	5	3	7	6	5	5	Existing production technologies Zero carbon fuel	High cost of production Toxicity issues for carriage Hazardous in transportation	5.12
Hydrogen	2	2	10	2	2	5	Zero carbon fuel Can be produced using renewable energy	Immature technology in shipping Requires cryogenic storage for transportation Lower energy density High cost for production using non-renewable sources	3.72

High	10	
Low	0	

Table 2 : Comparative study of various energy efficiency technologies (EETs) based on multiple decision making criteria

Weightage Factor Wj	Technical	Cost	GHG	Energy	Maintenance	Benefits	Challenges	ACC
	0.214	0.211	0.182	0.191	0.202			
Data Driven Decarbonisation	7	8	7	9	6	Easy to install, Technology will further improve, low-cost high benefit solution, Ample suppliers are available	Recurring payment, Frequent software and database updates	7.39
LED Lighting	7	9	2	8	9	Longer service life, No hazardous substances like mercury or lead, Easy to implement, generate less heat	Blue light pollution which is harmful to eyes is higher.	7.11
VFD installation	8	8	3	8	8	Relatively low cost, Longer life time for equipment, Crew comfort level improvement, Accurate process control	VFD can create electrical harmonics, electromagnetic interference that interfere with other equipment.	7.09
Ultrasonic Antifouling	5	8	5	8	7	Works even when the ship is stationary, can be applied to difficult to access areas, Reduces hull resistance	Over time, hull fouling happens even with ultrasonic anti fouling. Not fully developed,	6.61
Low Friction Paints	6	6	4	7	5	Speed improvement, Easily applied using standard practice and equipment, reduces transfer of invasive species	Less effective for ships that remain stagnant for long periods,	5.62
Hybrid/Battery technology	6	3	10	4	5	Highly efficient in decarbonizing, enhanced flexibility and reliability, renewable energy sources and battery technology is fast developing	High initial cost, larger space and weight requirements of components, complex integration and control. Generate more heat and require more cooling water	5.51
Cold Ironing	7	4	4	5	7	Quieter vessel operation in ports, Necessary for regulatory compliance in certain ports like California and many European ports by 2025.	High initial cost, Not all ports provide cold ironing facility, Large space requirements	5.44
Additives and alternate fuel injection	5	4	5	5	7	No modification needed to the engine as such, Smoother engine	Varying CAPEX depending upon the additives and	5.19

						operation, reduces engine maintenance, prolong components life, Low ROI	technology, Additional space requirement in engine room, NOC to be obtained from engine manufacturer	
High	10							
Low	0							

5. Authors' conclusions

From the Acceptability index assessed above and detailed analysis of the advantages and disadvantages of each technology, we are able to identify the trend of acceptability of the EETs and the alternate fuels to the industry.

Among the EETs

- Relatively easier-to-implement technologies with least cost impact like Data driven decarbonization, installation of LEDs and VFDs are strongly favoured to be the first steps that OSV owners would adopt.
- Hybrid power/battery technology has very high GHG reduction potential. If the challenges on space, cost and cooling requirements are addressed due to advancement of technology, it could soon be widely adopted by the industry.
- Shore power is a technology that could gain wide implementation due to mandatory requirements from ports.

For the Alternate fuels

- Fuel oil is still relevant and is the most significant as a proven and readily available fuel now.
- LNG, Methanol and biofuels are proven, however need to develop the distribution network for shipping use, create demand, enhance production especially using renewable sources and meet the supply requirements. Therefore, these could be developed as a transition fuel during the coming decade.
- For ammonia and hydrogen, the technology need to be proven for larger utilizations. However their relevance as a zero emission fuel is invaluable. Hence those are the fuels that must be developed as future fuels.

6. Future trends

Although there is a discernable lack of regulatory initiatives demanding adoption of decarbonization technologies in the OSV sector, major owners and operators have started adopting energy efficiency technologies as a result of the global awareness on the importance of emissions reductions. The work of IMO, EU and other national authorities to reduce emissions from commercial vessel fleet has contributed to this awareness. Major stake holders in offshore shipping including Oil & Gas majors have already taken measures in this direction and had included energy efficiency measures in their sustainability goals.

