Discussion paper

Batteries in Offshore Support vessels - Pollution, climate impact and economics

BY
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This paper assesses the pros and the cons of installing batteries on offshore support vessels. These vessels are specially designed to provide services to oil and gas operations, such as anchor handling, supply and subsea operations. They have multiple engines and advanced dynamic positioning systems to ensure that they can perform their duties with high reliability at nearly any sea state. Combined with high safety requirements, this has resulted in general operational patterns with vessels running multiple combustion engines even at calm water conditions. For emissions, low engine loads yield high emissions of exhaust gases such as nitrogen oxides (NOx) and aerosols such as black carbon (BC), due to less favorable combustion conditions. The high span for these vessels between low loads and high, and their great need for potential power at short notice, motivate our examination of hybrid setups with electric: the vessel segment should be more favorable than many. We find that combining batteries with combustion engines reduces local pollution and climate impact, while the economics with current battery cost and fuel prices is good enough for new vessels, but not good enough for retrofits.

1. INTRODUCTION

Offshore support vessels, i.e. vessels for supply, standby, anchor handling and subsea operations, have multiple combustion engines and dynamic positioning systems to ensure that they can perform their duties with a high reliability at nearly any sea state. Dynamic positioning (DP) is a computer-controlled system that automatically maintains a vessel's position and heading using its own propellers and thrusters. The DP mode must keep power resources available at any time sufficient to handle peak loads caused by extreme waves and wind variations, even in combination with failure of one of the main vessel engines. This has resulted in a general operational pattern with vessels running multiple engines simultaneously even at calm sea conditions when serving the oil and gas installations, i.e. inside a radius of 500 meters.

When engines operate at lower power, fuel consumption per unit of output (per kWh) produced increases. For the cost of the operation, this increase in specific fuel consumption at lower loads makes a small impact compared to the total cost of the operation. In contrast, for emissions, low loads yield a greater increase in emissions of exhaust gases such as nitrogen oxides (NOx) (Duran et al., 2012; Ehleskog, 2012) and aerosols such as black carbon (BC) (Kasper et al., 2007; Ristimaki et al., 2010; Lack and Corbett, 2012; Lindstad et al., 2015). Complicating matters, emissions in one region may lead to a direct climate forcing that differs in magnitude to the same quantity emitted in another region (Corbett et al., 2010; Lindstad et al., 2016). This is due to regional differences in sea ice extent, solar radiation and atmospheric optical conditions (Myhre and Shindell, 2013). For example, the deposition of black carbon over highly reflective surfaces such as snow and sea ice reduces the albedo of these surfaces, thereby increasing their temperature. This in turn leads to increased melting and additional reductions in snow/sea ice extent and consequently further reductions in the surface albedo, i.e. it has a significant reinforcing effect (Hansen and Nazarenko, 2004; Zender, 2012; Sand et al., 2013). Region-specific global warming potential (GWP) characterizations with emission impacts

expressed as "*CO₂ equivalents*" (CO$_2$ eq.) are therefore needed to more accurately quantify the climate impact of each emission species (Shine, 2009). Negative values are used for exhaust gases and particles that have a cooling effect and positive figures are used for those that have a warming effect. Some of the emission gases are short-lived climate forcers, with an impact on climate over relatively short timescales. Others such as CO$_2$ are retained in the atmosphere on a millennial timescale.

One option for reducing the emissions and climate impacts in maritime shipping is through hybrid power technology. It is particularly promising for vessels operating under varying conditions, and we conduct this analysis on offshore vessels because of their great variation in actual loads and their great need for potential load at short notice.

In this context, hybrid means adding electric battery capacity to the conventional power setup, facilitating a power production more adapted to the demand in various operating modes. Batteries have the following advantages: First, they can compensate for load fluctuations, enabling the combustion engine(s) to run at a more constant – and optimized - load. Second, operation of combustion engines at very low loads is avoided and the engine (s) can run more at medium to high power with lower specific fuel consumption and lower emissions. Third, batteries engage instantly and can provide any peak power required by the DP system. Fourth they enable the vessel to abort its DP operation safely supposing all engines should stop and not start again. For these reasons, installing batteries may enable a reduction of the number of main combustion engines currently installed, namely from four or three to three or two.

This paper assesses the pros and the cons of installing batteries on offshore support vessels, with regard to pollution, climate impact and economics. The employed model is described in the next section, followed by its application and data. The obtained results are discussed in the final section.

2. MODEL DESCRIPTION

We need assessment of costs, fuel consumption and emissions as function of power demand (see Lindstad et al. (2011; 2014; 2015)), limiting our attention to the vessels and their use. The model consists of five main equations where the first calculates the power requirement. The power for any given mode, P_i, is expressed by equation 1. This setup is established practice (Lewis, 1988; Lloyd, 1988; Lindstad et al., 2013).

$$P_i = \left(\frac{P_s + P_w + P_a}{\eta}\right) \cdot (1 + Safetyfactor_i) + P_{aux} \tag{1}$$

The power model takes into account propulsion efficiency η, the power needed for still water conditions P_s, the additional power required for waves P_w, the power needed for wind P_a, and the necessary auxiliary power P_{aux} as a function of sea state, wind ,vessel speed and the required $Safetyfactor_i$ in DP modes. This factor is 0 for all other operational modes such as transit.

