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Hybridization of General Cargo Ships to meet the Required Energy Efficiency Design Index

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MASTER THESIS IN MARINE TECHNOLOGY

for

Stud. techn. Magnus Anders Øverleir

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"Hybridization of General Cargo Ships to meet the Required Energy Efficiency Design Index"

Background

The global shipping industry emits around 3% of the global greenhouse gas emissions; this is a relatively small number taking into account that the fleet stands for approximately 90% of the worlds trade volume. Although shipping is the best way of transporting large volumes of goods (per today), the industry stands before large improvements in the years to come. The commercial shipping sector's volume will, according to Lloyd's, double from 2010 to 2030. The Energy Emission Design Index adopted by the IMO in 2011 will affect most of these new ships. Phase 1, 2 and 3 will force an EEDI reduction of respectively 10%, 20% and 30% relative to the reference line for the ship type. The design of the newbuidings in the different phases must take the EEDI into account – this will affect the whole chain from naval architects to the ship owners to the yards.

For many ship types the EEDI requirements can be achieved by simply decreasing the design speed and with that the CO_2-emissions. Many of the smaller ships that transport goods along the coast are general cargo ships. These ships have a special role in the worlds trade, carrying almost any type of goods. This may lead to a poorer EEDI, due to the complex and diverse composition of carried goods (low dwt). These ship types may have to reduce their speed to comply with the EEDI requirements. This implicates that the sea margin gets smaller and the maneuverability in adverse sea conditions poorer.

A possible way of complying with the required EEDI (phase 1, 2 or 3) can be to install a hybrid electrical system. Under design conditions (i.e. NCR on main engine(s)) the battery-pack can be charged and the stored energy can be used when the ship needs more power in adverse conditions. The idea is to have an energy buffer in case of the need for extra propulsion power and being able to install less engine power. The battery pack can be combined with systems onboard, for example cargo cranes and give a more efficient energy usage onboard.

Objective

Perform a study on installing a hybrid system with energy storage in general cargo vessels and examine how this will influence the ships EEDI.

Scope and main activities

1. **Present the EEDI regulation from IMO**
2. **Provide a theoretical summary for the possibility of hybridization with energy storage of general cargo ships.**
    a. **Technical feasibility**
    b. **Economical feasibility**
3. **Evaluate the advantages and disadvantages of a hybrid system with energy storage.**
4. **Perform a case study with battery energy storage in general cargo ships.**
5. **Discuss the results and conclude.**

Modus operandi

The responsible advisor will be Professor Stein Ove Erikstad at Department of Marine Technology NTNU.

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

Deadline: 10.06.2015

Stein Ove Erikstad
Professor/Responsible Advisor

Preface

This report represents my master thesis for the degree of Master of Science in Marine Technology at The Norwegian University of Science and Technology, NTNU. The thesis is a part of the specialization programme in Marine Systems Design & Logistics. The workload is carried out by the author during the spring semester 2015 and represents 30 ECTS.

The scope of the thesis was developed by the author and has been an attempt to enter a current theme that has not yet been widely explored. The overall aim has been to find out if installing a battery hybrid system in small general cargo ships can help the segment in complying with the energy efficiency design index regulation.

I have learned a great deal about working independent this semester. Trying to meet the expectations set in the beginning of the semester has been demanding and challenging. It was hard to retrieve the right information, but some help from few in the industry has been helpful.

I would like to thank my academic supervisor Professor Stein Ove Erikstad and Dr. Haakon Lindstad at MARINTEK for interesting discussions. From the industry I would like to thank Knut Selle at Eidesvik, Hans Anton Tvete at DNV GL, Egil Mollestad at ZEM and Roman Stoiber at Grenland Energy. I would also thank my classmates for five memorable years and my friends at office A1.015 for making the days fly by. Last but not least, I am filled with gratitude for my girlfriend's support during the studies and in life; I could not have done it without her.

Trondheim June 10th 2015

Magnus Øverleir

Summary

In this thesis a hybrid propulsion system is proposed for a general cargo ship with the aim to meet the required Energy Efficiency Design Index (EEDI). The study has investigated how a hybrid propulsion system will influence the ship's EEDI value and fuel economy. The central problem is the coming challenge for the general cargo segment meeting the required efficiency value. Especially small vessels (3 000-15 000 DWT) with high speed will have troubles complying with the stricter regulations. This topic is highly relevant because of stricter regulations on ships' energy efficiency and because hybrid technology has a large potential in the maritime industry.

