IOP Conference Series: Materials Science and Engineering

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To cite this article: M L Eliassen and O T Gudmestad 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **700** 012040

IOP Conf. Series: Materials Science and Engineering **700** (2019) 012040 doi:10.1088/1757-899X/700/1/012040

Choice of fuel system for the offshore support fleet

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Abstract. The stringent requirements of the IMO´s emission regulations call for alternative fuels and new ways of powering ships. However, the IMO predicts that technology which could reduce ship emission to zero, will either not be available, nor cost-efficient over the next 40 years. However, technological innovations in ship power & propulsion systems; such as duel-fuel LNG engines, and the utilization of energy storage technology in the form of lithium-ion batteries have been found to reduce harmful emissions; and are already utilized to quite some extent in the offshore support fleet. This paper elaborates on the reliability and sustainability of newer ship power technologies, where equal to existing levels of reliability are expected as a minimum.

1. Introduction

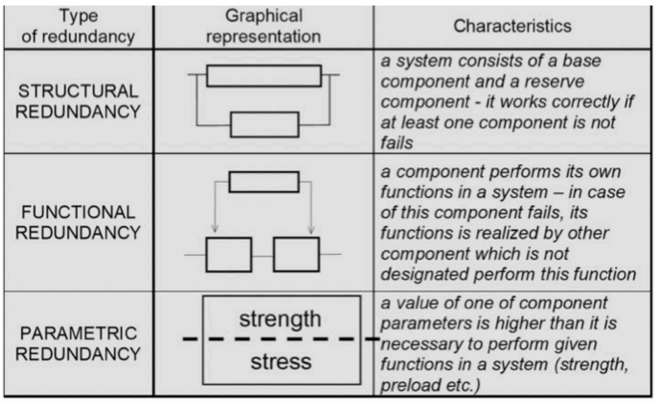
Forces calling for "greener" maritime- offshore operations have resulted in the development of and utilization of newer technologies related to ship´s propulsion systems. The vision of the International Maritime Organization is to reduce greenhouse gas (GHG) emission from international shipping, and to eventually eliminate GHG emission during the current century [1]. More specifically, the IMO pursues a 50% GHG emission reduction by the year of 2050, compared to 2008 emission data [2]. The IMO also aims at significantly reducing emission of air pollutants such as oxides of Sulphur (SO_x) and oxides of Nitrogen (NO_x) from ships [2], where ship emission is today limited by MARPOL Annex VI. Ship emission limitations will become more and more stringent. A tendency which is often referred to as decarbonization [3]. However, according to [3] and [4]; there is no single pathway to decarbonization of the shipping industry, for now, they point towards Liquefied Natural Gas as the most appropriate current and short-term mitigation of emission reduction demands.

Platform supply, anchor handling, and subsea vessels are often termed Offshore Support Vessels (OSV) [5]. These vessels typically service offshore units, floating or submerged, and other related equipment on the continental shelf. From a practical standpoint, these vessels can be regarded as a necessity in order to conduct any operations on the continental shelf. Here, the North Sea is classified as an Emission Control Area (ECA) which stipulate the most stringent emission limits, and thus vessels that operates in the North Sea ECA therefore need to be particularly technologically innovative, in order to be compliant. Starting at the origin, the choice of power & propulsion system heavily relies on a vessel´s operating profile [6]. As OSV´s have a rather varied operating profile, diesel-electric propulsion architectures are commonly used, as diesel-electric propulsion offer a high level of flexibility [6]. In diesel-electric propulsion, all consumers are principally connected to the same electrical network, which can lead to blackouts under fault conditions [6]. However, with a propulsion system with separated busbars, the risk of a full blackout is significantly reduced [6], [7]. This will be emphasized later on.

Further, Marine operations offshore can be quite complex [8], thus involving multiple interconnected aspects such as; operational safety, client´s requirements of power availability, preferences of high levels of manoeuvrability, and also the application of Dynamic Positioning (DP) [8]. In general terms, the design principle of an offshore vessel´s propulsion system revolves around designing a system which ensure safe operations at nearly any sea state [9]. As a consequence, highly reliable propulsion systems are pursued as certain failures such as power failures may compromise marine operations and can further cause high economical losses [10], starting at the low-consequence end.