Based on the above and current industry trend, solutions such as hybrid technology are very attractive to the industry for a retrofit on an existing vessel. As far as new builds that opt for alternate fuels, biofuels and LNG are the likely interim or transitional fuels in the near term. In the mid to long term, hydrogen and its carriers (e.g., ammonia, e-methanol) as well as bio-LNG, may also become viable low or zero-carbon marine fuels. Digital twin technology is also fast growing, and it is likely to be engaged during this period for performance monitoring, preventive / predictive maintenance.

List of References

- [1] J. Faber, S. Hanayama, S. Zhang, P. Pereda, B. Comer, E. Hauerhof, W. S. v. d. Loeff, T. Smith, Y. Zhang, H. Kosaka, M. Adachi and J.-M. Bonello, "Fourth IMO GHG Study 2020," International Maritime Organisation, 2020.
- [2] UNFCCC. Secretariat, "Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Addendum. Part two: Action taken by the Conference of the Parties at its twenty-first session.," in *Paris Climate Change Conference - November 2015*, 2015.
- [3] European Parliamentary Research Service, "Sustainable maritime fuels - 'Fit for 55' package: The Fuel : EU Maritime proposal," in *EU Legislation in Progress*, 2023.
- [4] R. MEPC.377(80), "2023 IMO Strategy On Reduction of GHG emissions from Ships," 2023.
- [5] R. Adland, P. Cariou and F.-C. Wolff, "When energy efficiency is secondary: The case of Offshore Support Vessels," *Transportation Research Part D*, 2019.
- [6] S. O. Erikstad and K. Levander, "System Based Design of Offshore Support Vessels," in *IMDC12 - The 11th International Marine Design Conference*, Glasgow, 2012.
- [7] A. Hessevik, "Green shipping networks as drivers of decarbonization in offshore," *Maritime Transport Research*, 2022.
- [8] 26 July 2023. [Online]. Available: <https://marine-digital.com/fueloptimizationsystem>.
- [9] 23 July 2023. [Online]. Available: <https://trimis.ec.europa.eu/project/new-ultrasonic-cost-effective-equipment-anti-fouling-system-vessels>.
- [10] Poikola, R. R. Chan and Jori, "Holistic Approach in Design and Operation of Energy Efficient Offshore Vessels," in *Proceedings of the 6th International Conference on Technology and Operation of Offshore Support Vessels*, Singapore, 2016.
- [11] L. K. Mylapilli, "Battery-Powered Propulsion for Offshore Support Vessels," 2020.
- [12] 23 July 2023. [Online]. Available: <https://fuelsave.de/losungen/fs-marine/>.
- [13] D. A. M. Environment Advisory, "Project Report - EE appraisal tool for IMO," International Maritime Organisation, 2016.
- [14] I. Arabatzis, "www.safety4sea.com/hull-coatings-technologies/," 16 April 2018. [Online]. Available: <https://safety4sea.com/hull-coatings-technologies/>.
- [15] July 2011. [Online]. Available: <https://www.marinelink.com/news/lowfriction-adopts-paint339646#:~:text=The%20ultra-smooth%20finish%20minimizes%20friction%20drag%20between%20the,an%20identical%20vessel%20with%20a%20conventional%20hull%20coating..>
- [16] IRENA and Methanol Institute, "Innovation Outlook : Renewable Methanol," International Renewable Energy Agency, Abudhabi, 2021.
- [17] European Maritime Safety Agency, "Update on potential of biofuels in shipping," EMSA, London, 2022.
- [18] C.-w. C. Hsieh and C. Felby, "Biofuels for the marine shipping sector - An overview and analysis of sector infrastructure, fuel technologies and regulations," IEA Bioenergy, 2017.
- [19] TAQA and ADPorts, "TAQA Group and Abu Dhabi Ports Planning 2GW Green Hydrogen to Ammonia Project," Abudhabi, 2022.
- [20]
- [21] T. N. R. J. A. P. O. W. Y. & B. M. G. H. Zis, "Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports," *Maritime Economics & Logistics*, 2014.
- [22] "Information Portal for Energy Efficiency Technologies for Ships," 2016. [Online]. Available: <https://greenvoyage2050.imo.org/technology/energy-efficient-lighting-system/>.

- [23] H. E. Lindstad, G. S. Eskeland and A. Rialland, "Batteries in offshore support vessels – Pollution, climate impact and economics," *Transportation Research Part D*, 2017.
- [24] IRENA, "A pathway to decarbonise the shipping sector by 2050," IRENA, 2021.