The theme has been investigated throughout a systems study, assessing the advantages and disadvantages of a hybrid propulsion system. The technical and economical feasibility has been studied and a case has been performed to exemplify the hybrid propulsion system in general cargo ships. Based on the information obtained from the industry, a broad literature study and a case study, conclusions were drawn on the feasibility of the system.

The results of the study showed that it is fully possible to install a hybrid propulsion system in a general cargo vessel with the result of lowering the attained EEDI value. A hybrid battery system will increase the operational energy efficiency of a general cargo ship. Due to the lack of real ship operational data, some generalizations had to be made regarding values. The sizing of the battery was based on how much could be saved by installing a smaller main engine. Lithium-ion battery packs are the most fitting technology for the hybrid system. A high energy battery system with the ability to handle load variations is the most suiting for general cargo operation. It is also suggested that the cargo handling gear should be electric and served by the hybrid power system onboard. Based on the estimates of fuel reduction in the case study it will be economically feasible to install a hybrid system in small general cargo ship.

Sammendrag

I denne avhandlingen er et hybrid fremdriftssystem foreslått installert i små stykkgodsskip med mål om å senke verdien av designindeksen for energieffektivitet (EEDI). Studien har undersøkt hvordan et hybrid fremdriftssystem vil påvirke skipets EEDI-verdi og drivstofføkonomi. Det sentrale problemet er de kommende utfordringene for stykkgodsskip i møte med nye effektivitetskrav. Spesielt små skip (3 000-15 000 DWT) med høy hastighet vil ha problemer med effektivitetskrav i de kommende årene. Dette emnet er høyst relevant på grunn av nye regler nå og i nær fremtid og fordi hybridteknologi har et stort potensial i den maritime næringen.

Temaet har vært undersøkt gjennom et systemstudie, hvor fordeler og ulemper ved et hybrid fremdriftssystem har blitt vurdert. Den tekniske og økonomiske gjennomførbarhet har blitt studert og en case-studie har blitt utført for å eksemplifisere hybride fremdriftssystem i stykkgodsskip. Basert på informasjon innhentet fra bransjen, en bred litteraturstudie og case ble det truffet konklusjoner.

Resultatene av undersøkelsen viste at det er fullt mulig å installere et hybrid fremdriftssystem i et stykkgodsskip for å senke EEDI-verdien. På grunn av mangel på ekte skipsdata måtte noen generaliseringer i studien gjøres vedrørende tallverdier. Dimensjonering av batteriet var basert på et estimat om hvor mye som kan spares ved å installere en mindre hovedmotor. Lithium-ion batteripakker er mest passende batteriteknologi for bruk i våre eksempelskip. Et høy-energi batterisystem med evnen til å håndtere belastningsvariasjoner er det mest egnede for operasjonsprofilen til stykkgodsskip. Det er også foreslått at laste- og losseinnretninger skal være elektrisk og betjent av det hybride systemet ombord. Basert på estimater fra casestudien vil det være økonomisk forsvarlig å installere hybridsystemer i nybygg av typen små, raske stykkgodsskip.

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1. Introduction

The world stands before major challenges in our generation. It is commonly agreed upon that a threat of global warming is happening right at this moment. Global shipping is not just a part of the global warming problem; it is also a part of the solution. Shipping is the most environmentally friendly way of transporting goods today, but the potential is bigger. The International Maritime Organisation has given the shipping industry a goal for development, the Energy Efficient Design Index (EEDI). The EEDI is a performance-based index that forces newbuildings to fulfil a minimum value of energy efficiency in transporting goods. Ship designers and builders stand free to choose which technology to use for complying with the regulations. In the automotive industry there has been an electrical revolution – the hybrid cars are becoming better and cheaper. DNV GL has stated that "the future is hybrid" and the technology is just in the beginning.

For some ship types the EEDI will be hard to comply with. The general cargo ship segment is a shipping sector that is crucial for the global trade to function. Steaming out from the larger hubs with all kinds of cargo onboard. These small workhorses of the sea are often specialized for niche markets, but also optimized for carrying many types of cargo. The optimization towards flexibility in cargo and operation has lead to a poor performance in the EEDI equation. Especially smaller ships with high speed will have big problems facing the required value in the EEDI.

