

Medium and high-speed engines in marine hybrid applications

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Master's thesis
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ABSTRACT

Hybrid Technologies, which means combining traditional combustion engines with energy storage devices like batteries, are a new development within the marine sector. Due to stricter emission regulations, the demand on lower fuel consumption, developments in battery technology and image of being environmentally aware hybrid technologies will become more popular in the future.

The objective of this thesis was to investigate differences between medium-speed engines and high-speed engines when pairing them with batteries in terms of fuel consumption, service costs and emissions. For the comparison, three different vessel types where the advantage of hybrid systems is great were chosen. These were: tug boat, platform support vessel and short route ferry. Four different engines were chosen to be compared: two medium-speed and two high-speed paired with different battery sizes. Both mechanically driven and electrically driven propulsion systems were compared.

In this thesis, different Excel-based programs were used to compare the different hybrid setups consisting of various engine types and battery sizes. A program was developed specifically to suit the calculation needs of this thesis. For one voyage a load profile consisting of both hotel and propulsion load was defined. Depending on battery size the way of operating was decided in order to have engines operating on optimal load for shortest possible time, which would be economically most beneficial.

The results show that hybrid systems are beneficial for the selected vessels in all cases in terms of reducing fuel consumption, emissions and service costs compared to traditional setups. The same type of reduction can be noticed from real-life cases, which were used to validate the results. Important in the future will be developing a well-functioning automation system that optimizes the interplay between engines and energy storage devices. Engines and batteries should be considered as only components in a hybrid system. Since engines would theoretically only be used within their optimal operating range, some functionalities could be excluded when used in a hybrid system. Specific strongpoints and weaknesses of medium and high-speed engines would become less significant, since batteries should be used whenever possible.

Further research within this field could focus on when it is economically efficient to swap engines to batteries, calculating where the split between engine output and energy storage capacity is most efficient. Also, development of efficient simulation for vessels with both engines and batteries would bring much value to all involved parties.

Key words: Hybrid, battery, energy storage, high-speed engine, medium-speed engine

ABSTRAKT

Hybridteknologier, det vill säga kombinationer av traditionella motorer och energilagringssystem så som batterier, är en ny utvecklingsriktning inom den marina sektorn. På grund av hårdare utsläppskrav, krav på lägre bränsleförbrukning, utveckling inom batteriteknologin och bilden av att vara miljövänlig kommer hybridteknologier bli mer populära i framtiden.

Målet med detta arbete var att undersöka skillnader mellan mellanvarviga och högvarviga marinmotorer då de kombineras med batterier. Skillnader i bränsleförbrukning, underhållskostnader och utsläpp undersöktes. För jämförelsen valdes tre olika fartygstyper i vilka hybridsystem vore lämpliga att använda; bogserbåtar, underhållsfartyg för plattformar och färjor. Fyra olika motormodeller valdes, två mellanvarviga och två högvarviga samt olika batteristorlekar. Både mekaniska och elektriska framdrivningssystem togs i beaktande.

För att jämföra olika hybridkombinationer med diverse motortyper och batteristorlekar användes olika kalkyleringsverktyg. Ett program utvecklades specifikt för detta arbete. För en resa specificerades en lastprofil med både hotellast och framdrivningslast. Beroende på batteristorlek bestämdes hur fartygets framdrivningssystem skulle agera för att motorerna skulle gå med optimal last på kortast möjliga tid. Det mest ekonomiskt fördelaktiga sättet att använda motorer och batterier togs fram.

Resultaten visar att hybridteknologin är fördelaktig jämfört med traditionell teknologi då det gäller att sänka förbrukning, utsläpp och underhållskostnader. Resultaten är enhetliga med fall som använts för att verifiera resultaten. I framtiden kommer det att vara viktigt att utveckla välfungerande automationssystem för att optimera samspelet mellan motorer och batterier. Motorer och batterier ska ses som ett hybridsystem. Eftersom motorer teoretiskt sett endast skulle användas nära deras optimala lastnivå kunde vissa funktioner lämnas bort när de används i ett hybridsystem. Motortypspecifika styrkor och svagheter på medelvarviga och högvarviga marinmotorer blir mindre viktiga då batteriers fördelar kan kompensera för motorers svagheter vid behov.

I framtiden kunde man fokusera på beräkningar som visar när det vore lönsamt att byta ut motor(er) mot batterier, och var delning mellan motoreffekt och batteriers lagringskapacitet är mest effektiv. Utveckling av bra simuleringsverktyg för hybridfartyg kunde alla inblandade parter dra nytta av.

Nyckelord: Hybrid, batteri, energilagring, högvarvig dieselmotor, mellanvarvig dieselmotor

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LIST OF ABBREVIATIONS

AC	Alternating current
CAT3516B	Caterpillar engine 16-cylinder engine in v-configuration. Diesel fuel
CPP	Controllable pitch propeller
DC	Direct current
DNV-GL	Classification society, Det norske veritas – Germanische Lloyd
DE	Diesel electrical drive
DM	Diesel mechanical drive
DP	Dynamic positioning
DWT	Dead weight tonnage
EMS	Energy management system
ESS	Energy storage system
FPP	Fixed pitch propeller
IMO	International maritime organization
LNG	Liquified natural gas
OSV	Offshore support vessel
PMS	Power management system
PTI	Power take in
PTO	Power take off
PSV	Platform supply vessel
SFOC	Specific fuel oil consumption (g/kWh)
SOC	State of charge for battery
USD	US dollar
W8L20	Wärtsilä inline 8-cylinder engine with cylinder bore 20cm. Diesel fuel
W6L34DF	Wärtsilä inline 6-cylinder engine with cylinder bore diameter 34cm, dual fuel

1 INTRODUCTION

Driven by society's demand on lowering emissions for the marine sector, different laws and legislations have been implemented and over time become more and more strict. The Paris agreement is one example which was set to reduce greenhouse gas emissions. Reductions to be completed within the following decades will be a driving factor for technological development. (UN, 2015)

Stricter emission laws and the economic importance of lowering operational costs have led to engine manufacturers constantly looking to develop their products to meet the requirements of customers. A new solution is to implement different new technologies together with traditional engines in so-called hybrids to achieve these goals. The term hybrid means that also other energy sources or energy storage devices are combined with traditional combustion engines to reach lower emission levels and operating costs, much like in the automobile industry. Hybrid installations will offer large benefits in certain vessel segments, whilst in others only small advantages can be gained. Studies have, however, shown that in every segment there is potential for utilization of hybrid solutions. The market for hybrids does not have a "big player" yet, so there are great opportunities to be seized by developing functioning systems. For this purpose, it is important to know what the requirements are for both hybrid systems and components within the system. (Späth, 2018) (Jaurola;Hedin;Tikkanen;& Huhtala, 2018)

In the marine industry, reciprocating engines can be categorized by their turning speed: low-speed, medium-speed and high-speed. The big company present in Ostrobothnia, Wärtsilä, is the market leading medium-speed engine manufacturer in marine industry. In 2017, 47% of medium-speed engines for the marine market were supplied by Wärtsilä. A combination of engines and batteries sets other requirements on the components compared to traditional setups with only engines. Therefore, the different engine categories need to be compared in hybrid applications to clarify in which direction the development of hybrid systems and engines needs to move. (Wärtsilä, 2018f)

In this thesis, different in-house developed simulation and calculation tools based on Microsoft Excel software will be used to calculate and simulate different kinds of vessel setups with both engine categories and batteries installed. The Excel-based hybrid medium/high-speed calculation tool was developed specifically to suit the needs of this thesis. The general purpose of this thesis is to study the differences, strengths and weaknesses of medium-speed and high-speed engines in different hybrid vessels, as well as to clarify what engine functions are of importance in hybrid vessels. The objective of this study is to make a comparison between medium-speed and high-speed engines when paired with batteries in hybrid applications for different vessel types. Economic, environmental and technical aspects are considered when conducting the comparison.

Low-speed engines are not included in this study, since they are not regarded as a contender in hybrid applications for the selected vessel types, due to low-speed engines being used mostly in vessels that benefit less from hybrid solutions. The engine unit

size is restricted to 500kW to 2MW since the majority of high-speed engines is within this power range. The most commonly used solution in a hybrid vessel is batteries paired with engines, and this thesis will be limited to only these combinations. The thesis focuses only on fuel oil engines.

2 THEORY / LITERATURE REVIEW

2.1 Hybrids in general

Definition of a hybrid: “a vehicle that is powered by an internal-combustion engine and another source of power such as a battery”. (Collins, 2012)

When mentioning the word hybrid today most people tend to think about hybrid cars which in recent years have become more and more popular. Most known is the first mass-produced hybrid electric car, the Toyota Prius. Hybrid electric means that it uses a combustion engine together with batteries to lower emissions and fuel consumption. The Prius uses battery only, battery and combustion engine or combustion engine only (battery charging) depending on the driving conditions. When braking, the system uses the car’s kinetic energy to charge the batteries. A Prius produces around 100 kW with the petrol engine and the electric engine (third generation, 1.8 litre petrol engine). (Voelcker, 2015)

The first hybrid car was the Lohner-Porsche Mixte Hybrid which was developed in 1901. The car was driven by hub mounted electric motors. The electric motors could be powered by a battery and/or a petrol engine. The power output for this vehicle was around 7.5-10.5 kW.

Also bicycles, motorcycles and other heavy vehicles, such as buses and trains, have been equipped with hybrid systems. In addition, cranes and other similar equipment that have a high kinetic energy workload can utilise different types of energy storage systems besides primary power source.

2.2 Marine hybrid history

The earliest form of hybrid vessels utilised both sails and steam engines. When it comes to batteries paired with combustion engine, the first vessels were submarines. Submerged, it is not possible to run combustion engines for extended time periods due to a lack of oxygen and other restrictions. In 1900, the USS Holland was commissioned. It was the first modern submarine which utilised both an electric motor and a combustion engine as a power source. A 66-cell battery powered a 37kW electric motor, the range of which was around 55km at a speed of 10km/h when submerged. For sailing surfaced the submarine was equipped with a 34kW 4-stroke petrol engine. (Pike, 2011)

2.2.1 Viking Lady

Viking Lady which was built in 2009, was the first merchant vessel to utilise a fuel cell technology (320kW). In 2012, a battery pack (450kWh) was installed making Viking Lady the first hybrid platform supply vessel. Furthermore, the vessel is equipped with dual fuel engines (4x W6L34DF) with possibility to be run on natural

gas. Natural gas running lowers emissions significantly compared to fuel oil. The vessel is part of the so-called FellowSHIP project, a project that was initiated by Det Norske Veritas (DNV, classification society), Eidesvik offshore (owner) and Wärtsilä. The project was funded by a research Council of Norway and various other organisations. Viking Lady is claimed to be the most environmentally friendly vessel ever built. (Wärtsilä, 2017c) (Ship-technology, 2014)

2.2.2 Viking Princess

In autumn 2017, Wärtsilä handed over to the customer the first ever hybrid offshore supply vessel where a generator set is replaced with a battery pack (500kWh). Viking Princess was originally fitted with 4 Wärtsilä engines running on LNG in 2012 (2x W6L34DF & 2x W6L20DF), going hybrid one of the engines was replaced with a battery system. Due to an offshore supply vessel type of use high power redundancy is needed, this means all engines are not running simultaneously under normal conditions. Also, some of the engines are not running on optimal load depending on power need. This makes it feasible to install a hybrid system. In the case of Viking Princess, the fuel savings can be up to 30% in various operations and CO2 emissions can be reduced by 13-18% per year compared to previously without batteries. (Wärtsilä, 2017g) (Eidesvik, 2018)

2.2.3 Wärtsilä HY

Wärtsilä HY is a so-called integrated hybrid power module. This means the package includes engines/generating sets, energy storage systems (batteries) and other required components that are optimised together for a specific vessel. The brain behind these components is a so-called energy management system which controls in which fashion the different components behave. The solution is tailor made depending on the kind of vessel and intended use. The HY concept was launched in 2017. The first version of HY was specifically for tug boats but other vessel type specific HY systems will follow in the near future. (Wärtsilä, 2017a)

2.3 Components in marine hybrids

2.3.1 Engine

The device producing power is a central part of the vessel propulsion system. The power is most commonly produced by combustion engines, but also other alternatives like nuclear power plants are possible. There are two main types of combustion engines used in vessels: internal combustion engines (piston engines) and continuous combustion engines (turbines). Depending on the vessel type of use and the requirements from the user the type of engines is chosen. The selection of engine type and size is not only decided by vessel type of use, but also by the load profile and other parameters, like fuel price in the operating region. The load needs of a vessel can be divided into propulsion load and hotel load. Propulsion load consists of the different

propulsion equipment power consumption. Hotel load is the power consumption of equipment on board the vessel.

In this thesis, the focus is only on two types of engines: medium-speed and high-speed internal combustion engines. The distinction between the different engine categories is not officially defined, Wärtsilä definition is low-speed engines has a running speed of under 300 rpm, medium-speed have a running speed between 300 rpm and 1200 rpm and high-speed engines are running over 1200 rpm. Other manufacturers might use other definitions. Low-speed engines are usually 2-stroke engines and will not be taken into consideration in this thesis. All current engines in Wärtsilä's 4-stroke portfolio are medium-speed engines. Competitors like MAN, Cummins and CAT all have high-speed engines in their line of products. In Table 1, a comparison between some different engines from different manufacturers is made. Since it is most common to produce alternating current with the generators, the engines are "locked" to running at certain speeds, for instance 1000 rpm for 50 Hz and 1500 rpm for 60 Hz. (Möllenbauer & Tschöke, 2010) (Griffiths, 1999) (Mahon, 1992)

*Table 1 Engine comparison. *Dry weight only given in manuals etc. Wärtsilä engine weights with fluids. **calculated from l/h using equation 1. *** world record set with w31 engine to 165 g/kWh. (Caterpillar, 2017) (Cummins, 2017) (MAN, 2017) (Wärtsilä, 2017f)*

Engine	Rpm	Weight	Dimension (length, width, height)	Power	Power to weight ratio	Emission data	Fuel consumption
		kg	mm	kW	kg/kW		g/kWh
Wärtsilä 6L26	1000	17000	4387, 2107, 2832	2040	8.3	IMO Tier II (Tier III with SCR)	195 (100%)
Wärtsilä 8L20DF	1200	11100	3783, 1756, 2438	1480	7.5	IMO Tier II (Tier III in gas mode)	198 (100%) in diesel mode
Wärtsilä 8V31DF	750	56700	6175 x 3113 x 4701	4400	12.9	IMO Tier III in gas mode or diesel with SCR	173 (85%) *** in diesel mode
CAT 3516E	1800	9600*	3192 x 2284 x 2251	2873	3.4*	IMO Tier II	210
MAN 12V175 D	1800	8500*	3012 x 1633 x 2115	2200	3.8*	IMO Tier II (Tier III with SCR)	199 (100%)
Cummins QSK50	1500	6270*	2780 x 1573 x 2231	1108	5.7*	IMO Tier II	230**

One may draw conclusions about the characteristics of the engine based on the engine specifications. The relationship between output and weight of the engine is very much determined by the engine rotating speed. The investment cost of the engine is closely related to the engine weight. The lifetime of the engine can usually be determined by the power to weight ratio of the engine. The most significant factor when choosing between medium-speed engines and high-speed engines, is operating hours. A medium-speed engine has an approximate lifetime of 100,000 hours after which it has to be rebuilt to some extent. A high-speed engine has an approximate lifetime of 30,000 hours, after which the whole engine is usually replaced. The investment cost of a high-speed engine is lower than for a corresponding medium-speed engine. Fuel oil consumption is more efficient in medium-speed engines at the intended load level whereas in low-load conditions a high-speed engine usually has lower fuel consumption. As seen in Table 1, the physical size of the engine does not differ greatly between the listed high-speed and medium-speed engines. Weight is less of a factor when the vessel size grows. In high-speed vessels, light propulsion equipment is essential.

High-speed engines can, for the most part, only be driven on medium density fuel oil (diesel) or in some instances gas. Medium-speed engines may be operated with poorer quality fuel, e.g., heavy fuel oil. Gas and dual fuel engines are also available from multiple manufacturers as medium-speed engines. Dual fuel is an engine that can change seamlessly between fuel oil and gas during operation. (Wärtsilä, 2017f), (Mahon, 1992), (Möllenhauer & Tschöke, 2010), (Harshal, 2017), (Caterpillar, 2017)

Emissions

In an ideal fossil fuel combustion, the only produced products are heat, water (H₂O) and carbon dioxide (CO₂). The amount of these products are in direct correlation with their content in the fuel, which means that the only way to reduce carbon dioxide emissions in a combustion engine are to:

- a) Change to a fuel with less carbon content (fuel oil → LNG)
- b) Lower the specific fuel consumption.

Because the combustion process in a diesel, gas or gasoline engine is never ideal, other by-products will be produced. Incomplete combustion will result in harmful gases like nitrogen oxide (NO_x), carbon monoxide (CO) and unburned hydrocarbons (HC). If the fuel contains sulphur, there will also be sulphur oxides (SO_x) in the exhaust gases. (Heywood, 1988)

IMO emission regulations are set by the International Maritime Organisation (IMO) and the aim is to restrict emissions like sulphur oxides (SO_x) and nitrogen oxides (NO_x). Tier III emission regulations are applied in emission controlled areas (ECA's), e.g., the coastal waters of North America, the North Sea and the Baltic Sea. This means vessels sailing in these waters have to comply with these regulations. As can be seen in Table 2, the emission limits differ depending on engine rotational speed, which means an engine with lower rotational speed is allowed to pollute more. (DNV, 2017), (IMO, 2017a)

Table 2 IMO tier NOx regulations for vessels, allowed limits dependant on engine rotating speed. (IMO, 2017a)

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n= engine rated speed (rpm)		
		n < 130	n = 130-1999	n ≥ 2000
I	1.1.2000	17.0	45*n ^(-0.2)	9.8
II	1.1.2011	14.4	44*n ^(-0.23)	7.7
III	1.1.2016	3.4	9*n ^(-0.2)	2.0

Depending on when a vessel was built, it must comply with these regulations in order to sail within areas where these regulations are enforced. Older vessels are assigned a time limit in which to be upgraded in order to comply with regulations requiring 0,5% SOx emissions within ECA areas from 2020.

There are several ways to lower the NOx and SOx emissions according to Det Norske Veritas classification society:

- Natural gas as fuel will massively reduce NOx and SOx emissions compared to fuel oils.
- Selective Catalytic Reactor (SCR). Cleaning device for exhaust gases.
- Exhaust gas recirculation.
- Fuel cells.
- Electric or **Hybrid systems**.

(DNV, 2017) (Jaurola;Hedin;Tikkanen;& Huhtala, 2018)

Energy consumption

Energy consumption is the amount of fuel needed to generate a unit of power. Energy consumption can be divided into two categories; liquid fuel consumption and gaseous fuel consumption, depending on what fuel the engine uses. If the engine is of so-called dual fuel type, it will consume fuel at low rate even though the engine operates on gaseous fuel. Because the gas mix is ignited by so-called pilot fuel. The consumption of liquid fuel is usually measured by the specific fuel oil consumption (SFOC) which has the unit g/kWh (grams per kilowatt hour). However, some manufacturers use l/h (litres per hour) as unit. Conversion between these can be done fairly easy by formula 1. The density used for all calculations is 890 kg/m³, which is a standard value for medium density fuel oils.

$$SFOC\left(\frac{g}{kWh}\right) = \frac{\text{fuel consumption}\left(\frac{l}{h}\right) * \text{density of fuel}\left(\frac{g}{l}\right)}{\text{Power}\left(kW\right)} \quad (1)$$

Consumption of gaseous fuels is set by the brake specific energy consumption (BSEC) and has the unit kJ/kWh (kilojoule per kilowatt hour).

Differences in fuel consumption between medium-speed engines and high-speed engines can be quite significant. Whereas a medium-speed engine usually achieves its

lowest consumption at around 85% load, a high-speed engine has lowest consumption usually at 100% load. This is also visualised in Figure 1. As the graph illustrates, higher rotation speed tends to result in higher fuel oil consumption per kilo watt hour output.

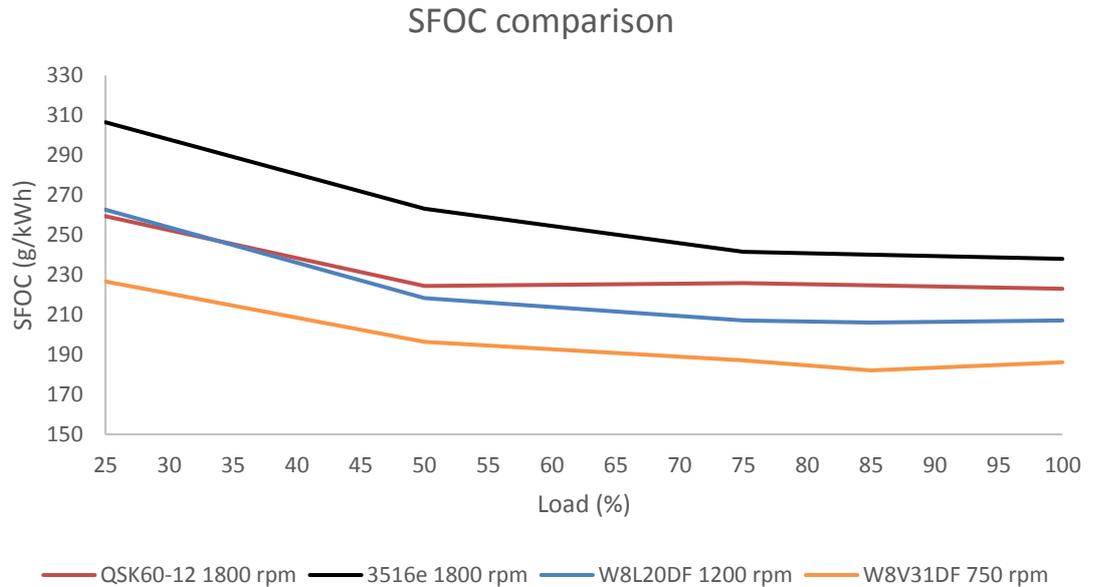


Figure 1 SFOC comparison between Wärtsilä 8L20DF, 8V31DF, Caterpillar 3516e and Cummins QS60-12 all 60 Hz versions. (Wärtsilä, 2017), (Caterpillar, 2017), (Cummins, 2017), (Vermeire, 2012), (Griffiths, 1999)

Lube oil consumption is important to take in consideration. The amount of Lube oil consumed is relative to the power output. A rule of thumb for this ratio is 1 gram lube oil per kWh.