During a year, the engine load will vary depending on operating modes and the total annual fuel consumption can be found by summarizing the consumption for the time spent in each of these operating modes as expressed by equation 2.

$$F = \sum_{i=1}^{n} K_{fp} \cdot P_i \cdot T_i \tag{2}$$

Here K_{fp} is specific fuel consumption as a function of engine load, P_i is the engine load for each operating mode and T_i is the time spend in each operating mode.

The annual emissions per pollutant in the exhaust gas are calculated as expressed by equation 3:

$$\varepsilon_e = \sum_{i=1}^{n} K_{ep} \cdot P_i \cdot T_i \tag{3}$$

Here K_{ep} is the emission factor for the pollutant e as a function of engine load. The relationship to engine load is that emissions per kWh produced increase when engine load is reduced.

The global warming potential (GWP) for the given time frame expressed as CO2 equivalents is calculated by equation 4:

$$GWP_t = \sum_{e=1}^{n} \varepsilon_e \cdot GWP_{et} \qquad (4)$$

Here, ε_e represents emissions per pollutant e for the given time frame and GWP_{et} is the global warming factor for each pollutant within the given time frame.

The annual cost per vessel comprises the annual fuel consumption, the cost of fuel and the annual time charter cost of the vessel as expressed by equation 5:

$$C = \left[(F \cdot C_{Fuel}) + \left(Capex_v \cdot (k_1 + k_2) \right) \right] \quad (5)$$

Here the first term gives the annual fuel cost as a function of fuel consumption F as calculated by equation 2 and the cost of the fuel C_{Fuel}. The second term gives the annual cost of operating a vessel based on its new-building price $Capex_v$, where $k_1\%$ of $Capex_v$ are fixed costs consisting of financial cost including depreciation and return on own capital, $k_2\%$ of $Capex_v$ is the variable cost.

