NTNU – Trondheim
Norwegian University of
Science and Technology

Factors Influencing Machinery System Selection for Complex Operational Profiles

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Marine Technology
Submission date: June 2014
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Master Thesis in Marine Systems Design
Stud. techn. Mats Johan Heian
"Factors Influencing Machinery System Selection for Complex Operational Profiles"
Spring 2014

Background

New and stricter regulations on emissions to air lie in the near future. The International Maritime Organization (IMO) has announced that by 2015 the regulations known as "Tier III" will take effect in the emission controlled areas (ECA) and globally by the year 2020. This has a great impact on the shipping industry, which is a large contributor to global emissions of green house gases (GHG). The shipping sector must adapt to these new regulations and has to reduce the emissions. Inspired, or pushed by this, manufacturers have to develop new and more energy efficient equipment and solutions to enter the market.

There are many benefits to installing a modern hybrid diesel electric propulsion system with energy storage capacity instead of a more traditional diesel mechanic system. The most important factor for the ship operator is the cost, both the investment cost and operating costs. The biggest contributor to the latter is the fuel cost. Even if the investment cost is larger for a diesel electric system it will pay off in the end, especially if the fuel price rises. However, not all ships will benefit equally from this system configuration, and the advantages will to a large extent be determined by the static and dynamic power requirements related to the vessel´s operating profile.

Overall aim and focus

The overall objective of this thesis is to identify the cutting point between selecting hybrid power systems which combine energy production with energy storage capacity and diesel electric systems based on operational profiles and external influences such as cost, route, distance, weather conditions, maneuvering and type of operations.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide an overview of state of the art hybrid power systems and diesel electric machinery configurations and trends for the future*

2. *Identify the limitations of the power systems*

3. *Identify todays decision criteria's and the influencing factors for the two machinery systems*

4. *Develop a set of possible operational profiles and a case for a PSV*

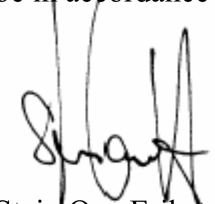
5. *Evaluate the selection of machinery system based on the operational profile and influencing factors*

6. *Discuss the results and conclude*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible supervisor.

The work shall follow the guidelines given by NTNU for the MSc thesis. The workload shall be in accordance with 30 ECTS, corresponding to 100% of one semester.



Stein Ove Erikstad

Professor/Responsible Advisor

Preface

This report, "Factors Influencing Machinery System Selection for Complex Operational Profiles" is the final result of my master thesis carried out in the spring of 2014 in Marine System Design at the department of Marine Technology, Norwegian University of Science and Technology (NTNU).

I especially wish to thank Professor Stein Ove Erikstad for taking on this project as an advisor and for his highly valued inputs and opinions.

Also a great thanks is carried out to fellow students who have been supportive all the way with discussions, motivation and help in general during the process of making this report.

Trondheim 09.06.2014

Mats Johan Heian

Summary

Background

The environmental consequences, caused by global emission of green house gases (GHG), have received increasingly concern in recent years. CO_2 emissions from the maritime sector represent 3,3% of the world's total CO_2 emissions and are forecast to increase the next decades. To meet the new and stricter regulations on emissions, the International Maritime Organization (IMO) has announced that by 2015 the regulations known as "Tier III" will take effect in the emission controlled areas (ECA), and globally by the year 2020. They are currently debating technical, operational and market-based measures for reducing GHG emissions from the shipping industry.

Hybrid power systems, which is a power system combining power production and energy storage, have been used in several industries and have received particular interest in the power production and car industries. Introducing it to power production onboard ships, the performance of the vessel can be improved and the emission of GHG can be reduced.

Overall Aim and Focus

The overall objective of this thesis is to identify the cutting point between selecting hybrid power systems which combine energy production with energy storage capacity and diesel electric systems based on operational profiles and external influences such as cost, route, distance, weather conditions, maneuvering and type of operations.

Method

This thesis is a research of the influencing factors on selection of the most efficient machinery solutions for vessels with complex operational profiles. The first part of the report is a review of diesel electric power and propulsion systems, and state of the art configurations of it, which have been proven able to handle variations in load in an efficient manner. The influencing factors, such as operations to perform, weather conditions, emissions and rules and regulations, have been evaluated and described in order to create a platform for supporting the decisions made when selecting a machinery system based on the planned operational profile of the vessel.

A stepwise method has been made to evaluate the influencing factors up against the operational profile. The first step is a simple overview of the operational profile to evaluate

the degree of variation in operations and loads. Further on, the power demands in the planned operations are evaluated with focus on the possible dynamic loads. Finally, a screening process is presented to evaluate whether a hybrid of diesel electric and energy storage configuration is beneficial for a type of ship, compared to a pure diesel electric system. To estimate the potential economical benefits of hybridization compared to a diesel electric configuration, a simple calculation on savings in lifetime costs is conducted as the fourth step.

Results

The ability of the vessels machinery to handle the dynamic loading picture during specialized operations in an efficient matter is of the utmost importance. Especially regarding operating costs, not only for the fuel consumption, but also the maintenance cost and emissions of green house gases.

To illustrate the selection process, a case, where selecting the best-suited machinery system for a PSV is the goal, was made and run through the method. Two scenarios were simulated, one where the fuel and battery prices were held constant over a period of 25 years. The other scenario, which is believed to be the most likely due to the last year's trend in fuel prices, has a 2% annual increase in fuel price and a 20% decrease in battery prices every 10 years. The calculations show, in both scenarios, that a hybrid of diesel electric and batteries as energy storage will give reductions in costs compared to pure diesel electric. The payback time of hybridization is less than five years in both cases which indicates that, in addition to reduce emissions, this might be a good investment for the ship-owner. However, the savings and potential benefits turned out to be larger for the case with varying prices. This had a potentially 10% reduction in cost after 25 years of operation.

For vessels operating with a large amount of variations in loads and which experience several transients and low loads, a hybrid system with an energy storage unit will assist the engines in handling the load peaks and troughs, which lead to a more efficient operation compared to diesel electric. Diesel electric system has been a preferred choice of machinery for ships with complex operational profiles in recent years. However, despite the higher installation cost, the hybrid system turns out to be a more profitable choice in the future.

Sammendrag

Bakgrunn

Nye og strengere regler for luftforurensende utslipp vil sannsynligvis bli innført i nær fremtid. The International Maritime Organization, IMO, har annonsert at etter 2015 vil kravene kjent som "Tier III" tre i kraft i utslippskontrollerte områder, og på verdensbasis innen 2020. Dette vil ha en stor innvirkning på skipsindustrien, som i stor grad bidrar til globale utslipp av drivhusgasser. Industrien er nødt til å tilpasse seg de nye forskriftene og er med det nødt til å redusere utslippene. Inspirert eller presset av dette er produsentene nødt til å utvikle ny og mer energieffektiv teknologi og løsninger og introdusere det ut i markedet.

Hybride kraftsystemer som kombinerer kraftproduksjon og energilagring blir møtt med spesiell interesse i flere industrier som kraftproduksjon og bilindustrien. Ved å introdusere denne typen kraftproduksjon til skip kan ytelsen bedres, samt at utslipp av drivhusgasser kan reduseres.

Overordnet mål

Det overordnete målet med denne oppgaven er å identifisere hvor grensen går mellom å velge hybride maskinerisystemer som kombinerer kraftproduksjon med muligheten til å lagre energi og konvensjonelle diesel elektriske maskinerisystemer om bord på skip. Dette skal være basert på operasjonsprofilen til et skip, samt eksterne påvirkende faktorer som kostnader, værforhold og type operasjoner som skal utføres av skipet.

Metode

Denne avhandlingen undersøker hvilke faktorer som påvirker valg av den mest effektive maskineriløsningen for skip med komplekse operasjonsprofiler. Den første delen av rapporten består av en gjennomgang av et typisk diesel elektrisk kraft- og propulsjonssystem, som har vist seg å håndtere store variasjoner i belastningen svært effektivt. I tillegg blir moderne og nyskapende konfigurasjoner av systemet presentert. Påvirkende faktorer, som type operasjoner som skal utføres, værforhold, utslipp og krav og forskrifter, blir evaluert og beskrevet for å kunne danne et grunnlag for å støtte opp under valgene som gjøres når et maskineri skal velges basert på planlagt operasjonsprofil. En stegvis metode er utviklet for å evaluere de påvirkende faktorene mot operasjonsprofilen. Det første steget går ut på å gi en oversikt over graden av variasjon i operasjoner og laster i operasjonsprofilen. Videre vil kraftbehovet i de forskjellige operasjonstilstandene bli evaluert med særlig fokus på

dynamiske laster. Til slutt er det satt opp en utvelgelsesprosess for å evaluere hvorvidt et hybrid system vil være fordelaktig for skipet sammenliknet med et rent diesel elektrisk anlegg. For å estimere de potensielle økonomiske fordelene med hybrid kontra diesel elektrisk er det gjort en beregning av livstidskostnader.

Resultater

Evnen skipets maskineri har til å håndtere et dynamisk lastbilde under spesialiserte operasjoner på en effektiv måte er særdeles viktig. Dette gjelder spesielt med tanke på operasjonskostnader, ikke bare for forbruk av drivstoff, men også vedlikeholdskostnader og utslipp av drivhusgasser.

For å illustrere utvelgelsesprosessen av det best egnede maskinerisystemet for en PSV er det laget en fiktiv case som skal gå gjennom den foreslåtte stegvise metoden. To scenarioer er laget, i det første holdes oljeprisen og kostnadene for nye batterier konstant over en periode på 25 år. I det andre scenarioet, som anses som det mest virkelighetsnære grunnet de siste års trend for oljepriser, økes oljeprisen med 2% årlig samtidig som kostnadene for nye batterier reduseres med 20% hvert tiende år. Beregningene viser at i begge scenarioene vil et hybridsystem gi reduksjoner i kostnader sammenliknet med et rent diesel elektrisk system. Tilbakebetalingstiden for et hybrid system er mindre enn fem år i begge tilfellene, noe som indikerer, i tillegg til å minke utslippene, at det kan være en god investering for skipseieren. Innsparingen og de potensielle fordelene viser seg imidlertid å være større i tilfellet med økende oljepriser og minkende priser på batteriene. Det dreier seg om potensielt 10% reduksjon i kostnadene etter 25 års operasjon.

For skip som opererer med store mengder variasjon i belastning, med hyppige tilfeller av transienter og lav last, vil et hybrid system med energilagringsfasiliteter hjelpe hovedmotorene med å håndtere tilfellene av plutselige topper og bunner i belastningssituasjonen. Et slikt system fører dermed til en mer skånsom og effektiv operasjon enn et konvensjonelt diesel elektrisk system. Det foretrukne valget av maskinerisystem for skip med en kompleks operasjonsprofil har til nå vært diesel elektrisk. Det hybride systemet viser seg imidlertid å være mer fordelaktig og lønnsomt, på tross av høyere installasjonskostnader.

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Nomenclature

DE	Diesel Electric
DM	Diesel Mechanic
Hybrid	DE with Energy Storage
IMO	International Maritime Organization
ECA	Emission Controlled Area
SECA	Sulphur Emission Controlled Area
GHG	Green House Gas
DP	Dynamic Positioning
MCR	Maximum Continuous Rating
HFO	Heavy Fuel Oil
MDO	Marine Diesel Oil
AC	Alternating Current
DC	Direct Current
AVR	Automatic Voltage Regulator
DOL	Direct On-Line
FPP	Fixed Pitch Propeller
CPP	Controlled Pitch Propeller
CPR	Contra Rotating Propeller
VSI	Voltage Source Inverter
CSI	Current Source Inverter
SCR	Silicon Controlled Rectifier
LNG	Liquefied Natural Gas
CO_2	Carbon Dioxide
NO_x	Oxide of Nitrogen
SO_x	Oxide of Sulphur
H_2O	Water (Di hydrogen Oxide)
O_2	Oxygen
O_3	Ozone
N	Nitrogen
PM	Particulate Matter
FOC	Fuel Oil Consumption

SFOC	Specific Fuel Oil Consumption
PSV	Platform Support Vessel
AHTS	Anchor Handling Tug Supply Vessel
ROV	Remotely Controlled Vehicle
MPSV	Multi Purpose Support Vessel
OSV	Offshore Supply Vessel
DNV	Det Norske Veritas
LR	Lloyd’s Register
ABS	American Bureau of Shipping
BV	Bureau Veritas

1 Introduction

1.1 Background

New and stricter regulations on emissions to air lie in the near future. The International Maritime Organization, IMO, has announced that by 2015 the regulations known as "Tier III" will take effect in the emission controlled areas, ECA, and globally by the year 2020. This has a great impact on the shipping industry, which is a large contributor to global emissions of green house gases, GHG. The shipping sector must adapt to these new regulations and has to reduce the emissions. Inspired, or pushed by this, manufacturers have to develop new and more energy efficient technology and solutions to enter the market.

There are many benefits to installing a modern hybrid diesel electric propulsion system with energy storage capacity, instead of a more traditional diesel mechanic system. In this thesis a DE system with energy storage will be referred to as a hybrid system. The most important factor for the ship operator is the cost, both the investment cost and operating costs. The biggest contributor to the latter is the fuel cost. Even if the investment cost is higher for a diesel electric system it will pay off in the long run, especially if the fuel price rises, due to reduced fuel consumption. However, not all ships will benefit equally from this system configuration, and the advantages will to a large extent be determined by the static and dynamic power requirements related to the vessel´s operating profile.

Several studies have been conducted on methods for reducing emissions for the shipping industry. Weather routing, slow steaming and the effects of economy of scale are methods that are theoretically proven to have benefits for deep sea shipping with large sailing distances and a significant volume of cargo. These are typically types of vessels with a "straight forward" operational profile. When it comes to more advanced vessels performing a variety of operations representing a more complex operational profile with a high amount of dynamic loads and large variations in power demand, other measures must be considered to reduce the fuel consumption and emissions and also the operating cost, which should be a huge motivator for the ship operators.

Batteries, supercapacitors and superconducting magnetic energy storage are candidates for energy storage systems on the next generation shipboard power systems. Batteries have the highest energy density of them and are considered the most suitable unit. The utilization of energy storage systems applied in onboard power systems have not been extensively explored, though such systems are broadly being examined for future land vehicles and trucks.

1.2 Overall aim and focus

The overall objective of this thesis is to identify the cutting point between selecting hybrid power systems which combine energy production with energy storage capacity and diesel electric systems based on operational profiles and external influences such as cost, route, distance, weather conditions, maneuvering and type of operations.

1.3 Structure of the Thesis

This thesis has been divided into six main parts, aiming to categorize the influencing factors for selection of machinery systems for complex operational profiles early in the design phase. The first part will introduce the reader to the motivation and background for the thesis. In the second part an introduction to diesel electric power and propulsion systems is given. A short description of the main types of offshore supply vessels is given, as well as future projects involving state of the art technology concerning diesel electric systems. Furthermore, in part three, the main influencing factors for selecting machinery configuration for complex operational profiles are presented. A stepwise method for evaluating the operational profile, the dynamic loading picture and costs is presented in part four. The influencing factors are considered and evaluated together with the operational profile of the vessel. In part five a case where a ship owner must select the best-suited machinery system on a PSV is made up. The selection process is done with the method proposed in part four. Calculations on lifetime costs concerning investment of machinery and operational costs are made for different configurations of the machinery and compared. In part six, the findings are discussed, and suggested further work is presented.

2 Theoretical Foundation

2.1 Diesel Electric Power and Propulsion System

The use of electrical propulsion has increased the last few decades. This is especially the case for ships with an extra demand on electrical power and with a variable operation profile regarding loads such as large cruise vessels, ferries and offshore support vessels. Also the use of dynamic positioning systems, DP, (described in chapter 3.2.3) requires a huge amount of electrical power due to the electrically driven thrusters and requirements to redundancy, as described in chapter 3.3.

2.1.1 AC Distribution

2.1.1.1 General System Description

The idea behind this type of propulsion system is to replace the main diesel propulsion engines with diesel engines running generators and electrical motors with a much higher efficiency, and split the power production in sections to increase the redundancy of the system. The use of electrical motors enables the vessel to operate with a high efficiency for the whole range of operations. The configuration can be optimized to operate at the highest efficiency at all times by selecting the optimal number of generators to fit the load profile that is expected during operation. A typical configuration of a diesel electric propulsion system may look like it is shown in Figure 2-1 below.

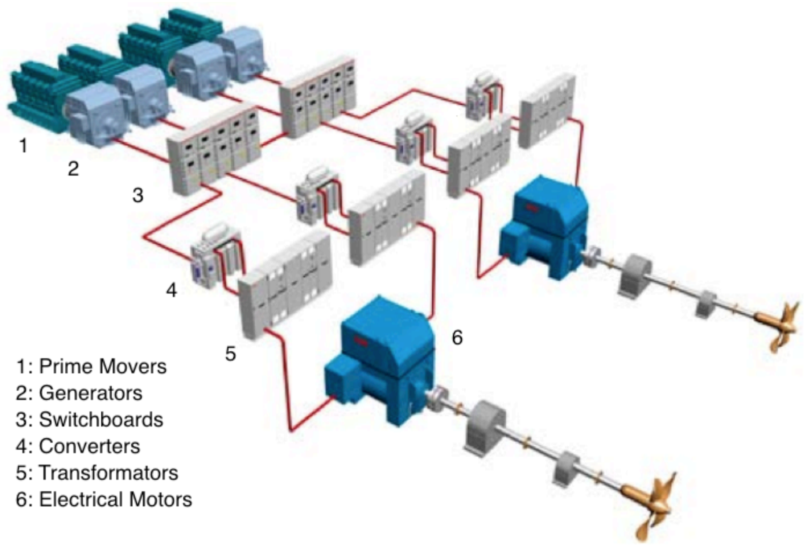

Figure 2-1 Typical Configuration of a Diesel Electric Propulsion System (1)

Generators are driven by diesel engines and generate electrical power. Other types of prime movers like gas turbines can also be installed. The power is distributed to the consumers through the switchboards. Several switchboards are often used to ensure redundancy and availability to the system. The higher the total installed load is, the higher the voltage level will be. Also, a high voltage level holds the load and short circuit currents low.