Because high-speed engines typically achieve their lowest consumption at 100% load and medium-speed engines has their lowest consumption at approximately 85% load, the SFOC curve has to be interpolated for high-speed engine's fuel consumption data in order to get a corresponding 85% load point. Interpolation is done with Equation 2. Y for value x is the value you find and y_1 , y_2 , x_1 and x_2 are known values.

$$y = y_1 + (x - x_1) \frac{y_2 - y_1}{x_2 - x_1} \quad (2)$$

Mechanical versus electrical power

Different engine/generating set manufacturers use different units to define the output of their product; the power outputs must be aligned to make fair comparisons. Since the comparison is made between engines, all power outputs that are given in electrical power or kWe (kilowatt electrical) are converted to kWm (kilowatt mechanical) by using a factor of 4.5 % which is a commonly used generator loss. (ABB, 2015)

2.3.2 Electronics in hybrid system

Generator/Electric motor

The task of a generator is to convert mechanical energy to electrical energy, coupled together with an engine directly or through gearbox or shaft. Mechanical energy is converted to electrical energy by a spinning rotor inside magnetic fields. Depending on the number of poles and the rotational speed the electrical frequency is determined. When produced in a generator, the electrical energy is in the form of alternating current (AC). If direct current (DC) is needed, a rectifier must be used. (Jaurola;Hedin;Tikkanen;& Huhtala, 2018)

However, in a marine hybrid where the propulsion system is not electrically driven but coupled to gearbox or shaft arrangement, the generator has to have the option of working in reverse direction as a motor.

DC-link/inverter switchboard

Since the energy storage technology is mainly based on DC (direct current) technology and the output of constant speed generating sets are in alternating current, it has to be converted. The current has to first be converted from AC (alternating current) to DC for energy storage and then back to AC for use when discharging the batteries. In Figure 2, the different currents and the direction of power flow are visualised. The generating sets produce power in alternating current form and the power is then divided according to the load needs of the system. If the batteries need charging, the current is transformed from alternating current to direct current. If power is needed from the batteries, the power from the batteries are transformed from direct current to alternating current. The hotel load need and load need for propulsion are in AC so no conversion needed. (Sorffonn, 2016)

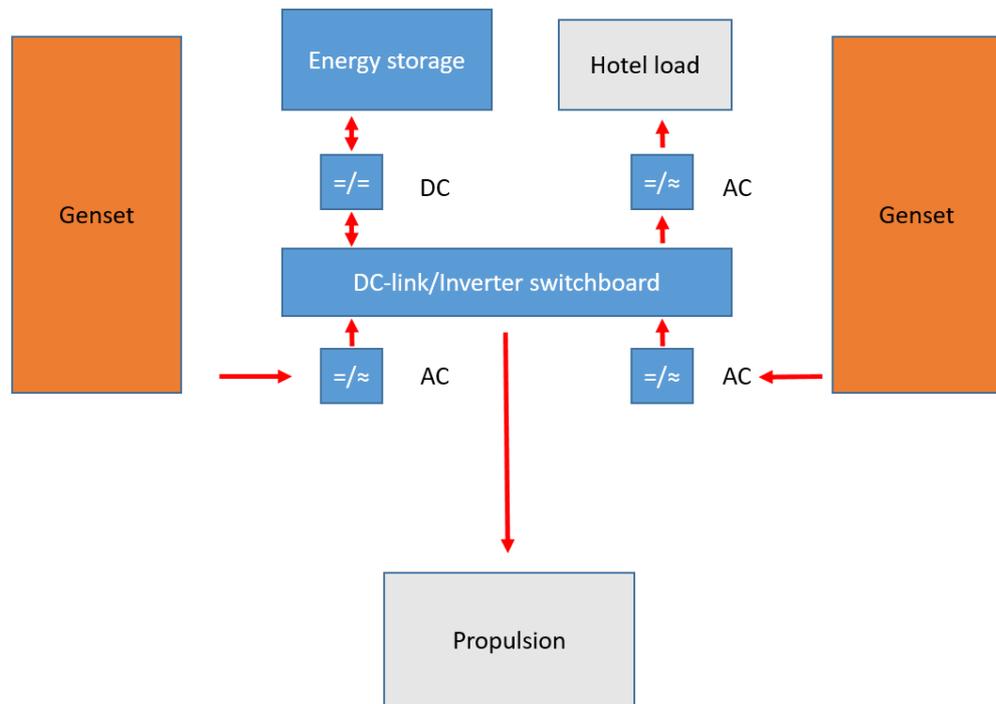


Figure 2 Schematic of currents and flow directions in marine hybrid system.

Energy management system

The key part of a hybrid system is the communication between all the components and systems. This system is called an energy management system or EMS. The main task of the EMS is to direct energy flow between power sources and storage systems to optimize performance for the different operating modes.

Other solutions/equipment in hybrid systems

Direct current (DC) system

Traditionally generating sets in vessels have been equipped with alternating current (AC) generators, leading to engines having to operate at constant speed to supply the needed frequency for equipment on board. A problem with operating at constant speed is when load levels fall low, fuel consumption and emissions will increase.

By using a DC system instead of an AC system, the engines could operate on variable speed, meaning that when the load is low the engine speed could be lowered to compensate. This would result in lower fuel consumption and lower emission levels. A DC-grid is easier to control since parameters like phase angle, frequency or reactive power do not need to be taken into consideration. The current in batteries is also DC, which means that no conversion is needed before storing power. This would mean that a DC generator is coupled to the power-producing device instead of an AC generator. The price of a DC system is, however, higher than a corresponding AC system and therefore not as commonly used. (Wärtsilä, 2017e), (Kyunghwa, 2017)

Low loss concept

The Wärtsilä low loss concept was developed due to bigger demand on diesel electric drives for vessels. As the name suggests, the system lowers the electronic losses by control of the electric motors in propulsion. Control is performed by variable frequency drive devices which can control both frequency and voltage resulting in that both speed and power of the electric motor can be controlled. (Wärtsilä, 2017a)

Shore connection

When docked in port the only power need is for the hotel loads which usually means only one engine is operating at low-load. If the vessel is fitted with batteries, they could accommodate the power need for a limited time. Since low-load operating results in high fuel consumption and higher pollutions, it is more suitable to take electricity from the shore when possible. This would both reduce fuel consumption costs and lower emissions. Shore connection can be used to charge batteries in hybrid vessels, as seen in Figure 9. Shore connections are available in multiple different applications, both traditional with cable connection and wireless charging through induction. Areas with unstable power supply in port could also utilise a battery bank on shore that would bunker electricity for vessel charging purposes. (Wärtsilä, 2016)



Figure 3 Wärtsilä and Cavotec joint concept of wireless shore charging using induction technology. (Wärtsilä, 2016)

2.3.3 Energy storage devices

In marine hybrids, the most utilised technologies for energy storage are currently different battery technologies. Other possibilities, such as flywheels, compressed air energy storage, thermal storage, pumped hydro-power and fuel cells will not be taken into consideration in this thesis since all of them are not applicable in vessels. A battery is an electrochemical device, where electrical energy is converted to chemical energy for storage and back to electrical energy, when needed for use. A battery contains one or more cells. One cell consists of a positive terminal (cathode) and a negative terminal (anode). There is no physical contact between these terminals, but an electrolyte allows ions to move between the two terminals. This flow of ions determines how the battery operates, charging when there is energy entering the battery and discharging when energy is extracted from the battery. The first battery is said to have been developed in 1800 by Alessandro Volta. (Energy-storage, 2017)

In marine applications, the most commonly used battery variants are lithium-ion type batteries. The reason for this is that they are currently the most efficient battery type available. There are alternatives that would be cheaper, but they are also heavier and more space demanding. To be taken into consideration with batteries is the difference between energy (Watt per hour) and power (Watt), and also specific values of these. Power – the ability to do work and energy – how long is it possible do the work. The output power of a battery is usually rated with a C, so for instance a battery with a capacity of 500kWh with a 3C rating has the power output of three times the storage capacity, which means 1500kW. Other important parameters when comparing batteries are:

- Charge and discharge time: The time needed to charge and discharge the battery.
- Cycle life: The number of cycles the battery is rated for, essentially lifetime of battery.
- Cost: The cost per Wh, the cost per W, the cost per kg etc.
- Self-discharge: The rate of how much a battery discharges itself when not in operation.
- Efficiency: The amount of energy that goes to the intended task.
- Depth of discharge: The amount to which the battery should be discharged to ensure longest lifetime.

Prices for suitable marine lithium-ion batteries are still high, approximately 750 USD/kWh, but the estimation is that with the current development, prices will be around 500 USD/kWh by year 2020. There is also a possibility of new technologies being developed that would be even cheaper and more suitable for marine use. Figure 4, includes a graph showing the estimated price development of lithium ion batteries according to one research. Some studies show an even bigger decrease. However, it is difficult to estimate these price developments since supply of lithium and other needed materials in future are difficult to predict. (DNV-GL, 2016)

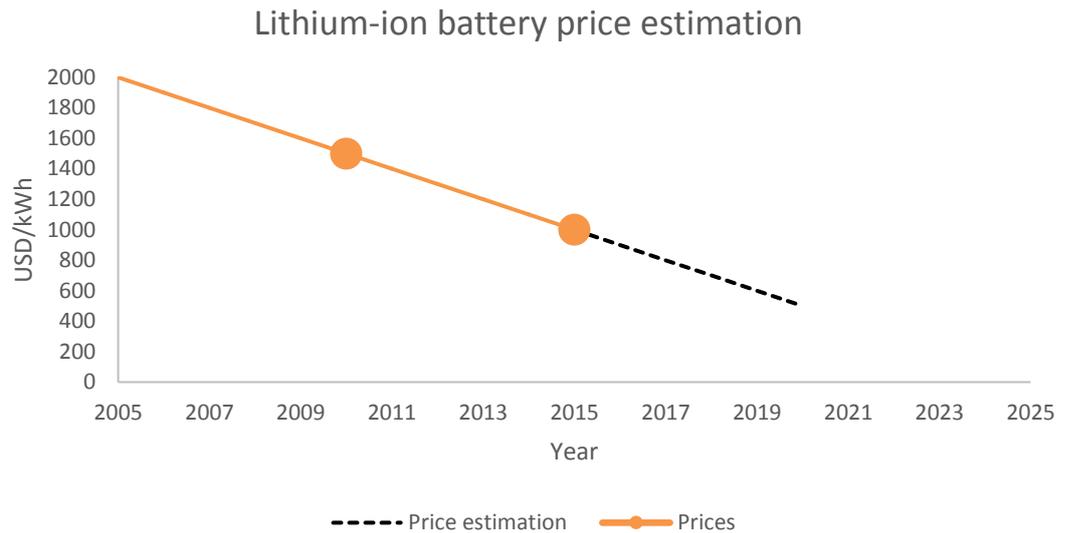


Figure 4 Lithium battery price estimation. (DNV-GL, 2016), (Curry, 2017)

Electrochemical capacitors

More known as super-capacitors, electrochemical capacitors are suitable in applications that require high power and fast discharge time (<1 seconds). The energy storage is done as a static charge compared to chemical (like in batteries). This results in a theoretically infinite number of charge/discharge cycles that can be made. Capacitor charge/discharge is also less temperature sensitive compared to batteries. Combinations with batteries are one possibility to be utilised in marine hybrids. (IEA, 2011)

Lithium-Ion batteries

Lithium-Ion batteries or Li-ion are the fastest growing battery type, mostly because of the high energy density, high power density and possibility of large number of charging cycles. A drawback for these types of batteries is that the charging procedure has to be closely monitored, since overcharging can result in fire or even explosion. There are multiple chemical combinations that can be used in Li-Ion batteries. (IEA, 2011)

Lead Acid batteries

Lead acid batteries are the most widely used battery type today due to cheap price and low discharge capabilities. However, lead acid batteries have very low power and energy density and thus are not usable in all applications. Lifetime and charge cycle number is also low compared to Lithium-Ion batteries, for example. (Buchmann, 2017)

Flow batteries

A flow battery contains two storage tanks, one for a positive and one for a negative electrolyte and the flow battery stack where the reaction takes place. The two liquids are transported with pumps and separated by an ion-selective membrane in the battery stack. There are three types of flow batteries: vanadium redox (VRB), iron chromium (ICB) and zinc bromine (ZNBR) which offers different properties. Storage capacity is connected to tank size, with bigger tank resulting in more storage capacity, by coupling multiple flow batteries together the power output can be increased. By replacing the electrolyte liquid, the battery can almost instantly be recharged. Flow batteries must be permanently mounted and require much space compared to other battery types, and are therefore not applicable in all marine applications. (IEA, 2011)

Energy storage system in marine applications

Energy storage systems (ESS) used in both Viking Princess and Viking Lady are both supplied by battery manufacturer Corvus energy. For Viking Princess batteries, needed safety systems and power electronics are installed inside a container, which made it an easy installation on the vessel when retrofitting. On a newbuilt vessel, usually a dedicated battery room is built. Manufacturers Corvus and Plan B use nickel-manganese-cobalt as materials for their batteries. Other manufacturers use different technologies, lithium iron phosphate (Saft and Valence) and lithium titanate (Leclanche) for instance. (Corvus, 2017)



Figure 5 Viking Princess with containerized ESS. (Skipsrevyen, 2017)

Depending on how the energy is transferred to and from the battery, there will be losses in the different equipment between the engine and the battery. If mechanical energy is transferred through a gearbox, the losses will naturally be higher than if the engine were directly connected to a generator. The difference between these are 4-5%. (Wärtsilä, 2017a)

2.3.4 Propulsion

There are multiple different variations of propulsion systems available depending on vessel type. Not only does the vessel type set requirements on what propulsion systems is needed but also on parameters like operating area, ambient conditions, hull design and so on. There is no propulsion system that is suitable for every application and therefore, it is important to consider what are important requirements. A simple split of which propulsion system is favourable for which vessel can be found in Table 3.

Table 3 Propulsion types for different vessels. (Wärtsilä 2018d)

Propulsion type	Operating conditions	Vessel type
Fixed pitch propeller	Long distances with constant speed	Container vessels, tankers
Controllable pitch propeller	Varying conditions with frequent port calls	Ferries
Steerable thrusters	Rough conditions, dynamic positioning	Offshore supply vessel
Waterjet	High-speeds, shallow waters	Offshore patrol vessel

Combinations of these are possible, for example, a ferry can have fixed pitch propellers in the stern (rear) and transverse thrusters in the bow (front) of the vessel. Depending on the type of operation different combinations can be used, for example, instead of transverse thrusters the vessel can be installed with steerable thrusters (retractable ones as well). With the different propeller-driven variants of propulsion systems, there is the possibility of fitting a duct or nozzle which improves thrust at lower speeds. (Wärtsilä, 2018a), (Chakraborty, 2017) (Molland, 2008)

Steerable thrusters

A steerable thruster is a propulsion device that can turn 360° around its own axle. This makes a steerable thruster good for manoeuvring, and also breaking is possible by turning the thruster 180°. Steerable thrusters are ideal for dynamic positioning, making them common in OSV. Both diesel-electrical and direct-drive arrangements are possible with steerable thrusters. If the thruster is directly driven, the arrangement is called a Z-drive, due to axle routing. With a directly driven solution, no gearbox is required since the reduction gear is built in. When paired with diesel electrical drive, both Z-drive and L-drive are possible, depending on space restriction. In an L-drive, the electric engine is mounted vertically on top of the thruster, in contrast to the Z-drive, where the shaft/electric motor is mounted horizontally to the thruster. (Wärtsilä, 2018e)

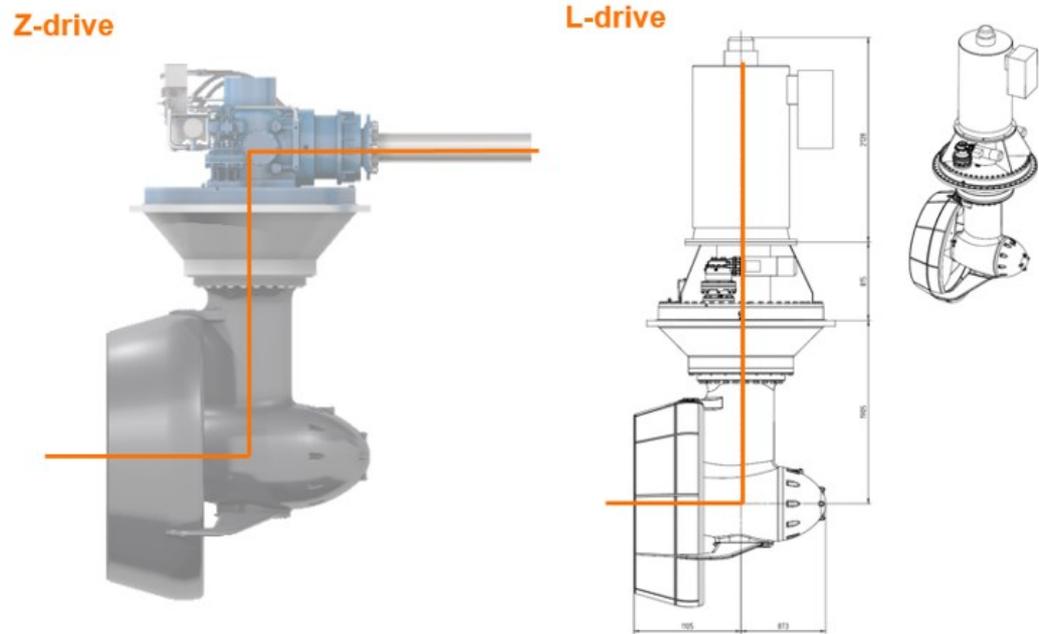


Figure 6 Steerable thrusters in Z and L drive configuration. (Wärtsilä, 2018e)

In addition, how the thruster is driven can differentiate (mechanically or electrically), there are also different propeller variations. There are for example fixed pitch propellers, controllable pitch propellers, open and closed constructions, pulling and pushing propulsion, depending on the requirements from the application. Retractable thrusters, which are only used for manoeuvring but stay retracted inside the hull during transit, also fall under the steerable thruster category. (Wärtsilä, 2018e) (Molland, 2008)

Transverse thrusters

A transverse thruster (also called bow/stern thruster or tunnel thruster) task is to provide side force when the vessel is docking (mooring operation) or in dynamic positioning. Transverse thrusters can be driven both electrically and directly. They are usually used in merchant, cruise and offshore vessels. A transverse thruster can use both fixed pitch and controllable pitch propeller. (Wärtsilä, 2018e) (Molland, 2008)

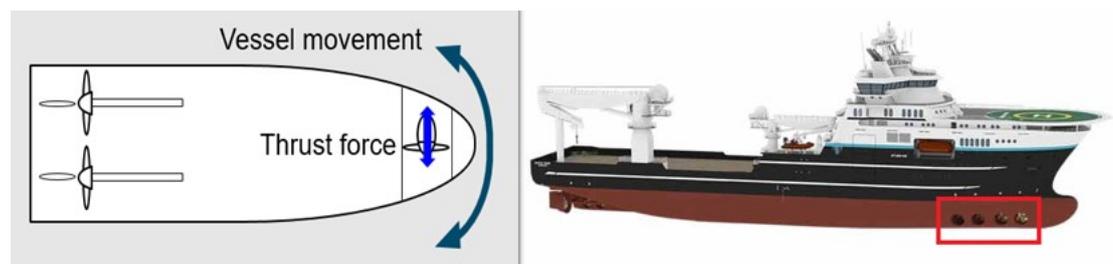


Figure 7 Operation of transverse thruster, installation of transverse thrusters in bow of an OSV. (Wärtsilä, 2018e)

Fixed pitch propellers

A fixed pitch propeller or FPP is casted in one piece or built up of different components (for example: centre part and fins), as seen in Figure 8. The main use of fixed pitch propeller is in ships that does not require much manoeuvring, travel at constant speed and require a simple and robust propulsion system (container vessels and tankers for instance). Common is pairing fixed pitch propeller with direct drive and 2-stroke engine. Paired with a 2-stroke engine there is no need for a gearbox/reduction gear depending on engine speed. When reversing, the engine is stopped and started in other rotating direction (only possible with some 4-stroke engines). Fixed pitch propellers can also be driven with an electrical motor. (Wärtsilä, 2018c) (Molland, 2008)



Figure 8 Viking Grace fixed pitch propeller. (Wärtsilä, 2018c)

Controllable pitch propellers

A controllable pitch propeller or CPP is beneficial when the vessel is operating in multiple types of conditions, because the thrust from the propeller can be changed by adjusting the pitch. Also reversing is possible by adjusting the pitch. This means the engine does not have to be stopped and started in opposite direction. A controllable pitch propeller can be driven both electrically and directly, for 4-stroke engines driven directly usually in combination with a gearbox or reduction gear. A shaft generator is easily paired with a directly driven CPP application, since the engine speed is constant. (Wärtsilä, Wärtsilä controllable pitch propeller product training, 2018b) (Molland, 2008)