There are in general two structural approaches towards improving vessels reliability. Either using components of higher quality, or designing-in redundancy in such as the power/propulsion system [10]. This either – or approach can be seen as an implicit compromise [10] as high-quality components are costly. However, when it comes to offshore support vessels, their operational requirement of a highly reliable propulsion system therefore involves a combination of both design approaches [10]. As a consequence of designing-in redundancy, power availability is increased, which is a typical attribute for these types of ships, [6, 7].

Reliability and safety in some ways walk hand in hand [11]: Reliability deals with the concept of failures, while safety concerns the consequences of these failures [11]. Continuing our focus on redundancy; there are different categories as can be seen in *Figure 1*. A common offshore support vessel design involves, among other things, including structural redundancy [12] for key systems such as generating sets. These gensets feed two or even three main switchboards (MSWB) with power, which is distributed to electrical consumers. The MSWB´s can be physically isolated from another by so-called bus-tie breakers, enabling the vessel to operate with two independent "sides" at the power & propulsion system. These conditions are normally operation dependant; and/or can also be a client requirement. This design philosophy is in connection to the principle of *spinning-reserve*, which is generally aimed at reducing the risk of blackouts [8]. More specifically, spinning-reserve means the running of more gensets than what is required in order to cope with unintentional shutdown of gensets, or other power failures [13].



Type of redundancy	Graphical representation	Characteristics
STRUCTURAL REDUNDANCY		*a system consists of a base component and a reserve component - it works correctly if at least one component is not fails*
FUNCTIONAL REDUNDANCY		*a component performs its own functions in a system – in case of this component fails, its functions is realized by other component which is not designated perform this function*
PARAMETRIC REDUNDANCY	strength / stress	*a value of one of component parameters is higher than it is necessary to perform given functions in a system (strength, preload etc.)*

Figure 1. Types of redundancy [12].

However, designing-in redundancy and meeting operational requirements of *spinning-reserve* have a significant downside. They generally lead to the running of marine engines at low to medium loads [5, 7 - 9]; somewhat inefficient operational patterns. During these engine loading conditions, generating sets (gensets) generate each kWh at a higher fuel consumption and with less favourable emissions compared to when engines run at medium to high loads [9]. Further, these operating conditions generally lead to vessel operational patterns that generate a lot of emission [5].

Meanwhile, as offshore support vessels are subject to increasingly more stringent emission limits, this have led to the utilization of newer and alternative technology related to offshore vessels propulsion system. However, with respect to the above, and according to [14]; new technologies need to pertain the same level of reliability and safety as the more conventional propulsion system [14]. Hence; ship-owners and builders needs to account for multiple aspects, where several trade-offs can be identified. In this paper, we will focus on the choice of fuel system and alternative ways of powering offshore support vessels, considering reliability, operational safety, and sustainability in terms of emission. What options related to offshore support vessels propulsion system are there amongst existing technology today that can accommodate these aspects?

2. Methods

In development of this paper, a literature study was carried out, which was supplemented by raw data as found in the preparation of the first author´s master thesis [15]; which focused on similar topics. In addition, in order to provide a more pragmatic approach, the first author´s operational experience as a deck officer and Dynamic Positioning Operator (DPO) on board a variety of offshore vessels such as geotechnical drilling, construction, subsea, and platform supply is referred to, where found applicable.

2.1. Literature study

The majority of the used literature was found during the development of the first author´s master thesis. The strategy therein involved pursuing the application of published works as references, and to apply other sources such as regulatory publications, paper articles, manufacturers' statements, to supplement the above. However, as the initial literature study was done for the sole purpose of the master thesis, additional literature was needed in order to elaborate more specifically on the title of this paper. The literature study was primarily carried out in databases such as Web of Science, Research Gate, and Science Direct.

3. Results

In presentation of our results, the domain considering ECA and general approaches towards compliance are elaborated on. Then, applied technologies within the offshore support fleet is elaborated on, with regards to the focus areas of this paper.

3.1. Emission Control Area compliance

According to [16] there are three different approaches toward ECA compliance. The first involve using Heavy Fuel Oil (HFO) with emission reducing technology such as Selective Catalytic Reduction (SCR) and seawater scrubber technology. However, HFO, which often fuel large two-stroke marine engines, cannot in our case be considered to be relevant for OSV´s where diesel-electric propulsion is predominately applied; in which four-stroke diesel engines are dominant [17]. In addition, the emission regulations abolish this approach, i.e. sulphur limits of 0,1% in the North Sea ECA applies, which should render HFO inapplicable, Hence; is not considered here. The second approach involve using low sulphur fuels such as MGO (Marine Gas Oil) combined with SCR (Selective Catalytic Reduction). There are MGO´s today that meet the 0,1% sulphur content limit [18]. Further, if a low-sulphur MGO is combined with SCR technology which reduces NO_x emission by exhaust treatment in a urea plant [18], hence; MGO is still a viable fuel. The third approach towards ECA compliance, involve using LNG as a marine fuel [16].