The main power consumers are the main propulsion and the thruster motors of different kinds. The motor drivers are usually synchronous for high power demand and asynchronous for lower power demands. Other loads are service loads as ventilation and lighting for the hotel, and pumps and compressors for systems all over the ship.

Many of the power consumers operate at different voltage levels and thus need transformers. A method of controlling the speed of the motors, where that is necessary, is installing a frequency converter. An overall control of the system is the power management system, which controls and monitors the operation of the entire system. If the load increases and more power is needed, more generator(s) are started and connected to the network.

2.1.1.2 Advantages of Electrical Propulsion

Improved life cycle cost by reduced fuel oil consumption is one of the advantages. This depends on the operational profile. By optimizing the number of generators for every load condition the engines may run at an optimal MCR and the fuel oil consumption is minimized.

The redundancy and availability is improved by implementing the DE system. By installing several generators delivering power to separated switchboards, the system can handle a single failure without losing power to the main components.

The maneuverability of the ship is improved by the use of electrical podded propulsion. In addition, the flexibility in the placing of the pods and the generators makes the engine room arrangement more flexible.

The advantages should be considered and weighed against some disadvantages. The investment cost increases compared to conventional diesel mechanic machinery due to additional components and electrical equipment, such as generators, transformers motors and electrical cabling. The additional units between the prime mover and the propeller will also increase the transmission losses at full load. The operational profile of the vessel will determine the payback time of the implementation of the DE system

2.1.1.3 Prime Mover

The most common source of power is the diesel engine, running on heavy fuel oil, HFO, or marine diesel oil, MDO, driving a generator. Other types of sources may be used. For high power levels gas engines or turbines, or steam turbines can be used. The engines are usually medium to high-speed engines. They are often lighter and less costly than engines used for direct mechanical propulsion. The combination of several engines in a redundant network ensures a high reliability and easy maintenance. New and more efficient engines with lower emissions are being developed continuously. As of today, the average fuel consumption for an engine running on the optimum point, about 80 percent MCR, is around 190 grams per kWh. And this is the key for the efficiency of this system, to keep the average loading of each engine as close as possible to its optimum operating point.

2.1.1.4 Generator

The generators driven by the diesel engine are synchronous machines. They have a magnetizing winding in the rotor with DC, from either a brush and slip ring, or a brushless excitation system, and a three-phase stator winding where the magnetic field from the rotor current induces a three phase voltage with a sinusoidal form when the rotor is rotated by the prime mover. This is the most commonly used type of generator, which is an AC generator. The rotational speed and number of poles in the synchronous machine decides the frequency of the induced voltage.

An automatic voltage regulator, AVR, senses the terminal voltage of the generator and measures it up against a reference value. This is done to control the excitation. It has a generic control loop feedback, PID, characteristic, and gives a feedback on the voltage drop depending on the generator load. There are requirements to the variation in the stationary voltage on the generator terminals, which states that it shall not exceed ±2,5% of nominal voltage due to large transient load variations. To stabilize the oscillations in the frequency and the load shearing, the rotor is equipped with a damper winding. This introduces an electromagnetic damping to the rotor and stator dynamics.

2.1.1.5 Electric Power Distribution

To accomplish the required level of redundancy in the system, when operating in dynamic positioning, DP, the switchboards used for distribution are divided into minimum two sections. The rules and regulations for electric propulsion state that the system shall not shut down with one single failure, as for example a short circuit. There are several different ways of configuring the switchboards in order to obtain different levels of redundancy by splitting them into two, three or four parts.

With increasing level of installed power connected to the system, the nominal load currents and short circuit fault currents also raises. This will induce higher stress on the equipment and higher physical requirements for safety of equipment and the switching capacity. A way of reducing this is to increase the voltage level on the bus. The most commonly used alternatives for voltage levels in the main distribution system are as follows, according to NORSOK standard E-001 chapter 5.

- 11kV Generation and distribution voltage. Should be used when total installed generator capacity exceeds 20MW. Should be used for motors from 400kW and above for DOL starting.
- 6,6kV Generation and distribution voltage. Should be used when total installed generator capacity is between 4 to 20MW. Should be used for motors from 400 kW and above for DOL starting.
- 690V Generation and distribution voltage. Should be used when total installed generator capacity is below 4MW. Should be used for DOL starting of motors, below 400kW and as primary voltage for converters for drilling motors.
- 400/230V for the utility low volt distribution

The electrical power distribution system should be provided with duplicate incoming circuit breakers and a bus-section circuit breaker for all major switchboards. The bus-section circuit breaker should normally be open and the incoming circuit breakers normally closed. Duplicate equipment should be supplied from different bus-bar sections. For switchboards fed directly from generators, the bus-tie breaker should normally be closed. Circuit breakers are used to connect and disconnect generators and loads to the switchboard.

2.1.1.6 Transformers

The transformers are isolating different parts of the electric power distribution system into several partitions. They transform the voltage levels and also sometimes the phase angle. Phase shifting transformers can be used to feed frequency converters for variable speed drives in order to reduce the distorted currents in the network by cancelling some of the dominant harmonic currents. This reduces the voltage distortion for generators and consumers. Another effect of the transformer is that it reduces high frequency conductor emitted noise. The transformers come in a variation of designs and abilities with different insulation technology. They consist of a solid magnetic iron core with a primary winding and a secondary winding. The ratio of the number of windings decides what the voltage level will be at the secondary terminals. The coils may be connected in either a why-connection (Y) or delta-connection (Δ). They can be connected different on the primary and secondary side. In this configuration not only the voltage amplitude will be transformed, but also a phase shift will happen. This can be adjusted by the use of Z-connected windings and is determined by the ratio of turns in the segment of the Z-windings.

2.1.1.7 Motor Drives for Propulsion and Thrusters

There are several types of motors; DC motors, asynchronous, synchronous and permanent magnet synchronous motors. The synchronous and asynchronous motors can be used as either a fixed speed motor connected directly to the network, depending on the type of grid, or as a variable speed motor fed from a static frequency converter. The high efficiency and relatively small size of the permanent magnet synchronous motor makes it very suitable for podded propulsion.

Shaft propulsion is often selected if the demand of transversal thrust is relatively small in contrast to the longitudinal demand. It is also selected where the power needed for propulsion is exceeding the available power in azimuth thrusters. This is typical for shuttle tankers, which usually have more straight forward operating profiles. In electric propulsion with a shaft propeller, variable speed electric motors are the most common. The propeller is usually a fixed pitch propeller, FPP. This solution gives a solid and simple propeller design.

In cases where the azimuth thrusters may give enough power for propulsion, or the demand of transverse thrust is higher, they will be a good alternative to the shafted propulsion. The azimuth thrusters can rotate 360 degrees and thus give thrust in any desired direction. The most common configurations are either a variable speed motor with a FPP, or a constant speed drive with a controllable pitch propeller, CPP. The variable speed FPP design has the simplest construction with low thrust losses. Azimuth thrusters can be used both for main propulsion and positioning. The motor is installed in-board with mechanical transmission to the propeller.

Podded propulsion is basically the same as azimuth thrusters. The technology of podded propulsion has made huge steps forward in recent years. This will have an impact on the future design and efficiency of ships. They are electrically driven with high efficiency. The main difference is that the motor drive is integrated and directly connected to the shaft inside a sealed compact pod submerged below the vessels hull. Usually a variable speed drive with FPP is used. This makes the construction solid and the transmission effective due to no transmission gear. This type of propulsion has a large variation in size and power available, up to about 30MW and can be used for both propulsion and station keeping.

The contra rotating pod (CRP) concept has turned out to give large improvements in propeller efficiency. It consists of a fixed electrically driven variable speed pod placed right behind the main propulsion. This has resulted in higher propulsion efficiency and also better redundancy as well as higher propulsion power.

2.1.1.8 Drive Control

In order to optimize and control the different drives running in all the systems onboard, a control system will be beneficial. There is an extra investment cost in conjunction with installing a drive control. However, this will most likely pay back due to reduced operational costs. The control system is a computer-controlled system for the converters and variable speed drives. It ensures safe operation of the converters with constant and stable power supply to the electric propulsion drives. The speed of the engines are controlled by variable speed drives, as voltage source inverters, VSI, for AC motors, current source inverters, CSI, and cycloconverters, normally for AC synchronous motors, and DC converters, or silicon controlled rectifier, SCR, for DC motors. The drive control system interfaces with the propulsion control system, vessel management system, maneuvering system and the overall power management system.

2.1.1.9 Power and Energy Management

A vessel has several different systems that require power. All of the systems are governed by control systems. The positioning system controls the thruster drives, the off-loading control system may involve drives for cranes and pumps, and a process control system interacts with compressors and cooling and/or heating systems. The interconnection point of all the different systems acts as the brain, the power management system, which monitors and controls all the systems. The main function of the power management system is to start and stop the generator sets according to the total network load. If the total power demand rises above the available power, due to faults in running generator sets, or increased loading, more generators need to be connected to the network. A power management system may also monitor and control the energy flow in a way that utilizes the installed and running power equipment with optimum fuel efficiency. With this ability the system is called an energy management system. The main functionality of the management system is:

- Power generation management:
  Overall control with frequency and voltage monitoring with active and passive load shearing monitoring, and possibly control, and load dependent start and stop of generators. Since control logic and interlocking functions are significant parts of the power system switchboard design, the functionality of these systems must be coordinated.
- Load management:
  Load power monitoring and coordinating of power limitation functions in other systems, load shedding, and start interlock of heavy consumers based on available power monitoring.

- Distribution management:
  Configuration and sequence control of reconfiguring the power distribution system. The distribution system should be configured to fit requirements in the actual operation mode for the vessel.

With more complex power system configurations and advanced protection and relaying philosophies in modern vessels, certain challenges come to the designers. There are close connections between functional design, performance of the energy management system and the power protection system. Total blackout of the system is unacceptable and would put people and equipment in danger. The mechanisms to prevent blackout are many, and are linked to the power management system. This can be automatic start and stop functions, reduction of different loads, or shedding of non-critical loads. Also, backup systems and a system for sequence control of start-up and reconfiguration of the power system are normally required in case of total blackout.

2.1.2 DC grid as an Alternative to AC distribution in Electric Propulsion

Vessels with a varying operating profile and high dynamic electrical load factor have the most to gain by electric propulsion. In particular ships with positioning systems with thrusters will see higher fuel efficiency due to large variations in the load. In addition, the use of electric propulsion raises the availability and redundancy of the system as well as the flexibility in placing of equipment and reduction in noise and vibration.

2.1.2.1 Efficiency

The traditional system usually has medium to high speed diesel engines running generators, which produce AC power, at a constant rotational speed as close as possible to the optimal operating point. High-speed engines are mostly used when the total installed power is high or, in light high-speed vessels. Constant speed of the engines is necessary to keep the frequency of the voltage at 50 or 60 Hz (usually 60 Hz onboard ships), which is crucial for many of the power consumers. The power is distributed in AC switchboards to all the different power consumers through converter transformers and distributed rectifiers. Variable frequency drives used for propulsion and positioning are usually the heaviest power consumers in this type of systems and often represent more than 80 percent of the total installed power.

By converting the AC current produced by the generators to DC current and feeding this directly to a distribution network, the need for large switchboards are eliminated. The DC system is not dependent on keeping a constant frequency and the engines can vary the speed to operate with optimal fuel efficiency at all times. This enables the use of high-speed engines or turbines without disturbing any frequency. Especially the LNG engines are well suited for a DC grid with the possibility to work at more stable loads with higher efficiency, which gives less methane slip and lower emissions of GHG as CO_2, NOx and SOx, according to (2).

A study from the Helsinki University of Technology on behalf of ABB was made on a test engine. At various speeds and torque on the engine the specific fuel oil consumption, SFOC, was measured, Figure 2-2 and Figure 2-3. The dark blue area indicates a low SFOC.

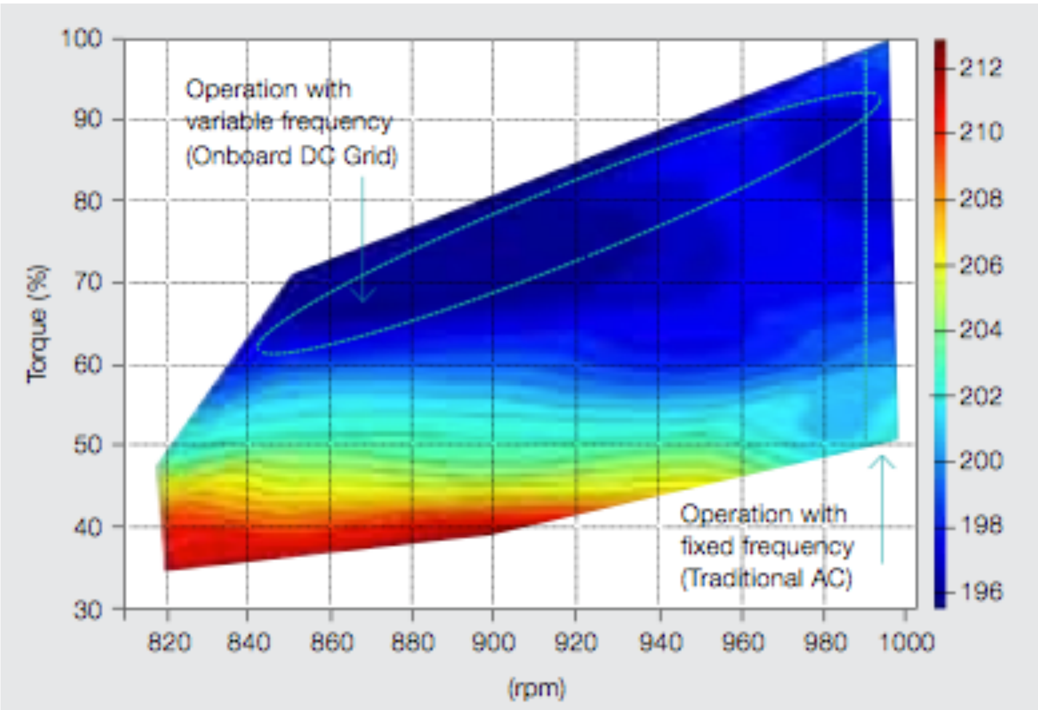

Figure 2-2 Fuel efficiency ABB DC grid (3)

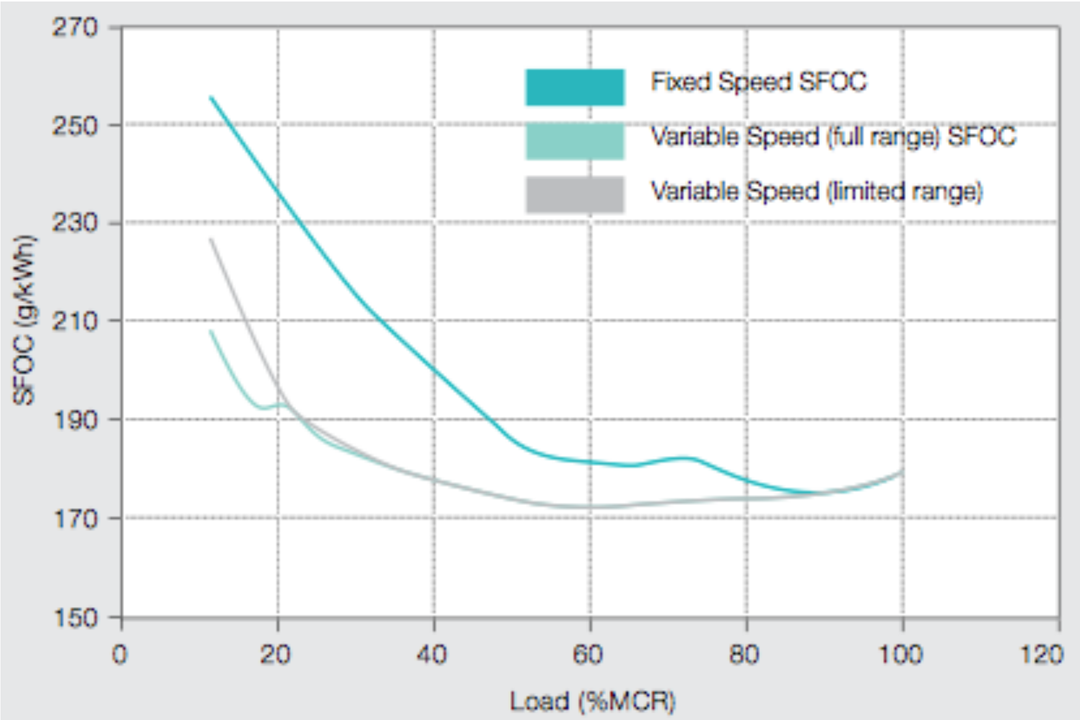

Figure 2-3 SFOC ABB DC grid (3)

ABB introduced a new concept with DC distribution in 2012 (4). It is called the "onboard DC grid". It is a simple rearrangement of the AC system. Most of the equipment from an "old" AC electric propulsion system may still be used after the rebuild, which will improve the efficiency of the system. It is a low voltage system operating at a nominal voltage of 1000 volts DC and can be used for any vessel up to a total installed power of 20 MW. ABB claim that by using all the facilities available on vessels with a large variable operating profile, the savings may be as high as 20 percent compared to a traditional AC DE system.