Waterjets

Waterjet propulsion is suitable for vessels operating over 25-30 knots and for shallow water operation. Operation of waterjet propulsion differs from normal propeller propulsion by building up more pressure inside the inlet, which means that smaller dimensions are required for waterjets to achieve the same power as propeller propulsion systems (Figure 9). The manoeuvrability is very good with waterjets. Both direct and electrical drive is possible. (Wärtsilä, 2017j) (Molland, 2008)

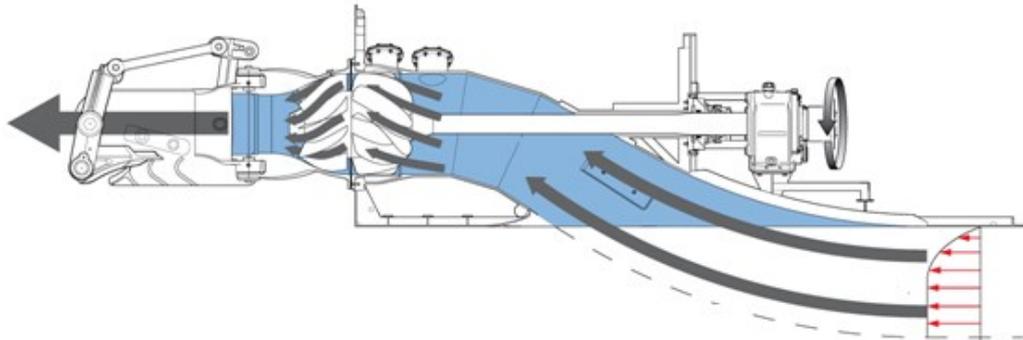


Figure 9 Working principle of waterjet propulsion system. (Wärtsilä, 2017j)

2.4 Hybrid drives

In Figure 10 different types of drives are visualised. The two first alternatives can be paired with hybrid systems by coupling the generator/electric motor in the system. The third alternative is most suitable to add a hybrid system to, from mechanical point of view. Depending on vessel type and operating conditions, the drive type is chosen. (Wärtsilä, 2018d)

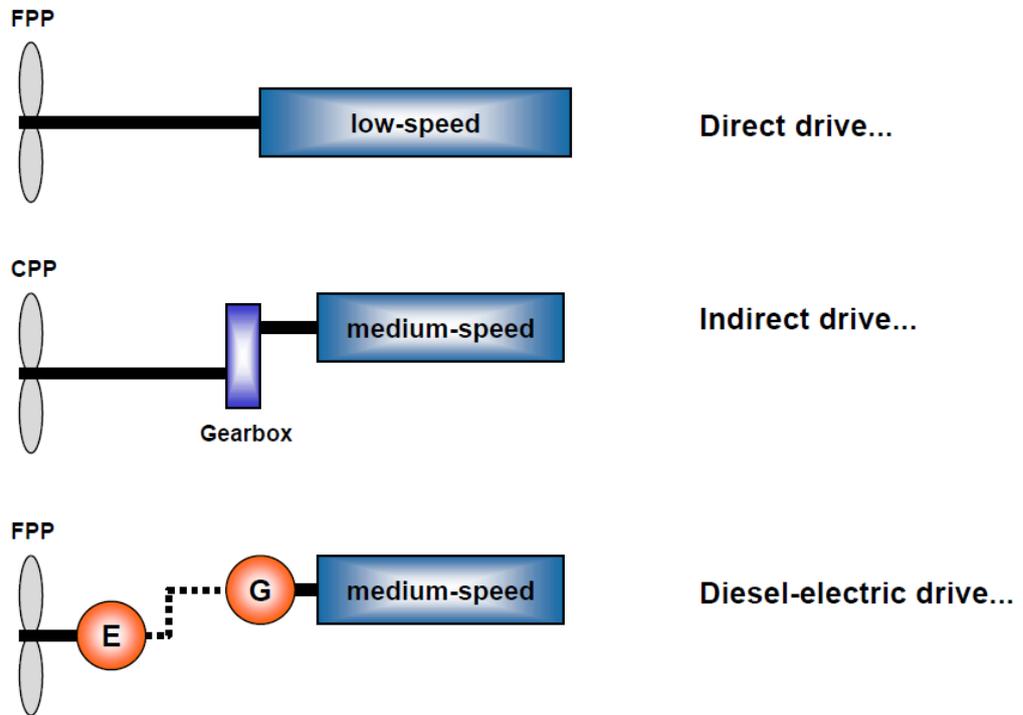


Figure 10 Vessel drives. (Wärtsilä, 2018d)

2.4.1 Electric drive

In this setup, each engine is connected to its own generator and only electricity is transferred through an inverter switchboard to the propulsion equipment, battery and hotel consumers (Figure 11). Electricity from batteries is transferred through the inverter switchboard to the propulsion equipment and hotel consumers. From a ship design point of view, this kind of solution is good because the placement of engines is not restricted by shaft line, which makes it possible to lower fuel consumption due to better hull hydrodynamic design. Since no engine is connected directly to the propulsion, the running time of engines can be optimised which will lower service costs. If one engine fails, there is redundancy available. Investment cost is, however, higher with this type of layout. (Ådhanes, 2003)

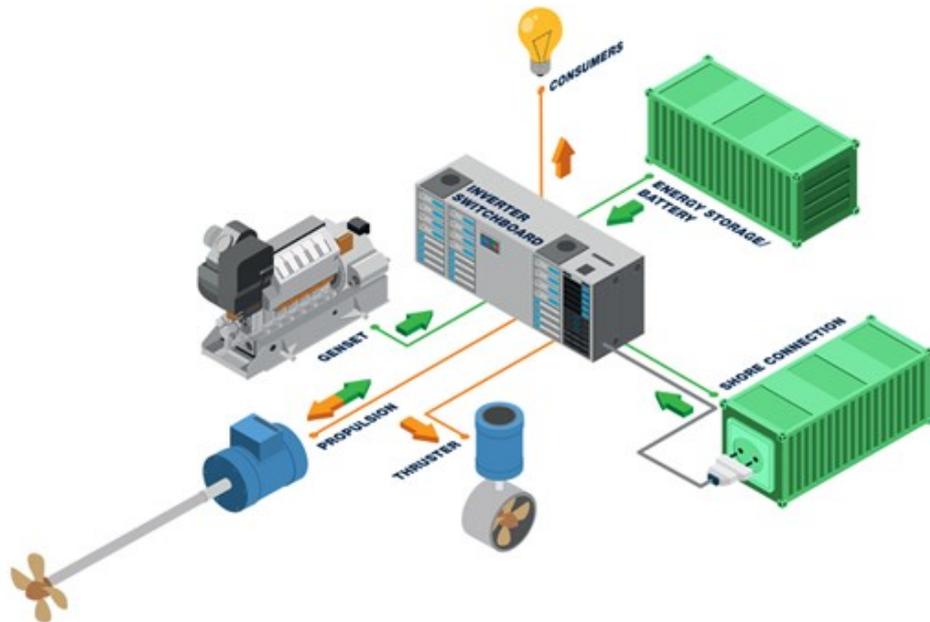


Figure 11 Example of hybrid setup in diesel electric propulsion arrangement. (Wärtsilä, 2017)

2.4.2 Mechanical drive

Depending on the engine type, the propulsion equipment can be driven straight from engine (low-speed engines) or through a gearbox/reduction gear (medium-speed and high-speed engines), please refer to Figure 10. This means the ship design is more limited since engines and shaft line have to be taken into consideration. A mechanical drive can be paired with an energy storage system. There are two alternatives for mechanical hybrid systems, shaft generator or gearbox with multiple inputs/outputs. A shaft generator can be installed in the shaft line to avoid need of operating additional generating sets to power the electricity need of vessel hotel consumers. The shaft generator has to be connected to a frequency converter if the engine is operating in variable speed, if the engine only operates at constant speed it is not necessary with a frequency converter, since the engine speed is chosen to correspond with the electric frequency. The other option is to use a gearbox that has the capability of multiple power intakes (Figure 12). In this setup, the engine and generator are connected separate input in the gearbox (output for generator as well). Propulsion equipment is then also connected to the gearbox. The generator is then used as an engine when drawing energy from batteries. This setup requires a well-tuned management system to avoid damages on the gearbox when engine and battery are used simultaneously and situations when power input/output are changed. (Wärtsilä, 2017a)

Wärtsilä HY – Diesel-mechanical

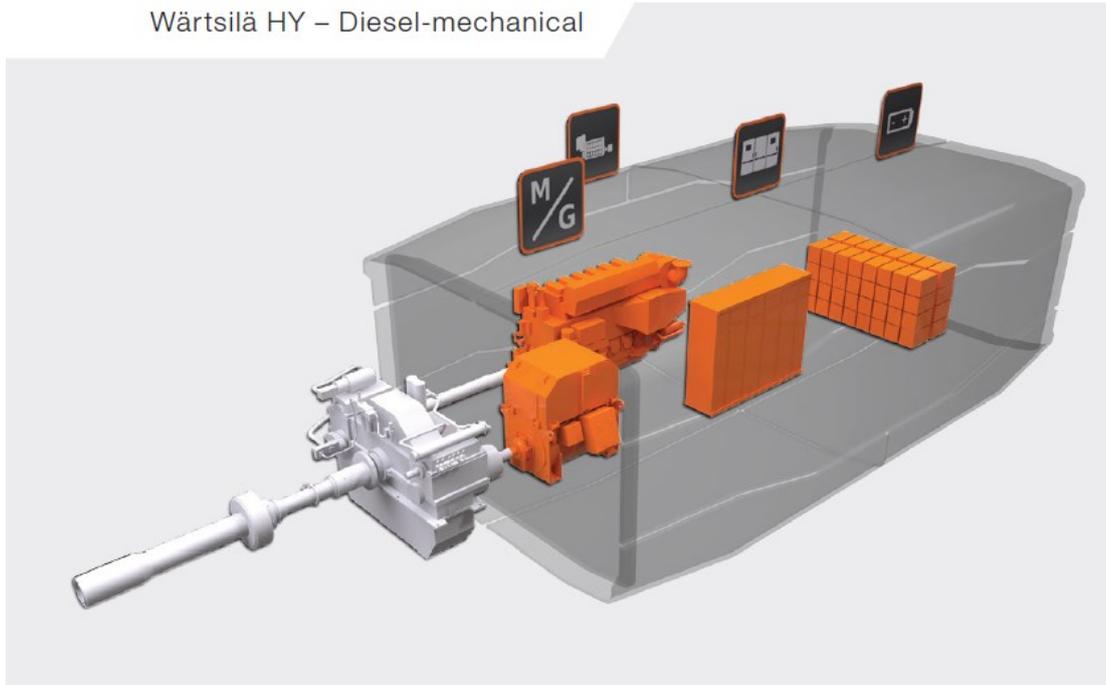


Figure 12 Diesel mechanical hybrid setup with generator/electric motor coupled to gearbox. (Wärtsilä, 2017a)

2.4.3 Difference between drives

Depending on the vessel type, the size often determines which type of drive is used. For instance, in an offshore supply vessel, an electric drive is most common in over 4000 DWT (deadweight tonnage) vessels, in vessels smaller than that, mechanical drive is more common. The mechanical drive is better suited for use in extended transits and the electric drive is more suited for when better manoeuvrability is needed (dynamic positioning for instance). A mechanical drive is simpler to install and easier to maintain however, when paired with energy storage the difference becomes smaller. A major advantage with an electric drive is that the placement of engines can be more freely done resulting in better possibilities for storage and flexibility of vessel design. Electrical drive is more expensive than direct drive. (Wärtsilä, 2017h)

2.4.4 Hybrid operating modes

The main functional principle of a hybrid system using both combustion engines and batteries as its energy storage system is not very complicated. The engine has two alternatives, on or off. Battery has three ways of working: charging (energy in), discharge (energy out) and storage (theoretically nothing in or out). The complicated part is managing the combinations. In Table 4, the energy flow in a hybrid application with only one engine is explained, in systems with multiple engines the management is even more complex depending on redundancy and load. Modes that transfer energy back and forth energy wear more on the batteries than other modes affecting the battery lifetime.

Table 4 Hybrid operating modes. (Wärtsilä, 2017a), (Wärtsilä, 2017h), (Wärtsilä, 2017i)

Mode	Engines	Battery
Peak shaving	Operating at optimal load.	Discharging/Charging depending on load.
Start/stop	Operating until battery is charged to desired level, then shut off.	Charging to desired level, after that discharging.
Boost	Running.	Discharging.
Green mode	Off.	Discharging.

Peak shaving

Peak shaving mode is used to lower fuel consumption and emissions. The best use for this mode is when the load on the propulsion equipment varies. Without a hybrid system, the engines would operate outside of the optimal operating window when the demanded propulsion load is lower, resulting in an unnecessarily high consumption. As the name implies, the energy storage system shaves the low and high peaks of load fluctuations by charging/discharging the battery (Figure 13). The blue curve symbolizes the load fluctuation of the propulsion, the orange line is the engine operating at a constant speed on optimal load. Where the blue curve goes under the orange line excess energy is stored in batteries (charging condition) and where the blue curve goes over the yellow line the batteries supplies energy to propulsion (discharging condition). The orange line is a bit offset due to losses when transferring energy to and from battery. (Wärtsilä, 2017a)

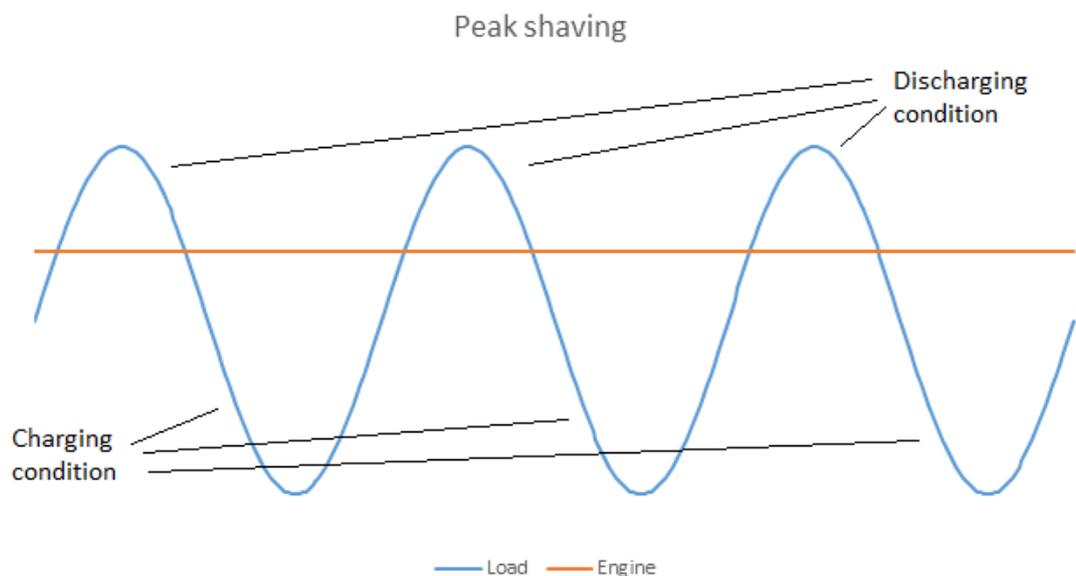


Figure 13 Peak shaving operating mode. (Wärtsilä, 2017a)

Start stop

Start stop operating mode is when the engines are running at optimal load and both powering the propulsion and excess energy are transferred to the battery for storage. When the batteries are charged to the set limit some engines (or all) are turned off and propulsion is powered from the batteries. (Wärtsilä, 2017a)

Boost

Boost mode is when both the engines and the batteries are powering the propulsion at the same time, the energy storage system works as a “booster”. Boost mode can be utilised when performing tasks that require much power, for example, dynamic positioning for a OSV/PSV, operating cranes and so on. (Wärtsilä, 2017a)

Green mode

When using only the batteries to power the vessel it is referred to as green mode. Green mode is used for example, when going in and out from ports etc. (Wärtsilä, 2017a)

2.5 Vessel types

There are multiple types of vessels intended for different uses. Not only the use of vessel sets the requirements on the design, but also in what conditions and where in the world it will be used will affect greatly what requirements the vessel has. In this thesis, three different types of vessels will be taken into consideration; these vessels are shortly described in this chapter.

2.5.1 Tug

“A tug is a vessel that supports manoeuvring of large vessels by pushing or towing them” (Wärtsilä, 2017i)

A tug boat or “tow boat” is a smaller vessel intended for assisting larger vessels, for example, when going into harbour. Other than for assisting and escorting purposes some tug boats also have firefighting and salvaging capabilities. The hull design and propulsion arrangement vary greatly depending on the intended use.

All tug types have one common dominator which is the need of major power redundancy. The load profile of a tug is very different from other vessels (Figure 14). Approximately 70% of the time, a tug is operating on low-load, which means unnecessarily high fuel consumption and emissions. (Cavalier & Caughlan 2008) (Wärtsilä, 2017i)

Harbour tug load profile

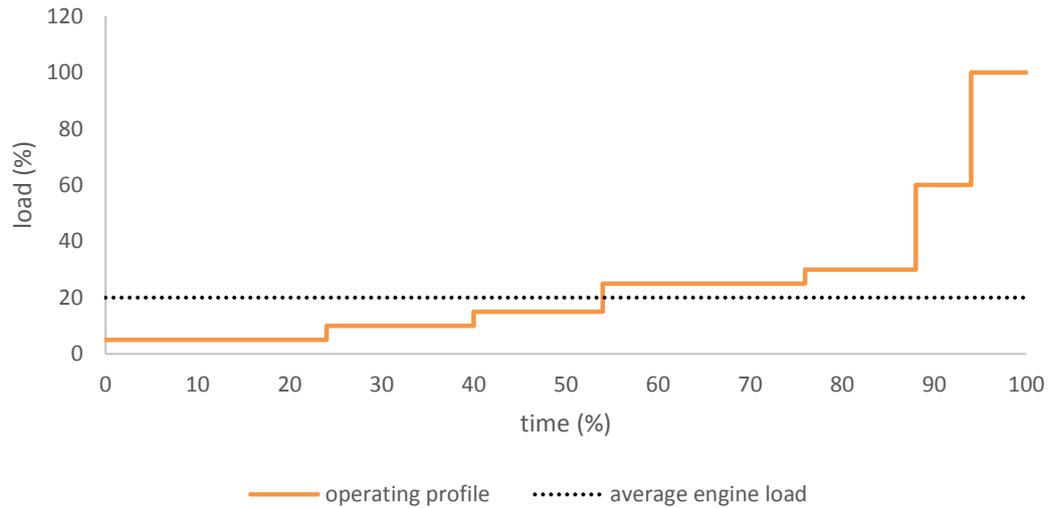


Figure 14 Harbour TUG load profile. (Wärtsilä, 2017i)

Due to the load profile of a tug, the option of using batteries in combination with engines is very attractive. The batteries could be used for the power redundancy needs and for operating on very low-loads (waiting on vessels or in port for instance). Using a hybrid solution in a tug would lower the fuel consumption and reduce emissions considerably. Since the capacity of a tug is determined by *Bollard Pull* a hybrid solution would not compromise the tug rating. Bollard pull is a practical test where the vessel pulling force is measured. (Cavalier & Caughlan 2008) (Molland, 2008)



Figure 15 A typical TUG for towing purposes, equipped with two engines powering two turnable thrusters through reduction gear in Z configuration. (Wärtsilä, 2017i)

2.5.2 Ferries

There is no official definition of different types of ferries, however, they can be divided into different segments depending on use, size and other factors. What is important for ferries is power redundancy and emission requirements, for example, to a ferry company, operation with no smoke coming out of the exhaust pipes is important for brand image.

Cruise ferry

A cruise ferry is intended for transportation and pleasure. Typical trip time is around 24 hours and a cruise ferry offers overnighing capabilities, usually the majority of passengers return to the same harbour their trip started from. The cargo usually mostly consists of passenger cars on a so-called RO-RO deck (roll on – roll off). Example: Viking Grace, Figure 16.

Double-ended ferry

This kind of ferry is used for short routes and to save time by not having to turn around they have an identical fore and aft body, with propulsion systems at both ends. They are used for both transporting people and vehicles.

High-speed ferry

A high-speed ferry is usually either a catamaran or a monohulled type. To be defined as a high-speed ferry the vessel has to be built by different rules and have a maximum speed which is determined by displacement and the designed waterline. The cargo consists mainly of passengers and in some cases also passenger vehicles. Example: HSC Karolin, Linda line Helsinki-Tallinn

RoPax/PaxCar ferry

Ferries with a large capability to transport vehicles, but with limited passenger facilities are called RoPax vessels, a PaxCar ferry has more accommodation for passengers. Both are intended for longer routes. A RoPax ferry often has ramps at both the stern and bow ramps for fast loading/unloading.

Short route ferry

The same as double ended ferry, but always open decked and used in protected waters. Example: ferry going to Bergö outside Vasa. Operation profile of a typical short route ferry in Figure 17.