Having elaborated on approaches towards ECA compliance, the significance of LNG as a marine fuel is here considered. Other fuels should, however, be mentioned; even though it can prove difficult to predict whether these fuels are suited for offshore support vessels or not. A scientific comparison of alternative fuels for was carried out by [19], with a strong emphasis on environmental and economic performance. The alternative fuels that was included in the study [19] were methanol, ethanol, LNG, and hydrogen. These fuels were evaluated on the basis of numerous criterions: Ship safety, global usage, bunker capability, durability, ease of application, rules & regulations, engine performance & emission, effect on engine components, as well as commercial issues. On the basis of their analysis, [19] found LNG to be the most applicable alternative fuel for ships.

Hydrogen came out second in their evaluation, however, it was found that more studies and improvements are required with regards to emission regulation compliance and with regards to concerns involving hydrogen´s effect on engine components. This need for further Research & Development (R&D) are also mentioned by others [20]. In continuance of our paper, LNG and possible combinations will therefore receive focus. In addition, the first author has served on board several LNG powered OSV´s, and therefore possess some insight.

3.2. Liquefied Natural Gas

For approximately 15 years ago, some offshore shipping companies decided to utilize LNG as a marine fuel. LNG medium speed engines can be regarded as a proven technology [21], and can be divided into three different categories when turbine engines are not considered (Balcombe et al., 2019). LNG powered offshore support vessels, utilizing low-pressure dual-fuel engines is one, while the other categories are; high-pressure dual-fuel engines, and lean burn spark-ignition (LBSI) engines [3], of which the latter is installed on board a couple of ferries [21]. LNG is a fossil fuel, which for the most part consist of Methane (CH_4) [22]. According to [23] LNG is heading into oversupply, which makes it cheaper than other fossil fuels. But, in order to utilize natural gas effectively, it is converted to its liquid form (LNG), and then takes up 1/600th of the volume, compared to its gaseous state [22]. Natural gas becomes liquid at approximately-162°C and is therefore considered to be a *cryogenic liquid* (-100°C and colder) [22]. Further, and according to GIIGN [22] it is highly important to bear in mind that it is the very properties of LNG as a good source of energy that also makes the fuel hazardous if not contained properly. Using LNG as a marine fuel involve additional safety measures compared to conventional diesel-electric propulsion; both structural/technical, and operational measures. Characteristically, the use of LNG as a marine fuel involve a higher sensitivity towards variable propulsive loads, as these types of engines typically have a narrower operating window (air-fuel ratio between 2.1 and 2.3) [21], than other fossil marine fuels.

The low-pressure dual-fuel LNG engine does not require any additional technology for compliance with IMO tier III emission requirements [9], the fuel is Sulphur-free [18], but, however, CO_2 reductions can only be said to be marginal [21]. The utilization of LNG also meets the Energy Efficiency Design Index (EEDI) baseline requirements [23]. However, literature [9], [3] identifies challenges such as *methane-slip*, and as a consequence, GHG reduction is limited to 8-20% [3]. Methane-slip is caused by misfire and incomplete fuel combustion as a consequence of a too lean gas/air mixture [21]. Methane-slip tends to occur in LNG combustion engines during low-load engine operation [18], which is a typical condition for these vessels when in ports [18]. Interestingly and according to the Intergovernmental Panel on Climate Change [24]; in a one-hundred years perspective, the emission of methane impacts the climate 28-34 times more than CO_2. Because of these conditions, [3] finds that the application of LNG as a fuel alone is not sufficient for meeting the future 50% GHG emission reduction as depicted by the [1]. However, it is as mentioned by [21] a proven technology, and, should the LNG supply feeding the DF engine be interrupted, the DF engines seamlessly switches from *gas mode* over to *Diesel mode*, without any effect on ongoing operations. Further, and according to [25]; marine engine technology can be regarded as technologically mature and reliable, where LNG can be utilized as a fuel in such applications as DF engines, without compromising safety at sea. However, capital investment is higher than for the more traditional marine fuels [21], [25].