2.1.2.2 Renewable energy

Another great benefit with the DC grid instead of the AC grid is the possibility of installing fuel cells, batteries, solar energy and super capacitors. They can be used as energy storage and come in handy when the system is facing high transient loads, and even out power variations. The technology in this area has developed significantly in the last few years, and is still under development. There is not much data available on this at the time being, but it is a well known fact that variations in the load may cause trouble for the generator set and that the system will run more smoothly with this kind of "damper" system. With new stricter restrictions on emission of GHG this might become important in order to meet new demands. Even though the new engines on the marked shows great improvements in efficiency and emissions the use of renewable energy will have lower emissions. And maybe, in the future, sources of renewable energy will be powerful enough to support the power production even more, if not to take over completely.

2.1.2.3 Propulsion

The technology of podded propulsion has made huge steps forward in recent years. This will have an impact on the future design and efficiency of ships. The pods are electrically driven with high efficiency. There are several types of motors, such as DC motors, asynchronous, synchronous and permanent magnet synchronous motors. The synchronous and asynchronous motors can be used as either fixed speed motors connected directly to the network, depending on the type of grid, or as variable speed motors fed from a static frequency converter. The high efficiency and relatively small size of the permanent magnet synchronous motor makes it very suitable for podded propulsion.

2.1.2.4 Flexibility

For a ship owner the available space for cargo is very important. This is where the possibilities for income lie. Again, the electrical propulsion system may give some advantages. According to ABB, and their recent delivery of a DC grid system onboard the PSV “Dina Star”, the weight and space arrangement led to lower total weight of the whole system and a smaller footprint in the available space. This is mainly due to the elimination of the main switchboards, transformers and converters. By using DC motors there is no need for transformers, they can be connected directly to the grid. Some of the loads still require AC voltage, such as the hotel load, and thus still needs transformers and converters. The placing of the thrusters and pods is flexible and can be optimized for the most efficient performance. If podded propulsion is chosen, it eliminates the use of long shaft line transmission and increases the flexibility in designing the system. Figure 2-4 below shows a simple DC distribution network.

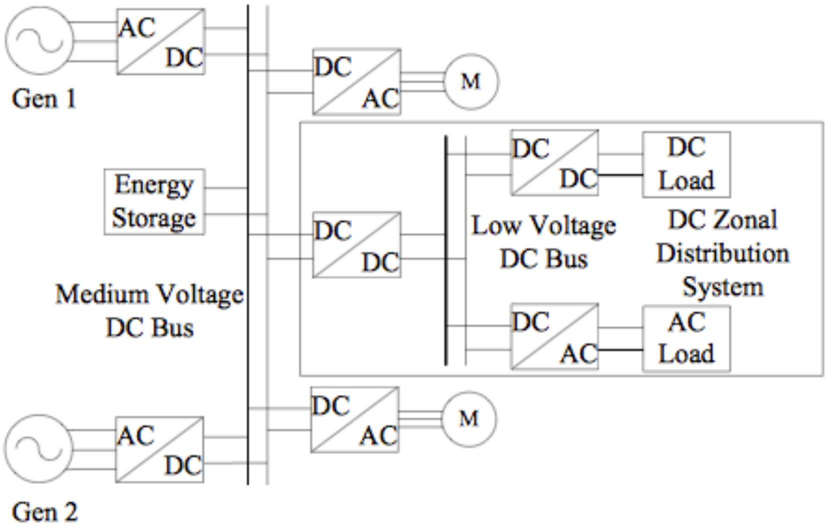

Figure 2-4 Configuration of a DC distribution system (5)

2.1.2.5 Feasibility

A DC distribution system is not an unfamiliar technology, but is still quite new in the marine business. There is still a lot of research that needs to be done, especially on the renewable energy part. The DC grid introduces a great opportunity to connect renewable energy sources in the future, when they are developed to the next level. As for now they may be used as a power reserve to handle sudden loads, heavy start up loads and large variations in the load. By having the system developed already now, however with potential for improvements, the electric propulsion system is ready for the future. As we are waiting for the future technology, this kind of electric propulsion system shows improvements by as much as 20 percent in fuel saving if all features including energy storage and variable speed engines are utilized.

Except for the technology related to renewable energy, all the other equipment is already on the market. This means that the investment cost for an upgrade from AC to DC not necessarily has to be very costly or challenging. Furthermore, with the possibilities of saving fuel costs, and increasing the area for payload, this is a feasible and positive economic choice of electric propulsion system.

2.1.3 Hybrid Power and Propulsion System

A hybrid power system is in this thesis referred to as a power system, which combines energy production with energy storage. This is a relatively new concept for the marine industry, despite the fact that the technology has been applied for decades in several industries.

Especially in the car industry, which has taken a huge interest in hybrid power systems over the past few years. Up to recently the implementation of large-scale energy storage on ships has not been considered practical and cost effective. However, predictions of yet raising fuel oil prices in the future, a growing focus on emissions and restrictions and advances in the technology on energy storage have made the introduction of large-scale energy storage on ships practical, performance enhancing, environmental friendly and potentially cost effective.

2.1.3.1 Overview

The hybrid power system mainly consists of two units. This is the power production unit, usually a prime mover, and the energy storage unit. The power produced can either be used to satisfy the power demand of the consumers in the system, or intermittently stored in an energy storage unit and vice versa. The energy storage unit is the new addition to the machinery system that defines it as a hybrid power system.

The total efficiency of the system will depend on the type of prime mover installed and efficiency losses associated with the number of components as energy converters, transmission and energy storage, which all represent independent losses. Due to the fact that the hybrid system is not utilized to a large extent on ships, real time numbers and experiences are hard to come across. Nevertheless, several simulations and studies on fuel consumption and other benefits linked to hybrid power systems of various cases and ship types have been conducted in the last years (6) (7) (8) (9). Most of them show significant improvements in performance for operations, energy efficiency and related savings in fuel costs and emissions. One should be aware that the benefits are strongly dependent on the operational profile of the ship and they must be weighed against other important factors, such as safety, reliability, flexibility and cost.

The energy and/or power available in the storage units are crucial for the potential gain of a hybrid system compared to other systems in terms of improved performance. This is the area where the advances in the technology are most visible. The desired performance of the battery is the highest possible power and energy capacity. However, with the state of the art storage units there is a trade off between power and energy density. A high power density unit (flywheels) often has lower energy density and vice versa (fuel cells). See Figure 2-5 below.

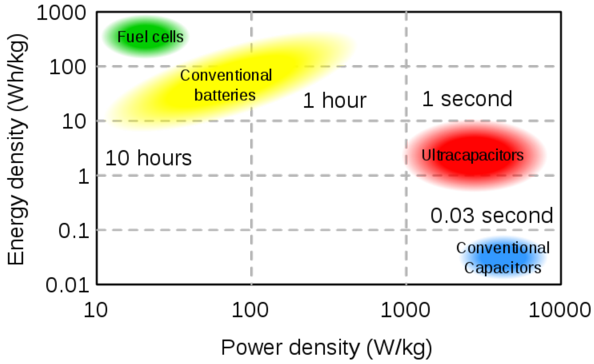

Figure 2-5 Ragone Diagram for Typical Energy Storage Units (10)

2.1.3.2 Load Response

Most of the prime movers used in today's ships have limitations in load response. The engine's ability to respond to load changes depends on fuel quality, combustion cycle, engine geometry and the size of the turbocharger. The response time of the engine depends on several factors such as the initial condition where the load change is initiated, the load acceptance of the engine, the recovery time of the turbocharger to respond to the load change and how much time it takes to reach a stable operation point to handle the final load. Even for a warm engine this may take minutes, and to start up a cold engine takes even longer. Gas turbines and fuel cells have even longer response time to handle load variations. Energy storage units such as batteries and supercapacitors have, on the other hand, virtually immediate response time. By assigning the prime mover to work at a more constant and optimal load and letting the storage unit absorb the load variations, the ship's load response will be limited by the consumers rather than by the power system.

2.1.3.3 Power Available

The power available in the system depends on the type and number of prime movers. The number of running prime movers at any time sets the immediate power available. In a hybrid system the available power will have the addition of the available power in the energy storage units. It will be restricted in time as the energy content in the storage unit is limited when compared to energy in the prime movers, which is determined by the fuel available. For a short period of time the hybrid system can therefore deliver a very high power. For the system to work optimally, a sophisticated energy management system, in addition to the power management system, is necessary to make sure that the power from the storage units are available when it is needed.

2.1.3.4 Redundancy

All ships with dynamic positioning have requirements to power redundancy in the machinery system. In case of failure in a part of the system there should still be sufficient power left to operate. This may not allow start up of prime movers during operation and the running engines must provide the power redundancy. In most cases this leads to more prime movers operating than needed to deliver the required power to ensure satisfactory redundancy. A known challenge to this type of operation is when the engines operate at low loads where they are disposed of blackening and wearing. In that state, they are inefficient and cause high emissions. If the energy storage unit in a hybrid system can provide sufficient power to the ship for the required amount of time to safely complete the operation, it could feasibly give sufficient redundancy. This may lead to a reduced number of engines running and they can operate at a more optimal load, which leads to a reduction in fuel consumption, emissions and maintenance.

2.1.3.5 Optimization of Engine Loads

The engine load is determinative for the specific fuel consumption and emissions from an internal combustion engine. For vessels with a typically varying operational profile the introduction of an accumulator may allow the engines to operate at the optimal point. This may be achieved by selecting the number and size of the engines so they work at the optimal point most of the time, while the accumulator will apply any extra power needed. The efficiency of such a system can be further optimized by the introduction of engines of different sizes. When the power demand gets low, the energy storage unit can be charged with the extra produced power resulting from the engines working at the optimal load. In very low power demanding operations the batteries alone may give enough power to operate the vessel. This will eliminate the emissions completely. It may also be beneficial when considering the maintenance. The total running hours of the engines are reduced as well as the low load operation, which cause wear on the engines.

2.1.3.6 Load Transients

The effects of load transients depend on the engine type and the rate of change of the engine load. Introducing an accumulator can eliminate the engine load transients by accounting for a base load through the engines and the transient additional loads through the energy storage unit. The engine base load can then be set according to the state of charge of the accumulator in order to make sure that enough energy is available to handle the rapid load changes at all times.

2.1.3.7 Cold Ironing at Port

The use of power produced on shore as a power source on marine vessel in port is called cold ironing. By applying this technology the emissions to air, such as NOx, SOx, particulate matter and green house gases may be reduced significantly, and even sometimes completely eliminated. The magnitude of reduction of air pollution depends on how the shore-based power is produced. The land-based power may be utilized to power the ship's operations when in harbor. For vessels with energy storage capacity the power may also be used to charge batteries and be stored for later operations.

The cost effectiveness of using land-based power for ship operations will primarily depend on the capital costs of the accumulator and land-based infrastructure required for the on-shore power supply, in terms of reduced fuel consumption in the long run. Cost savings may also result from regulatory incentives in form of taxes on emissions. As of today the facilities for cold ironing is not utilized to a large degree. However, it is likely that it will be offered in more ports in the years to come as the number of hybrid and electric ships is increasing.

In 2012, The Port of Oslo and Color Line installed an onshore power supply to supply the cruise vessels with energy while in berth. It has not been a significant economical investment; they estimate a payback time on approximately 15 years with today's fuel and energy prices. However, it has been a great success in regard to reduction of local emission and noise. When the Color Line ferries are connected to the onshore power supply, the CO_2 emissions in Oslo are reduced by 3,000 tons each year and NO_x emissions are reduced by 50 tons per year.

2.1.3.8 Reduction of Local Emissions

In areas where emissions are considered specially harmful or regulated by officials, the hybrid system may use power from the energy storage device, if sufficient capacity is available, to power the ship and its operations with no emissions. These areas can be densely populated areas, harbors, coastal areas, rivers and lakes. In certain areas where local regulatory bodies give reduced tax incentives for the reduction of pollution, this may be financially beneficial. By fulfilling the emission regulations of the ECA's, which are expanding, one can operate within these areas.

2.1.3.9 Noise and Vibration

Noise and vibration is another form of local pollution, which may be reduced with a hybrid system. This will increase the comfort and working environment for the crew. Also, for vessels such as research and naval ships, reduction of under water noise is desirable. For passenger vessels the issue of reducing noise and vibration is important to increase the comfort of the passengers.

2.1.3.10 Energy Harvesting

There are several potential energy sources for harvesting power on board a ship. Some are solar, wind and wave energy. Energy from mechanical equipment on board such as cranes and winches through regenerative braking may also be feasible. Moreover, as in electric cars, energy recovery systems can be used to retrieve energy when the ship is decelerating. These systems include energy recovery from the propeller, motion damping systems and hydro-turbines that can be activated during ship deceleration. To be able to exploit this energy the vessel must be equipped with energy storage capacity such as an accumulator. This will also make the waste heat recovery system more efficiently, due to the reduced level of engines running at low loads. It may also utilize the energy, even when the engines are running at low loads as the energy normally goes to waste in a system without energy storage capacity.

2.2 Offshore Supply Vessels

Offshore support vessel is a general description of several types of vessels. There are different kinds of ships with different purposes and tasks to perform. Some are more specialized towards a specific role, while others have a more widespread area of work.

2.2.1 Platform Supply Vessel

The PSV is considered as the workhorse of the offshore supply chain between mainland and offshore installations. They are designed for transport of cargo, usually with a large open deck area in the aft where a wide range of cargo can be placed. Some typical operations for the PSV are transport of pipes, cement, containers, liquids as water, mud, brine and chemicals and other types of deck cargo. In addition to transport services they may support an offshore platform as temporary storage space for short periods of time. If needed, PSV’s may also contribute in rescue and emergency situations. A typical vessel of this type has DP, fire-fighting equipment and sometimes cranes for lifting operations. Good maneuverability and dynamic positioning is essential for a PSV in order to keep the vessel steady during loading and offloading at the platforms.

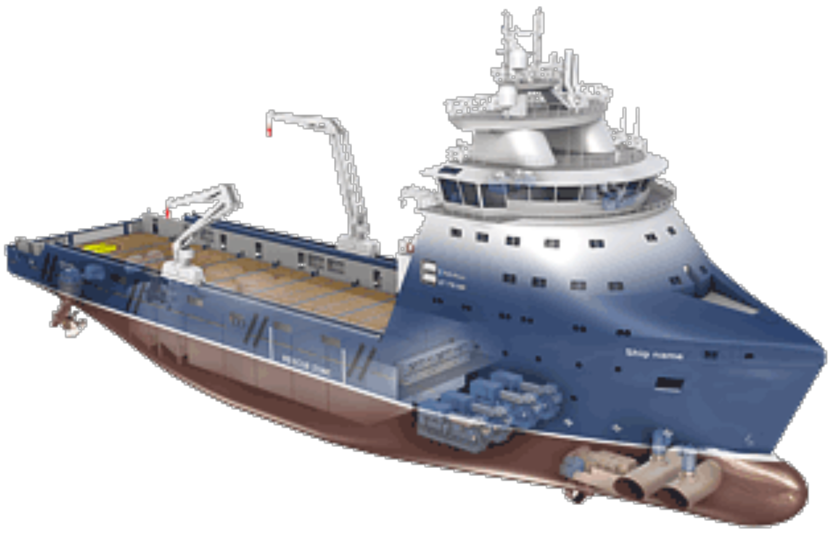

Figure 2-6 Platform Supply Vessel (11)

2.2.2 Anchor Handling/Tug/Supply Vessel

As the PSV, the AHTS’s have a large open deck area in the aft. In order to perform operations as setting and lifting anchors and towing movable offshore units, they are outfitted with large and powerful cranes and winches. This will reduce some of the cargo and storage capacity, however, they can still undertake some supply and transport operations. If needed, they may also perform ROV services if they have the right equipment, as well as standby and emergency tasks. They typically have DP, fire-fighting systems and sometimes oil spill recovery equipment. A powerful machinery is needed for this type of vessel due to heavy lifting operations and the need for a high bollard pull when handling the anchors and towing.

Figure 2-7 Anchor Handling/Tug Supply Vessel (11)

2.2.3 Multi Purpose Support Vessel

The MPSV's are complex and sophisticated vessels, designed to provide several types of subsea operations. This makes them large and often costly and not suitable for simpler supply services. Its areas of operation are usually ROV support, subsea construction, flexible pipe laying, cable-handling, well intervention and post drilling well operations. A variety of equipment may be installed and the choice is dependent on the desire of the ship-owner. Usually there is a demand for large accommodation areas due to the additional work force onboard. Some common features are moon pool, helicopter landing platform, heavy cranes and winches, cable carousels and pipe storage. High electrical power production due to the heavy machinery onboard and the power demanding operations performed, is necessary on these types of vessels.

Figure 2-8 Multi Purpose Support Vessel (11)

An Overview of the most common operations to be performed by an OSV is presented in table Table 2-1 below:

Platform Supply Vessel	Transport cargo Platform support (Rescue/standby)
Anchor Handling Offshore Vessels	Towing Anchor Handling ROV (Rescue/standby) (Emergency duties) (Transport/platform support)
Multi Purpose Service Vessels	Sub-Sea support Well Intervention Post drilling operations ROV Construction Flexible Pipe laying Cable-handling (Supply functions)

Table 2-1 Overview of Operations Performed by different Offshore Support Vessels

2.3 Viking Lady

The platform supply vessel “Viking Lady” is a part of the FellowSHIP project that has been going on since 2003, in three phases. The project is a joint industry R&D project with the objective to answer a growing demand for sustainable energy generation for marine and offshore use. FellowSHIP was initiated with the goal to develop and demonstrate maritime fuel cell power packs. The fuel cell installed onboard the Viking Lady was the first large-scale fuel cell ever to be installed as a part of a propulsion system in a merchant vessel (12). The aim of the project is to develop power packs with a significant potential to reduce the emissions of CO_2 and improve energy efficiency in comparison to conventional power systems. Emission of harmful substances, such as NO_x, SO_x and particulate matter, will be completely eradicated.