Figure 16 Viking Grace. (VikingLine, 2017)

(Wärtsilä, 2017d) (Molland, 2008)

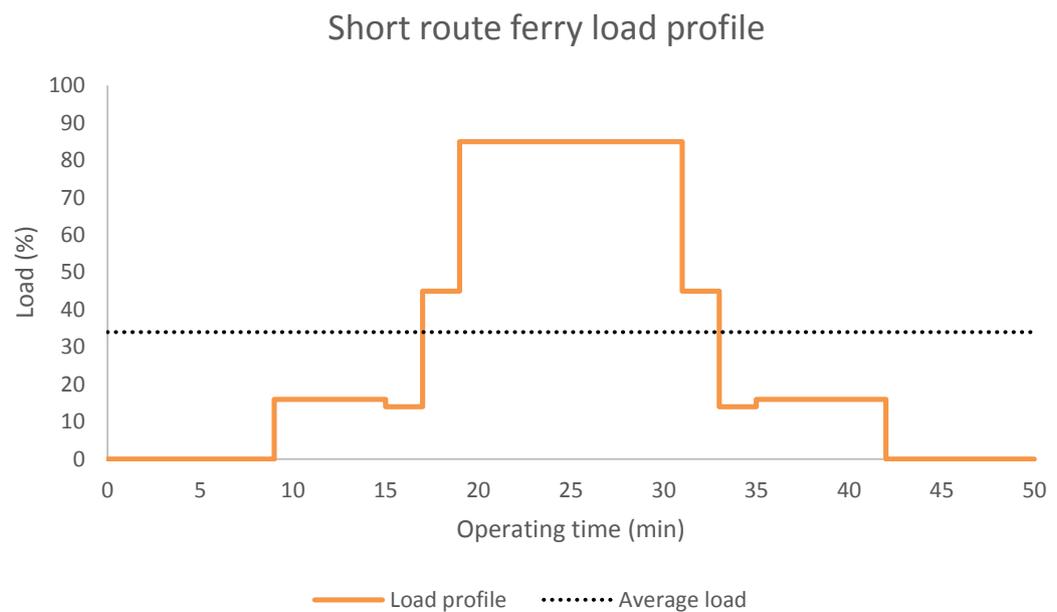


Figure 17. Short route ferry load profile. (Wärtsilä, 2017d)

2.5.3 Offshore supply vessel

An Offshore Supply Vessel (OSV) is a vessel intended for different kinds of operations in assisting an offshore installation (drilling rig or wind farm for example). There are three main categories of OSV, Platform Supply Vessel (PSV), Anchor Handling Tug Supply (AHTS) and Construction Support Vessel. A Platform Supply Vessel is the most common OSV. The task of a PSV is to supply the offshore installation with consumables, personnel and equipment. Other tasks of a PSV are participating in rescue and firefighting operations. (Wärtsilä, 2017d)

Due to operating conditions, which usually are harsh sea and ambient conditions, there are strict requirements on vessel components. Great depths at offshore installations mean anchors are not possible to use, therefore a dynamic positioning system is required. The dynamic positioning system sets certain requirements on propulsion equipment and engines. Dynamic positioning is more suitable for diesel-electric

arrangement, since there should be engine redundancy meaning in some cases an “extra” engine must be operating in the background without load if there is a sudden power need. For instance waves during dynamic positioning. The risk would be to collide with the platform if sufficient power output is unavailable. Redundancy is also needed in case an engine suffers failure. (Wärtsilä, 2017d)

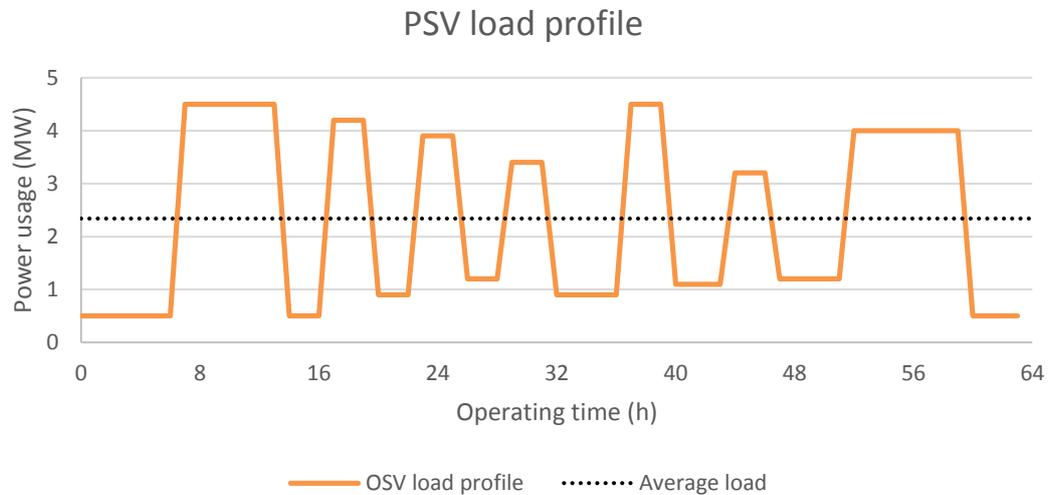


Figure 18 PSV load profile. (Wärtsilä, 2017d)

The majority of a PSV operating time is spent in transit or dynamic positioning, roughly 25% of time in harbour loading/unloading, 40% in transit and 35% in dynamic positioning when loading/unloading at offshore installation. When the vessel is in dynamic positioning or under heavy sea the use of a hybrid system would be very beneficial due to large load fluctuations and need for power redundancy. The batteries could take care of redundancy part and be operated in peak shaving mode. When sailing in protected waters the vessel could operate in green mode, batteries powering the propulsion with engines shut off. (Wärtsilä, 2017d)



Figure 19 Viking Princess, a platform support vessel. (Shipspotting, 2017)

3 METHOD

3.1 Calculations, principles and tools

3.1.1 ESStimator

ESStimator is an Excel based tool developed by Wärtsilä for calculating differences between regular vessel propulsion solutions and propulsion solutions equipped with battery-based energy storage systems, Wärtsilä HY in particular. Different types of engines and propulsion systems can be defined and combined in the tool, 10 different vessel propulsion solutions can be compared in one calculation. A load profile is created by defining up to 20 different points of power consumption and duration for a voyage, both propulsion and hotel loads. The load profile is based on hydrodynamic resistance and possible bollard pull for one voyage. In the settings it is also possible to set how many voyages is done per year to acquire consumptions per year for economic calculations. For these different load points, it is then possible to define how power is supplied by the engines and/or battery. Prices of the different consumables can be changed to accommodate price fluctuations.

When calculations are made in ESStimator the results are shown for multiple different parameters, for instance: fuel oil/gas consumption, lube oil consumption, emissions etc. Intention with this tool is not to obtain pinpoint accurate numbers but to get a comparison between different engine types and propulsion solutions. Since also prices for different components can be inserted operating expenses (OPEX) and capital expenses (CAPEX) for the solutions are calculated, meaning also proximate payback times can be compared. Different features as manoeuvre thrusters, shore power etc. can be utilised in the tool.

The equations used in ESStimator are quite simple, the load curve together with specific fuel oil consumption (SFOC) data for the engines and settings for engine usage are used to calculate the fuel consumption in ton/year. From the fuel consumption, operating expenses can be calculated together with engine hours. Also, emissions (CO₂) are easily calculated from consumption data and fuel data.

$$\text{Fuel oil consumption (g)}_{loadpoint\ x} = SFOC \left(\frac{g}{kWh} \right) * P(kW) * t(h) \quad (3)$$

$$\text{Lube oil consumption (g)}_{loadpoint\ x} = SLOC \left(\frac{g}{kWh} \right) * P(kW) * t(h) \quad (4)$$

The different load points can then be added to form the consumptions for a complete voyage. If numbers of voyages per year is known the consumptions can be calculated as well as expenditures of these. The engine manufacturers also have estimate of what the service cost is per engine running hour. Other consumables are everything else that is necessary for the vessel to operate, for example amount of urea if the vessel is equipped with selective catalytic reduction (SCR) for removal of NO_x. Use of shore power/shore charging can be taken into consideration in the ESStimator tool.

$$\begin{aligned}
OPEX(kEUR) = & \left[\text{fuel oil consumption} \left(\frac{\text{ton}}{\text{year}} \right) * \text{fuel price} \left(\frac{kEUR}{\text{ton}} \right) \right] + \\
& \left[\text{lube oil consumption} \left(\frac{\text{ton}}{\text{year}} \right) * \text{lube oil price} \left(\frac{kEUR}{\text{ton}} \right) \right] + \\
& \left[\text{service costs} \left(\frac{kEur}{h_{engine}} \right) * \text{engine running hours} (h_{engine}) \right] + \\
& \text{shore charging} \left(\frac{kWh}{kEUR} \right) + \text{other consumables} (kEUR).
\end{aligned} \tag{5}$$

As the carbon and sulphur content of the used fuel is known also CO₂ and SO₂ emissions can be calculated in the tool.

$$CO_2 \text{ produced (ton)} = \text{Mass fuel(ton)} * \text{carbon content(\%)} * \left(\frac{\text{molar mass } CO_2 \left(\frac{g}{\text{mol}} \right)}{\text{molar mass carbon} \left(\frac{g}{\text{mol}} \right)} \right) \tag{6}$$

$$SO_2 \text{ produced(ton)} = \text{Mass fuel(ton)} * \text{sulphur content(\%)} * \left(\frac{\text{molar mass } SO_2 \left(\frac{g}{\text{mol}} \right)}{\text{molar mass sulphur} \left(\frac{g}{\text{mol}} \right)} \right) \tag{7}$$

NO_x emissions and particulate emissions are defined in the tool for: 25%, 50%, 75%, 85% and 100% loads, however, this type of information can be difficult to obtain on competitors' products. Also lube oil emissions can be calculated in same manner. When OPEX is known it is also easy to calculate the payback for the different solutions if CAPEX is known.

$$\text{Payback time (year)} = \frac{CAPEX (kEUR)_{\text{solution } x}}{OPEX \left(\frac{kEUR}{\text{year}} \right)_{\text{reference solution}} - OPEX \left(\frac{kEUR}{\text{year}} \right)_{\text{solution } x}} \tag{8}$$

3.1.2 Low-load consumption calculations

These calculations are simple and do not take into consideration the battery part of system. They focus only on how an engine should operate in a hybrid system. Calculations are based on the difference in engine hours between a standard engine and one paired with battery operating at optimal load for the same amount of energy. The energy of a load is calculated by assigning the engine hours a fixed number of, e.g., 100 hours. After this, the difference is calculated between a hybrid engine operating at a load percentage suitable for the energy need and a non-hybrid operating at optimal load level for the necessary amount of time. Naturally electrical losses need to be taken into consideration when storing energy in batteries.

The consumption of a standard engine is calculated with Equation 3 and the operating hours for the “hybrid” engine are calculated with Equation 9.

$$\text{Engine hours (h)}_{\text{hybrid engine}} = \frac{\frac{\text{Load level (\%*100)} * \text{Energy (kWh)}}{\text{Energy transfer efficiency (\%)}}}{\text{Engine power (kW)}_{\text{hybrid engine at optimal load}}} \tag{9}$$

3.1.3 Hybrid medium/high-speed comparison tool

This Excel-based tool was created specifically for this thesis in order to clarify the differences between medium-speed and high-speed engines in marine hybrid applications. The idea behind this tool was to visualise how different engines and battery setups behave under different loads and in this way to gain a deeper understanding of the different engine types' strengths and weaknesses when paired with batteries. A reference case without batteries is used to calculate what load the engines would operate on without batteries (Equation 10). In Equation 11 the energy transfer is calculated to and from the batteries. If the amount is negative, energy is transferred from the battery. Depending on whether the propulsion layout is a mechanical or electrical drive, the losses to and from the battery will be different. The losses differ based on whether energy is transferred to or from the battery.

$$Engine\ load\ (\%) = \frac{(Hotel\ load + propulsion\ load)\ (kW)}{(Amount\ of\ running\ engines * Engine\ rated\ power)\ (kW)} \quad (10)$$

$$Energy\ transfer\ (kWh) = \left((Optimal\ load(\%)) * \right. \\ \left. amount\ of\ running\ engines * rated\ power\ (kW) * electrical\ losses\ (\%) \right) - \\ \left. power\ need(kW) \right) * running\ time(h) \quad (11)$$

Fuel consumption can easily be calculated by using Equation 3 and engine operation hours by Equation 9.

From the economic perspective, it is also important to consider maintenance costs and lube oil consumption. Lube oil consumption can be calculated by using Equation 4. The price of lube oil is case specific. Maintenance cost calculation is difficult to calculate because it consists of both spare part costs and labour, in this thesis the man hour part is neglected and only spare parts are considered as maintenance. Labour costs fluctuate greatly depending on service contracts and other factors. The cost of spare parts for high-speed engines is not publicly available so prices are only estimations based on other studies and experts' verdicts.

$$Maintenance\ cost\ \left(\frac{\text{€}}{year} \right) = \left(voyage\ duration\ (h) * \right. \\ \left. voyage\ amount\ \left(\frac{1}{year} \right) \right) * maintenance\ cost\ \left(\frac{\text{€}}{hour} \right) \quad (12)$$

When fuel oil consumption, lube oil consumption and maintenance costs are calculated, it is possible to calculate operating expenses. There are also smaller expenses, but in a comparison between medium and high-speed engines, these can be neglected because they are similar for both engine types. In order to visualise the differences in expenses for different solutions, investment cost or CAPEX should also be included, for this calculation Equation 13 is used. The lifetime of the battery should be considered if they must be replaced during vessel lifetime. If a battery must be replaced, the price development of batteries should be taken into consideration. The

cost difference between mechanical and electric drives is also of significance.

$$CAPEX (\text{€}) = \left(\text{Engine cost} \left(\frac{\text{€}}{\text{engine}} \right) * \text{engine amount} \right) + \text{battery cost} (\text{€}) + \text{difference between DM and DE} (\text{€}) \quad (13)$$

Both CAPEX and OPEX are known for solution graphs can be drawn that visualise which solution is most economically feasible.

Other important aspects to be taken into consideration are the space requirement, footprint and weight of equipment because this can be a deciding factor in some cases. However, the space requirement is difficult to determine without knowing the layout of a specific vessel. In general, a mechanical drive will take less space but is not as flexible when it comes to the positioning of components compared to an electrical drive. The space requirement/weight of the shaft line is not taken in consideration since that is very much dependent on vessel design. Auxiliary equipment will not be taken in consideration since these will probably not differ much between the different engine types. Generating set sizes and weights may differ depending on the generator used, however, the values used are the ones supplied by engine manufacturers.

3.2 Case 1 - Tug

3.2.1 ESStimator calculations for tug

As in the first case, various solutions for a 75-ton bollard pull (TBP) hybrid tug with approximately 5MW of power will be evaluated. This tug is within the 65-85 TBP range which is particularly applicable to hybrid solutions. This specific case was chosen because there already had been a comparison made between hybrid and non-hybrid solutions in ESStimator providing a good starting point. A solution containing high-speed and batteries was added to this comparison. The load profile for this vessel was identified (Figure 20) by measurements on similar tugs used in target area



Figure 20 75 TBP TUG load profile. (Wärtsilä, 2017a)

The load profile of this tug represents that of an “average” tug with a lot of low-load operation and a couple of spikes as needed for high power output. In Figure 21, the load profile from Figure 20, has been simplified to fit in ESStimator.

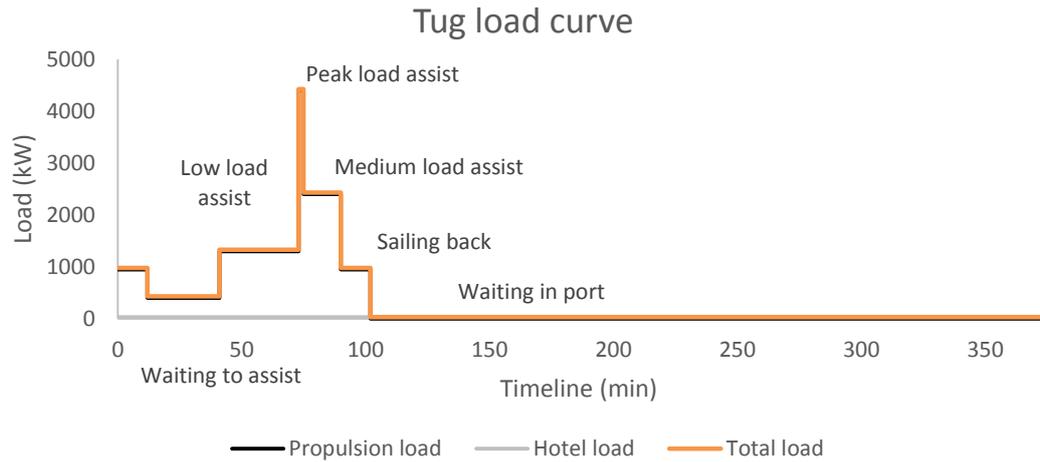


Figure 21 75 TBP tug simplified load profile for calculations.

Figure 21, shows the simplified load profile of the tug. The black line is the propulsion load, the grey line is the hotel load and the orange line is the total load of the vessel. In the load profile, one can see the voyage begins with the tug manoeuvring and sailing out. After which, it waits to assist another vessel. The assistance begins with low-load assist, followed by a short, peak load assist, then a period of medium load assist before finally sailing back. After this, the vessel remains docked waiting for next assisting mission. During docking the vessel has only a hotel load. The batteries are used for manoeuvring, sailing out/in and waiting. For low, medium and heavy assist, engines are utilised and their batteries should be charged as well. In port, shore charging is utilised. The various solutions have been selected on the basis of their load profile. Because peak load is around 4MW, the combined power output should exceed this peak in order to maintain some redundancy. Because battery size is determined by engine output and load profile, it is important to consider the manner in which the battery will be utilised.

In Table 5, a variety of solutions are explained in terms of propulsion, components etc.

Table 5 Tug case solution characteristics.

	Reference case	Wärtsilä conventional	Wärtsilä HY	Wärtsilä hybrid	High-speed hybrid
Main engines	2x CAT3516C (2x2240kW)	2x W6L26 (2x 2100kW)	2x W6L26 (2x 2040kW)	2x W8L20 (2x 1760kW)	2x CAT3516 (2x2240kW)
Auxiliary engines	3x HS genset (3x100kW)	2x HS genset (2x100kW)	1x HS genset (1x100kW)	1x HS genset (1x100kW)	1x HS genset (1x100kW)
Energy storage	-	-	500kWh	500kWh	500kWh
Drive	Mechanical drive	Mechanical drive	Mechanical drive	Electrical drive	Mechanical drive
Propulsion	FPP	FPP	CPP	FPP	FPP

The configuration of how the vessel utilizes the batteries and the engine greatly affects its fuel efficiency and functionality. Therefore, it is of highest importance to tune each setup in order to bring out their best properties. Non-hybrid solutions use both main engines for all operational situations. According to this load profile, the different solutions should be tuned to operate in the following manner: the HY solution (W6L26) sails to and from port on battery power and idles on battery power and start/stop function. Depending on load when assisting batteries are charged/discharged. The hybrid solution (W8L20) sails to and from port as well as idles on battery power and during an assist the main engines and batteries are utilised as well as an auxiliary engine if needed. Of course, if there are changes to the operating profile for instance weather, operating modes must change to suit the power required.

3.2.2 Hybrid medium/high-speed comparison tool for tug

The same load curve is used as in the ESStimator calculation for a tug (Figure 21). For different load points, a number of engines could be needed to cover power demand. The engines needed to operate the different load points will differ depending on engine output, battery size and type of drive.

For this application, three different battery sizes are used: 500kWh (1500kW), 750kWh (2250kW) and 1MWh (3MW). The two latter battery options would be considered too expensive for this application based on current battery prices but they were included in the comparison because when the batteries need to be replaced it might be feasible to fit the vessel with bigger batteries depending on price development. The different battery sizes enable different ways of operating at the load points. By using bigger batteries, it is possible to shut off engines for longer periods and possibly to install fewer engines on the vessel (on theory level at least, need of redundancy and legislations might prevent this). It might be required to always have one engine operating, depending on operation for redundancy, even though a battery would be able to cover the power needs. Theoretically this would mean using a bigger battery that would lower the operating expenditures; however, the investment cost of system would be higher.

For this load curve, the engine number that would suffice is listed in Table 6. However, this is only on theoretical level, requirements for redundancy can be set by ship owner, classification society as well as other factors.

Table 6 Tug case different solution characteristics.

	Ref (no ESS)	500kWh ESS	750kWh ESS	1MWh ESS
W8L20 (1600kW)	3 engines	2	2	1
W6L26 (2040kW)	2 engines	2	1	1
3516B (1800kW)	2 engines	2	1	1

Some of these cases are not feasible in the real world, for instance, the use of three engines in a diesel mechanical configuration. All different hybrid solutions have the same method of operation within the load profile; a battery is used whenever the state of charge allows. Manoeuvring and sailing to and from port, as well as other operation modes that require low-load, are ideal for battery operation. Another advantage is that no smoke would be generated when operating on battery power in harbour which is good for public image. Batteries should be charged when the state of charge is low. No real boost from batteries is used in this comparison case. In this case, the tug is estimated undertake do 1412 voyages per year, with an average voyage length of 372 minutes. The lifetime of this vessel is 20 years. For example, in a tug boat the space requirement and the weight of propulsion components is of less importance than in a ferry. In Appendix 2, a comparison of the different solutions is shown. In port batteries are charged to 100% state of charge.

3.3 Case 2 - Ferry

3.3.1 ESStimator calculations for ferry

For the case of the ferry a double ended short route ferry was chosen. This case is applicable due to the fluctuation of the load profile and the involvement of high and medium speed engines in this vessel segment. Due to the short route and high number of voyages per day, the shore charging option should be taken into consideration. This ferry is intended to operate short routes between two ports with a round trip duration of around 100 minutes. Annually, the ferry makes 3650 trips, or 10 trips per day. The lifetime of the vessel is determined to be 25 years. The propulsion arrangement for this vessel makes it suitable for an electrical drive, as it has four propellers and a low power requirement. However, a high-speed alternative using four engines, one for each propeller in direct drive configuration, is as well calculated. This solution would most likely be the cheapest alternative to buy but lacks redundancy and operating costs would likely be significantly higher.