Another mentionable challenge, is that LNG bunkering may; depending on the chosen method, be quite ineffective [26], i.e. bunkering from trucks where bunker facilities don’t exist can be quite time-consuming. Apparently, a lack of infrastructure has been found to be one of the main reasons that the utilization of LNG as a fuel has not reached the heights as first predicted [27]. However, for offshore support vessels, arguably, this does not need to be the case. The first author knows from experience that many of the offshore bases in Norway today offer suitable LNG bunkering facilities. On the other hand, some does not, and LNG needs to be transported by trucks, which involve the bunker ineffectiveness as mentioned by [26]. When it comes to the choice of marine fuel, there are as depicted many aspects to consider. For now, focusing on commercialized fuel technology applicable for offshore support vessels; the options are somewhat confined to low-sulphur diesel oils, or LNG. However, commercialized technology such as energy storage can be combined with the use of these types of marine fuels.

3.3. Energy storage technology

It is reported in [6] that hybrid systems involving the application of energy storage technology supported by advanced control strategies, can reduce fuel consumption and emission in the range of 10-35%, while at the same time improve maintainability, manoeuvrability, comfort, as well as reducing noise. Further, energy storage technology has been found to be well-suited for vessels with a diverse operating profile [6], [28], [29], hence; a particular relevancy for offshore support vessels [8]. As operational requirements during DP operations usually call for the application of spinning-reserve, engines will as mentioned typically run at low loads, which result in fuel-inefficiency and a lot of emission [6]. Importantly, even if spinning-reserve is principally related to the design philosophy involving redundancy, it is not the same thing. Nor is it equal to such efforts as DP operations with an open bus-tie. Spinning-reserve, can, however, be regarded as the additional generating capacity that is easily available, and that is already connected to the switchboard.

The rise of energy storage technology for ships is said to originate from the FellowSHIP project [30]. In this project, which endured for 15 years, fuel cell technology and battery energy storage were installed and tested on board an LNG powered platform supply vessel.

At first, the project focused on fuel cell technology, but later shifted towards applying lithium batteries in a battery energy storage system, because fuel cells had a slower response time, where batteries could compensate [30]. Today, there are numerous OSV´s that utilize battery energy storage in form of lithium batteries. To the knowledge of the first author, there are, however, no OSV´s that currently utilize fuel cell technology. Fuel cells can be fuelled by natural gas, hydrogen, and other fuels [20] to generate electricity, however, and according to [31] fuel cells are technologically immature. The main problem according to [31] concerns the storage of hydrogen. As a testimony to these concerns, the explosion of a hydrogen tank at a Norwegian gas station is here mentioned [32].

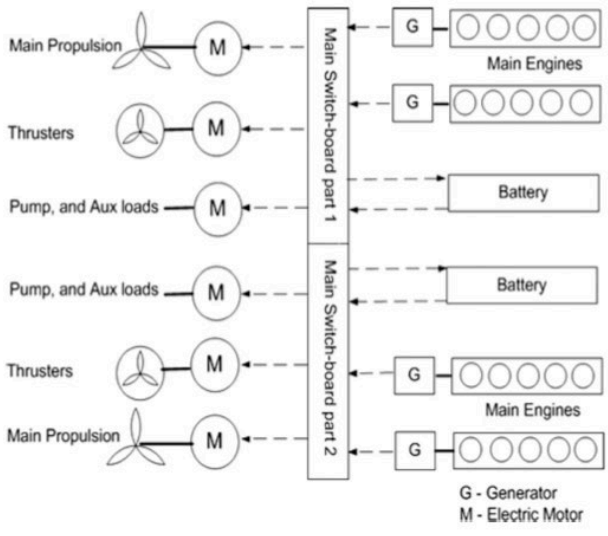


Figure 2. Hybrid propulsion layout [9].

There are many types of energy storage systems, and their applicability can partly be summarized by *Figure 3*. The various types of batteries are significantly more mature than fuel cell technology, hence; the trend today of installing battery energy storage.

Most offshore shipping companies today that have pursued energy storage technology utilizes some kind of lithium batteries in their systems [16], of which there are several [31, 33]. Battery energy storage systems are either installed as containerized solutions, or they are integrated in the ships structure. Usually, retrofits involve the containerized solution, and new builds involve integrating the battery energy storage system in the ships structure.