The first phase (2003-2005) was a feasibility study on various concepts for utilization of fuel cell technology on board ships to replace both propulsion and auxiliary machinery currently in use. A 320kW fuel cell was selected, to operate on LNG, for the ship.

In phase two (2007-2010) the fuel cell technology was integrated in the ship's system with advanced marine technology specially adapted for this project. The fuel cell was installed and became operational on board Viking Lady in 2009.

In March 2012, DNV announced that a true hybrid energy system is currently being developed for installation onboard "Viking Lady" (12). A battery pack for energy storage will be added to the system, which will reduce the emissions even more.

Other projects with battery systems are according to (13):

- Østensjø: Edda Ferd, hybrid supply ship
- SVITZER: 4 hybrid tugboatss
- KOTUG: RT Adriaan, hybrid tugboat
- Foss: Carolyn Dorothy and Campbell, hybrid tugboats
- NORLED: Finnøy, hybrid ferry
- NORLED: Folgefonn, hybrid/pure battery ferry
- Scandlines: 4 battery hybrid ferries

Part 2

3 Influencing Factors

3.1 Operational Profile

When a customer, ship owner or operator wants to order a new vessel he or she has a set of requirements and specifications related to type of ship, and operation of the ship. In the process of designing the optimal machinery with the right performance features corresponding to the owner's requirements, an accurate operational profile of the vessel is necessary. In what area will the ship operate, what are the conditions and regulations there, what is the itinerary, what are the specific operations to be performed and for how long time?

For a medium size OSV operating in the North Sea a typical average operating profile may look something like shown in Table 3-1, and for a tanker in Table 3-2 based on the operational modes described in chapter 3.2. This operational profile is made by comparing other profiles available and may vary for different vessels. The operational profile is strongly dependent on the tasks it is designed for and often "tailor made" to a specific operation and site by the operator.

Operation PSV	Duration [% of Total Time]	Power Demand [%MCR]
Port	20	5
Transit High	5	80-90
Transit Low	25	40
DP High	10	30-60
DP Low	40	10-30

Table 3-1 Example of Operational Profile PSV

Operation Tanker	Duration [% of Total Time]	Power Demand [%MCR]
Port	15	5
Maneuvering	5	10
Transit	80	80

Table 3-2 Example of Operational Profile Tanker

The PSV represents a typical varying operating profile. In contrast to a profile of a tanker going from A to B it is challenging to design a machinery system that will operate efficiently due to the high rate of low loads and variations. The diesel electric system has proven to handle this kind of operating profiles efficiently. However, small changes in the profile may lead to the selection of a different configuration.

Moreover, if we take a closer look at a specific operating profile for a PSV, different types of variations will appear. Some are very high lasting for seconds only, e.g. propeller appears above the surface of the water due to waves. Others may last for longer periods as for example sudden need of thrust for small changes in position when in DP-mode caused by wind, current or other factors. This will have a great influence on the selection of the best-suited machinery system for the specific operational profile and needs to be analyzed thoroughly.

3.2 Operational Modes

During a period of time an Offshore Support Vessel may experience several different and varying load demands due to the many different types of operations and conditions they may encounter. Usually the supply vessels have a total installed power between 6 and 10 MW. Large construction and anchor handling vessels may have installed up to 20 MW of power. An example of an engine operating profile for a typical OSV is given in Figure 3-1 below. As it can be seen, the engines operate below 50% load for almost 75% of the time (14).

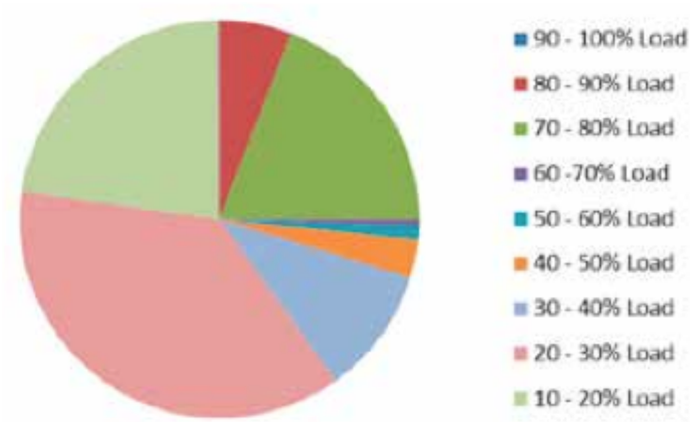

Figure 3-1 Example of Engine Operating Profile for typical OSV (14)

3.2.1 In Port

When a vessel is in harbor there is no need for power to propulsion. The main power consumer is the low voltage hotel load and miscellaneous pumps for on and offloading of liquids. In some cases where the vessel is equipped with cranes on deck, these may be used for on and offloading of dry bulk cargo. If the ship has installed a modern hybrid power system with facilities for cold ironing, it can also harvest energy from onshore-generated power. In that way there will be no need for running any prime movers for power production.

3.2.2 Transit

The OSV's does not necessarily have long distances of transit. Even so, especially for PSV's, which makes several trips back and forth between base on shore and the offshore installations, they spend some time in this condition. Most of the power production goes to propulsion at a more or less constant load except when maneuvering in and out of port with smaller load variations due to use of the thrusters. Steaming at full speed leads to a high and uneconomical fuel consumption. Due to high demand of equipment in short time the supply vessels sometimes have no choice but to go at full speed.

The load and fuel consumption (and emissions) vary with the speed of the vessel. In recent years there has been an increasing focus on optimizing the speed in order to reduce both cost and emissions. The weather and sea conditions play an important part in this, and reducing the speed with a few knots may lead to large reductions in fuel costs and emissions to air (15).

3.2.3 Dynamic Positioning

Whenever it is necessary to keep the vessel stable, either at a point over ground or in relation to another offshore structure, and mooring is not possible or desirable, the DP system is used. For many of the operations an OSV will perform, this is required. Some of the operations may be loading and offloading offshore, standby mode, anchor handling, repairs, lifting operations on the sea bed, diving support, ROV operations, etc.

In DP mode all thrusters and pods are used to keep the vessel in correct position regardless of wind and sea conditions. In calm weather, the power consumption may be as low as 10-20% of total installed power. When the weather gets rough more thrust is needed and the power demand from the thrusters may be as high as 60%. The transient loads and variations may also vary with as much as ±30-40% in short periods of time. Due to heavy seas, the main propellers or thrusters may come into free air in transit or DP mode in rough weather. This will represent the largest load transient for the propulsion system.

A vessel in DP mode operating close to offshore installations may, in an emergency situation, need all power available to bring the vessel away to a safe distance from the installation as fast as possible. The operational requirement is to establish full power within one minute for the onboard power station.

3.2.4 Anchor Handling

Anchor handling is generally about setting out, removing or relocating anchors. With rigs going out on deeper waters the mooring lines get even longer. This means that the AHTV's must be equipped with huge drums to handle hundreds of meters with chain or wires connected to the anchors. To operate the drums and heavy chains, powerful winches and cranes are required. In addition to this, when in anchor handling mode the vessels usually utilize DP and the thrusters work hard to keep the vessel in position due to the heavy loads of the anchors.

3.3 DP guidelines and requirements to redundancy

Reliable and robust methods on positioning of vessels are required for safe supply vessel operations at offshore installations. To a large extent, offshore supply vessels are now being fitted with dynamic positioning systems. The growth in use of DP over the last decades has been accompanied by the development of internationally recognized rules and standards against which DP vessels are designed, constructed and operated. These include IMO MSC Circ.645, "Guidelines for Vessels with Dynamic Positioning Systems", DP rules of the main classification societies and IMCA M 103, "Guidelines for the Design and Operation of Dynamically Positioned Vessels". The rules and guidelines are focused principally on design, construction and operation of DP vessels and, in particular, apply the principles of redundancy and creating a hierarchy of DP equipment classes.

3.3.1 IMO Guidelines

"Guidelines for Vessels with Dynamic Positioning" (IMO 1994) provide an international standard approach to achieve acceptable reliability of position keeping. They define three equipment classes, which in practice are different levels of redundancy, and allow the owner to select the appropriate class based on the consequences of loss of position, as determined by a risk analysis. The three equipment classes are:

- Equipment class 1: Loss of position may occur in the event of a single failure

- Equipment class 2: Loss of position should not occur from a single failure of an active component or system (e.g. generators, thrusters, switchboards, remote controlled valves etc.) This includes a single inadvertent act by a person on board, if it is reasonably probable. However, loss of position may occur from the failure of a static component such as cables, pipes, manual valves etc, provided it has adequately documented protection reliability.

- Equipment class 3: Loss of position should not occur from any single failure of an active component or system, any single failure of a static component, any single inadvertent act, fire or flooding in any one fire sub-division or watertight compartment.

In effect, these classes require the following levels of redundancy:

- Equipment class 1: no redundancy.
- Equipment class 2: redundancy for all active components.
- Equipment class 3: redundancy for all active and static components and physical separation of all compartments.

3.3.2 Classification Society Requirements

The class societies Det Norske Veritas, Loyd's Register, American Bureau of Shipping and Bureau Veritas issue requirements in the form of class notations for DP vessels. These implement the IMO Guidelines, with more specific requirements, and specify the documentation that must be provided for approval, and specify the scope of testing. Each classification society's requirements differ slightly, and each awards different notations, but they correspond roughly to the IMO equipment classes as shown in Table 3-3 below.

IMO Equipment class	DNV	LR	ABS
Class 1	DYNPROS-AUT	DP (AM)	DPS-1
Class 2	DYNPROS-AUTR	DP (AA)	DPS-2
Class 3	DYNPROS-AUTRO	DP (AAA)	DPS-3

Table 3-3 DP Class Overview

The guidelines from DNV on which of the IMO equipment class that should be selected for different DP operations are given in Table 3-4.

Application on DP	Minimum Recommended DP Equipment Class (see notes below)	Remarks
Drilling	2	
Diving	2	
Pipelay	2	
Umbilical Lay	2	
Lifting	2	
Accommodation	2	
Shuttle Offtake	2	
ROV support (Open Water)	1	
ROV Support (Close Proximity – Surface/Subsea)	2	
Floating Production	2	
Seismic and Survey vessels (Open Water – outside 500m zone)	**	**Class in accordance to contractual requirements
Well stimulation	2*	*Vessels of lesser Class may be used with the appropriate structured risk identification and mitigation measures in place.
Logistic Operations	2*	

Table 3-4 DNV Recommendations to DP Class

Note 1: The vessel's DP system should normally be set up and operated to deliver the intent of the DP class notation. However, on occasion and after a proper assessment of the risks, the vessel may be set up in accordance with the requirements of the Task Appropriate Mode.

Note 2: For operations close to another vessel or installation the equipment class should be 3 or equivalent. Class 2 may be accepted based on considerations of procedures, equipment and consequence analysis.

Note 3: It is noted that there have been standards developed outside the IMO DP equipment class systematics where an identical (or higher) level of redundancy has been realized based on a different philosophy and system approach.

3.3.3 Redundancy

The requirements to redundancy, in the power system when operating on DP, are maybe the main reason for low loads on the prime movers. In the Norwegian sector of the North Sea, rules and regulations from the government prohibits the operators to run all switch boards connected. This is done to prevent a total blackout of the whole system. With a split system a worst-case failure will be a partial blackout and the system can continue to operate. To ensure enough power to operate after a single fault most of the engines must be running at all times, even though the power demand is not necessarily very high.

3.4 Environmental Effects

CO_2 emissions from maritime transport represent a significant part of the total global GHG emissions and have a severe negative effect on global warming. According to IMO the emissions from the maritime industry represents over three per cent of the world's total CO_2 emission. If actions are not taken and business goes on as usual with a tripling of world trade, it is expected that the emissions are going to increase by as much as 150-250% by 2050 (15). IMO is currently considering and debating both technical and marked based measures for reducing the emissions of green house gases from shipping.

It is possible to reduce the polluting emissions by measures associated with the fuel, the combustion process and treatment of the exhaust. The fuel is the source of CO_2, SO_x and partially PM. A low content of sulphur leads to lower emissions of SO_x. Lower fuel consumption will in general lead to lower emissions. Alternative fuels as LNG may also lead to a considerable reduction in emissions. The combustion process is the source for forming of NOx, HC and PM. The configuration of the power system determines to a large extent the emissions, and technical improvements and optimization may lead to lower emissions. Treatment of the exhaust may also lead to lower emissions to satisfy restrictions, such as in ECAs and SECAs. Sulphur in the exhaust can be removed by installing a scrubber, which also reduces the emissions of PM. Some NO_x may also be transformed into harmless substances by adding ammonia or urea in a selective catalytic reduction system (SCR system). Nevertheless, there is a huge technical challenge linked to reducing harmful emissions in the exhaust from internal combustion engines. An overview of the emissions from a high-speed 4-stroke, Tier II NO_x level classified engine running on MDO and is given in Table 3-5.

CO_2 [g/kg fuel]	3206
NO_x [g/kg fuel]	50,5
CO [g/kg fuel]	2,63
HC [g/kg fuel]	2,63
PM [g/kg fuel]	2,3
SO_2 [g/kg fuel]	21,0

Table 3-5 Average Emissions from a 4-stroke Engine Running at MDO (16)

3.4.1 Carbon Dioxide

CO_2 and water vapor will be formed in any combustion process in which complete, or nearly complete, combustion of hydrocarbon fuel takes place. The production of both CO_2 and water vapor is a function of the amount of fuel burnt, which is to a large extent determined by the engine power required, the system efficiency and the elemental composition of the fuel. Due to the global trend of rising CO_2 concentration in the atmosphere, the IMO is focusing on the emission of CO_2 from the marine sector. The shipping industry is growing steadily and rapidly and new legislation on a new Energy Efficiency Design Index (EEDI) entered into force on the first of January last year (2013) as a measure to reduce the emissions.

3.4.2 Oxides of Nitrogen

The formation of nitrogen oxides occurs as a result of the oxidation of nitrogen in the combustion air or the oxidation of organic nitrogen in the fuel. Dependent on the type of fuel and its quality, the nitrogen may account for a significant proportion of the total NO_x emissions, particularly for engines operating on heavy fuel oil. The conditions in the combustion chamber of the engine will have a great influence on the oxidation of the nitrogen in the combustion air. At high temperatures the production of nitric oxide (NO), which is the primary reaction product, is at its highest. Later in the combustion cycle and during the flow through the exhaust system, some of the NO formed will convert largely to nitrogen dioxide (NO_2) and a limited proportion of nitrous oxide (N_2O). Due to more strict rules for the allowable emissions of NO_x and the increasing number of emission controlled areas in certain regions of the world, under MARPOL Annex VI, different technologies and ways to control the combustion process are used, and will be used extensively in the coming years when these rules enter into force. Adverse effects due to NO_x are diverse. It is of a particular concern as it has, in addition to the above mentioned causes, together with volatile organic compounds (VOC), also effects as photochemical reactions leading to an increase in tropospheric ozone. This may in time adversely affect human health, crop yield and natural vegetation.

3.4.3 Oxides of Sulphur

The oxides of sulphur are derived directly from the content of sulphur in the fuel used. The sulphur that oxides in the combustion chamber primarily takes form as SO_2. The concern related to emission of SO_2 lies with the detrimental effects to human respiration and vegetation. As for NO_x emissions, new and more strict regulations for reduction of SOx are now coming into force and will be even more stringent in the coming years by imposing strict sulphur limitations to the fuel used for marine applications, as stated in the regulation 14 of the MARPOL Annex VI legislation.

3.4.4 Particulate Matter

Particles resulting from combustion in the exhaust represents a complex mixture of inorganic and organic substances largely comprising elemental carbon, ash minerals and heavy metals and a variety of non, or partially combusted hydrocarbon components of the fuel lubricating oils. The majority of diesel particulates are likely to be less than micro millimeters in diameter, which makes them able to be transported by the air currents with a low settling velocity. Potentially detrimental effects may thus be encountered away from the immediate vicinity of the source of the exhaust. The studies on particulate matter have not come as far as on the other above mentioned emissions. However, they are known to potentially cause respiratory problems as well as more serious toxic, mutagenic and carcinogenic effects.

3.4.5 Emission Controlled Area ECA

The 1997 Protocol from MARPOL sets, in Annex VI, limits on NO_x and SO_x emissions from ship exhaust, and prohibits deliberate emissions of ozone depleting substances. The IMO emission standards are commonly referred to as Tier I, II and III standards. The Tier I standards were defined in the 1997 version of Annex VI, whereas the Tier II and III were introduced by Annex VI amendments adopted in 2008, as follows (17).

- 1997 Protocol (Tier I), which includes Annex VI, becomes effective 12 months after being accepted by 15 states with not less than 50% of world merchant shipping tonnage. On the 18th of May 2004, Samoa deposited its ratification as the 15th state (joining Bahamas, Bangladesh, Barbados, Denmark, Germany, Greece, Liberia, Marshal Islands, Norway, Panama, Singapore, Spain, Sweden and Vanuatu). At that date, Annex VI was ratified by states with almost 55% of world shipping tonnage. Accordingly, Annex VI entered into force on 19th of May 2005. It applies retroactively to new engines greater than 130 kW installed on vessels constructed on or after January 1st, 2000, or which undergo a major conversion after that date. The regulation also applies to fixed and floating rigs and to drilling platforms (except for emissions associated directly with exploration and/or handling of sea-bed minerals). In anticipation of the Annex VI ratification, most marine engine manufacturers have been building engines compliant with the above standards since 2000.

- 2008 amendments (Tier II/III) Annex VI amendments adopted in October 2008 introduces [1] new fuel quality requirements beginning from July 2010, [2] Tier II and III NO_x emission standards for new engines, and [3] Tier I NO_x requirements for existing pre-2000 engines. The revised Annex VI entered into force at July 1st 2010. By October 2008, 53 countries, including the United States, representing almost 82% of tonnage, ratified annex VI.