3. APPLICATION AND ANALYSIS

Offshore support vessels support different aspects of oil and gas installations, such as supply, standby, anchor handling and subsea operations. Still, they have common distinctive operational modes, such as: waiting in port; loading and discharging in port; transit to and from the oil fields; waiting at the oilfields or performing standby functions; and performing their intended work at the oil and gas installations in DP mode. The annual duration of each mode will vary depending on their support role and on the geographical region in which they serve. Figure 1 shows a typical annual operational profile with the associated power demands for a supply vessel operating in the North Sea (Troms Offshore, 2015; in house data; Fagerholt and Lindstad, 2000). It indicates that the vessels will stay around 25 % of time in port (loading, unloading and waiting). Around 40 % of the time will be used in transit to and from the oil fields where the speed reflects voyage priorities, like urgency, focus on fuel savings or the scheduled arrival time. 35% of the time will be used serving the oil and gas installations either waiting in standby mode or in DP mode serving the platform. The large share of travelling at economy speed, i.e. 10 knots instead of 12 or 15 knots, reflects the current over-capacity of offshore support vessels and the slowdown of the whole oil and gas sector. Standby vessels will be less in transit and in ports than the typical Supply Vessels, Anchor handlers will be less DP mode, and subsea vessels, which operate (remotely) underwater vehicles serving oil and gas installations at the seabed, might spend more time in DP mode. However, these variations in operational profile do not affect the main conclusions of the present study.
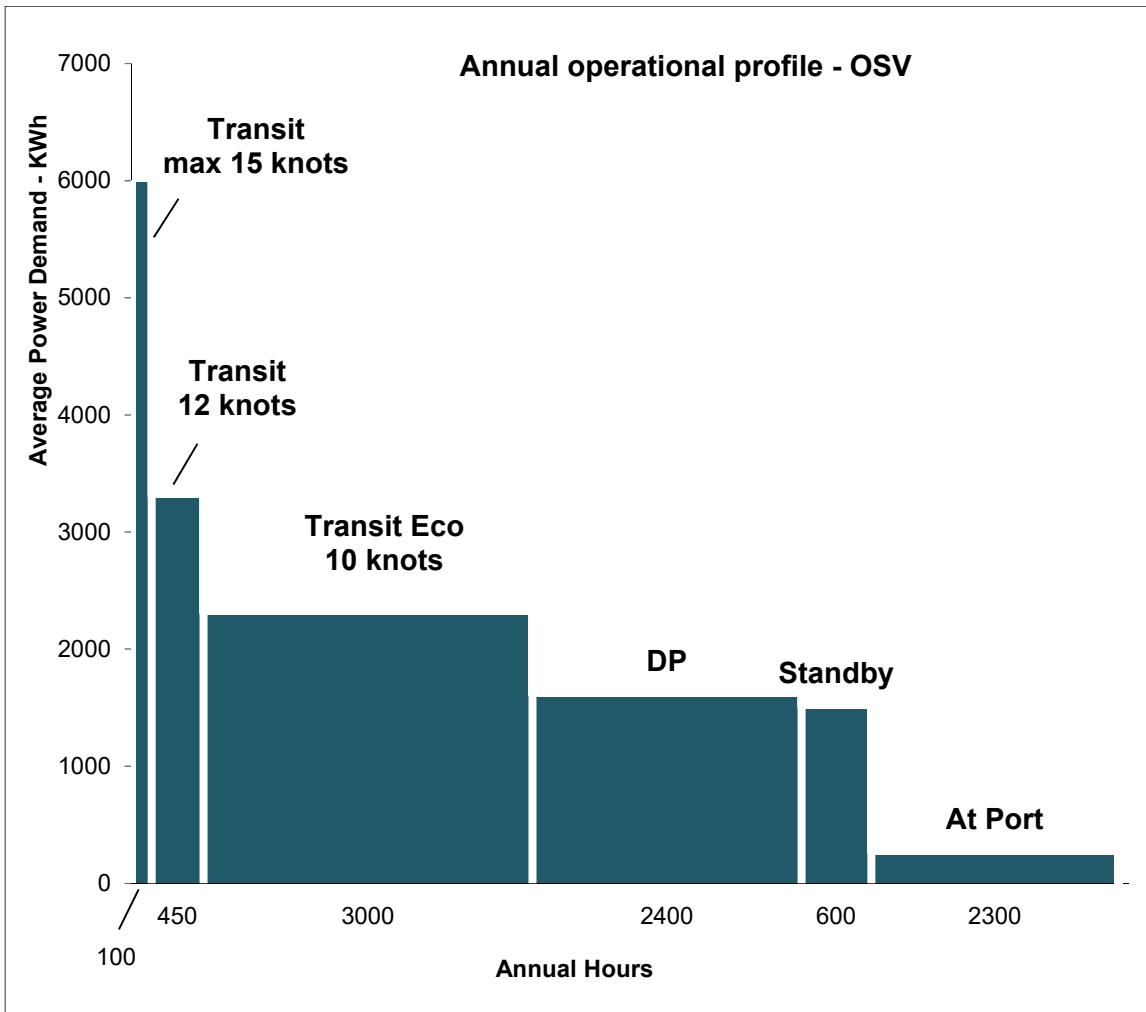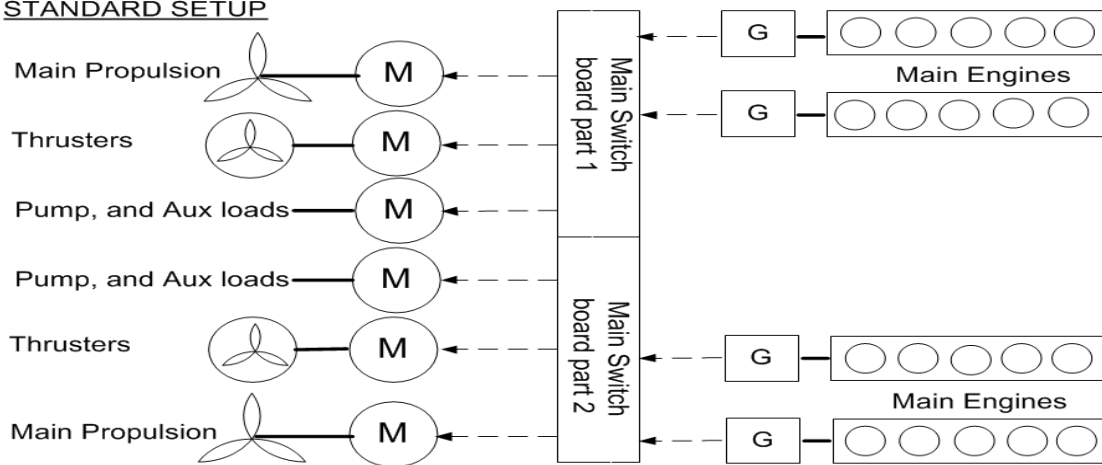
Figure 1: Annual operational profile for offshore support vessels

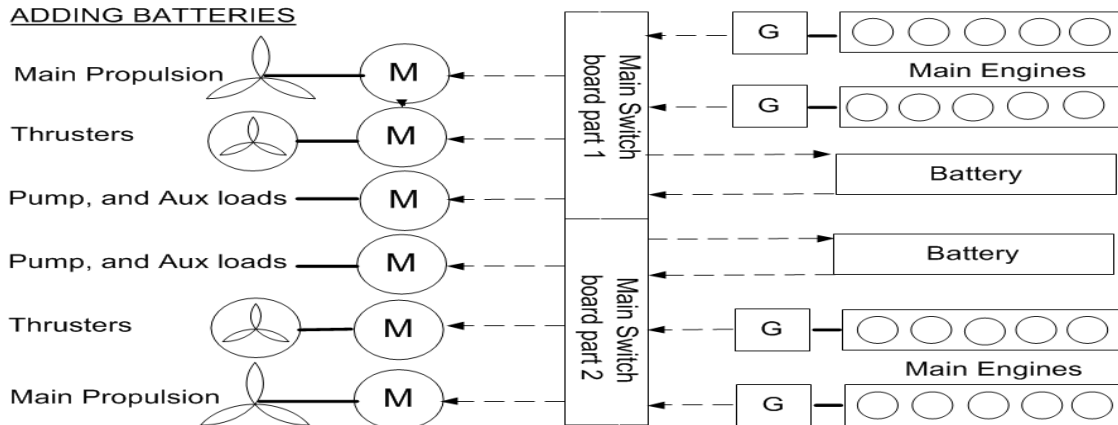## 3.1. *Power and propulsion setups for offshore support vessels*