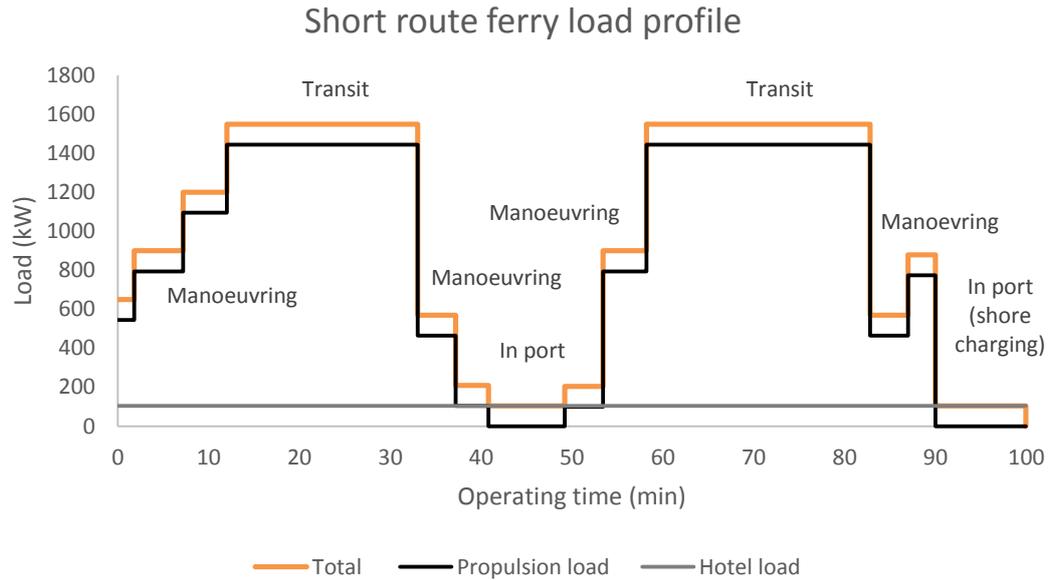


Figure 22 Short route ferry load profile.

The short route ferry load profile in Figure 22, consists of a couple of different modes. Firstly the voyage starts with manoeuvring out from port. The high load parts of the graph represent the actual crossing; between these are the manoeuvring and loading/unloading at port. The total time for one voyage is 100 minutes. The batteries are utilised for all parts of voyage except the crossing parts where the engines are used. During manoeuvring parts the engines remains shut off. Shore charging is utilised when the ferry has returned to the starting point, and a new voyage always begins with a 100% state of charge. In Table 7, the variables in terms of propulsion components etc. are explained.

Table 7 Ferry solution characteristics.

	Reference case	Wärtsilä Hybrid	High-speed Hybrid 1	High-speed Hybrid 2
Main engines	3x W4L20 (3x740kW)	3x W4L20 (3x740kW)	2x CAT3516B (2x1400kW)	4x CAT3412C (4x540kW)
Energy storage	-	350kWh	350kWh	350kWh
Drive	Electrical drive	Electrical drive	Electrical drive	Mechanical drive

3.3.2 Hybrid medium/high-speed comparison tool calculations for short route ferry.

In this case, the same operation profile is used as with ESStimator calculations. However, since the voyage from port a to b does not differ much from the voyage from port b to a, the load profile is “cut” in half to simplify calculations. The 500kWh battery solution is added as well in order to benchmark different engine and battery combinations. For the solutions without batteries, all are electrical drive besides the one equipped with four CAT3412C engines, which are in mechanical drive

configuration. The hybrid solutions, both with 350kWh and 500kWh batteries, only need one engine theory. All the hybrid solutions operate in a similar fashion; the engines only run during transit. The batteries are utilised when sailing into port, manoeuvring and waiting in port. The same formulas are used as in the tug case. Calculation is set up in a manner that would allow the batteries to have a state of charge after 50 min that would suffice until the engines are switched on during transit. Because the ferry operates in protected waters with no hard wave conditions, peak shaving is not utilised in these calculations. In Appendix 3, different battery and engine comparisons can be found.

3.4 Case 3 – Platform supply vessel

3.4.1 ESStimator calculations for platform supply vessel

The load profile for the offshore supply vessel/platform supply vessel is shown in Figure 23. It differs from the ferry and tug cases because a voyage for an offshore supply vessel is much longer. This means use of battery will differentiate a lot from the previous cases.

Because the operation profile of a PSV differs from the two previous cases in voyage duration, hours are compared to minutes. Because of this, the way in batteries are utilised will differ. For example, the first load peak is eight hours long and requires 4500kW. During this time, battery is used for peak shaving because of load fluctuations; e.g., rough sea. When the load is lower in the profile, most of the battery capacity isn't enough to power the complete duration of the valley. The result is that the batteries/engines would be used in a start/stop mode. If the load is higher and start/stop mode would not be considered beneficial, the engines would need to operate on a higher load in order to charge the batteries. No shore charging is used for this type of vessel. The batteries will have no or little charge when leaving port.

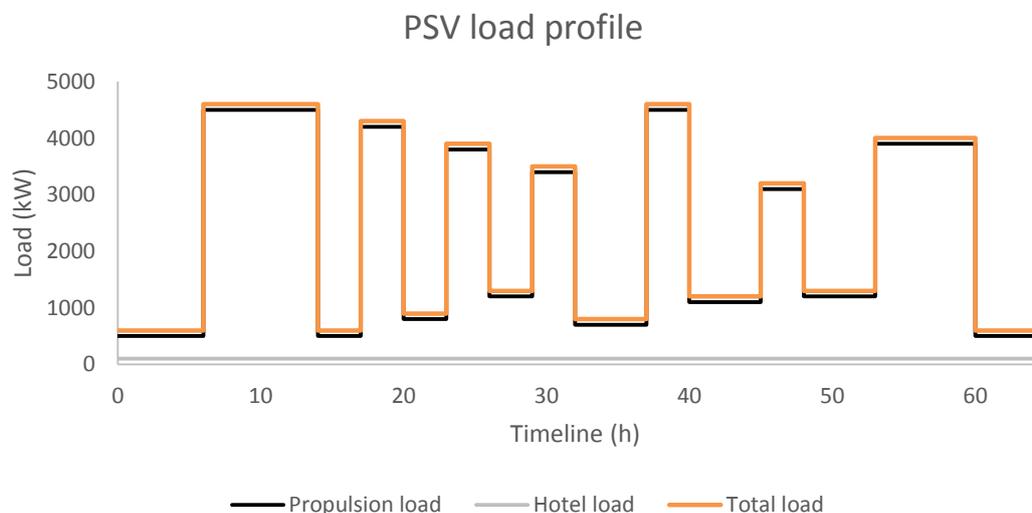


Figure 23 PSV load profile for calculation tool.

3.4.2 Hybrid medium/high-speed comparison tool for PSV

The same load profile is used for PSV as was used in the ESStimator case. Because the different load points are much longer in comparison to those of the ferry and tug, the engines may need to be started and stopped multiple times within the indicated load points. This is due to the fact that the capacity of ESS is not sufficient to hold enough energy for the entire load point. Some load points may have a load level that make it unnecessary to utilise batteries; in these cases, engines operate close to the optimal load level. Because engine outputs differ, the number of engines in operation will differ for some load points. Because port calls are not as frequent as in other cases, no shore charging is considered. Therefore, the state of battery charge is always considered 0% at start of voyage. In Appendix 4, different comparisons for the PSV case can be found. For the non-hybrid solutions, 3x CAT3516B and 4x W8L20 are needed, same number of engines for both the high-speed and medium-speed solutions equipped with 500kWh battery.

3.5 Input data

For all these cases, the energy storage system lifetime is approximated to half the vessel lifetime. The same prices are used throughout this thesis for better comparison; however, some parameters, such as fuel oil price, are heavily dependent on location. These are parameters that must be taken into consideration in real life cases. Battery price development must be taken into consideration when the battery is replaced after half the vessel lifetime. These figures were taken from a calculated ESStimator case and fuel prices etc. correspond with prices in central Europe during the autumn/winter of 2017. Service prices, as explained earlier, are dependent on various factors: rotating speed, power output, robustness of components, etc.

Table 8 Input data for calculations. (Wärtsilä, 2017a), (Wärtsilä, 2017e), (DNV-GL, 2016)

Prices	
Battery price original price	615 €/kWh
Battery price when replaced	410 €/kWh
Fuel oil price	480 €/ton
Lube oil price	2300 €/ton
Maintenance cost 3516B	2,8x€/h
Maintenance cost 3412C	3,3x€/h
Maintenance cost W20	1,2x€/h
Maintenance cost W26	x€/h
Electricity price (shore charging)	0,09 €/kWh
DE capex difference (to DM)	500k€
Energy transfer losses	
From battery to propulsion (DE)	7,7%
From engine through gearbox to battery (DM)	9,1%
From battery through gearbox to propulsion (DM)	9,1%
From engine to battery (DE)	5,8%
From shore to battery	2,2%

3.6 Reference cases

3.6.1 Existing hybrid vessels

Already existing hybrid vessels with Wärtsilä technology are the Viking vessels previously mentioned in theory chapter of this thesis. Data from these vessels was used to validate the calculation and simulation results in this thesis.

3.6.2 FESSMI

FESSMI or Future Energy Storage Solutions for Marine Industry is a TEKES funded project in which both companies and universities are involved; one of the driving forces being Wärtsilä. The objectives of this study were to identify attractive, marine segments for hybrid solutions and to gain knowledge of hybrid technology through simulations. Data from this study can be used to verify the calculation and simulation results of medium-speed, hybrid solutions.

4 RESULTS

Calculations conducted with the low-load consumption tool clearly show that in terms of fuel consumption there is no gain in using batteries when the load on engines is over 50%. This is due to the electrical and chemical losses when storing and using the energy in the batteries. At lower loads the fuel consumption savings can be up to 40% when using a hybrid system. The comparison was made between the same type of engine for both hybrid and non-hybrid. Difference in fuel consumption between a medium-speed hybrid and high-speed hybrid is around 48%, calculation for load points 100%, 85%, 75%, 50%, 25% and 10% for W8L20 and CAT3516B engines. Another important aspect of using a hybrid system is savings in running hours which result in less maintenance costs. This is strictly in relation to engine output, meaning that more output equals less time needed to have engines operating.

4.1 Case 1 - Tug

In the tug case, two medium-speed engine solutions, W8L20 (1600kW) and W6L26 (2040kW), were compared to CAT3516B (1800kW). ESStimator calculations for the tug case show a drop of 33% in running hours when using a medium-speed hybrid solution (W8L20 engines with electric drive) compared to the high-speed solution (CAT3516B engines with mechanical drive). The fuel consumption is lower by 24% in favour of the medium-speed solution. The difference is smaller when comparing a medium-speed solution with a mechanical drive (W6L26 engines), only 16% in fuel consumption with the same number of running hours. No difference in running hours is because they are both set up to run with the same modes in the different load points. All solutions use a 500 kWh battery.

When comparing fuel consumption for solutions with a 500 kWh battery the hybrid calculation tool shows 31% lower for the W8L20 solution compared to the CAT3516B solution, and 30% lower for the W6L26 solution compared to the CAT3516B solution. A 750kWh battery will make the difference bigger between the W8L20 solution and the CAT3516B by 36% lower fuel consumption for the medium-speed solution, 26% lower for W6L26 solution compared to same high-speed solution. A 1 MWh battery shows same trend with difference between medium-speed and high-speed solutions, W8L20 has 38% lower consumption and W6L26 27% lower compared to the 3516B solution. Operating costs are gathered in Figure 24. The difference between highest cost (2x CAT3516B with mechanical drive) and lowest (2x W6L26 with mechanical drive) is 10% lower at the end of the lifetime, even though the investment cost is around 54% lower in favour of the high-speed solution. The difference between 2x W8L20 and CAT3516B both with mechanical drive is around 7% lower at the end of the lifetime for the medium-speed solution. The investment cost is 2% lower for the high-speed solution. In Appendix 2, more graphs for different comparisons, about same difference can be seen with bigger battery sizes. With a 750kWh battery cost at the end of the lifetime will be lower by 8% in favour of the medium-speed solution (1xW6L26 compared to 1xCAT3516B paired with 750kWh ESS), with the investment cost being 20% higher for the medium-speed solution. With the same battery

difference between medium-speed solution equipped with 2xW8L20 and 1xCAT3516B, the difference will be 4% lower at the end of the lifetime for the medium-speed solution, and 25% lower investment for the high-speed solution. With a 1MWh battery the situation changes, with the W8L20 solution has the lowest cost at the end of the lifetime 12% lower than CAT3516B solution both using electric drive. The high-speed solution having 2% lower investment cost.

TUG - cost analysis

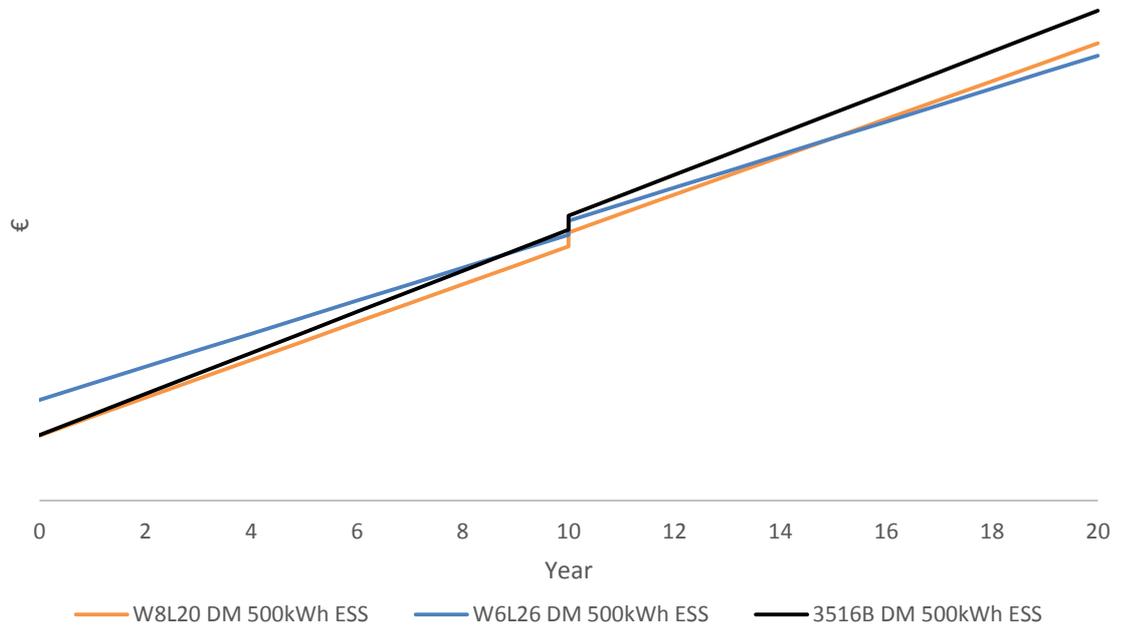


Figure 23 Lifetime cost analysis for tug case equipped with 500kWh battery. Battery replaced after 10 years.

4.2 Case 2 - Ferry

For the ESStimator calculations ferry case fuel consumption is lower by 10-15% depending on solution in favour of the medium-speed. Medium-speed solution 1 (2x W6L20 + 350kWh battery, electric drive) compared to high-speed solution 1 (2x CAT3516C + 350kWh battery, electric drive) results in a 15% lower consumption. Medium-speed solution 2 (3x W4L20 + 350kWh battery, electric drive) compared to high-speed solution 1 results in 13% lower consumption. Medium-speed solution 1 compared to high-speed solution 2 (4x CAT3412C + 350kWh battery, mechanical drive) results in 12% lower fuel consumption. Medium-speed solution 2 compared to high-speed solution 2 results in 10% lower fuel consumption. Like earlier seen from calculations running hour savings are in relation to installed power output. This means that high-speed solution 1 will have the lowest number of running hours and high-speed solution 2 will have the highest (due to being mechanical drive, not possible to shut of one engine).

Results with hybrid calculation tool show 350kWh battery size being sufficient for this vessel in intended conditions. The fuel consumption is 15% lower with the W4L20 engines compared to the CAT3412C engines. In Figure 25, cost analysis is shown for the whole lifetime. Difference at the end of lifetime is 14% higher, however, investment cost is 3% lower for the high-speed solution. 500kWh battery results in lifetime cost is 13% lower for the medium-speed solution, investment cost 3% lower for high-speed solution. In Appendix 3, more comparisons can be found for the ferry case.

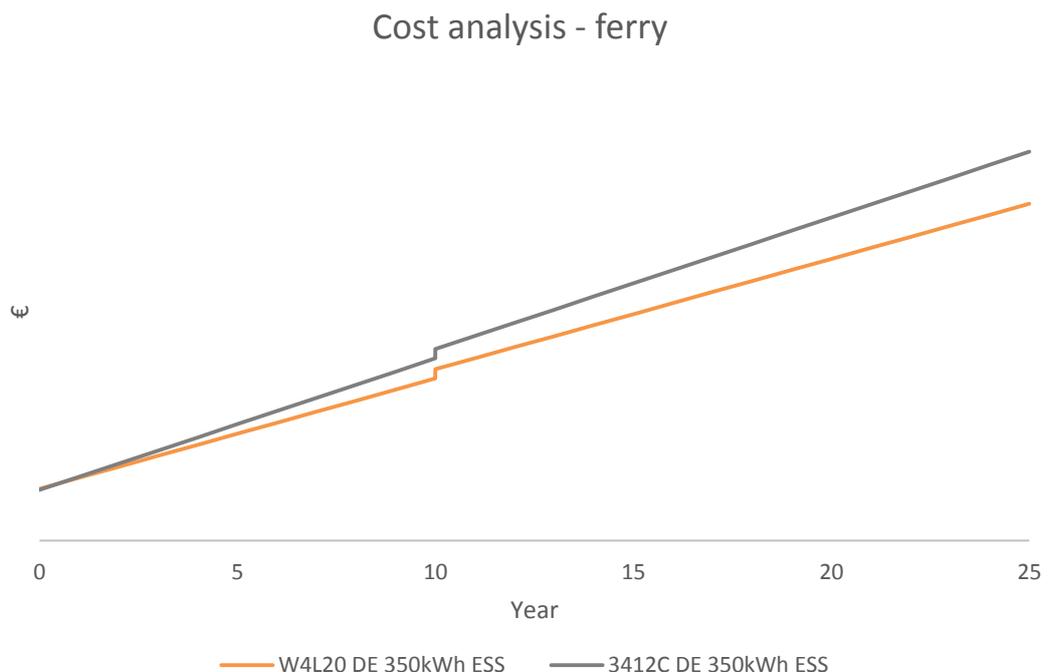


Figure 24 Lifetime cost analysis for ferry case equipped with 350kWh battery. Battery replaced after 10 years

4.3 Case 3 – Platform supply vessel

The PSV case differs somewhat from the tug and ferry case, since a voyage length is much longer. This means the battery will not be enough to last a whole load point. Peak shaving and start & stop operating modes will need to be used. In this case the difference between the medium-speed engines and the high-speed engines are much smaller, only about 3% lower fuel consumption for both medium-speed solutions (4x W8L20 and 3x W6L26) compared to the high-speed solution (3x CAT3516B), all solutions equipped with a 500kWh battery and electrical drive.

Results from the hybrid calculation tool show that the difference between 4x W8L20 and 3x CAT3516B paired with a 500kWh battery, is 9% lower than the fuel consumption for the medium-speed solution. The high-speed solution will have 31% lower running hours due to higher output resulting a smaller number of engines needed. In Figure 26, the lifetime costs are compared. More comparisons can be found in Appendix 4.

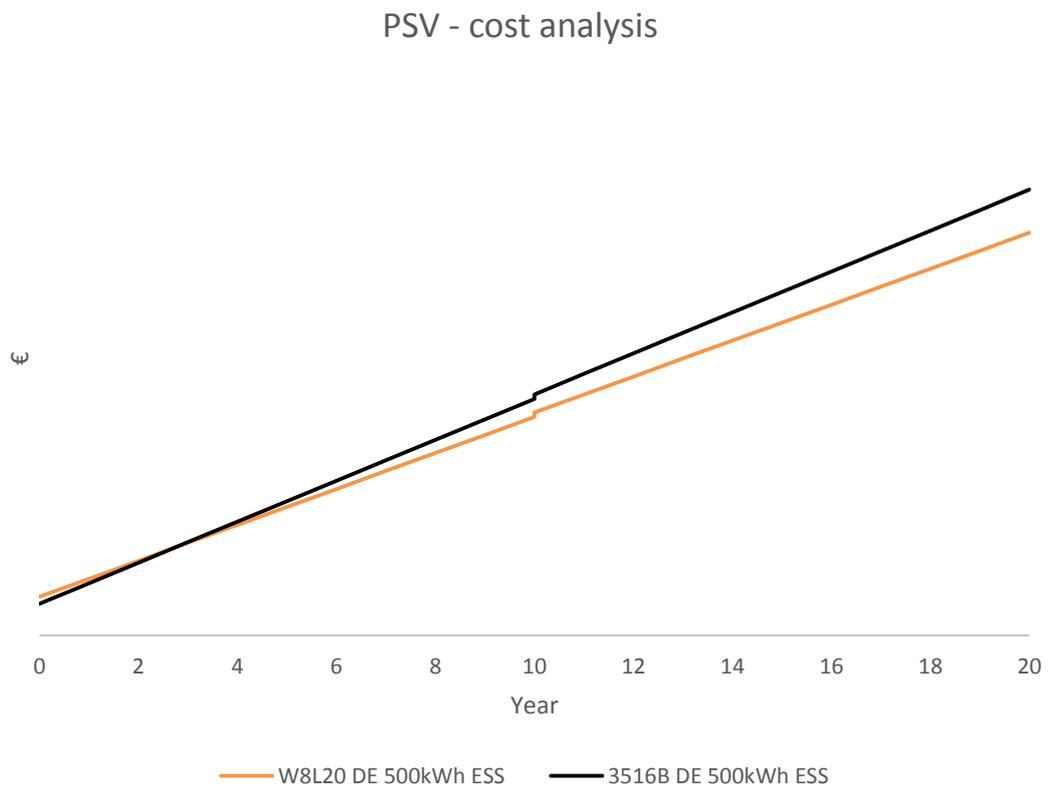


Figure 5 Lifetime cost analysis for PSV case equipped with 500kWh battery. Battery replaced after 10 years.