1.1. Problem description

The main scope of the thesis will be to address the possibility of installing a hybrid system in a general cargo ship with the purpose of complying with the required EEDI. A theoretical assessment of the possibility of installing a hybrid system with batteries shall be shall be carried out. Advantages and disadvantages of installing a battery hybrid in a general cargo ship will be addressed and discussed. A case study shall together with the result form a basis for concluding upon the feasibility of hybrid systems in general cargo ships.

1.2. Limitations

Some limitations in the work with the thesis should be mentioned. The thesis was based on an idea of solving an upcoming challenge that the maritime industry and the general cargo segment will face soon. Using innovative technology to solve a challenge is both very interesting and hard and today there have not been many studies on the theme before.

Retrieving information has been one of the greatest challenges during the process. Some potentially helpful sources have not been answering on requests of sharing information. The result of not cooperating with an industry partner has been lack of real ship operation data to analyze; this may have influenced some of the results. The thesis has not been based on work done in project thesis of fall 2014, this may have influence on the dept of the study.

1.3. Structure of report

The report has the aim show the reader a logical insight in the study on battery hybrid propulsion system for general cargo ships with focus on EEDI.
Chapter 1 – Gives an introduction to the problem and sets the limitations for the scope.
Chapter 2 – Describes the background for the thesis – why there is a need for investigating the chosen subject.
Chapter 3 – The assessment of the operation of a hybrid system. What do the hybrid system contribute with in operating the ship.
Chapter 4 – Investigates the main types of hybrid propulsion systems and discusses the different technical aspects.
Chapter 5 – Studies the components in a hybrid system and discusses the advantages and disadvantages of the different parts and choices. Address the impact the system have on ship design and discusses the costs.
Chapter 6 – Using case ships to perform a study based on results sound in the latter chapters and assumptions made by the author. Justifies the assumptions by technical and economical results.
Chapter 7 – The drawn conclusion based on the study.
Chapter 8 – Propose further work on the theme.

2. Background

2.1. Emissions from shipping

It is generally accepted that shipping stands for more than 90 percent of international trade (IMO 2012). Shipping routes of raw materials and goods are the veins that nurture the global economy – without shipping it will not be possible to develop the world as seen today. In 2010 the total amount of seaborne cargo was 8 408 million tons (IMO 2012). Today there are no other transportation options than shipping that can transport the same amount of cargo with less use of energy. Seaborne trade will also in the future grow alongside with the growth in economy. According to "Global Maritime Trends 2030" the energy demand will be 40% higher than in 2010, the tanker tonnage will grow 1,7-1,8 times and container/bulk carriers/LNG carriers is expected to grow between 1,8 to 3 times (Qinetiq, Lloyd's et al. 2013)

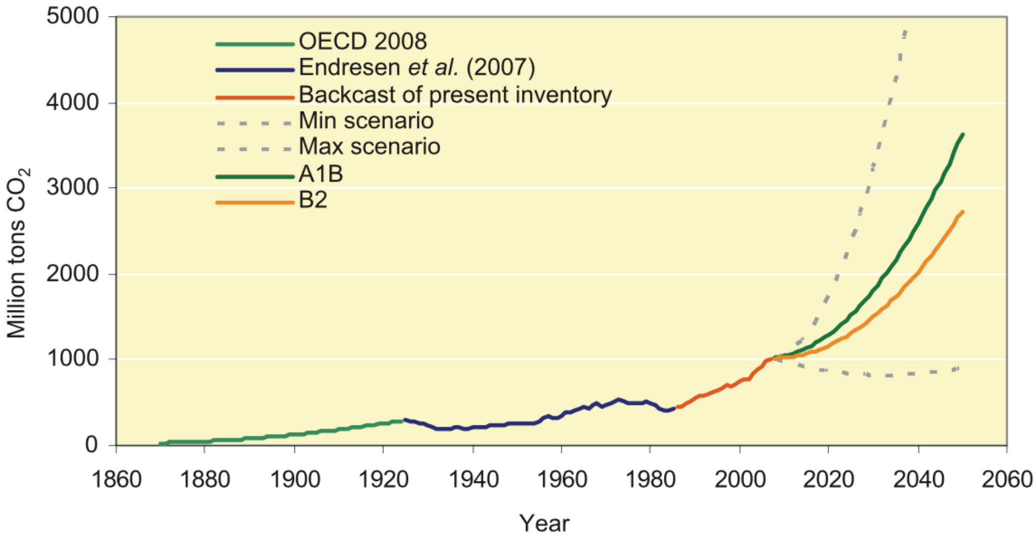

Figure 1 - Scenarios for ship emissions in historic perspective (IMO GHG study 2009)