To handle large variation in power demand as shown by Figure 1 and the strict dynamic positioning requirements, offshore support vessels are equipped with multiple engines, advanced control systems and a propulsion systems consisting of propellers and thrusters. Figure 2 shows three alternative engine setups for a typical offshore support vessel. The first is the standard setup consisting of four diesel generator sets, which may be of equal size or with two slightly larger and two slightly smaller ones. These generator sets are paired, then linked respectively with part one (1) and part two (2) of the main switchboard. The second alternative

setup is to add batteries to the standard setup, one for each part of the switchboard. The third option is to replace two of the engines from the standard setup with batteries, keep one of the remaining engines unchanged and double the installed power of the last one. These three alternatives will be referred to in the remaining of the paper as alternative 0 for the standard setup, alternative 1 when batteries are added, and alternative 2 when two engines are replaced with batteries.
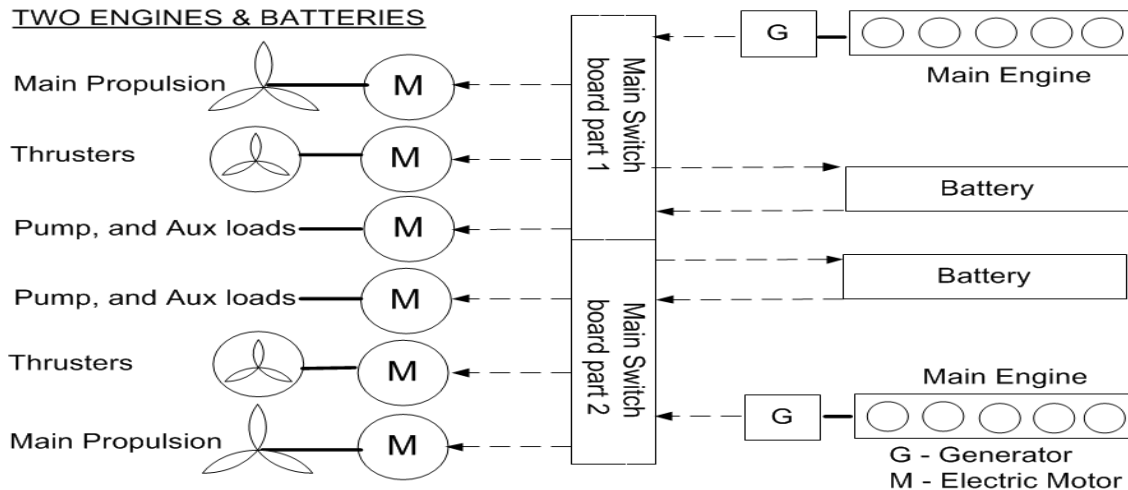
Figure 2: Alternative power and propulsion setups for offshore support vessels

All these setups enable the vessel to meet the requirements of classification societies for operation in DP mode, even if the generators connected to one part of the switchboard or the switchboard itself stops working. The explanation is that the main engine(s) or battery (ies) connected to the other part of the switchboard will have sufficient capability to continue the DP operation. With a standard setup (alternative 0), two or three engines will have to run when the vessel is operating in DP mode to assure power delivery even in case of blackout of one or even two engines simultaneously. With the battery options (alternative 1 and 2), it be sufficient to have one engine running, because the battery (ies) will provide the required power instantly if the engine stops. When two or three engines are supporting a low overall power demand, each of these engines will be lightly loaded, resulting in higher fuel consumption per kWh and significantly higher emissions per kWh. Figure 3 shows the fuel consumption in gram per kWh as a function of power output for a diesel engine, when combined with a fixed revolt generator set based on fixed engine revolts (Constant speed diesel engine) and alternatively when the same engine is combined with a variable revolt generator (Variable speed diesel engine). These curves are based on laboratory data provided through personal communication with Wärtsilä (2015), annual real-time measurements provided by Troms Offshore (2015), and authors' calculations for this study. It should be noted that the curves and emissions figures in this paper represent typical operational figures for a vessel built after 2010, and not what is achievable with the newest engine technology such as the new four stroke Wärtsilä engine launched in 2015. The figure shows that the best performance, namely the lowest specific fuel consumption, is achieved at around 80% power, while at 30 % power output fuel consumption increases by around 5 % for a variable speed setup and around 10 % for a fixed speed setup. Since 30% power is a typical operational point per engine running when vessels run multiple engines in DP mode, the potential savings with batteries will be the difference in specific fuel consumption between 30 % and 80 % power. In addition, batteries will give savings for other operational modes like *at port* and *standby*, as well as for some transit speeds, since these imply lower or higher than 80 % power.
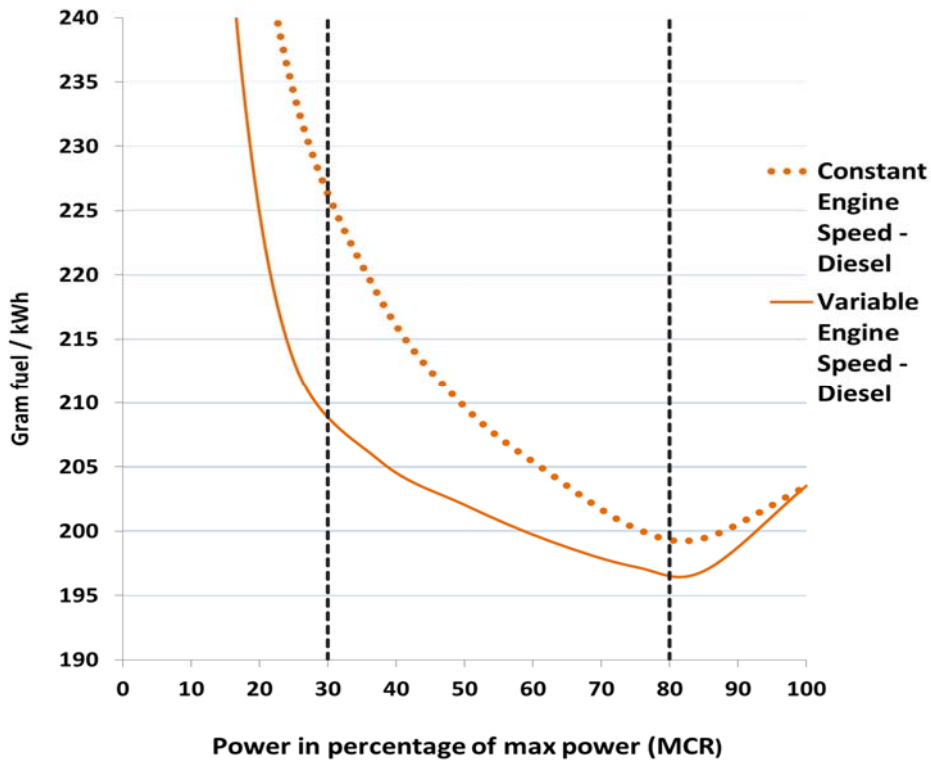
Figure 3: Gram fuel per kWh as a function of power and engine – generator setup