5 DISCUSSION / ASSESMENT OF RESULTS

When considering a hybrid vessel, it is not just the case of adding a battery to a propulsion layout. This can be done but will not be the most efficient option. It is far more complex than that. Engines and batteries need to be seen as an integrated system together with good automation systems to use the full potential of the equipment. Between the different tools there was, depending on the case, a discrepancy of a couple of percent. This is mostly due to the vessel operating in different modes in the load curve for the different tools, for example, in ESStimator calculation for tug peak shaving was used for some peaks but in the hybrid calculation tool start & stop mode was used for the same peak. The most complex of the tools is ESStimator which takes the most parameters into account. The hybrid calculation tool was made specifically for this thesis, since there were no tools intended to compare the different engine categories.

The difference between running hours between medium-speed and high-speed engines is not suitable to be analysed with the low-load consumption tool, since the engine size will strongly impact the engine running hours. These calculations are made in such fashion that the way of operating does not correspond very well with the real life situation. This is because the tool does not take into consideration what the load need is, only the load percentage on which the engine is operating. What this means is that even though fuel consumption is significantly higher, the power output is also somewhat higher and running hours will be affected in favour of the engine with more power output. This tool is better suited for comparing hybrid solutions with non-hybrid solutions using the same type of engine.

Since there are no emission data publicly available for high-speed engines used in this thesis, the only emission that can be compared is CO₂ and SO_x, which can be calculated from fuel consumption, with the difference in emissions between high-speed and medium-speed engines being the same as the fuel consumption. Carbon monoxide emissions can be compared on a theoretical level since fuel consumption will be at the lowest closest to the IMO emission limit. Limits (chapter 2.3.1) are determined by engine rotating speed, high-speed engines having a stricter emission limit than medium-speed engines. For example, W20 rotating at 1000 rpm the limit is 2.26 g/kWh compared to a CAT 3516B rotating at 1600 rpm has a limit at 2.05 g/kWh, a difference of 9% for IMO tier III. The problem with all comparisons in this thesis is a lack of information for the high-speed engines. For example, the fuel consumption for the CAT engines is only given for load points at 100%, 75% and 50%, which means the SFOC curve has to be drawn from these three points. The resulting SFOC values for lower loads should be higher, and the curve should be steeper (Appendix 1). The fairest engine-to-engine comparison is between W4L20 (740kW output) and CAT3412C (730kW output) since the engines have similar power output. In this comparison, the medium-speed engines have 6% lower fuel consumption. Since the medium-speed engine has the lowest fuel consumption at an 85% load and the high-speed engine has the lowest consumption at 100% load, these are the loads that are used in this comparison. This means that the engine hours will be slightly lower for the high-speed engines.

The investment cost for a hybrid vessel compared to a corresponding non-hybrid vessel will be significantly higher. There have to be clear benefits of the hybrid vessel for it to be a viable option. Like the calculations show, there are good opportunities to make savings regarding both fuel consumption and maintenance costs. Another key factor to some ship-owners is the image of being environmentally conscious, the so-called green image. If the vessel is equipped with a hybrid system, it will certainly be announced on the side of the vessel in big letters. Financial backing has also been obtained for some hybrid vessel builds. This has, for example, been implemented both in Sweden and Norway.

Case 1, the tug would be a typical application where a battery hybrid system would be utilised. Due to the way of operating this type of vessel is perhaps one of the most feasible to be equipped with a hybrid system. Difference in fuel consumption between tools is about 15%; this is because in ESStimator also peak shaving mode is used for some solutions where in the hybrid comparison tool only start/stop is used. The difference between medium-speed and high-speed hybrid vessels results is, however, very close in the two different tools which is of most importance to this thesis. In Appendix 2, a comparison between different engines has been conducted for a tug equipped with 500kWh battery, results show even though capex of the high-speed engine solutions is lower than for the medium-speed engine solutions the lifetime cost of HS solutions will pass the MS solutions within a few years, savings at end of lifetime will be significant. In Appendix 2, the space requirement and weight of different solutions is illustrated as well.

Case 2, a short route is also a vessel type that would be feasible to equip with energy storage system. With this case, also a similar difference in consumption can be seen, around 13% between the two tools. In Appendix 3, a comparison is made between different engine types used together with the 350kWh battery. For this vessel, a 350kWh battery can be considered suitable size. Appendix 3, shows the difference between a 350kWh and 500kWh battery when comparing lifetime cost. The same difference as in capex will be at end of the lifetime, meaning a 500kWh battery is too big for this application. In this type of vessel, the space requirement and weight of engines can be a deciding factor, which is illustrated in Appendix 3. The high-speed solution having a small advantage in this case.

Case 3, the platform supply vessel might in some cases be considered a feasible option to equip with batteries. However, the operation of them differs quite a bit from tugs and short route ferries, as stated earlier. Peak shaving and start/stop are modes that are more usable in an OSV/PSV, green mode not as usable. In Appendix 4, the different PSV solution lifetime costs can be seen, the difference may seem small in the figure but the cost difference after 20 years is in unit million euros.

Results from all three cases show that by increasing battery size the operating costs (consumption and maintenance) will decrease but at some point, the battery will become unnecessarily big and no more gain can be achieved. With bigger engine output the engine running time will decrease, since batteries will be charged faster compared to an engine with lower output. On the contrary, the battery lifetime will be lower since number of charge/discharge cycles will increase. Also by adding an energy storage device or increasing the size of the device it is possible to reduce the number

of engines needed.

To further lower fuel costs and reduce pollution other solutions combined with hybrids could be utilised. For example, using natural gas as fuel instead of fuel oil would lower emissions greatly. Fuel choice is determined by where the vessel will operate, since fuel prices can fluctuate considerably depending on region. Variable speed on engines would also be an option to reduce fuel consumption at lower loads.

The physical aspect of choosing different types of propulsion equipment is more important for some vessel segments. In the appendices, comparisons can be found for the different cases between different solutions, comparison parameters are: weight, size (volume) and footprint which is essentially how much floor space the equipment requires. A trend can be seen when comparing these parameters: by adding a bigger battery the possibility of removing engines grows thus decreasing space requirement and lowering total weight of propulsion equipment.

Since all costs for the high-speed engines are taken from different studies there is an uncertainty factor, for this thesis more conservative numbers for high-speed service costs have been used. Fuel consumption for high-speed engines was only given for 50%, 75% and 100% load meaning consumption for lower loads has been extrapolated. This will mean they are lower than in real life, however not affecting the hybrid parts of calculations, only reference cases. Energy losses when transferring energy to and from the battery are dependent on what electrical components are used in the transfer chain. For this thesis, losses for components in Wärtsilä HY have been used. Since the comparison is made mainly on a theoretical level, redundancy needs have not been taken into consideration. In some cases, battery might not be considered enough for redundancy needs but also an “extra” engine would be needed. This would, however, only affect CAPEX and not consumptions. Investment costs of engines and other equipment are only made on the basis of different studies, accurate pricing is difficult to obtain. Battery prices are difficult to predict, the trend for lithium-ion batteries has been that prices will go down in future, but some sources also say that due to high demand on some materials prices could as well go up in future. New battery technologies could also be developed in future and be more attractive than lithium-ion for marine hybrids. If shore charging is used also investment cost of equipment should be taken into consideration. The lifetime of high-speed engines being shorter than of medium-speed engines, also depreciation is a bigger factor for high-speed engines. This is, however, not taken into consideration in this thesis.

There is good possibility to do research in this area in future; most important would be to develop tools to make good simulations in order to clarify how a hybrid system should behave in order to perform best. Testing would also be needed in connection to the simulations. Battery size compared to engine output could be a good research topic, like with the ferry case in this thesis the bigger battery size did not offer any advantage over the smaller battery. In some cases, also one of the engines in the vessel could be substituted with a battery. If this would be favourable and how this would affect the vessel could also be investigated. In addition to the three vessel types included in this thesis, there are also other vessel types where hybrid systems could be of interest: dredgers, drill ships, luxury yachts and other types of ferries for instance. Due to electrical losses, there is a line between whether it is profitable to start utilizing

batteries or to operate engines outside optimal operating window, where this line goes could also be investigated. Batteries could also be utilised in other areas of the vessel. For example, batteries could be coupled to electric motors of spinning devices like pumps, turbochargers etc. If engines are shut off for extended periods, how would this affect equipment on board? SCR for example, need a certain operating temperature.

6 CONCLUSION AND RECOMMENDATIONS

In this thesis, three Excel-based tools were used to calculate different vessel types equipped with various engine and battery combinations:

- Low-load consumption tool which is a simple tool that does only take into consideration how the engine should operate in a hybrid under static load, no batteries included.
- ESStimator which is a complex tool for simulating hybrid vessel operation.
- Hybrid calculation tool which was developed specifically for simulating cases used in this thesis.

Engine operation in a hybrid was considered as always operating at the optimal load and batteries compensating in both directions accordingly. A functioning hybrid system does require more than just adding batteries and necessary electronical devices to an existing propulsion layout. It should be seen as a complete system instead of individual components. Important will be to have a well-functioning automation system that controls the cooperation of engines and batteries. Batteries should be utilised in such a fashion that they support engines and vice versa. Quick load taking, for instance, could be completely covered by batteries, meaning that some engine functionalities could be removed. The engine intended for use in a marine hybrid system could in future mean a very simple engine only optimized to operating within a small load window, where consumption and emissions are at the lowest.

The different cases calculated in this thesis were chosen based on what vessel segments are most attractive for hybrid systems. The size of the vessels were in range where both medium-speed and high-speed engines would be viable options. For all three cases, medium-speed solutions show an advantage over the high-speed solutions when it comes to the cost at end of the lifetime. To conduct an even more fair comparison, emissions should also be included. This was, however, not possible due to lack of emission data for high-speed engines used in this thesis. The choice between high-speed engines and medium-speed engines has mostly been made on the basis of investment cost. Based on the results from this thesis, introduction of hybrid systems would not greatly affect decisions made between medium-speed and high-speed engines. A tug that traditionally would be equipped with medium-speed engines could in the future be equipped with medium-speed engines plus batteries and vice versa. Correctly sizing batteries and engines to the vessel operating profile was also discovered to have a significant impact on both consumption and running hours. Surpassing the optimal size of battery capacity would not bring any added value for the calculated cases. Since high-speed engines are not available in as large output sizes as medium-speed engines, this will mean that larger vessels will automatically shift towards medium-speed engines.

Stricter emission regulations, lower operational costs, instant load taking as well as other advantages make hybrids an attractive alternative in the future. However, the investment cost will always be a driving factor and battery prices are still high. Even though there are savings to be made after a certain number of years, shipowners usually only regard a short payback time. The price development for suitable marine hybrid

batteries is difficult to estimate, and new battery technologies would need to be introduced to become more than an alternative for selected shipowners. If money were not a problem when selecting the engine type for a hybrid vessel, the choice would undoubtedly be a medium-speed engine. Size and weight should not be a deciding factor for choosing between the two engine categories for a hybrid vessel, since adding batteries will require space and add mass regardless.

The importance of developing good simulation tools and testing how engines, batteries and other electronic equipment work in different situations cannot be stressed enough. Future research could include calculating for different vessels where the breakpoint is for replacing the engine with bigger battery. This would be very much depend on operating profile. Another important factor to look at could be to investigate what the most beneficial split between engine output and battery capacity is. Factors like these should also be simple to include into a hybrid-vessel simulation tool.

SVENSK SAMMANFATTNING

Mellanvarviga och högvarviga motorer i marina hybridinstallationer

Inledning

Motortillverkare försöker ständigt utveckla nya metoder och teknologier p.g.a att lagstiftningen för utsläpp ständigt skärps. Ekonomiska faktorer som förbrukning och underhåll bidrar också till utvecklingen. En av de nya metoderna är att kombinera traditionella förbränningsmotorer med energilagringssystem, en kombination mer känd som hybridsystem. Installationer som dessa kan erbjuda fördelar som till exempel bidra med extra propulsionskraft vid behov.

Tidigare forskning har visat att hybridsystem är fördelaktiga jämfört med traditionella installationer för alla fartygstyper, men största nyttan har man i fartyg som opererar i varierande sjögång eller har varierande lastprofil. Marknaden har ingen för tillfället dominerande leverantör av hybridsystem och därför finns det ett stort behov av att utforska möjligheter och krav som ställs på utrustningen i hybridsystem.

Inom den marina sektorn kategoriseras motorer enligt deras rotationshastighet; lågvarviga, mellanvarviga och högvarviga. Wärtsilä tillverkar i dagsläget endast mellanvarviga motorer. När motorer och batterier kombineras i hybridfartyg kommer kravbilderna på komponenterna ändras jämfört med traditionella fartyg. Som en följd av detta bör olika motor- och batterikombinationer jämföras för att kunna bestämma i vilken riktning hybridsystem och motorer bör utvecklas.

I detta arbete kommer olika Excel-baserade simulerings- och kalkyleringsverktyg användas för att beräkna och simulera olika fartygstyper med diverse motor- och batterityper. Ett verktyg utvecklades specifikt för detta arbete, Hybrid medium/high-speed calculation tool. Målet med detta arbete är att studera skillnader, styrkor och svagheter hos mellanvarviga och högvarviga marinmotorer när de kombineras med batterier i hybridapplikationer för olika fartygstyper. Ekonomiska, miljömässiga och tekniska aspekter kommer tas i beaktande när jämförelsen görs.

Lågvarviga marinmotorer kommer inte inkluderas då de inte ses som konkurrenskraftiga i de valda fartygstyperna. Motorstorleken är begränsad till mellan 500 kW och 2 MW eftersom största delen av de högvarviga motorerna är inom detta effektområde. I arbetet ligger fokus på batterier som energilagringsform samt marindiesel som bränsletyp.

Metod

För detta arbete har tre olika verktyg använts för att beräkna hur de olika motortyperna reagerar baserat på förutbestämda lastprofiler för olika fartygstyper i kombination med olika batterier. Ett verktyg utvecklades för att jämföra mellanvarviga motorer med högvarviga i hybridinstallationer. En lastprofil skapades för en färd baserat på hur fartygets propulsionsystem belastas under färdens gång. Även last från

kringutrustning i fartyget togs i beaktande. Propulsionssystemets belastning beror på bl.a. hydrodynamiskt motstånd samt ifall om båten belastas utifrån, om något t.ex. bogseras. Belastning från kringutrustning är till största del fartygets egna elektricitetsproduktion. Utgående från lastprofilen bestäms sedan hur motorer och batterier används. För att sänka bränslekonsumtion, utsläpp och servicekostnader kan man med hjälp av batterier höja lasten för motorerna och ladda batterierna. En icke-hybrid installation skulle ha motorer att köra på låga laster.

Låglastkörning resulterar i för hög förbrukning samt högre servicekostnader. Batterierna dimensioneras så att kan batterier kan användas för att driva fartyget framåt vid behov. Detta gäller för t.ex. färjor när de seglar till och från hamn. Även tilläggseffekt kan alstras från batterierna vid behov, t.ex. för bogseringsbåtar. Då bränsleförbrukningen samt motorernas körtimmar beräknats för en färd kan även driftskostnader beräknas. Genom att uppskatta hur många färddar per år fartyget gör kan man även beräkna livstidskostnader och jämföra hur stora besparingar som kan göras på långsikt. Från bränsleförbrukning kan även vissa utsläpp beräknas. Eftersom utrymmeshantering är viktigt i vissa fartygstyper bör även det beaktas, likaså golvyta samt volym som motorerna och batterierna tar upp.

De två andra verktygen var ursprungligen endast ämnade för att jämföra hybridinstallationer med icke-hybridinstallationer vilket gör att de inte är optimala för användning i detta arbete. Information från dessa kan dock användas för att verifiera resultaten.

De tre olika fartygstyperna valdes på basis av hur lämpliga hybridsystemen är för dem. En bogserbåt kan ha nytta av att hybridsystem på grund av deras mycket varierande lastprofil. Bogserbåtar har extremt mycket effekt i förhållande till deras storlek, vilket krävs vid bogsering. Då bogserbåten seglar till och från bogseringsuppdrag körs motorerna på väldigt låg last och stiger även bränsleförbrukningen. Batterier skulle i sådant fall kunna användas för att ge extra effekt, vilket innebär att motorer med mindre effekt kunde installeras. Även körning in och ut från hamn kunde göras endast med batterikraft. För färjor som ofta lägger till i hamn är möjligheten att köra med batterikraft användbart eftersom låglastkörning ofta resulterar i synlig rök, vilket inte är så bra för företagets image. För offshore-försörjningsfartyg är hybridsystem användbara då fartygen står i s.k. dynamisk positionering. Detta kunde enkelt beskrivas som att fartyget är ”förankrat” med hjälp av en navigationspunkt och fartygets propulsion håller fartyget i position. I tuffa klimat kan plötsliga effektbehov uppstå, vilket för icke-hybrider innebär att en motor eller till och med flera motorer måste hållas på tomgång. Istället för att ha motorer på tomgång eller låglast kunde batterier täcka plötsliga effektbehov..

Resultat och diskussion

Resultaten visar klart och tydligt att det i samtliga undersökta fall finns besparingar att göra genom att välja ett hybridalternativ istället för icke-hybrider. Gällande hybridfartyg antogs att motorerna alltid körs på eller nära det optimala lastområdet, i fall där det inte var möjligt användes batterier. Enligt beräkningarna i ett av verktygen är det fördelaktigt att köra över energi till batterier först då lastnivån är under 50 %. Detta beror på elektriska förluster i systemet. Vad gäller jämförelsen mellan

mellanvarviga hybrider och högvarviga hybrider så har mellanvarviga lösningar i alla fall som beräknats lägre förbrukning. Gångtiden för motorerna har ett direkt samband till deras effekt, en större motor kan vara igång kortare tid för att producera samma mängd energi som en mindre motor och således kräva mindre underhåll. Genom att öka batteristorleken kan man göra större besparingar i både förbrukning och underhåll. Dock finns det en maximal batteristorlek då det inte går att göra mera besparingar för en specifik lastprofil. Mellan verktygen förekom det små skillnader, och dessa kan förklaras med skillnader i hur motorer och batterier använts då lastprofilen körts.

Ett hybridsystem skall inte ses som motorer och batterier skiljt utan som ett integrerat system. Det viktigaste i systemet är ett välfungerande automationssystem som styr samspelet. Motorerna i ett hybridsystem kunde förenklas och funktioner som möjliggör körning utanför det optimala lastområdet kunde tas bort eftersom batterier kunde utnyttjas för att kompensera för alla ofördelaktiga lastområden. Behovet för av motorer att snabbt ta last skulle också minska då batterier är optimala för det. För att ytterligare sänka bränsleförbrukning, servicekostnader och utsläpp kunde även andra teknologier kombineras med batterier, så som bränsleceller, andra bränsletyper och variabel rotationshastighet för motorer.

Dålig tillgång på information om högvarviga marinmotorer har varit ett genomgående problem i detta arbete. Därför finns det en liten osäkerhetsfaktor när det gäller deras förbrukning. Utsläpp är inte heller allmän information och därför har endast CO₂ och SO_x som kan bestämmas direkt ur bränsleförbrukningen, jämförts. Även de elektroniska förlusterna innehåller en viss osäkerhetsfaktor eftersom exakta kopplingscheman och information om komponenterna inte är tillgängliga.

I framtiden vore det viktigt att utveckla välfungerande simuleringsverktyg för att bättre beräkna och förstå möjligheter och svagheter med hybridsystem. Mera tekniskt specifika skillnader mellan mellanvarviga och högvarviga marinmotorer kunde då även utforskas. Det finns också ett förhållande mellan motoreffekt och batterikapacitet som är optimalt. Detta är något som kunde undersökas vidare. Vidare forskning kunde också göras om när det är lönsamt att byta ut en motor mot ett batteri och vad det har för ekonomisk inverkan på fartyget.

I alla beräknade fall är mellanvarviga hybridlösningar fördelaktiga men deras investeringskostnader är även betydligt högre, vilket också kan sägas om hybridlösningar jämfört med icke hybrida lösningar. Än så länge är andra faktorer viktigare för att man ska investera i batteri- och hybridlösningar; exempelvis att utåge en bild att man är miljömedveten eller tillgång till statlig finansiering. Prisutveckling på batterier kommer ha stor inverkan på om hybridlösningar i framtiden blir konkurrenskraftiga. Högst troligen kommer inte introduktionen av hybridlösningar skifta balansen mellan mellanvarviga och högvarviga marinmotorer. Ett fartyg som idag skulle använda sig av mellanvarviga motorer kunde i framtiden högst troligen använda sig av mellanvarviga motorer med batterier och vice versa.