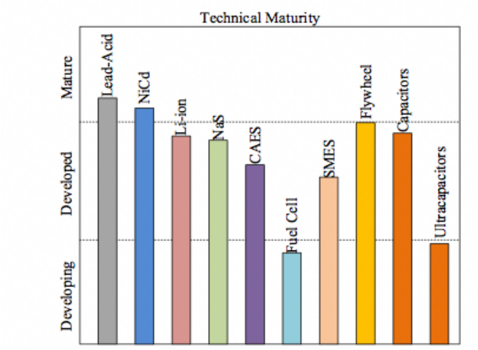


Figure 3. ESS technical maturity [31].

The main purpose of the battery energy storage system is shown in Figure 4, by applying so-called *peak-shaving* and *load-levelling* [31], which are controlled by rather advanced automated systems, such as the Energy Management System (EMS) [6]. Continuing our line on LNG, combined with battery energy storage, the following quote sums up an important benefit of this combination, which was discovered during the FellowShip project: *"... burning gas at low loads produces higher amounts of methane. Using batteries to cover low load requirements allowed us to reduce methane emissions".* Øystein Alnes, Principal Maritime Engineer DNV GL [34].

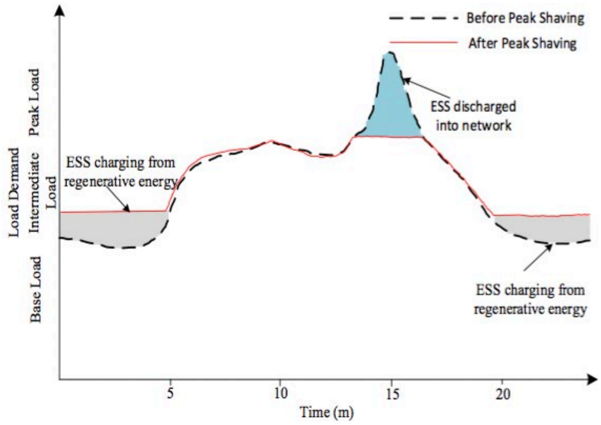


Figure 4. Peak-shaving and load-levelling [31].

In more general terms, which involve both LNG and MGO; ship owners' report of a reduction in fuel consumption in the range of 9-25%, as well as reduced maintenance costs due to the utilization of battery energy storage [16]. However, there are other benefits which are more relevant for this paper, which concerns the reliability of these systems. First, battery energy storage in the form of lithium batteries can be regarded as commercialized technology, as class notations do exists [35]. Here, we distinguish between the *battery power* and *battery safety* class notations. The main difference is that the battery power class notation allows for the battery energy storage system to serve as means of propulsive power, while the battery safety class notation does not.

However, the battery safety class notation have the potential of energizing the propulsion system for a shorter period of time and may therefore in this context be regarded as *functional redundancy* [12], 2018b). An example of this use, as mentioned by [7] may be to maneuver a platform supply vessel to a safe location, should failures at the propulsion system occur that could potentially lead to blackouts while the vessel is working alongside an installation. The other class notation, battery power, as mentioned, allows for the use of battery energy storage for purposes such as spinning-reserve. Hence, a battery energy storage system can replace the function of one or more gensets, during DP operations, and in other operational modes as required. This is well illustrated in *Figure 2*, but there are, however, other possible setups [6]. In this case, batteries act as additional redundancy, and can be considered as *structural redundancy* [12]. Considering *Figure 2*, where in the case of unintentional genset shutdown(s), or other power failures, the battery energy storage offer an increased level of power availability, further reducing the risk of blackouts. As an example, a captain of a platform supply vessel expressed that their everyday operations have been made safer, due to the application of battery energy storage [36].

Ultimately, the utilization of battery energy storage in vessels propulsion systems, as a rule of thumb support compliance with the newer stringent emission regulations for ECA´s as per MARPOL [12], and generally offer "healthier" operating conditions for gensets [16]. The utilization of battery energy storage here minimizes the running of combustion engines at low-loads [4], [5], [8], [9]

Further, it should be mentioned that even though it is clear that operating with an open bus-tie breaker (see *Figure 2*) reduces the probability of a full blackout significantly [7], this operating mode on the other hand becomes quite counter-productive with respect to the utilization of the battery energy storage system, depending on battery configuration [16]. Whether to operate with a closed or open bus-tie breaker depends on the specific maritime operation in question and/or client's requirements and appear to be a rather congested subject in the industry [16]. Aside from this, the additional redundancy that battery energy storage offers should not be underestimated, as marine operations offshore can be carried out even safer.