3.2.   Fuel consumption and cost for alternative hybrid power setups

Combining the operational profile given by Figure 1 with fuel oil consumption from Figure 3 enables us to calculate annual fuel consumption for four distinct options in Table 1. These options, documented in the last four columns of Table 1, are based on a combination of engine type (constant versus variable speed) and engine setup (standard versus hybrid). The hybrid setup here refers to both Alternative 1 and 2 presented in Figure 2, without distinction, because they will have the same fuel consumption and emissions.

Table 1: Annual fuel consumption as a function of engine, battery and technology

| Operational Mode | Annual Hours | Average Power | Constant engine Speed | Variable engine Speed | Fuel Consumption | | | |
					Constant engine Speed	Variable engine Speed	Constant engine speed & Battery	Variable engine speed & Battery
	hour	kW	gram/kWh		ton			
Dynamic Positioning - DP	2 400	1 600	225	210	864	806	768	756
Stand By	600	1 500	220	205	198	185	180	177
Port	2 270	225	290	265	148	135	102	101
Transit Eco - 10 knots	3 000	2 300	205	200	1 415	1 380	1 380	1 359
Transit - 12 knots	400	3 300	200	197	264	260	264	260
Transit Max - 15 knots	90	6 000	204	204	110	110	108	106
Totals	8 760	1 625			3 000	2 880	2 800	2 760

The main observations from Table 1 are: annual fuel consumption with constant speed engine and standard setup is around 3000 tons, and replacing it with a variable speed engine reduces the fuel consumption with 120 tons per year or 4 %. Furthermore, combining a constant speed engine setup with batteries reduces fuel consumption with 200 tons compared to the standard constant speed engine setup and with 80 tons compared to the standard variable speed setup. Finally, combining batteries and variable speed engine generator sets gives only a marginal additional reduction compared to fixed engine speed hybrid setups (40 tons). Given the fact that combining variable speed engine and generator setups with DP systems is novel technology, and hence comes at a high cost, we will in the remaining of the article focus on *fixed* speed engine and generator power trains.

3.3.   Cost and environmental assessment of hybrid power setups for offshore support vessels

To estimate the cost of a standard power setup (alternative 0), we can say that typically, around 8000 kW have been installed on offshore support vessels built for operation in the North Sea, which means four main engines at 2000 kW each with a total cost of 7.0 MUSD including the generators. Adding batteries to this standard setup (alternative 1) raises costs by 1.25 MUSD (for a battery capacity of 500 kWh including the battery-management systems), i.e. 8.25 MUSD. Removing two engines and then doubling the capacity of one of the remaining two engines (alternative 2), gives a total engine power of 6000 kW, for a cost of 5.0 MUSD. With less installed power, there is a need for a larger battery capacity of 1500kWh at a cost of 2.5 MUSD, resulting in a total cost of 7.5 MUSD for this second hybrid alternative. These costs can be compensated at first by the annual fuel saving of 0.1 MUSD, resulting from a saving of 200 tons at a current price (2016) of around 500 USD/ton for marine gas oil (MGO). There will also be savings on lower maintenance cost due to fewer engines and fewer generator running hours, but these will be offset by the costs related to the additional training and knowledge required on board. Table 2 shows capex, savings and payback based on the current fuel price and the 2014 price, i.e. 1000 USD per ton, for the three alternative power setups