Annex VI defines two sets of emission and fuel quality requirements, which are global requirements and more stringent requirements applicable to ships operating within in ECAs. An ECA can be designed for SO_x and PM, or NO_x, or all three types of emissions from ships, subject to a proposal from a Party to Annex VI.

3.4.5.1 Sulphur Emission Controlled Area

The Baltic Sea and the Northern Sea are now ECAs with sulphur limit of 1% in 2010 and set to reduce to 0,1% in 2015 as shown in Table 3-6. From 2010 only marine and gas oil with a sulphur content less than 0,1% is allowed in EU ports for ships at birth exceeding two hours. This also applies for passenger ships. The North American ECA for SO_x entered into effect at the 1st of August 2012. The same requirements as for The Baltic and the Northern Sea apply for this area, including the requirements for recording data on entry and exit. The sulphur limits and implementation dates are listed in Table 3-6 and Figure 3-2.

Date	Sulphur Limit in Fuel	
	SO_x ECA	Global
2000	1,5%	4,5%
2010	1,0%	
2012		3,5%
2015	0,1%	
2020*		0,5%
*Alternative date is 2025, to be decided by a review in 2018		

Table 3-6 MARPOL Annex VI Fuel Sulphur Limits

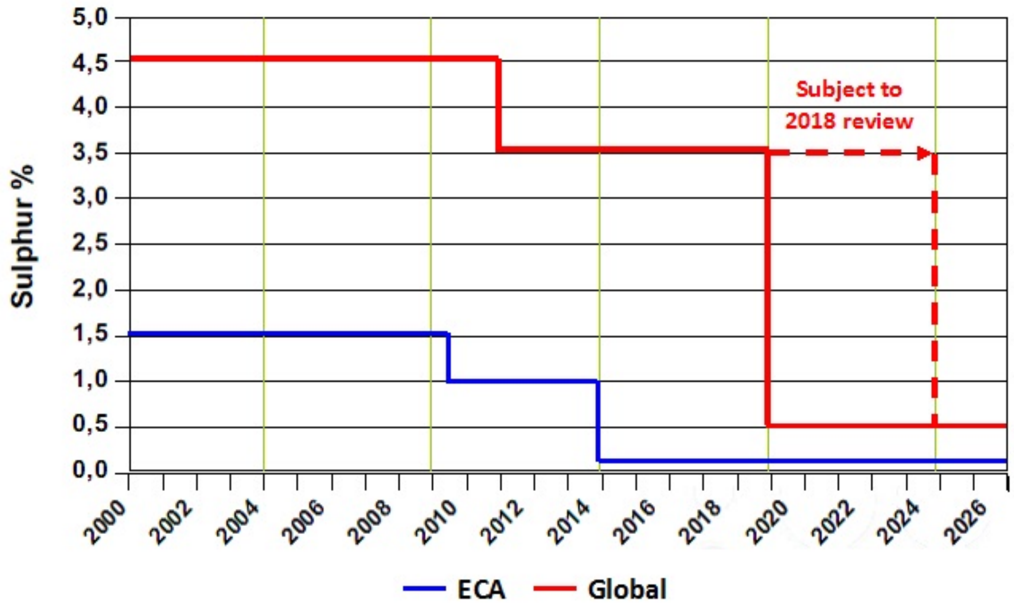

Figure 3-2 MARPOL Annex VI Fuel Sulphur Limits

3.4.5.2 NO_x Emission Controlled Area

NO_x emission limits are set for diesel engines depending on the engine maximum operating speed (n, rpm), as shown in Table 3-7 and Figure 3-3. Tier I and II limits are global, while Tier III standards apply only in NO_x ECAs. It is seen that there is an increasing focus on the NO_x emissions and the engine manufacturers are still improving engine performance in order to reduce the emissions.

Tier	Date	NO_x Limit (g/kWh)		
		n < 130	130 < n < 2000	n > 2000
Tier I	2000	17,0	$45n^{-0,2}$	9,8
Tier II	2011	14,4	$44n^{-0,23}$	7,7
Tier III	2016*	3,4	$9n^{-0,2}$	1,96
*In NO_x Emission Controlled Areas (Tier II standards apply outside ECAs)				

Table 3-7 MARPOL Annex VI NOx Emission Limits

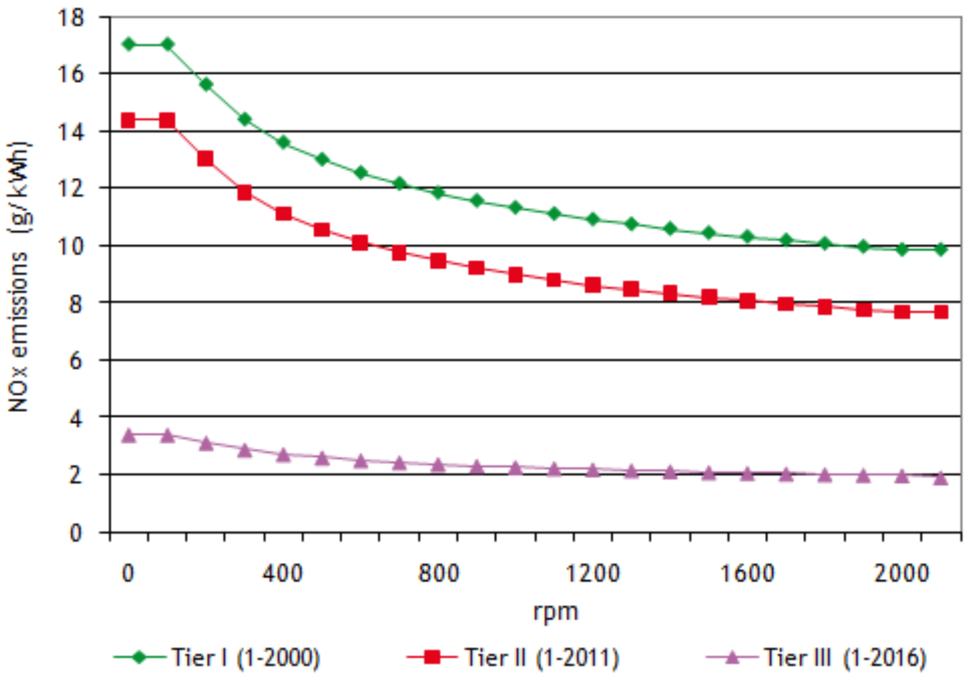

Figure 3-3 MARPOL Annex VI NOx Emission Limits

3.5 Weather Conditions

The weather conditions in the area of operation will affect the dynamic loading picture of the vessel. Weather characteristics and statistics are given for many of the operation areas such as the North Sea and the Gulf of Mexico. Especially waves, wind and currents in the area are factors that may influence the power demand of the vessel. These forces are dynamic and may change rapidly. The weather characteristics from the area of operation will give an overview of the average forces over the seasons from the sea and the water. This will give an indication of dynamic power demands needed for the vessel when e.g. operating in dynamic positioning mode, and must be taken into consideration when evaluating the best suited machinery system. The weather conditions will also have a huge impact on the operational time of the vessel. It cannot operate if the conditions get too rough. For most vessels weather routing is a possibility to avoid bad weather with a potential to save significant amounts of fuel. For special vessels with a given area of operation this is not possible. When the weather gets too rough it cannot operate and must wait for better conditions.

4 Decision Making

4.1 Method for Selecting Machinery System

A simple method has been suggested in order to efficiently evaluate whether a hybrid power and propulsion system with energy storage devices is suitable for any type of ship, and potential gains by hybridization. The method takes into consideration the general operational profile of the ship and also the operating profiles of all the engines. The battery in the hybrid configuration works as a “peak shaver”, which ideally will eliminate the effects of load transients on the system. Peak shaving means that peaks and troughs in power demand can be covered by the energy storage system, leading to engine operation at a more constant load. The size of the battery will be dimensioned based on the ship power demand as well as the variations in the loads. The idea is that with the battery installed the engines are allowed to run at constant load with small variations. The accumulator will work as a buffer by providing additional power when required and as a consumer by being charged when the load is low.

Except form the energy storage system, a hybrid system is assumed to have the same operating capacities as a conventional system and that the power requirements are approximately the same. Moreover, it is assumed that the implementation of a hybrid system will enable a more efficient operation of the power system, which will result in fuel savings, reduced maintenance cost due to less engine hours running at low loads, and reduced emissions.

In order to evaluate the potential benefits of installing a hybrid system, it is important to identify what type of ship that has the most potential for improvement of hybridization. In this method, three steps are taken to evaluate the operating profile of a vessel to determine the degree of suitability followed by a simple calculation on fuel consumption and lifetime costs to see whether there is an economical benefit in the long run.

4.1.1 Step One

By analyzing the power demand as a function of time in an operational profile one can get an impression of whether it is a profile with a varying power demand or a more constant profile where the engines most of the time may run at a constant speed. The idea behind this, is that a vessel which has a wide spread of average power demands during a cycle of operation, e.g. 20% of installed power is required for one type of operation over a time period (DP) and 70% for another period (transit) etc. Operating profiles that experience frequent changes in the power demand will have a higher variation from the mean value than vessels with more constant power demand during an operation cycle. This can be measured up against the ratio between the amounts of time spent in dynamic positioning, which leads to low load and a high amount of transients on the engines, and the time spent in transit mode, which normally allows the engines to operate at more constant loads. The result will give an impression on what kind of power system that might be suitable as seen in the example in Figure 4-1.

Ratio between percentages of time spent in transit and DP in operational profile:

$$r = \frac{\%transit}{\%DP} = \frac{t_{transit}}{t_{DP}} \tag{4.1}$$

r=1: transit = DP

r<1: transit < DP

r>1: transit > DP

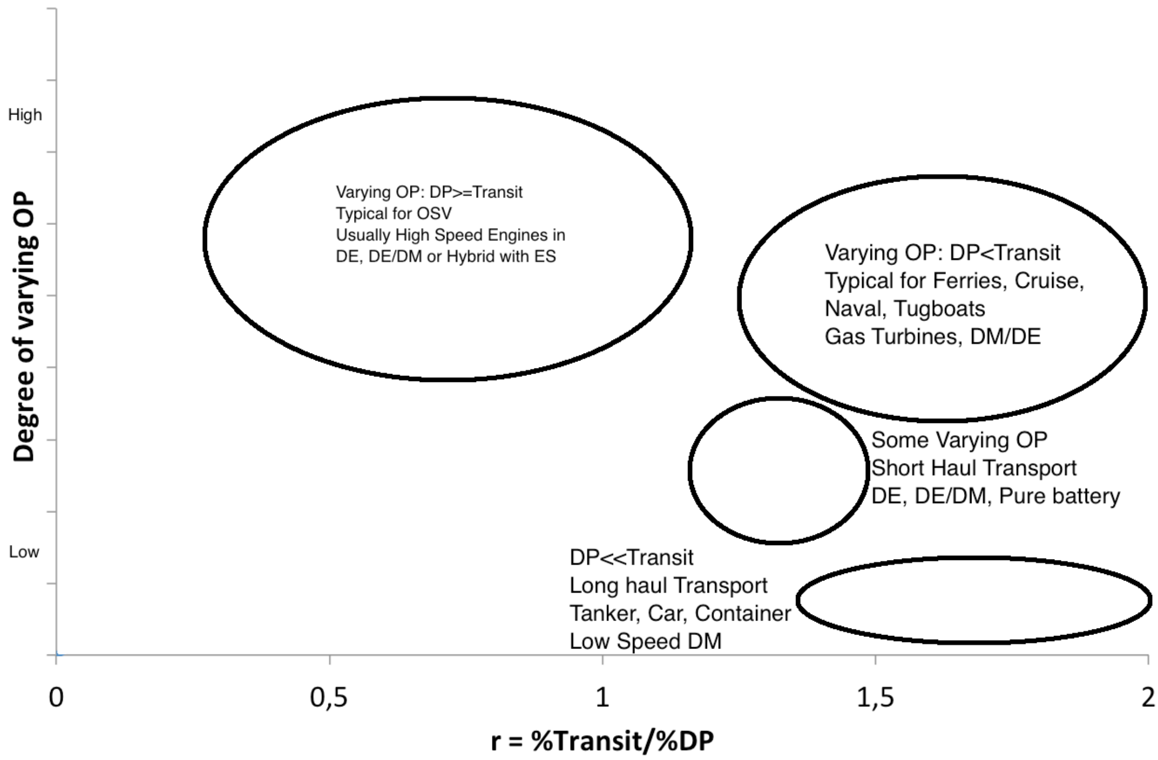

Figure 4-1 Variation in OP vs. Transit/DP

4.1.2 Step Two

The next step will be to look at the relationship between static and dynamic loads and disturbances on the generators caused by the different consumers in the power system. They may be classified in four main groups as follows according to (18):

Static disturbances due to ship operation and service functions such as:

- Servo motors for various hydraulic systems, such as winches, steering gear, etc.
- Pumps, compressors, ventilation, etc.
- Hotel loads, such as ventilation, air condition, lighting, etc.

The static disturbances due to ship operation and service functions are usually slowly varying and may be considered as static. They are somewhat dependent on the weather conditions, but the level of frequency is rarely changed significantly.

Low-frequency disturbances:

- Disturbances due to thruster loadings
- Crane operations
- Drilling loads
- Other systems

Typically, when the vessel is operating in DP mode, the wave, wind and current loads are affecting the thruster loadings with periods higher than about 15 seconds. This period is also applicable for the crane and drilling operations and is what determine a low-frequency disturbance. However, the magnitude of the sudden change in power demand may be of a size that requires more generators running or ramp-up of the running generators. This is a crucial situation due to the time it takes to start, or ramp up a new generator and the demand for power may be in the order of seconds, or even less. A battery, which can deliver a high amount of power almost immediately, may act as a buffer during the startup or ramp-up of a new generator. The engine may require several seconds, or even minutes, depending on the state of the engine, to meet the new requirements of power.

Medium-frequency disturbances:

- Fluctuations due to the propeller thrust and torque loss effects transmitted through electrical thrusters
- Active heave compensation system fluctuations
- Fluctuations from impact from the first order wave loads acting on the vessel both during DP operations and during transit

The wave encounter frequency fluctuations are caused by the vessel motions in waves and are affected by the weather conditions. However, they are typical in the magnitude of a period between 4 to 12 seconds and determine the medium-frequency disturbances. The heave compensation system is used for improved control over e.g. a suspended object when a ship moves it to and from the seabed or other lifting operations as on and offloading by reducing the vessel's movement in heave. These types of disturbances may create large frequency variations on the generators and affect the blackout resistance. Moreover, as well as for the low-frequency disturbances, the sudden change in load may lead to demand of more power generated within seconds.

High-frequency disturbances:

- Fluctuations in the range of the cylinder combustion frequency, affecting the engine torque
- Fluctuations in the range of propeller-blade frequency, affecting the mechanical torque on the electrical thrusters
- Various fast changing electric effects in the network, e.g. current and voltage harmonic distortion
- Noise, measurement error

Most of the high-frequency disturbances in the range of the propeller-blade frequency will be filtered by the power system due to the motor and generator inductances and inertia of the rotating parts. This means that the high frequency fluctuations will not be evaluated as a part of the network load when considering the risk of blackout and fuel consumption. However, the vibrations induced by these fluctuations may increase the rate of wear on components and increase the risk of component failure.

It is important to give a good estimation of the dynamic disturbances and separate them from the static power disturbances. The weather characteristics in the area of operations and what type of operation that is supposed to be performed have a great impact on the estimations of the dynamic power level.

The total power required for operating the vessel at each operating mode can be described as in function (4.2). It is the sum of the static loads and the dynamic loads the vessel may encounter during operation. The static loads are basically non-varying loads such as hotel loads, pumps, compressors, etc. which are needed for operating the ship and are more or less constant during normal operation. This is represented by equation (4.3). The dynamic loads are, as described above, loads that vary with time. They represent loads, which may appear suddenly and last for seconds or minutes, and are shown in equation (4.4).

$$P_i^R(t) = P_i^S(t) + P_i^D(t) \tag{4.2}$$

Subscript i = Operation mode, e.g. transit, DP, harbor, etc.
$P_i^R(t)$ = Required power for operation i
$P_i^S(t)$ = Static power demand for operation i
$P_i^D(t)$ = Dynamic power demand for operation i

$$P_i^S(t) = \sum_j P_{i,j}^S(t) = P_{i,lighting}(t) + P_{i,air\ condition}(t) + P_{i,pumps}(t) \ldots \tag{4.3}$$

Subscript i = Operation mode, e.g. transit, DP, harbor, etc.
Subscript j = type of load; e.g. hotel loads, lighting, pumps, air-condition, ventilation, etc.

$$P_i^D(t) = \sum_j P_{i,j}^{LF}(t) + \sum_j P_{i,j}^{MF}(t) + \sum_j P_{i,j}^{HF}(t) \tag{4.4}$$

Subscript i = Operation mode, e.g. transit, DP, harbor, etc.
Subscript j = type of load; thrusters, heave compensation, etc.
$P^{LF}(t)$ = Low frequent dynamic load j
$P^{MF}(t)$ = Medium frequent dynamic load j
$P^{HF}(t)$ = High frequent dynamic load j

The power required to handle the total load cannot exceed the total power installed.

$$P_i^R(t) < P^{Installed} \tag{4.5}$$

$$P^{Installed} = P^{Generators} + P^{Battery} \tag{4.6}$$

4.1.3 Step Three

As mentioned earlier in this report, the implementation of a hybrid power system has many advantages. Most of them are totally dependent on the operational profile of the engines. If the areas of benefit are systemized and measured up against the operating profile of a type of vessel it will be easier to get an overview of which ship types that will suit the hybridization as shown in Table 4-1. By giving a score for each ship type and the areas of benefit, the best-suited vessels can be found. The score can be given a value of 1 to 5, where a score of 1 means that the benefit area is not applicable for that vessel and a score of 5 is given to vessels where the benefit is very relevant.