On the ship side, directly related to utilizing battery energy storage, a discussed aspect in literature revolve around the risk of *thermal runaway* [14], [37], [38], [39] and [40]. Thermal runaway is caused by such as erroneous operation, and internal faults as a consequence of faulty manufacturing [37], [40] Conditions such as overcharging, short-circuits, and submission to heat can lead to an increase in temperature at the battery cell level [37], leading to so-called *exothermic reactions* [40]; which causes several battery components to degrade; further leading to batteries emitting toxic and flammable gases [37], [40]. The stages of thermal runaway are informatively presented below by *Figure 5*.

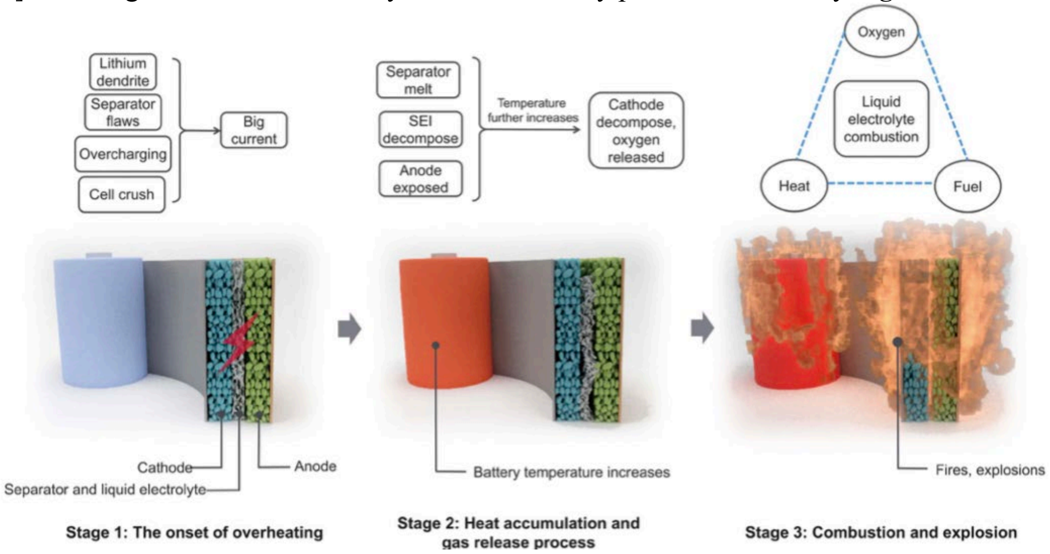


Figure 5. Stages of thermal runaway [37].

There exist several barriers, both battery internal and external, stipulated by class requirements [35] to prevent the occurrence and escalation of thermal runaway. However, even though this technology is considered to be safe [16], and even though battery energy storage is commercialized, the occurrence of thermal runaway is according to the [14] still possible; as failures of an internal kind within the battery cells might occur, in spite of the battery energy storage system´s internal safety systems. Suggestions to further increase battery energy storage safety and the prevention of thermal runaway revolve around the choice of materials for battery chemistry [37], which is regarded as the best prevention of the occurrence of thermal runaway. According to [41], the two most applied battery chemistries on board ships are

Lithium Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LiFePO4). NMC is the most applied chemistry per number of ships [41], considered to pertain a good stability and safety [42]. LiFEPO4 is the second most applied chemistry [41], and considered to be relatively safe during most conditions [37]. Other important aspects for the choice of battery chemistry are naturally energy density (kWh/kg) and power density (kW/kg) [31]. Therefore, and as mentioned by [42], when it comes to the choice of Li-ion battery, a trade-off between "*...efficiency, cost, and safety"* arises. Several other kinds of li-ion batteries exist [33]), with different characteristics; however, safety should always have the main priority.

On the more external side, other ways of improving the safety of the utilization of li-ion batteries in energy storage systems on board ships are suggested in literature. Reference [38] calls for battery water-cooling, and to abolish the use of air-cooling, as the water-cooling option is able to transport much more heat from the batteries, more effectively. Further, [31] highlights aspects such as preventing over-charging and over-discharging to prevent the rise of thermal runaway.