Table 2: Capex, Savings and Payback

			Annual Saving		Payback time	
	Capex	Fuel	Fuel cost 500 USD/ton	Fuel cost 1000 USD/ton	Fuel cost 500 USD/ton	Fuel cost 1000 USD/ton
	MUSD	Ton	MUSD	MUSD	Years	Years
Standard Setup	7.00					
Adding Batteries	8.25	200	0.1	0.2	12.5	6.3
Two Engines & Battery	7.50	200	0.1	0.2	5.0	2.5

The main observations from Table 2 are that, first, with the present fuel cost (500 USD/ton), the payback time of 12.5 years is too long if the batteries are added to the standard engine setup (even be longer than the expected duration of the batteries). Second, doubling the fuel price to the average 2012-2014 peak prices halves the payback time, i.e. but who will take the risk of fuel prices coming back to the 2012-2014 levels within the next years. Third, combining batteries with two engines gives shorter payback time, i.e. 2.5 to 5 year, but this is only an alternative for new vessels to be built, while Alternative 1 is also suitable for retrofit.

Offshore support vessels serve the oil and gas industry globally and, as described in the introduction, the climate impact of equal emissions may differ in magnitude from one region to another. Here we have chosen to limit the scope to compare North Sea vessel operations with Artic operations in the Barents Sea based on MGO with a Sulphur content of max 0.1 %. In Table 3 we compare emissions and GWP impact with a standard engine setup (alternative 0) with hybrid setups (alternative 1 and 2). The GWP World figures (IPCC, 2013) are representative of the impact of emissions in oil and gas regions such as the North Sea and the Gulf of Mexico. The Artic figures (IPCC, 2013) are representative of activities in the Barents Sea. GWP is usually integrated over 20, 100 or 500 years consistent with Hougthon et al. (1990) with the latter lending greater weight to the compounds with longer lasting warming effect. We choose to make the assessment with a 20 and a 100 year GWP (Lenton et al., 2008; Boé et al., 2009).

Table 3: Emission factors in gram per kWh and the applied GWP factors

Emission type	CO_2	BC	CH_4	CO	N_2O	NOx	SO_2	OC	CO_2 eq. Hybrid Power	CO_2 eq. Standard Power
Standard power - gram/kWh	630	0.025	0.050	1	0.02	6	0.45	0.2		
Hybrid power - gram/kWh	675	0.100	0.100	2	0.02	8	0.50	0.2		
GWP_{20} World factors	1	1200	85	5.4	264	-15.9	-141	-240	468	574
GWP_{20} Arctic factors	1	6200	85	5.4	264	-31.0	-47	-151	563	1016
GWP_{100} World factors	1	345	30	1.8	265	-11.6	-38	-69	547	596
GWP_{100} Arctic factors	1	1700	30	1.8	265	-25.0	-13	-43	517	641