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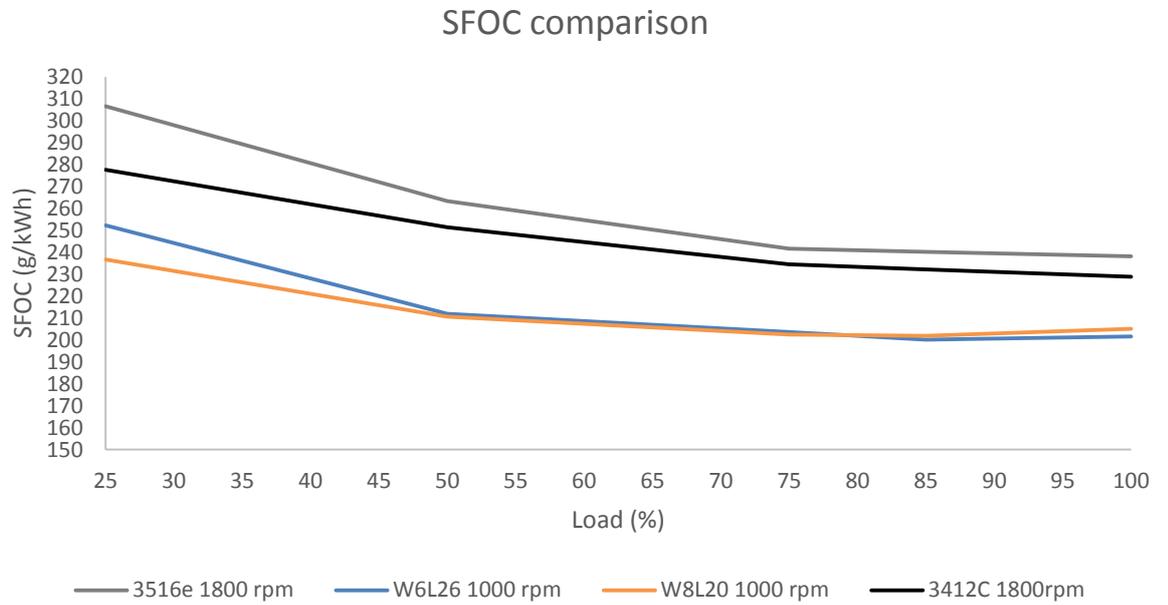
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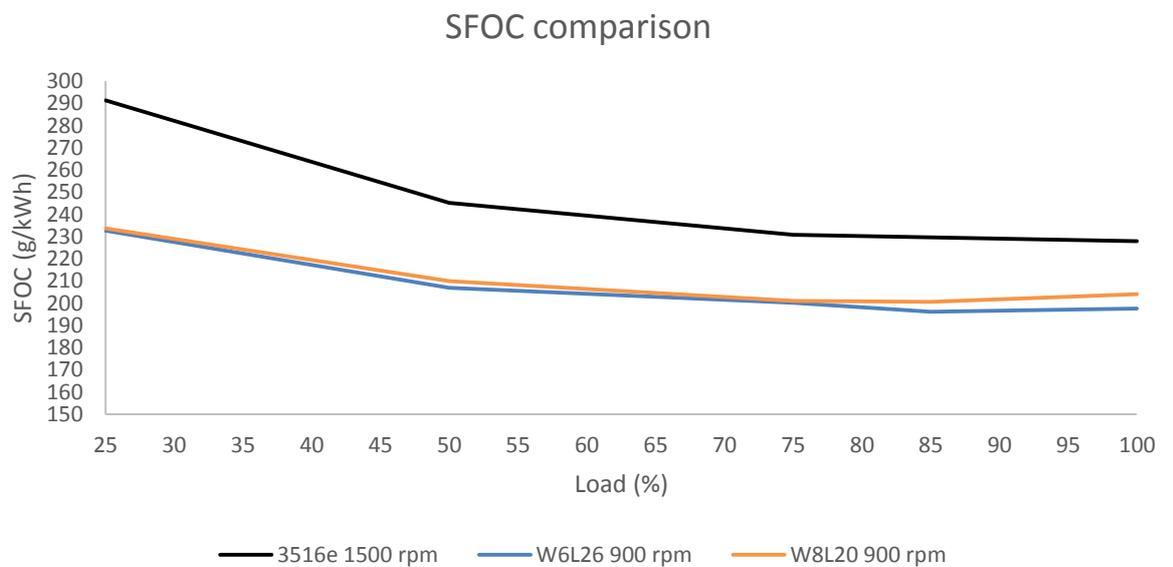
APPENDICES

Appendix 1 – SFOC curves

60 Hz electrical system.



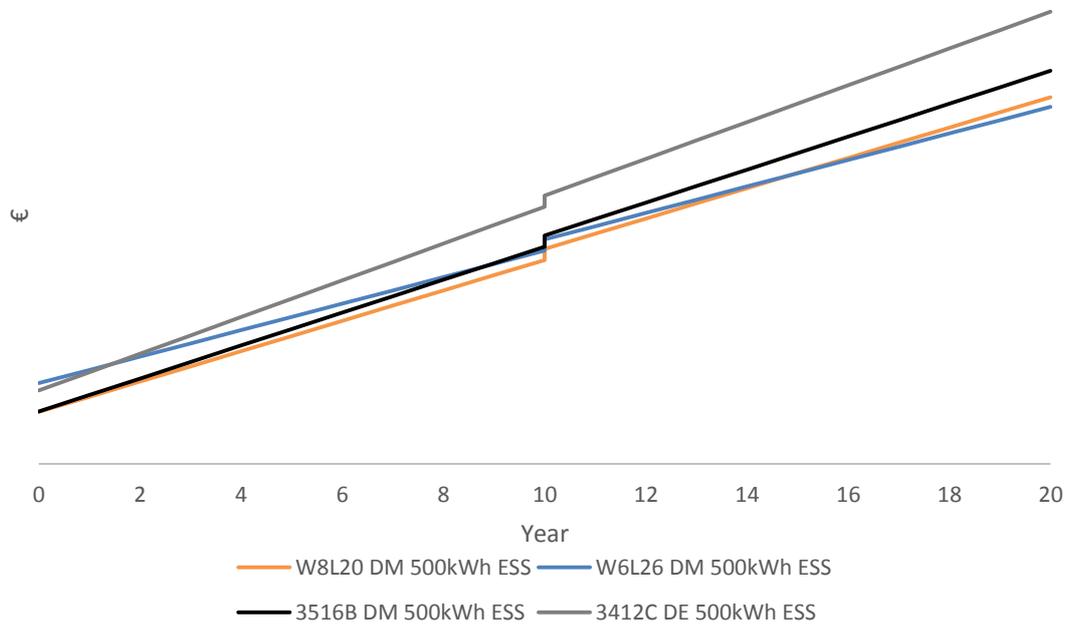
50 Hz electrical system (3412C no data).



Appendix 2 – Tug case

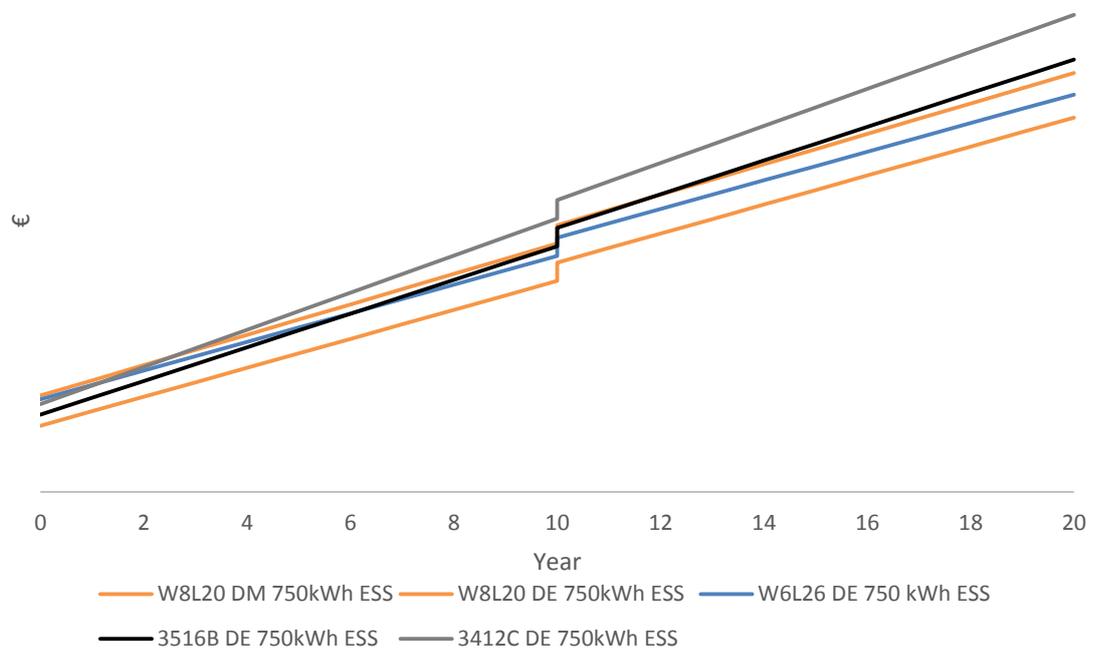
500kWh battery comparison for hybrid tug. (2x W8L20, 2x W6L26, 2x 3516B, 4x 3412C + 500kWh battery)

TUG - cost analysis



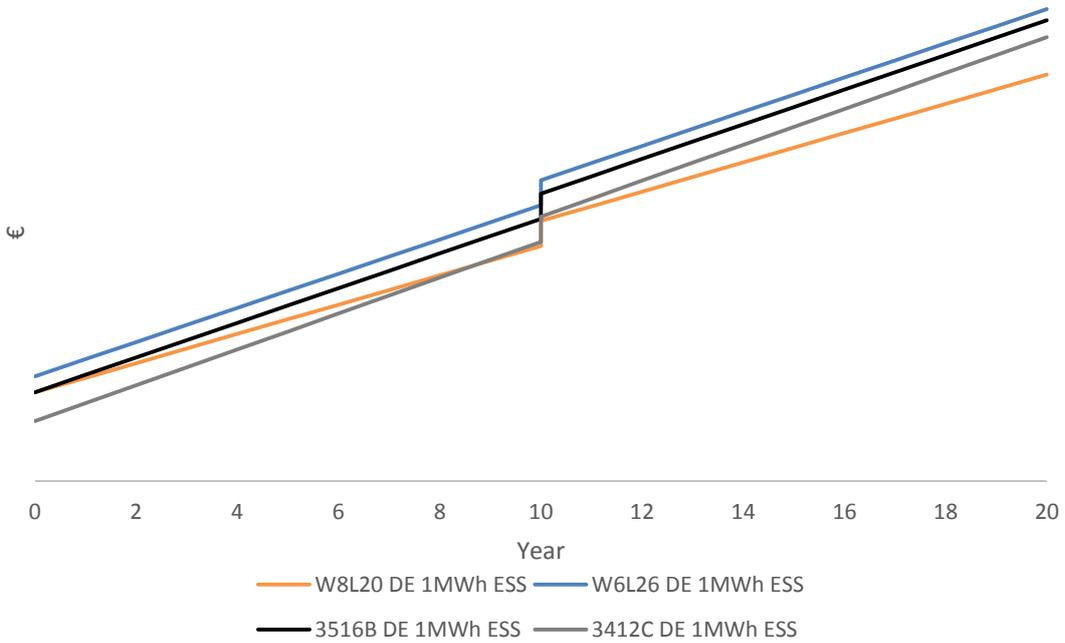
750kWh battery comparison for hybrid tug. (2x W8L20, 1x W6L26, 1x 3516B, 3x 3412C + 750kWh ESS. W8L20 possible as both DE and DM)

TUG - cost analysis



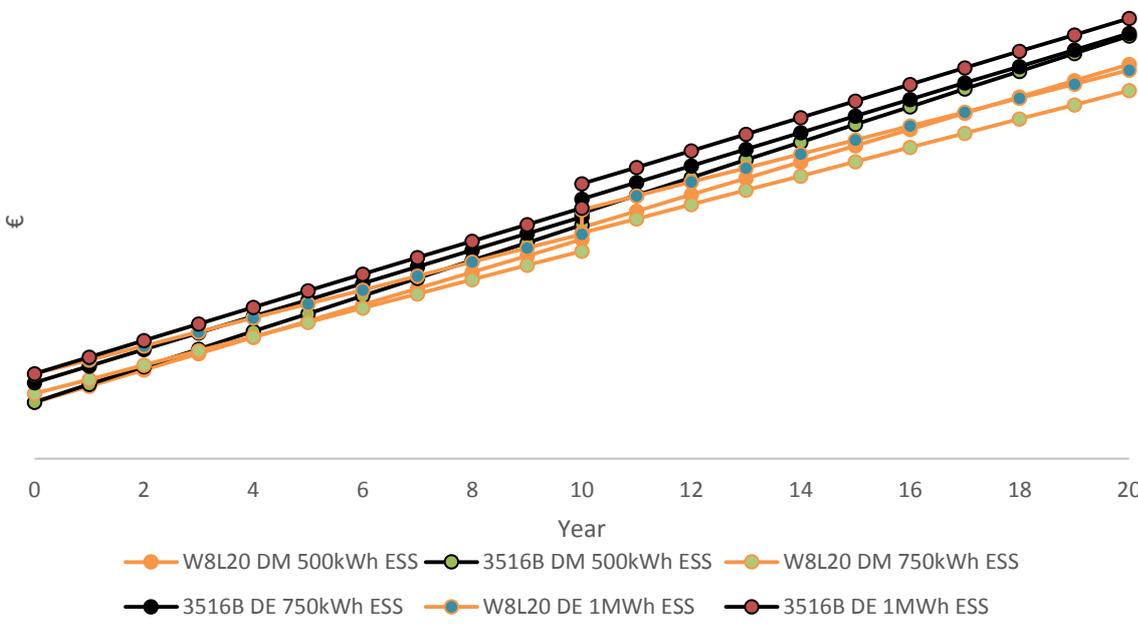
1MWh battery comparison for hybrid tug. (1x W8L20, 1x W6L26, 1x 3516B, 2x 3412C + 750kWh ESS. W8L20 possible as both DE and DM)

TUG - cost analysis



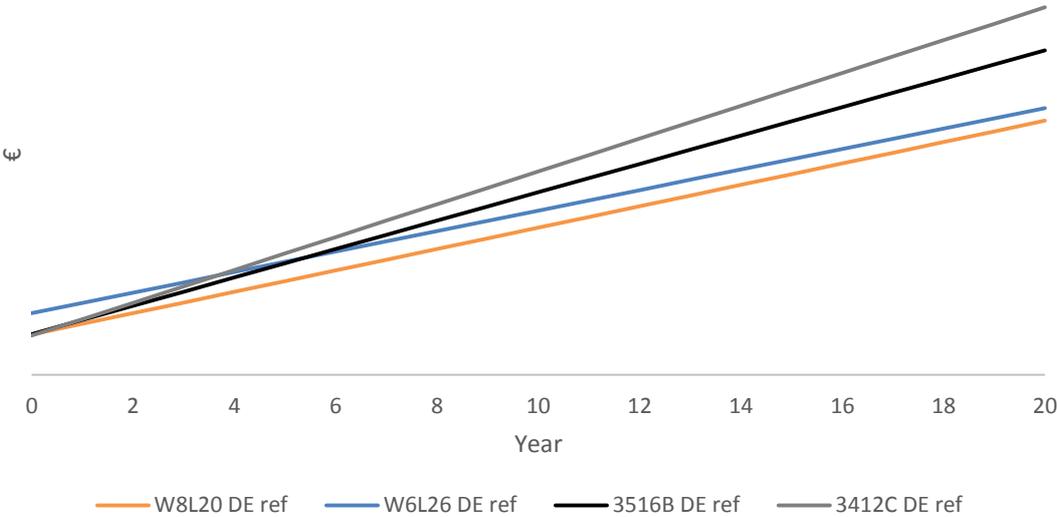
W8L20 compared to CAT3516B different battery size comparison for hybrid tug.

TUG - cost analysis



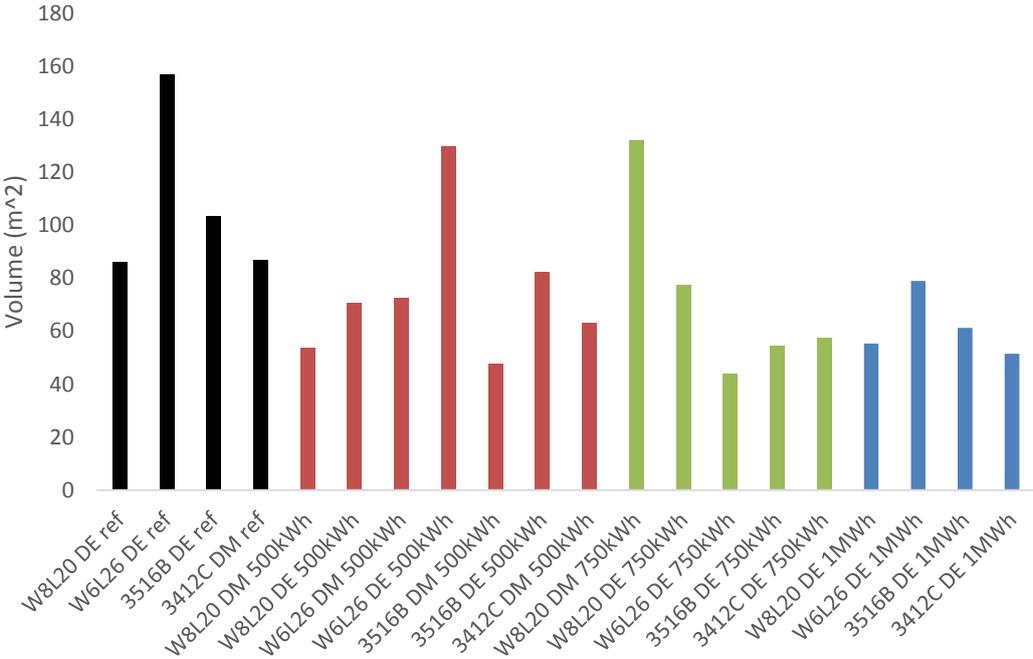
Tug reference case comparison, no batteries.

TUG - cost analysis

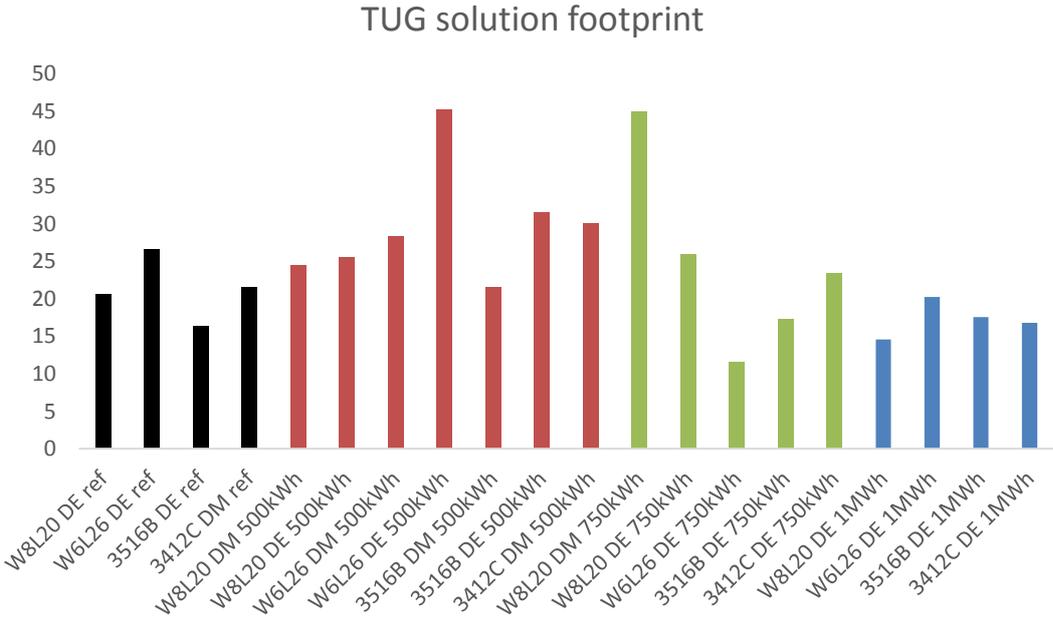
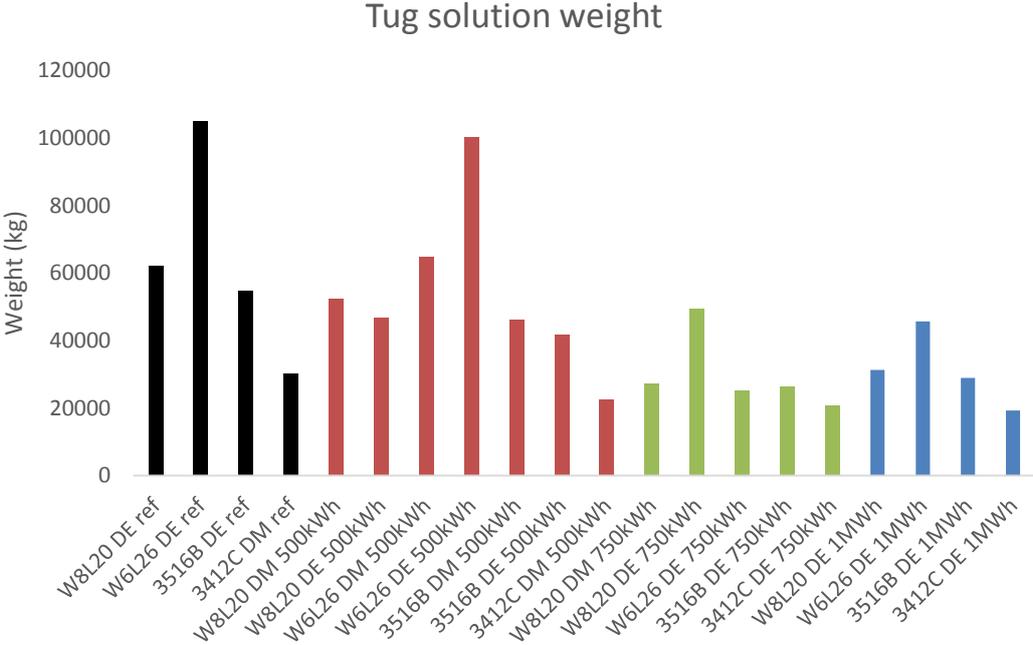


Size comparison for hybrid tug propulsion equipment.