Erroneous use of battery energy storage might as mentioned lead to thermal runaway. In addition, erroneous operation involving deep discharges [40] can damage the battery cells, and reduce their lifetime, which is normally considered to be a period of minimum 10 years [16], and should therefore be avoided.

Interestingly, DNV GL (2018b) has reported of a planned initiation of a joint development project which will pursue the increase of knowledge concerning the use of li-ion batteries in the shipping industry; involving a lot of partners in different parts of the battery energy storage chain. Further, and importantly, the partners will pursue higher inherent safety levels for li-ion battery energy storage [43].

3.4. Other approaches

Other approaches today related to OSV´s propulsion system involve whether to apply Alternating Current (AC) or Direct Current (DC) electrical distribution [6], [7], a rather complex subject, where the main difference can be said to be the use of fixed speed engines (AC) or variable speed engines (DC).

[31] Highlights the combination of several energy storage technologies as the future solution of the utilization of the technology, this is referred to as *hybrid energy storage systems`*.

Other approaches not directly associated with the propulsion system, but as efforts to reduce fuel consumption and emission involve strategies such as *slow steaming* [4], *cold-ironing* [44] the use of anti-fouling paint, various hull designs, and several others [3], [4]. There are as mentioned, and according to [3], [4] no single pathway to decarbonization, and a combination of several approaches are therefore suggested in literature.

However, a greener approach does not in all cases necessarily grant any market premium in the offshore segment [45]. Towards the ending of this paper, the following quote is here found to be befitting: "*The ultimate goal of any new technology is to be able to perform the same job more efficient, less polluting, with reduced cost and improved safety"* [13].

4. Discussion

In the preparation of this paper, we set out to elaborate on the choice of fuel system for offshore support vessels. Given the continuing and increasing focus towards greener maritime- offshore operations, and in the shipping industry in general, from alternative ways of powering OSV´s an emphasis on LNG as a marine fuel and the electrification trend arose. There exist, according to the International Maritime Organization, no alternative fuel which could eliminate harmful emission from ships. They predict that it will either not be available, nor cost-efficient over the next 40 years. Therefore, a combination of approaches (policy, strategy, technology etc.) are called for. Whichever chosen technology, it shall pertain the same level of safety as the more conventional technology. A suitable approach for offshore support vessels today, based on the aspects as presented in this paper, may be to combine dual-fuelled LNG-engines with battery energy storage, utilize the *cold-ironing* (shore power) concept while in port, and to adapt/apply strategies such as slow steaming when reasonably practicable.

Using LNG as a marine fuel for these vessels involve additional safety measures and other challenges related to the efficiency of bunkering operations, as well as methane-slip. To use LNG as a marine fuel is considered to be safe, given the technical maturity of marine engines. However, should failures related to the LNG fuel system occur, the dual-fuelled engines seamlessly switch to diesel mode, not affecting ongoing maritime- offshore operations. Further, methane-slip can be significantly reduced by the application of battery energy storage; as low-load engine operation is minimized. This can also be the case when these vessels are in port, as cold-ironing can be applied, if the port offer sufficient shore-power facilities. Most importantly, the additional redundancy and back-up power offered by the application of battery energy storage should not be underestimated, as operational safety increases.

Failure conditions within the propulsion system which could normally cause a partial or full blackout can be mitigated either indirectly or directly by the battery energy storage system, as a function of the increased redundancy it offers. Therefore, the probability of blackouts can be significantly reduced.

However, even though safety barriers are installed as required by classification societies, the occurrence of thermal runaway is still a possibility, and has already received focus, where corrective measures are sought for, referring to the launch of the planned project orchestrated by DNV GL.

5. Conclusions

Regulators stipulate emission limits that will become more and more stringent over time. Technologies that have the potential of accommodating these limits must therefore be pursued. Meanwhile, there exist no clear pathway towards decarbonization, therefore, a combination of approaches is advised.

Using LNG as a marine fuel contributes to reducing harmful emissions such as oxides of sulphur and oxides of nitrogen. However, LNG only marginally reduce GHG emissions. However, combing LNG and battery energy storage further reduce emission, as low-load engine operation becomes significantly reduced, amongst other effects. Application of battery energy storage result in even more reliable offshore support vessels, due to the additional redundancy the system offers, which further enhances safety in marine operations offshore.

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