Combining these emissions with the applicable GWP factors we get the total warming effect in terms of CO_2 equivalents for hybrid and standard engine setups, displayed in the two last columns of Table 3. The global warming potential is evaluated for North Sea and the Arctic, and for both a 20-year time horizon (GWP_{20}) and a 100-year time horizon (GWP_{100}). We can see that the effect of hybrid setups is valued more favourably by warming factors in the Arctic than in general, and more favourably by GWP_{20} than by GWP_{100}. Emissions contributing to global warming are positive values in Figure 4, while those contributing to global cooling are negative values. The red and white marker (total CO_2 eq.) denote net warming, as shown in the two right hand columns of Table 3. The size of the stack bars represents the CO2 eq. value from each emission type.
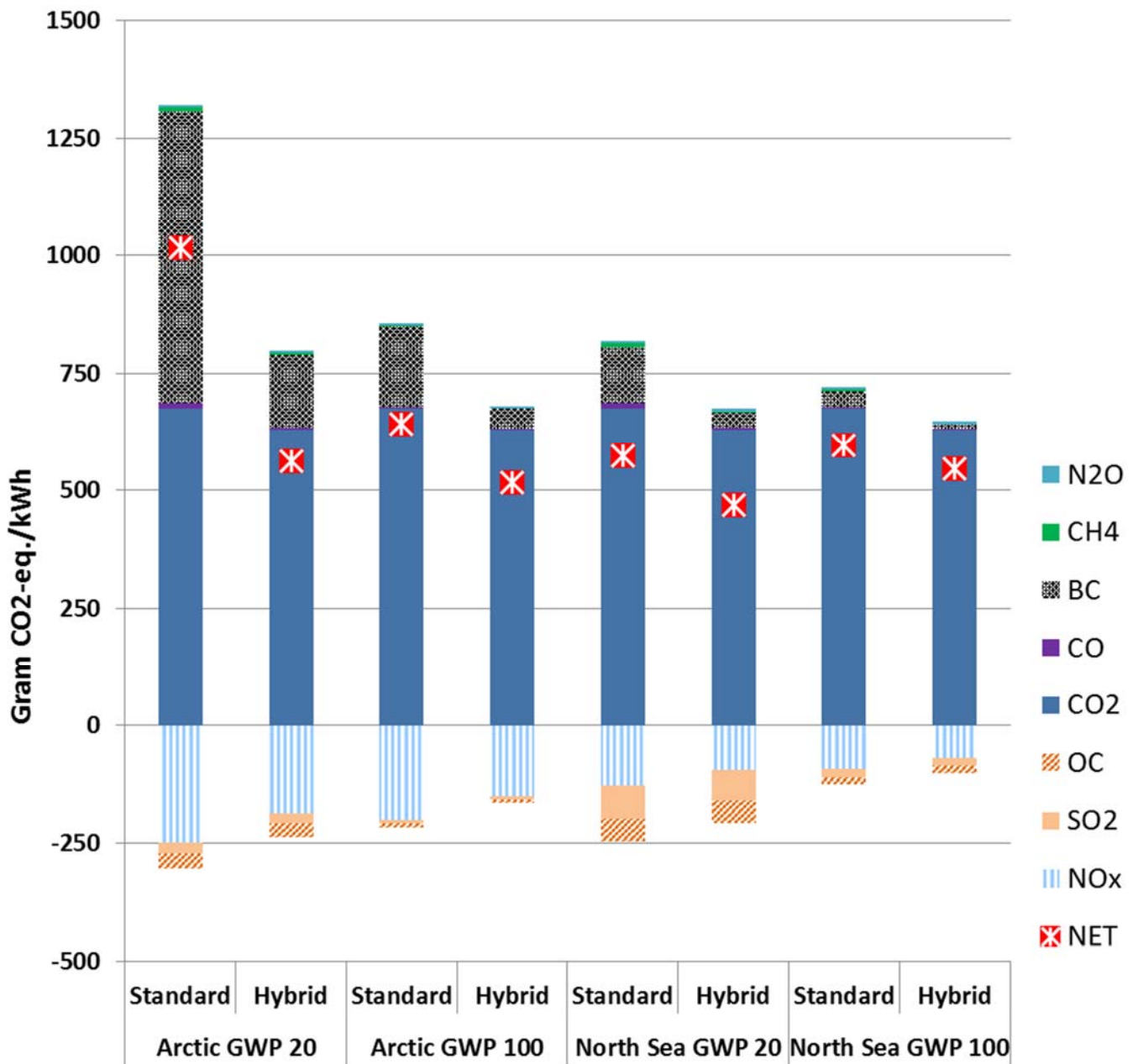
Figure 4: Gram CO₂ eq. impact per kWh with a 20 and 100 year time horizon as a function of operational area and power

The main observations from Figure 4 are that the standard setup gives higher CO₂ eq. emissions per kWh produced than the hybrid options, i.e. the NET label in the figure. This difference in CO₂ eq. emissions is

larger in the Arctic than in the North Sea, due to the impact of the Black Carbon (BC). When the time horizon becomes longer, i.e. 100 years, the effects of the short-lived exhaust gases diminish and the CO2-only emissions becomes dominant. This implies that hybrid power setups with batteries, which enable us to avoid low power, will contribute to reducing the climate effect of offshore support vessels, with the largest climate mitigation effect for Artic operations. Moreover, if the focus is on pollution, like in Bergen port in the Southern Norway on a winter day, the benefit of reduced local air pollution (smog) might be a strong argument on its own for encouraging increased use hybrid power setups also in non-Artic areas.