#	Benefit Area	Criterion
1	Utilizing energy from cold ironing during ship operation.	Time spent in harbor, likelihood that the harbor has, or will soon have, facilities for cold ironing.
2	Running engines at optimal load.	Percentage of time in in operation the engines run at, or close to, optimal loads.
3	Avoiding transient loads.	Amount of transient loads experienced during ship operation.
4	Use as power redundancy.	Requirements for power redundancy for the ship type.
5	Reduce local emissions.	Time spent in harbors, near shore operations, or in ECA's. More important for ships operating in areas where emission taxes apply. (Norway, California)
6	Reduce noise and vibrations.	Ship requirements related to noise and vibrations.
7	Facilitate energy harvesting.	Rated based on the potential for harvesting and storing alternative energy on the ship; e.g. ships with large areas suited for installation of solar panels.

Table 4-1 Areas of Benefit Criterion for Hybridization (6)

1. A high rating in the first area of benefit, utilizing energy from cold ironing, indicates that installing an energy storage unit may give potential benefits.

2. If the vessel's engines operate most of the time close to the optimal operation point, the potential of improvement is not very high, which indicates a more straight forward operational profile, which will give a low rating in this model.

3. When it comes to the amount of transients experienced during operation, a low score in this field indicates a low varying operational profile.

4. As for the requirements to redundancy, a high rating is given if the vessel is under the class rules (usually related to DP).

5. If the vessel operates in an ECA or other emission regulated areas most of the time, a high rating is given.

6. Ships with high requirements to noise and vibration reduction will receive a high rating in area number six.

7. Finally, vessels with the possibility of implementing renewable power sources as wind or solar energy, usually vessels with large outer areas with enough space to install such devices, will receive a high rating.

4.1.4 Lifetime and Payback Time Analysis

When designing a hybrid machinery system the selection of the engine sizes is a key element. Detailed operational profiles with power demand as a function of time, or similar designs with the same capabilities, are necessary in order to put together the best solution. With the operational profiles in hand the average power demand needed for operations as well as the number and size of the prime movers can be selected to cover this demand. The batteries should have the appropriate capacity to cover the dynamic load peaks above the average load during operation. During load troughs the engines can still run at the designed load by charging the batteries.

The annual operational profile in days may be expressed as in function (4.7). It consists of days spent in the different operation modes multiplied with the number of round trips.

$$T = N_{RT} \sum_{i} t_i \tag{4.7}$$

T = Annual operational profile

N_{RT} = Number of round trips

t_i = Time in operation mode i

In the calculations the engine load has been estimated as a function of time based on the operational profile. The fuel consumption of a vessel is the total fuel used over one round trip of operation multiplied by the number of round trips over a year expressed by equation (4.8)

$$FOC = N_{RT} \sum_{j} \sum_{i} sfoc_{gi} \times P_{gi}^{average} \times t_j \tag{4.8}$$

FOC = Fuel oil consumption

$sfoc_{gi}$ = Specific fuel consumption of generator i

$P_{gi}^{average}$ = Average power production of generator i

t_j = Time in operation mode j

The hourly fuel consumption curve for an internal combustion engine can be approximated by a quadric function of the load as expressed in function (4.9). This equation is valid for either variable-speed, or fixed-speed operation, using different sets of polynomial coefficients. The specific fuel oil consumption measured in grams per unit of power per hour is obtained by dividing equation (4.10) by P_m as done in equation (4.11), which also hold in dynamic conditions according to (19). The coefficients may be found by regression based on average numbers for a given engine type. However, in many cases, the engine manufacturer gives the necessary numbers and data on the specific fuel consumption.

$$foc = \sum_{i} C_i \times P_m^i \quad for\ i = 0,1,2 \tag{4.9}$$

$$foc = C_0 + C_1 P_m + C_2 P_m^2 \tag{4.10}$$

$$sfoc = \frac{C_0}{P_m} + C_1 + C_2 P_m \tag{4.11}$$

P_m^i = Mechanical power of generator i

C_i = Coefficients

Knowing the specific fuel consumption for each generator set in all load conditions, the next step will be to analyze the operational profile and optimize the utilization of the prime movers in every mode of operation. It is noted that the elimination of frequent load variations in fuel consumption has not been taken into consideration in the calculations to begin with for simplicity, and is based on average values of the operation modes.

5 Case

Due to the unavailability of real data, and the fact that the companies often classify sensitive information regarding operation, all the numbers and data in this section are assumed by the author. However, they are kept as close to the reality as his knowledge allows.

5.1 Operator Specifications

A certain ship-owner has a fleet of PSV's of varying size. They are all relatively new, operating at different fields and they are all equipped with combinations of diesel electric and diesel mechanic power and propulsion system. A new contract for support of four offshore installations in the North Sea is signed and the company needs to build a new PSV to handle the job. The ship-owner now faces a challenge in the choice of the machinery system. New technology has entered the market by introducing an energy storage unit to the power system, with potentially increased efficiency and reduced operational costs. Additional capital cost, weight and space consumption may be a backside of choosing the new configuration. Should he select the same system as in the existing fleet, which has proven to work well, or should he take the risk of trying the new potentially promising system, which on the other hand has not been tested in real life to the same extent as the diesel electric system?

The offshore installations are situated at a distance outside a supply base onshore. The operations that are to be performed are transport of cargo and equipment to all four installations from the one onshore base and to be at assistance in standby and other support operations for the offshore installations. The operator gives the specific input such as distances, speed and size of the vessel, operations to be performed, etc.

The vessel's speed during steaming from the shore base and the installations, and back again after a full round trip, depends on the weather. Under normal conditions it will sail with economical speed for reduced fuel consumption, which represents the "transit low" mode. Loading and offloading at the installations in the field must be done while the ship is in "DP High" mode due to the risk of collision with the installation. After loading and unloading at an installation the vessel is supposed to stay standby on site for a given time period. When in standby, the vessel is in the "DP Low" mode. This will also depend on the weather conditions. In harsh weather it might have to run in “DP High”. The shorter transit stretches between the installations is done at higher speed, which represents the “Transit High” mode.

The numbers given in Table 5-1 below are made up to illustrate a realistic cycle of operation for a PSV.

Type of vessel	PSV
DP Class (IMO/DNV)	3/DYNPROS-AUTRO
Area of Operation	North Sea
Speed Eco. [kn]	12
Speed Max [kn]	15
Distances:	
Sore Base – Installation A [nm]	200
Sore Base – Installation B [nm]	180
Sore Base – Installation C [nm]	250
Sore Base – Installation D [nm]	220
A – B [nm]	20
A – C [nm]	60
A – D [nm]	50
B – C [nm]	20
B – D [nm]	10
C – D [nm]	30

Table 5-1 Operation Spesification

With these numbers the operational profile of the power demand will be as shown below in Table 5-2 and Figure 5-1. The green column represents the mean power demand in each operation mode for a time interval. The red and blue column shows the variation in the power consumed as minimum and maximum values.

Operation	Duration [h]	Average P_demand [%]	Variation [+/-%]	Max P_demand [%]	Min P_demand [%]
Harbor shore base (load/unload)	6	2	0	2	2
Transit (low) shore base to installation A	17	40	10	45	35
Load/offload (DP high)	3	45	30	60	30
Standby (DP low)	8	20	50	30	10
Transit (high) A to installation B	1	70	10	100	80
Load/offload (DP high)	2	45	30	60	30
Standby (DP low)	8	20	50	30	10
Transit (high) B to installation C	1	70	10	100	80
Load/offload (DP high)	2	45	30	60	30
Standby (DP low)	8	20	50	30	10
Transit (high) C to installation D	2	70	10	100	80
Load/offload (DP high)	3	45	30	60	30
Standby (DP low)	15	20	50	30	10
Transit (low) installation D to Shore base	18	40	10	45	35

Table 5-2 Operational Profile

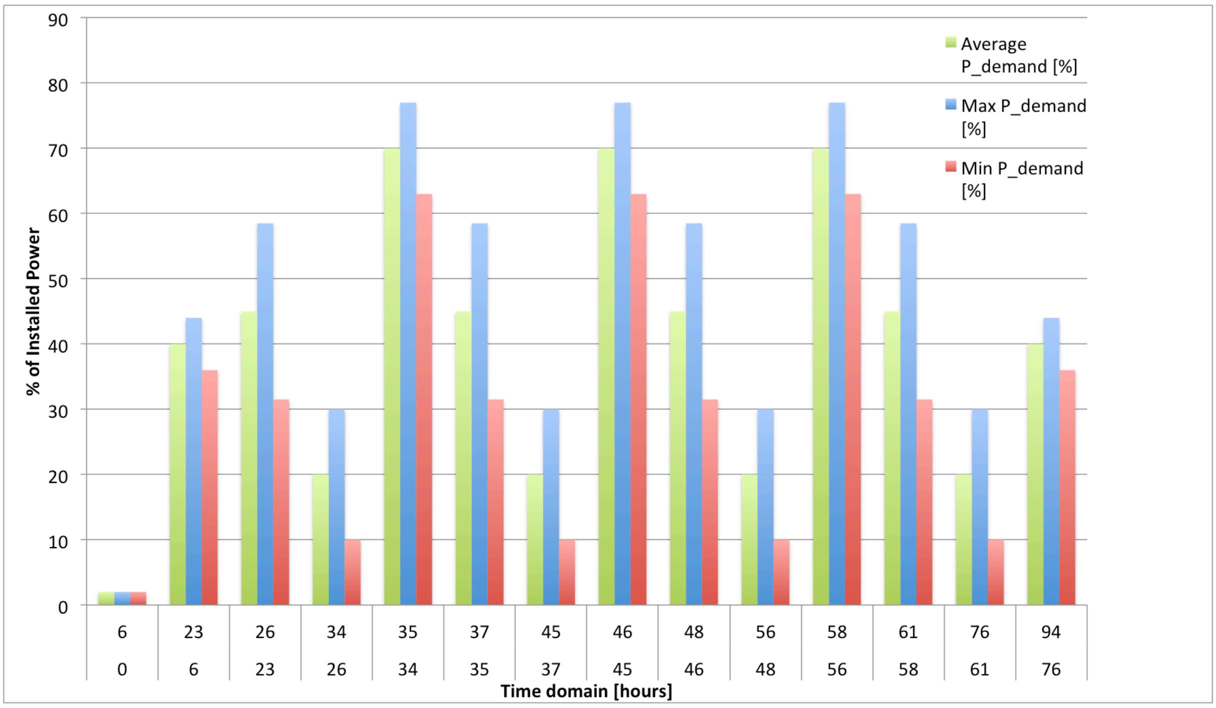

Figure 5-1 Operational Profile

As can be seen from the operational profile in Figure 5-1 above, the power demand is below 50 percent of MCR most of the time. In most cases, by not running all prime movers, the running engines may operate close to the optimal operating point at maximum energy efficiency. When operating in DP mode, on the other hand, the requirements to redundancy demands more engines than necessary to operate (see chapter 3.3 on DP guidelines and requirements to redundancy). To be able to operate close to another vessel, or installation, equipment class 3 is chosen for the PSV according to DNV's recommendations. Equipment class 2 could also have been sufficient, but the difference between class 2 and 3 does not have any effect on the requirements for redundancy during DP operations.

5.2 Selection of Machinery System based on Operational Profile

In this section the feasibility of hybridization on the PSV, from the presented case, will be analyzed stepwise following the steps of the model presented in part 4.

5.2.1 Step One

The planned operating profile for the PSV is a typical varying profile. It has five different operating modes with duration of one to 18 hours. During one round-trip it changes power demand with the different tasks to be performed several times as well as short time load peaks and transients. The ratio between time spent in transit and DP is 0,87, which means that it spends slightly more time in DP than in transit. That places the vessel in the upper left to middle area in Figure 4-1. A propulsion system that can handle this type of load profile will be a pure diesel electric system, combined diesel electric and diesel mechanic system, or a hybrid of diesel electric and energy storage system. High-speed engines will be needed due to their ability to handle changes in the load better than slow speed engines. Gas turbines may be used. However, the use of gas turbines in such systems is not common and will not be considered in this thesis.

5.2.2 Step Two

A PSV is a high technology ship and they usually perform a variety of advanced tasks. Nevertheless, the static power demand is not very much different from other merchant ships. The necessary auxiliary and support systems for operating the ship will be cooling systems, steering systems, hydraulics, pumps, compressors and hotel loads. In addition, they are usually equipped with a variety of deck equipment such as cranes and winches, which will require additional power. When the vessel is in harbor and usually in transit the power demand is in general static with some degree of transients. The power output needed for propulsion will mostly depend on the speed of the vessel and can be said to be a function of the speed to the power of three. In calm sea conditions the power demand remains mostly constant. However, when the vessel meets rougher sea conditions, more transients and a more dynamic power demand may appear.

The dynamic loads can be separated into two main groups: environmental impacts such as waves, wind and currents, which leads to demand of power from the thrusters to keep in position during DP, and operational impacts such as operation of deck equipment and lifting operations. Weather characteristics for specific areas can be obtained to evaluate the most likely environmental forces that will work on the vessel.

When it comes to the dynamic loads and power demand a PSV differs from most other ships. Especially with the dynamic positioning system and advanced operations under difficult conditions. As mentioned above, the ship may face dynamic power demands during transit in rough sea due to waves. However, the critical phases are usually during advanced operations. This can be lifting operations both above and beneath the surface of the water. The vessel will normally be using dynamic positioning during operations. This will introduce peaks and troughs in the power demand. The lifting operations are usually sensitive to heave motions and therefore require active heave compensation in addition. This combined with power to operate cranes, winches and other required deck equipment, as well as the normal required static power for operation of the ship, can lead to severe power demands that are varying for short periods of time. The probability for all these dynamic loads to hit a peak at the same time may be estimated and analyzed to predict the worst-case loading situation, which is very important when considering failure scenarios in the machinery due to redundancy and safety. However, this is beyond the scope of work and will not be considered in this thesis.

5.2.3 Step Three

The operating profile of the PSV can be weighed up against the criteria's in Table 4-1 for a first evaluation of the feasibility.

The round-trip of the vessel is less than four days, which means that it is in harbor frequently. This means that it can utilize energy from cold ironing at a regular basis if the facilities are available. For Norwegian shore bases in the offshore sector this is likely to happen in the near future, given that more vessels will install facilities for transfer energy from shore. The fact that the electrical power production on land in Norway is environmentally friendly in the way that is has no emissions by exploiting waterfalls in hydropower plants, gives the advantage of available and clean energy. Rating on potential benefits of hybridization on PSV: 4.

The operational profile shows that the engines do not run at, or close to the optimal point most of the time. This indicates that by implementing a hybrid system the percentage of time the engines are run at optimal loads can be increased. Rating on potential benefits of hybridization on PSV: 5.

In the different operation modes the vessel experiences during a round-trip the amount of transient loads the engines experience changes. In transit, both fast and eco, there may be some transients if there is rough sea. Otherwise the amount of transients is negligible. Moreover, when in DP mode the system will experience several sudden changes in the load over time. In the case described in chapter 5.1 it can be seen in Table 5-2 that the vessel spends about 45 per cent of the time on DP per round-trip and the amount of transients experienced during ship operation is substantial. Rating on potential benefits of hybridization on PSV: 5.

The fact that the ship operates with DP and is classed with equipment class 3, leads to the highest requirements to redundancy in the power production (see chapter 3.3.3 on requirements to redundancy). Rating on potential benefits of hybridization on PSV: 5.

The vessel in this case is going to operate on the Norwegian continental shelf and its shore base is located on the Norwegian coast. This means that it is going to operate in an Environmental Controlled Area (ECA) and falls under the restrictions and regulations of this area, which is explained in chapter 3.4 on environmental effects. In Norway taxes on emissions apply and must be taken into consideration when estimating the cost versus benefits of a hybrid system. When it comes to local emissions, the PSV is spending some time in harbor and there might be some regulations to emissions in that concern. Rating on potential benefits of hybridization on PSV: 5.

The ship requirements for reducing noise and vibrations are not of a great concern on a PSV, except, maybe for crew comfort, which is receiving increased focus on modern vessels. However, the need for it is not a pressing matter. Rating on potential benefits of hybridization on PSV: 1.

The PSV may have some benefits when it comes to the possibilities and potential for harvesting energy. Solar and wind power may be exploited, however, the deck area is limited, and the available space is needed for cranes, winches and free area to perform different tasks. Also the superstructure is rather small. During transit it may exploit wind energy. However, due to the large portion of operation on DP where it is of the utmost importance to keep the exact position, wind energy is out of the picture. Regenerative breaking is a possibility for cranes and winches, but there is still much research needed on this topic. Waste heat recovery on the other hand has even greater effect together with the possibilities for storing the energy and engines working at a higher rate of high loads. Nevertheless, it is not considered to be potential benefits related to energy harvesting in this case. Rating on potential benefits of hybridization on PSV: 1.

This gives a total rating of 26 out of 35 possible points. That is a relatively high rating, and thus a hybrid configuration with diesel electric combined with energy storage will potentially be beneficial for this PSV.

5.2.4 Calculation on Payback Time of Investment

Further on, calculations on the life cycle cost is performed as a final step to determine if a hybrid system will be beneficial in this case. The hybrid system is compared to a diesel electric system. The engines in a hybrid system have been reduced in power output due to the additional power from the batteries and chosen based on the power demand profiles. The engine load, or power output, for all engines has been estimated as an average power function of time. Fuel consumption for each prime mover has been calculated based on that power output, and the specific fuel oil consumption of the engine at the respective load and time at each load. An overview of the engine types is shown in Table 5-3.