Tug solution size



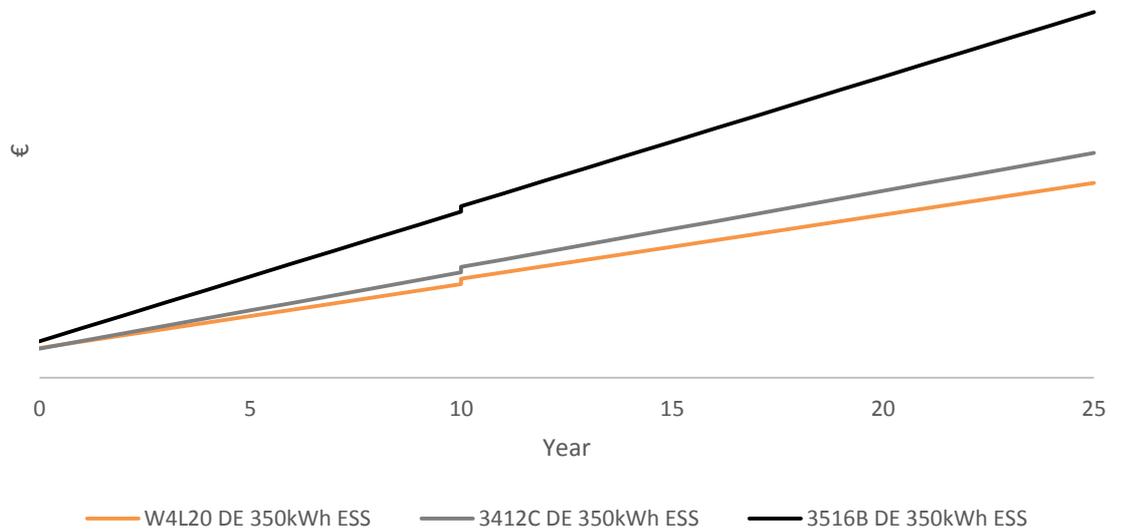
Weight comparison for hybrid tug propulsion equipment.



Appendix 3 – Ferry case

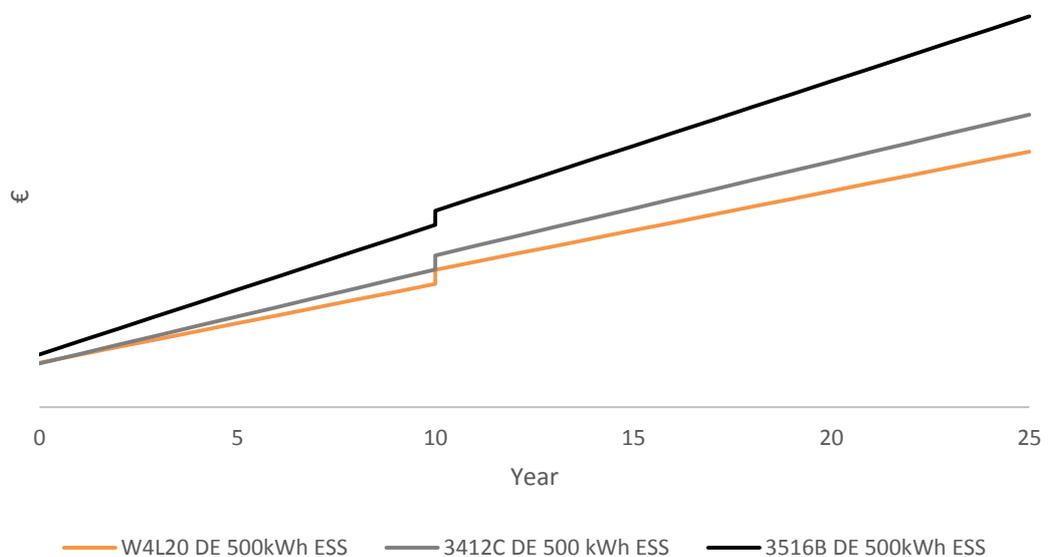
350kWh battery comparison for hybrid ferry case. (1x W8L20, 1x 3516B, 1x 3412C + 350kWh ESS)

Cost analysis - ferry

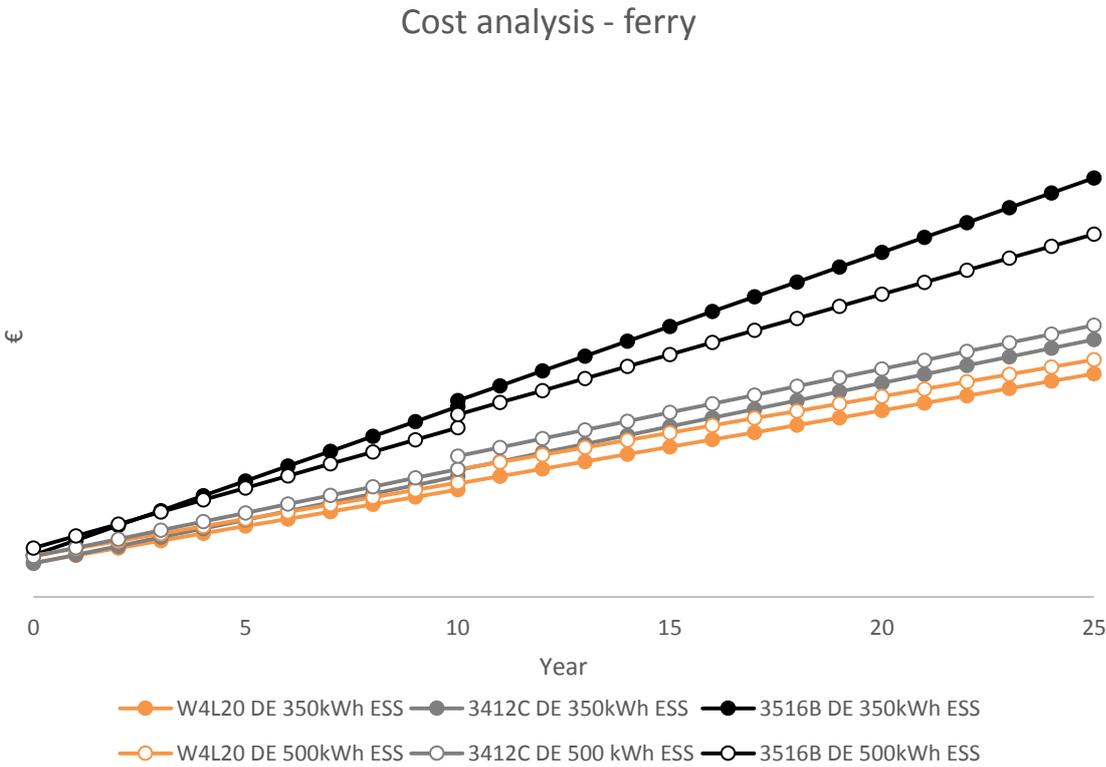


500kWh battery comparison for hybrid ferry case. (1x W8L20, 1x 3516B, 1x 3412C + 500kWh ESS)

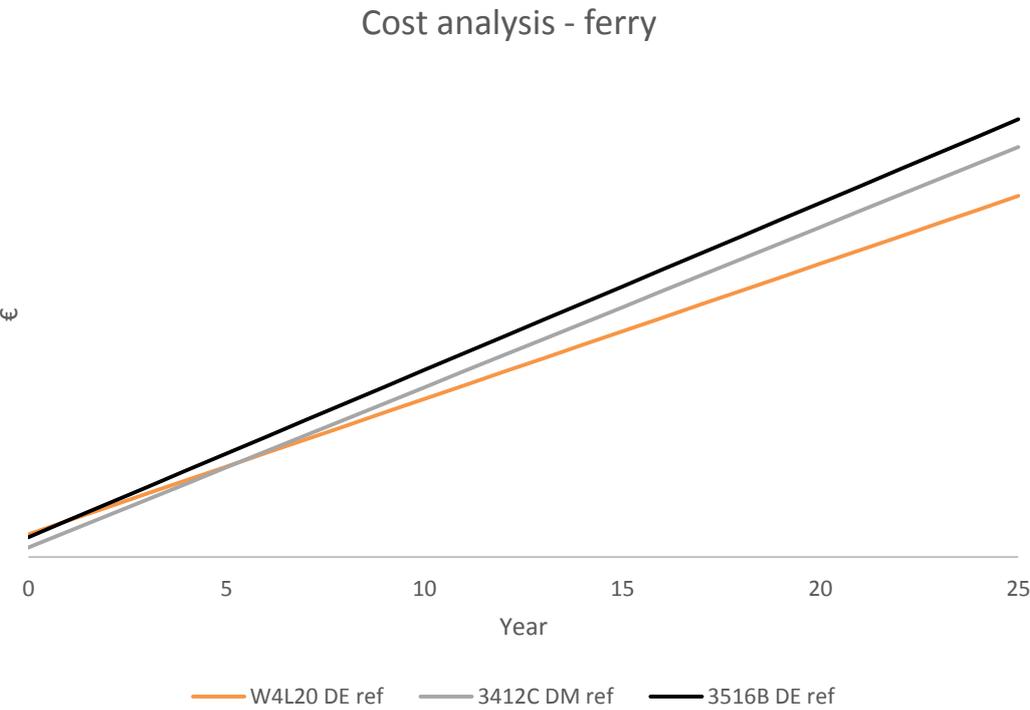
Cost analysis - ferry



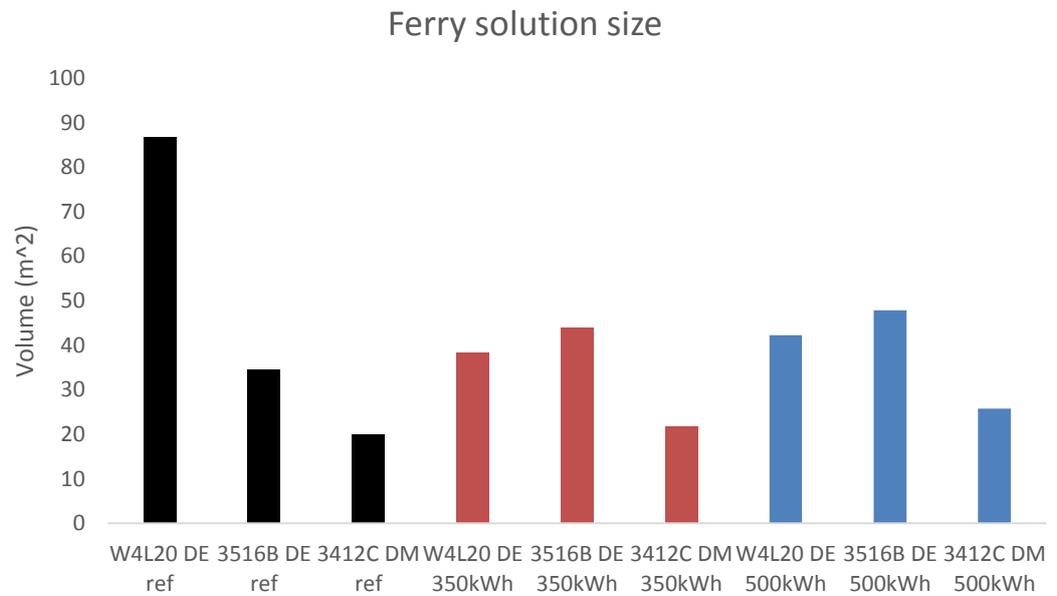
W4L20 compared to CAT3412C different battery size comparison for hybrid ferry.



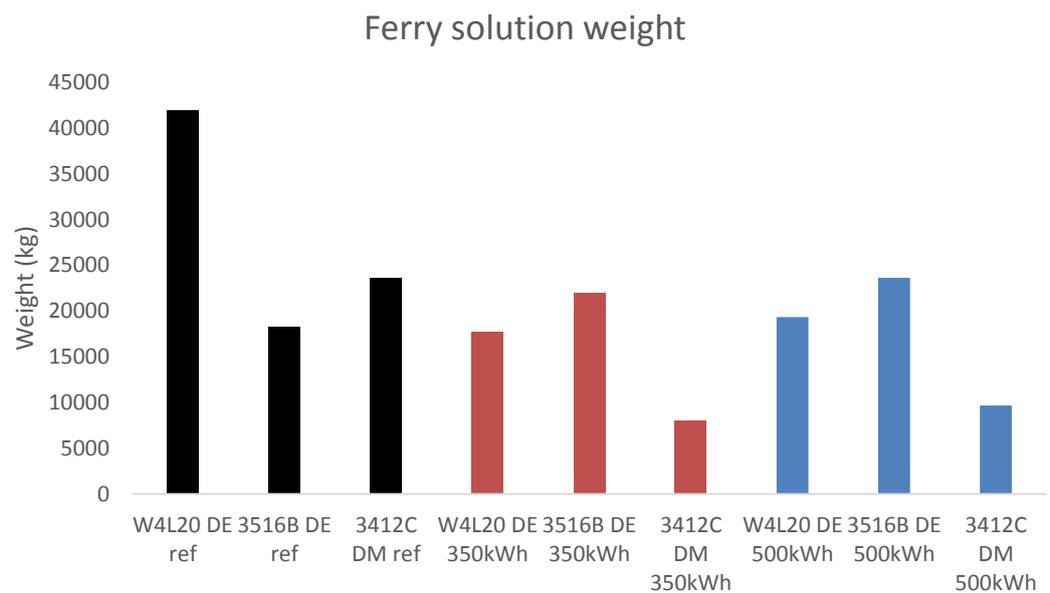
Ferry reference case comparison (no batteries).



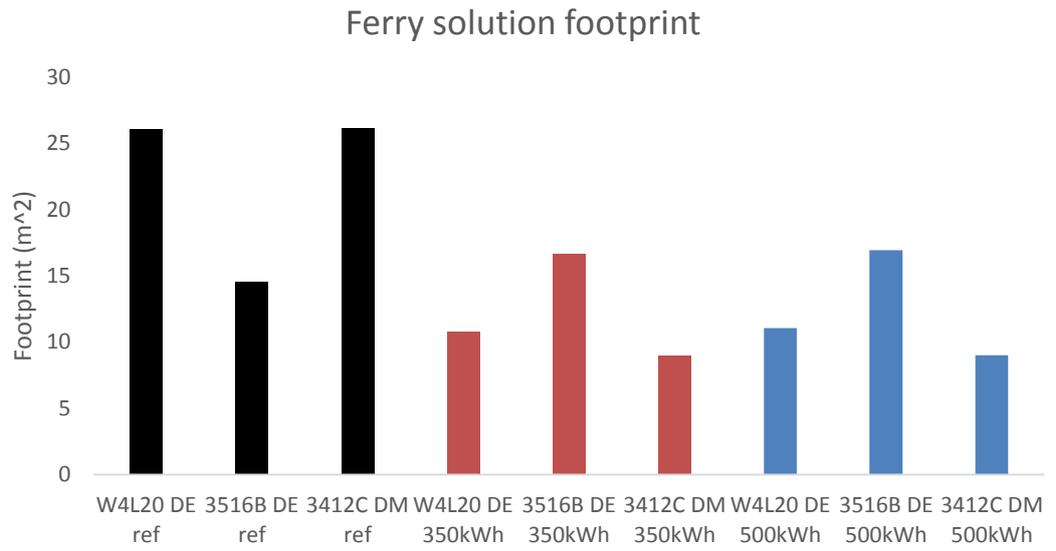
Size comparison for hybrid ferry propulsion equipment.



Weight comparison for hybrid ferry propulsion equipment.



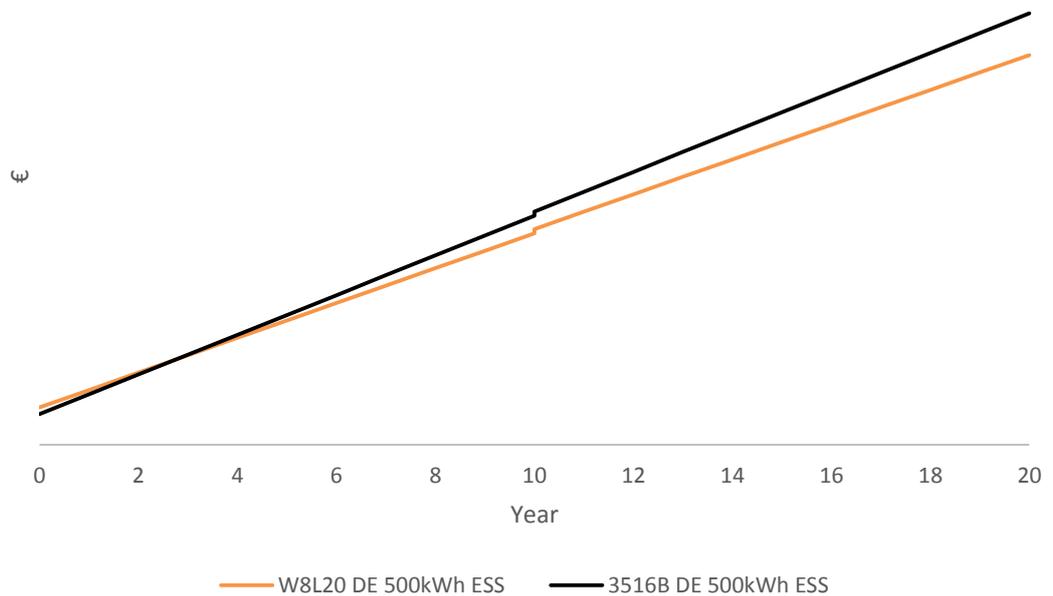
Footprint comparison for hybrid ferry propulsion equipment.



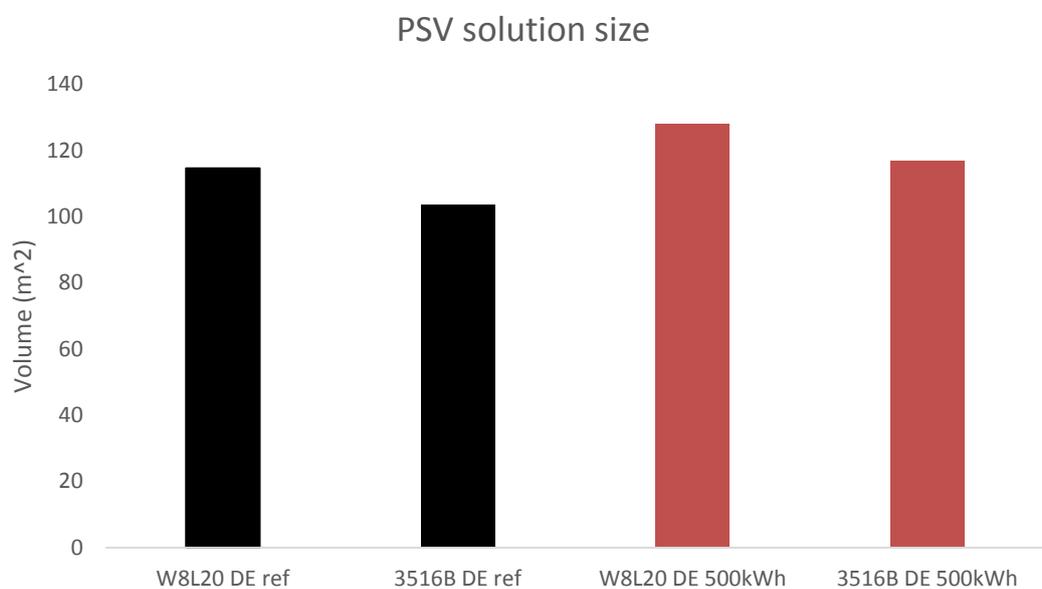
Appendix 4 – Platform supply vessel case

500kWh battery comparison for hybrid PSV case. (4x W8L20, 3x 3516B + 500kWh ESS)

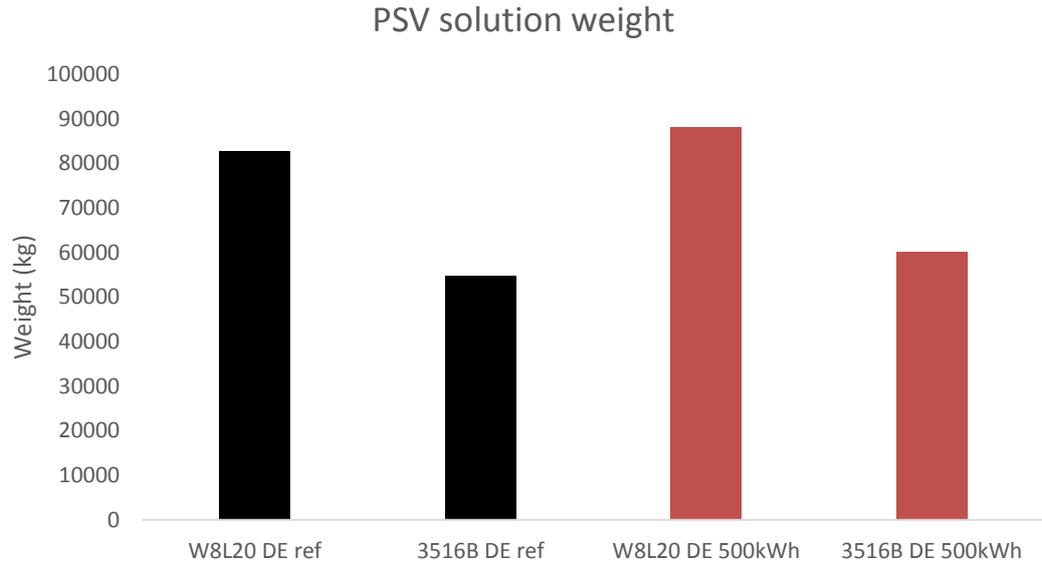
Cost analysis - PSV



Size comparison for hybrid PSV propulsion equipment.



Weight comparison for hybrid PSV propulsion equipment.



Footprint comparison for hybrid PSV propulsion equipment