Figure 5 summarizes the annual fuel consumption, emissions and abatement cost for the standard and hybrid setups, based on the operational profile given by table 1, which implies that the standard power setup will combust 50 % of its fuel at high power and 50 % at low power, while hybrid power option will combust all at high power. The CO_2 equivalent effects are calculated for a 20 year and 100 year time period based on figures from Table 3.
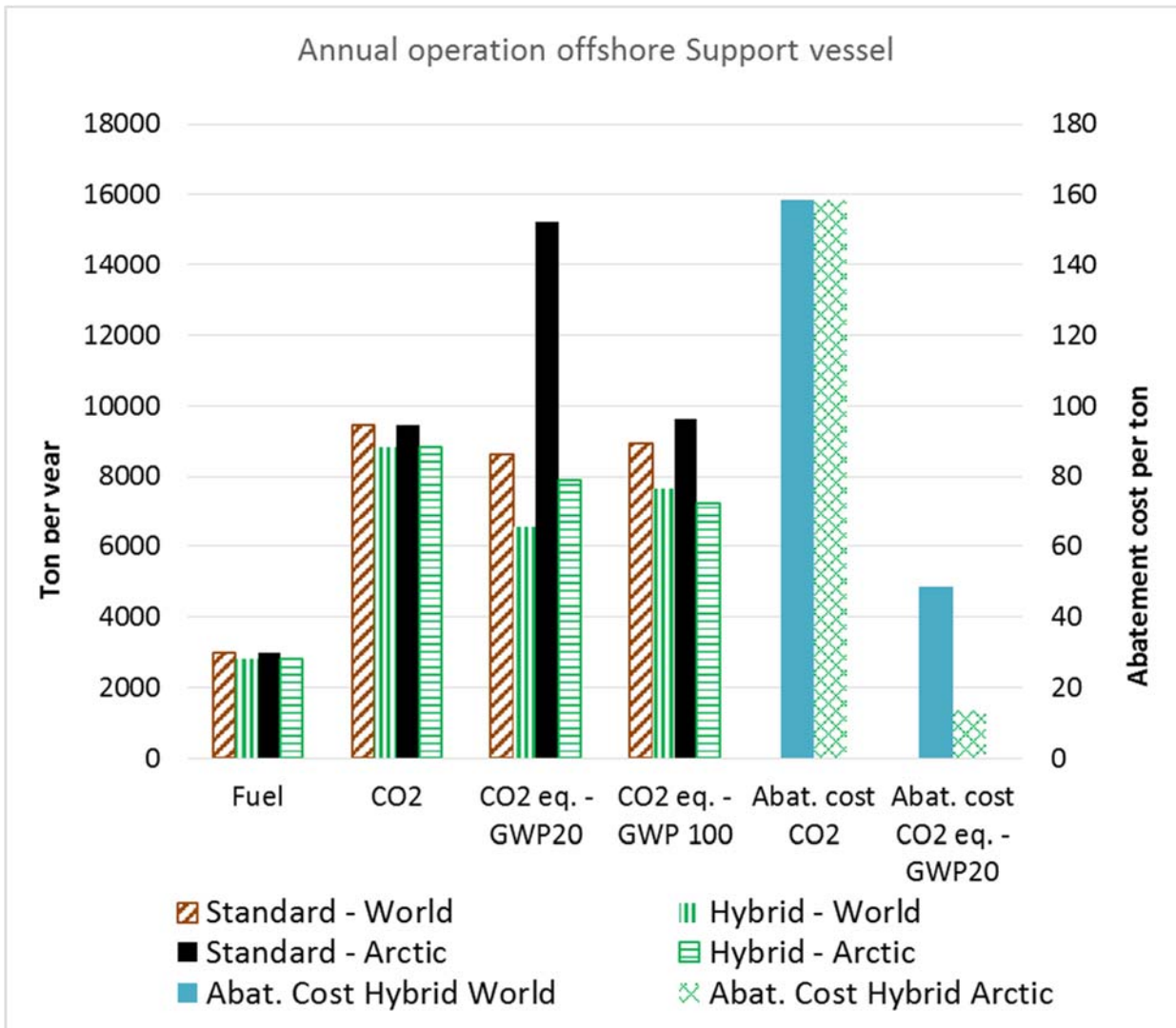
Figure 5: Annual fuel and emissions for the standard versus hybrid setup, and abatement cost with hybrid power setups

The following conclusions can be made from figure 5: First, with regard to fuel consumption and CO2-only emissions, hybrid power setups with batteries gives 6 – 8 % reduction compared to standard power setups. Second, when including all emissions expressed in CO2 eq., hybrid power setups give 40 – 45 % reduction in Artic areas and around 20 % reduction in the North Sea, compared to standard setup. Third, if the focus is in

local pollution the reduction in absolute emissions is even larger since the net reduction comes in combination with reduction of both cooling and warming exhaust gases. Fourth, abatement cost from hybrid solution for CO2-only is around 150 USD per ton, for either Artic or non-Artic operations. Fifth, including all exhaust gases reduces abatement cost per ton of CO2 eq. to 50 USD in non-Arctic areas and to 15 USD in Arctic.

4. CONCLUSIONS

This main objective of this study has been to investigate the pros and the cons of installing batteries on offshore support vessels. Our results indicate that combining batteries with combustion engines reduces local pollution and climate impact. For climate change mitigation, hybrid power setups gives 40 – 45 % reduction in annual global warming potential in Artic areas and around 20 % reduction in the North Sea (GWP 20). When focus is on reducing local pollution, the reduction of harmful exhaust gases enabled by a hybrid solution is independent of operational area and in the magnitude of 25 – 30%.When focus is on economics based on current fuel prices for marine gas oil, i.e. 500 USD/ton, the economics is more dubious. When retrofitted on an existing vessel the payback will be 10 – 15 years (12.5 years with 200 tons of saved fuel and an increase in capex of 1.25 MUSD). Therefore, unless the ship-owner is very concerned about the environment and has the financial resources, or the customer (oil companies) demands it, or there are regional incentive schemes available, batteries will not be retrofitted on existing vessels. For new-buildings, hybrid prospects look brighter, since batteries can replace one or two of the four main engine and generator sets, without compromising security or service standards. With only 0.5 MUSD in incremental capital expenditures compared to the present standard power setup, payback time is estimated to about 5 years for a new-built vessel, which will be found favourable by many.

Regarding sensitivity, for the economics of hybrid power setup solutions, future battery and fuel prices play a more important role than variations in future operational profiles. For the batteries and the battery management system, a consensus estimate is that the price will be lower than today, which implies that even retrofits will be profitable if prices comes down by 50 – 75 %. Furthermore, if fuel prices comes back to 2012-2014 levels, which is twice the present level, the payback time will also be reduced to half. However, history tells us that predicting future fuel prices is difficult, which is why it is important to consider large price ranges for assessing alternative emission abatement solutions.

Acknowledgements

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