Machinery Configuration:	DE	Hybrid
Main Engine Power [kW]	1800	1250
Number of Engines	4	4
Battery Pack [kWh]	0	2000
Total Installed Power [kW]	7200	7000

Table 5-3 Machinery Configuration

The batteries are assumed to be lithium-ion type. This is the most used battery technology for this type of system. The calculations concerning the reduction of emissions are based on numbers according to (16) which is; combustion of one ton of MDO in high speed four-stroke marine engines produces 3206 kg of CO_2, 50,5 kg of NO_x, 21 kg of SO_x and 2,3 kg of particulate matter. The taxes from emission of NO_x on the Norwegian shelf in the North Sea are based on numbers from The Norwegian Customs. The tax is currently just above 17 NOK per kg NO_x emitted, which is, with todays currency at 6 NOK per USD, approximately 3 USD per kg NO_x.

The following assumptions were done in the calculations on the life cycle cost on the PSV with a hybrid machinery system:

- Price on MDO: 900 USD/ton
- Engine installation cost: 350 USD/kW installed
- Hybrid engine installation cost: 20% addition to engine installation cost due to more complex electrical equipment
- Battery pack installation cost: 1200 USD/kWh
- Operating days per year: 230 days

The fuel consumption of each engine has been calculated based on the assumed engine loading profile as shown in Appendix A.4 and A.5. The results on fuel consumption and estimated savings are summarized in Table 5-4. During one round trip the results show that there is an approximate 16% reduction in fuel consumption. This is mainly due to the more efficient operation of the engines for the hybrid system and partly because of the utilization of smaller engines in the hybrid configuration. Moreover, the reduction of emission of CO_2, particulate matter and NO_x, as a result of reduced fuel consumption, is a positive effect.

	DE	Hybrid
Total FOC [ton/round trip]	**42**	**35**
Fuel Savings [ton/round trip]	0	7
Round trip/year	59	59
Fuel Savings [ton/year]	0	402
Fuel Cost [USD/year]	**2 203 137**	**1 841 716**
Engine Installation Cost [USD]	2 520 000	2 100 000
Battery Pack Installation Cost [USD]	0	2 400 000
Total Installation Cost [USD]	**2 520 000**	**4 500 000**
CO2 Emissions kg savings/year	0	1 287 463
NOx Emissions kg savings/year	0	20 280
PM Emissions kg savings/year	0	924
Emission savings [USD/year] (NOx)	0	58 575
Cost Emissions [USD/year] (NOx tax)	357 057	298 482

Table 5-4 Summary of Fuel Consumption and Emissions for the PSV

When considering the potential economic benefits of a hybrid system the lifetime of the batteries have to be taken into consideration. The Lithium-Ion batteries that are used in this case usually have a lifetime of 5-15 years, depending on the rate of discharge. The engines in the hybrid configuration are run at 70-75%MCR for as much of the time as possible, which gives a power output at 3500 kW. Only in the "transit high" mode the engines are running at 85%MCR, which yields a power output of 4250 kW. The energy contribution needed from the accumulators is given in Table 5-5 for each operation. It can be seen that during one round trip the battery pack goes through five cycles of charging and discharging. The rate of discharge in this case is to between 60% and 20% of its capacity. With the 230 operating days, the vessel will make 59 round trips in one year. That will give the battery pack approximately 300 cycles per year. With a battery self-discharge rate of about 3% each year the lifetime of the battery pack will be about 10 years. After 10 years the energy storage package must be replaced by a new one to uphold a sufficient energy capacity to cover the energy demand of the system.

Operating mode	Duration [h]	Power required [%MCR]	Power required [kW]	Battery Contribution [kW]	Energy from Battery [kWh]
Harbor	6	0,02	144	144	864
Transit low	17	0,4	2880	0	charging
DP high	3	0,45	3888	388	1164
DP low	8	0,2	1728	0	charging
Transit high	1	0,7	5040	1540	1540
DP high	2	0,45	3888	388	776
DP low	8	0,2	1728	0	charging
Transit high	1	0,7	5040	1540	1540
DP high	2	0,45	3888	388	776
DP low	8	0,2	1728	0	charging
Transit high	2	0,7	5040	790	1580
DP low	15	0,2	1728	0	charging
Transit low	18	0,4	2880	0	charging

Table 5-5 Power and Energy Demand for the PSV with Battery Pack

Based on these considerations and assumptions, a calculation of the differences in the annual costs of operating the ship with diesel electric and hybrid configuration over a period of 30 years has been performed. Only the capital and operational costs in form of installation cost, fuel costs and emission taxes are considered. Other costs as building costs, maintenance costs, etc. are not considered, because they are assumed equal for the vessel with both machinery systems.

Two scenarios are analyzed:

- (1) In this scenario, the fuel prices are assumed to remain constant over the time period. Only the annual costs for fuel and taxes to emissions are considered as well as the investment in machinery. The price of the battery pack is kept constant for the next 30 years. This is not likely to happen in the real world and is considered a worst-case scenario.

- (2) In this scenario the fuel price is assumed to follow the last year's trend and increase by 2% annually for the next 25 years. The cost of a new battery pack is assumed to drop by 20% every ten years due to the improvement and availability of the technology. This is considered a more likely scenario.

5.2.5 Results

The results are presented in Figure 5-2 and Figure 5-3 below. It can be seen that in the scenario with constant prices (Figure 5-2) the payback time for investing in a hybrid system is about five years. However, after ten years a new battery pack has to be installed. This will in this case lead to a higher total cost for the hybrid system than for the diesel electric configuration after ten years, despite the lower fuel consumptions and taxes. Moreover, after this point the investment in installing the battery pack will continue to be more profitable than the diesel electric system. After 15 years of operation the potential benefit in cost savings will be approximately 5% and after 25 years it will be close to 6%.

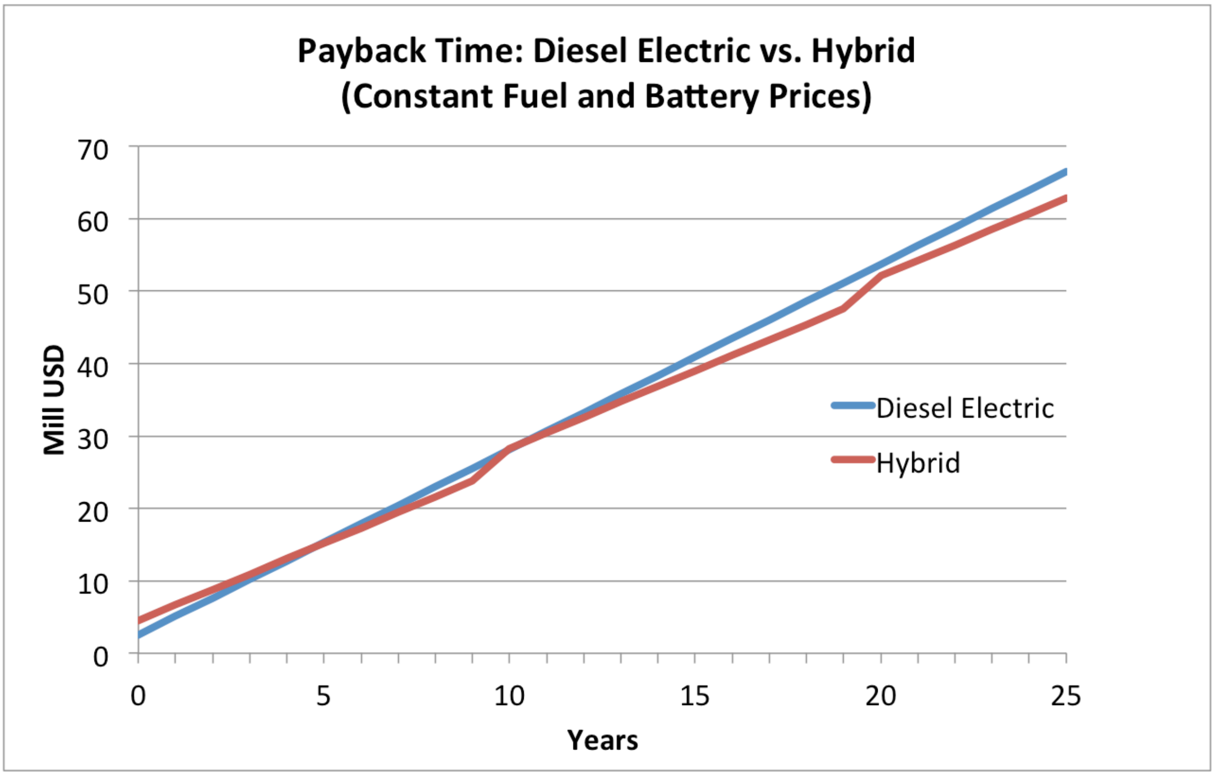

Figure 5-2 Payback Time Diesel Electric vs. Hybrid with Constant Prices

In the case with increased fuel prices and reduced cost for reinstalling the battery pack, Figure 5-3, the potential benefits are higher. The payback time for the hybrid system is about the same as in the constant price scenario, just below five years, and it will remain profitable for the rest of the period, even after the replacement of the battery pack. After 15 years of operation the potential benefit in cost savings will be approximately 7% and after 25 years it will be almost 10%.

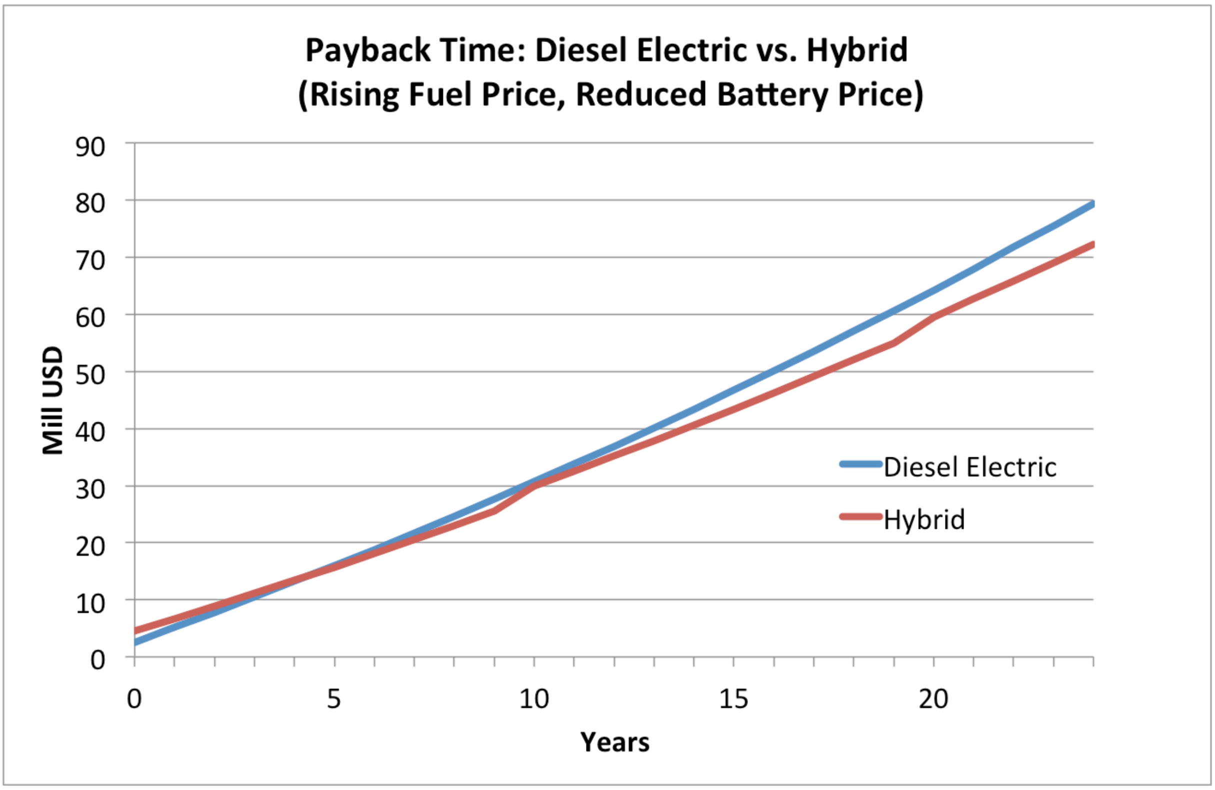

Figure 5-3 Payback Time Diesel Electric vs. Hybrid with Changing Prices

The analyses presented in this chapter introduce a way of deciding early in the design phase if a hybrid power system with energy storage will be a reasonable choice, based on the type of ship and the operations it is planned to perform, and a study of the potential benefits.

The significant amount of assumptions made in making the operational profile and engine utilization in this case leads to a certain degree of uncertainty in the results. However, the analyses show similar results as other simulations made on this topic (6), (8) and (19). Moreover, due to the fact that the effects of the dynamic loads are not covered completely in the calculations, the results may be somewhat conservative, meaning that the peak shaving is believed to have an additional effect on the fuel savings for the hybrid system. Other uncertainties are the fuel price and the battery cost. Even though the estimated development of the fuel price is based on the last year's trend, the price may change otherwise in a run of 30 years. The same goes for the cost of the batteries. It is impossible to say how this will develop in 20 to 30 years from now. However, the development of the technology is likely to decrease the price of the batteries in the future as we have seen with other advanced technology products.

6 Discussion, Conclusions and Recommendations

6.1 Discussion

The work presented in this thesis is a study of the influencing factors concerning selection of a machinery configuration for vessels with complex operational profiles, and to identify where a hybrid system will have the most advantageous effects. Depending on the type of vessel an operational profile with the average power demand as a function of time can be made. The profile will reflect the various power demands in different operational modes for the vessel. This may be as simple as maneuvering in and out of port and long distances of transit, which is considered a non-complex profile. Knowing the hydrodynamic resistance of the ship and the desired design speed, the engines can be optimized to operate at an efficient load most of the time.

Other vessels may have an operational profile, which is more complicated. Offshore supply vessels usually fit this characteristic with several different tasks to perform under difficult conditions and with a high amount of changing loads on the engines. The transport hauls are usually short and the variety in operations during one cycle of operation is larger than for example for a deep sea container ship. Other vessels, as small ferries with many short distances of transit in several different speed areas and maneuvering during a round trip, may represent a more complex profile of operation.

Going deeper into the operational profile, each operational mode and the respective power demand must be analyzed. Especially the dynamic loads and power demand should be evaluated. These types of loads represent the biggest challenge in dimensioning the on board power production plant. The average power only gives an overview of the power demand, whereas the loading may change rapidly over short periods of time. This will create peaks and troughs in the loading of the generators. To be able to handle a sudden need for extra power to e.g. a thruster during DP, the prime movers must be able to ramp up in a sufficient amount of time. The engines that handle this the best are high-speed engines, such as 4-stroke engines with a speed above 1100 rpm. A diesel electric system has proven able to handle load variations at a satisfactory level. However, by implementing an energy storage unit with almost immediate response to a load demand, this can be utilized for short periods of time to deliver the power needed. This way the prime movers can operate without the sudden need to ramp up and generate more power. The other positive effect is when the power demand gets low, typically below 40% of total installed power. This is a well-known challenge when operating in DP due to the restrictions in start up of engines. Instead of running engines in idle, they can charge the batteries and thus run at a more optimal load for a longer period of operation.

Another issue that may be a source of challenges for vessels with a DP system is the class requirements to redundancy. This is a requirement for separating engine compartments and switchboards due to safe operations regarding failures in the system. With all engines operating, this often leads to low load situations when operating in DP, which is a challenge due to wear on the engines, and normally a higher fuel consumption and emission of green house gasses. DNV is working on the rules and regulations for utilization of batteries, or other energy storage units, as a source of redundancy. If the batteries can be a sufficient source of redundancy, there is no longer a need for all the prime movers to operate during DP, and the amount of low loading on the system can be reduced significantly. This issue still lies somewhat in the future, and a battery is for now not approved sufficient as redundancy during DP operations.

The increasing focus on emission of green house gases also has some effect on the final choice of machinery. If the vessel is to operate in emission controlled areas, or along coasts with other regulations and taxes regarding emissions, there are potentially large economical benefits in choosing a machinery system with the lowest possible emissions. The engine manufacturers are continuously improving the efficiency of the engines in an attempt to meet the new Tier standards. Regardless of this, the optimal operation and utilization of the engine will determine the fuel consumption in the end.

A simple model was made to compare different configurations of the machinery in the matter of investment costs and operating costs such as fuel consumption and reduction of emissions. The first steps are about evaluating the profile and to get an impression of the degree of dynamic loads the vessel will experience. Further on, a simple screening process is made to evaluate the potential benefits of a hybridization of the vessel. The model takes in the average power demand from the operational profile and, if the data is available, the utilization of the engines in all the operation modes is implemented and the fuel consumption is calculated. In this case the utilization of the engines were estimated.

The study shows that for a vessel operating with DP, which implies large variations and dynamic loads, a form of diesel electric power system is the best suited. The dynamic power demand is often what tips the scales in favor of types of machinery systems such as diesel electric or other hybrids. This is due to the high amount of variable and dynamic loads the machinery experiences during such an operation. The diesel electric system, or hybrids of diesel electric and diesel mechanic, has been a first choice for vessels with a high utilization of DP during operations and high maneuverability requirements. The combination of DE/DM is often a good alternative if the vessel also has a high degree of transit in the operating cycle. However, with the advancing technology of batteries for energy storing in the recent years, the ability to handle a varying load demand increases even more as well as the ability to handle low loads and thus, the hybrid system will be a more economical and environmentally sustainable solution.

6.2 Conclusion

The results in this work shows that for complex operational profiles with a high degree of varying load demands, various forms of diesel electric machinery configurations or hybrids are the best suited systems. For complex operational profiles with a high degree of dynamic loads, transients and low loading situations, the introduction of an energy storage unit, such as batteries or supercapacitors, may further improve the performance of the system. Even though the investment costs are higher for a hybrid system, the savings in fuel consumption will make it profitable within few years. The reduced fuel consumption also leads to lower emissions and thus, lower costs in form of taxes due to operations in emission controlled areas. The maintenance costs in the machinery system may also be reduced due to the lower amounts of low loading and a higher amount of time operating close to the optimal operating point. The result will depend totally on the operational profile. In every case of selecting machinery system the operational profile must be thoroughly evaluated.

The conclusion is that the more varying the operational profile is, all the more it favors a hybrid solution. It is to a large extent the percentage of time in DP operations that is the most determinant influencing factor. Several different operations is performed with DP and the dynamic loading picture may change from significant low loads to up to maximum power demand in matter of minutes in the worst cases. As for now, the savings are of a relative small magnitude regarding economics. However, if the technology of the batteries improves power output and reliability, the hybrid system will be even more superior compared to the DE system. In a pure environmental point of view, the benefits of a hybrid system include, not only vessels with DP, but also vessels with several transit speeds, typically yachts and ferries.

6.2.1 Vessels Suited for Hybrid with Energy Storage

In general terms it can be said that ships that experience a significant amount of low engine utilization within an operating cycle and/or large power variations, will have potential benefits from installing an energy storage package. Types of vessels that fall into the category are usually:

- Ferries
- Offshore Supply Vessels
- Research Ships
- FPSO's
- Military Vessels
- Yachts
- Cruise Ships
- Other Special ships that may use solar power, wind power or other renewable power sources.

Some vessels may also utilize pure battery operation. For this to be possible, the vessels must have frequent stays in ports where charging stations must be available. Their energy demands cannot be of a large magnitude, which means that their sailing distances and speed must be within relative short limits. All this means that it is the charging facilities in the ports, as well as the operating profile that sets the limits for the utilization of pure battery operations. Some types of vessels that may fit this profile are listed below:

- Ferries
- Passenger Vessels
- Short Sea Shipping

6.3 Further Work

At present there does not exist much real time data on machinery configurations with energy storage and its real effects. Some theoretical simulations have been conducted, where all give positive results for this type of configuration, given a varying and complex operational profile. The ongoing joint project FellowSHIP will be a huge step forward in the hybrid technology combining fuel cells and energy storage. The performance of the machinery will be monitored continuously and important real time data on fuel consumptions, emissions, efficiency and overall performance for the system as a whole, and also the battery itself, will be collected. The information gathered in this project can be used to further optimize and develop the concept of energy storage to reduce the emissions even more.

The extensive research on several types of large-scale batteries, such as lithium batteries, must be sustained and even intensified to further develop the capacity. It has proved to be an efficient way of improving the performance of vessel machinery, which experiences variations in power demand and loads in the way that the engines may operate at a more constant and optimal speed. With higher capacity batteries, the diesel engines may be reduced in size and further reduce the fuel consumption and emissions.

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8 Appendices

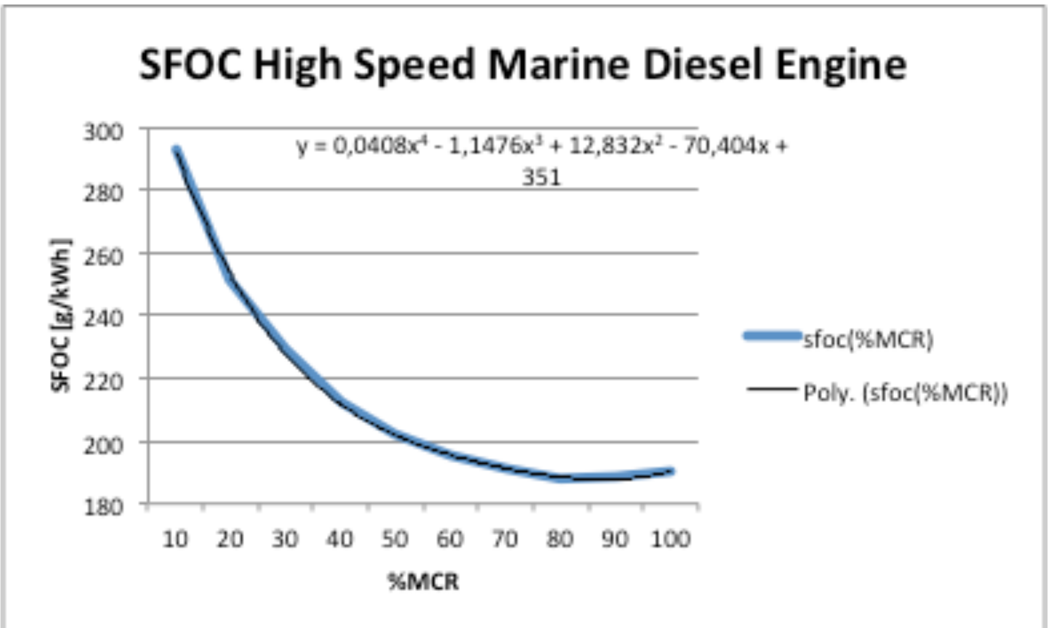
A.1 Engine Configuration

Machinery configuration:	DE	Hybrid
Main Engine Power [kW]	1800	1250
number of engines	4	4
Auxilary Engine Power [kW]	0	0
number of engines	0	0
Battery Pack [kWh]	0	2000
Total Installed Power [kW]	7200	7000

A.2 Calculated Sepcific Fuel Consumption

Engine Spec:	
%MCR	sfoc [g/kWh]
10	293
20	251
30	229
40	212
50	202
60	195
70	191
80	188
90	189
100	190

A.3 SFOC



A.4 DE Engine Loading Profile

Engine Load Profile:

Case 1: DE 4x2040kW@1000rpm					ME1 Power [%MCR]										ME2 Power [%MCR]									
Mode:	Time: [h]	%MCR	P [kW]	Var +/-%	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
1 Harbor	6	0,02	144	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2 Transit High	4	0,7	5040	0,1	0	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0	1	2	1	0
3 Transit Low	35	0,4	2880	0,1	0	0	0	0	15	20	0	0	0	0	0	0	0	0	15	20	0	0	0	0
4 DP high	10	0,45	3240	0,3	0	0	0	0	0	2	0	6	0	2	0	0	0	0	0	2	0	6	0	2
5 DP Low	39	0,2	1440	0,5	0	0	0	25	14	0	0	0	0	0	0	0	0	25	14	0	0	0	0	0
sfoc:					293	251	229	212	202	195	191	188	189	190	293	251	229	212	202	195	191	188	189	190
[kWh]					216	0	0	9000	15840	16020	1260	7380	1260	1620	0	0	0	9000	15840	16020	1260	7380	1260	1620
FOC [ton]					0,06	0,00	0,00	1,91	3,20	3,12	0,24	1,39	0,24	0,31	0,00	0,00	0,00	1,91	3,20	3,12	0,24	1,39	0,24	0,31

					ME3 Power [%MCR]										ME4 Power [%MCR]									
Mode:	Time: [h]	%MCR	P [kW]	Var +/-%	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
1 Harbor	6	0,02	144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2 Transit High	4	0,7	5040	0,1	0	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0	1	2	1	0
3 Transit Low	35	0,4	2880	0,1	0	0	0	0	15	20	0	0	0	0	0	0	0	0	15	20	0	0	0	0
4 DP high	10	0,45	3240	0,3	0	0	0	0	0	2	0	6	0	2	0	0	0	0	0	2	0	6	0	2
5 DP Low	39	0,2	1440	0,5	0	0	0	25	14	0	0	0	0	0	0	0	0	25	14	0	0	0	0	0
sfoc:					293	251	229	212	202	195	191	188	189	190	293	251	229	212	202	195	191	188	189	190
[kWh]					0	0	0	9000	15840	16020	1260	7380	1260	1620	0	0	0	9000	15840	16020	1260	7380	1260	1620
FOC [ton]					0,00	0,00	0,00	1,91	3,20	3,12	0,24	1,39	0,24	0,31	0,00	0,00	0,00	1,91	3,20	3,12	0,24	1,39	0,24	0,31

A.5 Hybrid Engine Loading Profile

Operational Load Profile:

Case 2:Hybrid 4x1250kW_Battery*2000kWh

					ME1 Power [%MCR]										ME2 Power [%MCR]									
Mode:	Time: [h]	%MCR	P [kW]	Var +/-%	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
1 Harbor	6	0,02	144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2 Transit High	4	0,7	5040	0,1	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	4
3 Transit Low	35	0,4	2880	0,1	0	0	0	0	0	0	0	0	35	0	0	0	0	0	0	0	0	0	35	0
4 DP high	10	0,45	3240	0,3	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	10
5 DP Low	39	0,2	1440	0,5	0	0	0	0	0	0	0	29	10	0	0	0	0	0	0	0	0	29	10	0
sfoc:					293	251	229	212	202	195	191	188	189	190	293	251	229	212	202	195	191	188	189	190
[kWh]					0	0	0	0	0	0	0	10440	28800	13140	0	0	0	0	0	0	0	10440	28800	13140
FOC [ton]					0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,96	5,44	2,50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,96	5,44	2,50

					ME3 Power [%MCR]										ME4 Power [%MCR]									
Mode:	Time: [h]	%MCR	P [kW]	Var +/-%	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
1 Harbor	6	0,02	144	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2 Transit High	4	0,7	5040	0,1	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	4
3 Transit Low	35	0,4	2880	0,1	0	0	0	0	0	0	0	0	35	0	0	0	0	0	0	0	0	0	0	0
4 DP high	10	0,45	3240	0,3	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	10
5 DP Low	39	0,2	1440	0,5	0	0	0	0	0	0	0	29	10	0	0	0	0	0	0	0	0	29	10	0
sfoc:					293	251	229	212	202	195	191	188	189	190	293	251	229	212	202	195	191	188	189	190
[kWh]					0	0	0	0	0	0	0	10440	28800	13140	0	0	0	0	0	0	0	10440	3600	13140
FOC [ton]					0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,96	5,44	2,50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,96	0,68	2,50

A.6 Fuel Consumption Diesel Electric

h/rt	94
rt/year	59
FOC ME1 [ton/rt]	10,4689
FOC ME2 [ton/rt]	10,4056
FOC ME3 [ton/rt]	10,4056
FOC ME4 [ton/rt]	10,4056
Total FOC [ton/rt]	41,6858

A.7 Fuel consumption Hybrid

h/rt	94
rt/year	59
FOC ME1 [ton/rt]	9,9025
FOC ME2 [ton/rt]	9,9025
FOC ME3 [ton/rt]	9,9025
FOC ME4 [ton/rt]	5,1397
Total FOC [ton/rt]	34,8473

Hybrid

A.8 Battery Cycles

Operating mode	Duration [h]	Prequired	Prequired [kW]	Battery Contribution [kW]	Energy from Battery [kWh]	%Battery Capacity
Harbor	6	0,02	144	144	864	0,43
Transit low	17	0,4	2880	0	charging	-
DP high	3	0,45	3888	388	1164	0,58
DP low	8	0,2	1728	0	charging	-
Transit high	1	0,7	5040	1540	1540	0,77
DP high	2	0,45	3888	388	776	0,39
DP low	8	0,2	1728	0	charging	-
Transit high	1	0,7	5040	1540	1540	0,77
DP high	2	0,45	3888	388	776	0,39
DP low	8	0,2	1728	0	charging	-
Transit high	2	0,7	5040	790	1580	0,79
DP low	15	0,2	1728	0	charging	-
Transit low	18	0,4	2880	0	charging	-

A.9 Battery Self Discharge Rate

self-discharge rate	0,03	%/year
year	battery capacity	
0	2000	kWh
1	1940	kWh
2	1882	kWh
3	1825	kWh
4	1771	kWh
5	1717	kWh
6	1666	kWh
7	1616	kWh
8	1567	kWh
9	1520	kWh
10	1475	kWh
11	1431	kWh
12	1388	kWh
13	1346	kWh
14	1306	kWh
15	1267	kWh
16	1229	kWh
17	1192	kWh
18	1156	kWh
19	1121	kWh
20	1088	kWh

A.10 Case with constant Fuel Price and Battery Cost of Renewal

year	fuel price	DE	Hybrid	Diesel Electric	Hybrid	Difference
0	900	2 520 000	4 500 000	3	5	-1 980 000
1	900	5 080 194	6 640 198	5	7	-1 560 004
2	900	7 640 389	8 780 397	8	9	-1 140 008
3	900	10 200 583	10 920 595	10	11	-720 012
4	900	12 760 777	13 060 793	13	13	-300 016
5	900	15 320 972	15 200 991	15	15	119 980
6	900	17 881 166	17 341 190	18	17	539 976
7	900	20 441 360	19 481 388	20	19	959 972
8	900	23 001 555	21 621 586	23	22	1 379 968
9	900	25 561 749	23 761 784	26	24	1 799 965
10	900	28 121 943	28 301 983	28	28	-180 039
11	900	30 682 138	30 442 181	31	30	239 957
12	900	33 242 332	32 582 379	33	33	659 953
13	900	35 802 526	34 722 577	36	35	1 079 949
14	900	38 362 721	36 862 776	38	37	1 499 945
15	900	40 922 915	39 002 974	41	39	1 919 941
16	900	43 483 109	41 143 172	43	41	2 339 937
17	900	46 043 304	43 283 371	46	43	2 759 933
18	900	48 603 498	45 423 569	49	45	3 179 929
19	900	51 163 692	47 563 767	51	48	3 599 925
20	900	53 723 887	52 103 965	54	52	1 619 921
21	900	56 284 081	54 244 164	56	54	2 039 917
22	900	58 844 275	56 384 362	59	56	2 459 913
23	900	61 404 469	58 524 560	61	59	2 879 909
24	900	63 964 664	60 664 758	64	61	3 299 905
25	900	66 524 858	62 804 957	67	63	3 719 901
26	900	69 085 052	64 945 155	69	65	4 139 897
27	900	71 645 247	67 085 353	72	67	4 559 894
28	900	74 205 441	69 225 552	74	69	4 979 890
29	900	76 765 635	71 365 750	77	71	5 399 886
30	900	79 325 830	75 905 948	79	76	3 419 882
31	900	81 886 024	78 046 146	82	78	3 839 878
32	900	84 446 218	80 186 345	84	80	4 259 874
33	900	87 006 413	82 326 543	87	82	4 679 870
34	900	89 566 607	84 466 741	90	84	5 099 866
35	900	92 126 801	86 606 939	92	87	5 519 862
36	900	94 686 996	88 747 138	95	89	5 939 858
37	900	97 247 190	90 887 336	97	91	6 359 854
38	900	99 807 384	93 027 534	100	93	6 779 850
39	900	102 367 579	95 167 732	102	95	7 199 846
40	900	104 927 773	99 707 931	105	100	5 219 842

A.11 Case with varying Fuel Price and Battery Cost of Renewal

year	fuel price	DE	Hybrid	Diesel Electric	Hybrid	Savings
0	900	2 520 000	4 500 000	3	5	-1 980 000
1	918	5 124 257	6 677 033	5	7	-1 552 776
2	936	7 773 458	8 891 636	8	9	-1 118 178
3	955	10 468 502	11 144 562	10	11	-676 060
4	974	13 210 306	13 436 577	13	13	-226 271
5	994	15 999 804	15 768 463	16	16	231 342
6	1 014	18 837 952	18 141 016	19	18	696 936
7	1 034	21 725 721	20 555 051	22	21	1 170 670
8	1 054	24 664 105	23 011 397	25	23	1 652 707
9	1 076	27 654 115	25 510 901	28	26	2 143 214
10	1 097	30 696 784	29 974 424	31	30	722 359
11	1 119	33 793 165	32 562 849	34	33	1 230 316
12	1 141	36 944 333	35 197 072	37	35	1 747 260
13	1 164	40 151 383	37 878 011	40	38	2 273 372
14	1 188	43 415 433	40 606 598	43	41	2 808 835
15	1 211	46 737 622	43 383 787	47	43	3 353 835
16	1 236	50 119 115	46 210 551	50	46	3 908 564
17	1 260	53 561 096	49 087 880	54	49	4 473 216
18	1 285	57 064 775	52 016 786	57	52	5 047 989
19	1 311	60 631 387	54 998 301	61	55	5 633 086
20	1 337	64 262 190	59 569 476	64	60	4 692 714
21	1 364	67 958 469	62 659 385	68	63	5 299 083
22	1 391	71 721 531	65 805 123	72	66	5 916 408
23	1 419	75 552 713	69 007 806	76	69	6 544 908
24	1 448	79 453 379	72 268 573	79	72	7 184 806
25	1 477	83 424 916	75 588 585	83	76	7 836 331
26	1 506	87 468 743	78 969 028	87	79	8 499 714
27	1 536	91 586 305	82 411 110	92	82	9 175 194
28	1 567	95 779 077	85 916 065	96	86	9 863 012
29	1 598	100 048 564	89 485 148	100	89	10 563 415
30	1 630	104 396 299	94 348 444	104	94	10 047 855
31	1 663	108 823 848	98 049 660	109	98	10 774 187
32	1 696	113 332 806	101 818 931	113	102	11 513 875
33	1 730	117 924 803	105 657 617	118	106	12 267 186
34	1 765	122 601 498	109 567 108	123	110	13 034 391
35	1 800	127 364 586	113 548 818	127	114	13 815 768
36	1 836	132 215 795	117 604 194	132	118	14 611 602
37	1 873	137 156 887	121 734 707	137	122	15 422 180
38	1 910	142 189 660	125 941 861	142	126	16 247 799
39	1 948	147 315 946	130 227 188	147	130	17 088 759
40	1 987	152 537 618	136 992 252	153	137	15 545 366