According to the third IMO GHG study 2014, international shipping, on average, accounted for approximately 3,1% of the annual global CO_2-emissions between 2007-2012. Annually 900 million tonnes of CO_2 is emitted from shipping (Hodne, Longva et al. 2014). The average percentage of the annual global CO_2e from shipping is 2,8%, when using a 100-year global warming potential convention. The amount of marine fuel used globally was in the same interval 250 million and 325 million tonnes, this reflecting the top-down and bottom-up methods, respectively (MEPC 2014:1). IMO states that these emissions are likely to rise between 50% and 250% to 2050 if the “business as usual” scenario sets into place, all depending on the future drivers development such as energy, politics and economic (MEPC 2014). As seen from the graph above, from the 2009 GHG report from IMO, different scenarios are possible for the future emissions. But it is certain that the maritime shipping shows significant advantages when it comes to GHG emissions compared to road and air born trade. It is also shown that it is highly competitive with rail (IMO 2009).The world’s shipping fleet will grow in the years to come and the newbuilds will meet new standards and demands set from both local and global legislators.

The principle of a combustion engine is to burn a mixture of fuel and air. This combustion shall result in mechanical energy converted to thrust throughout the shaft and propeller. This combustion cycle also produces exhaust gases: Carbon dioxide (CO_2) affects climate only, while carbon monoxide (CO), sulphur oxides (SO_x), nitrogen oxides (NO_x), methane (CH_4), black carbon (BC) and organic carbon (OC) have impact on both climate and health for human and animals (Lindstad and Sandaas 2014). The amount of CO_2 in the exhaust correlates with the amount of carbon in the fuel. To reduce the exhaust content of CO_2, one must use a fuel with less carbon content, or catch the CO_2 and store it. To reduce the CO_2 emissions total, a more energy efficient ship and alternative fuels/energy sources are the solution. This thesis will focus most on the CO_2 emissions from shipping; this is the pollutant the EEDI takes into account. The NO_x and SO_x have restrictions due to the harm to health for humans and animals, but the emissions of these gases mitigate against global warming (Lindstad and Sandaas 2014). In the future one will meet more focus on the CO_2 emissions from shipping and aim to reduce the amount of CO_2 emitted per tonne mile.

2.1.1. Drivers in global shipping

To change the trends in growing GHG emissions from shipping, there are several ways to the goal. One must also have more than one thought in mind at the same time. The change can be driven by legislative powers, globally with IMO and locally with port state regulations (there are of course much more organisations and legislative powers in the world which we will not discuss here). The ship owner and the charterer will also strive against a more energy efficient way of operating the ships. Energy efficiency is directly proportional with the money spent on fuel, so a decrease in fuel usage will decrease the expanses and the harm on the environment. The latter case of energy efficiency is what should be held up as a goal for shipping. Doing investments that will make shipping more energy efficient, less harmful for the environment and humans and can compete in price in the long term – will make it possible to have your cake and eat it too. If the investments are not economically sustainable the ship owners won't listen to the proposal. The naval architect shall make it possible to meet the coming regulations in a manner that makes sense both technical and economical.

2.2. Maritime pollution

The International convention for the Prevention of Pollution from Ships (MARPOL) was adopted in 1973 and put into force 2nd of October 1983. The Convention includes both pollution from marine accidents and normal operation and aims to prevent and minimize these (IMO 2015). The MARPOL convention lays the ground for all shipping pollution. In 1997 the air pollution annex was added to the MARPOL convention and the work with minimizing SO_x and NO_x was aimed. The IMO worked from this point with undertaking a study with the aim of determining the emissions from shipping. At the 59th MEPC session in 2009 the second Green House Gas study was presented and the principles of a mandatory Energy Efficiency Design Index (EEDI) was approved. Two years later at the 62nd MEPC the EEDI together with the SEEMP were adopted as parts of the MARPOL convention (Lindstad and Sandaas 2014).

2.2.1. Regulations

Heavy fuel oil (HFO) dominates as the preferred fuel for ships. In year 2010 the total consumption for maritime transportation was 330 [million TOE/year][1], of which HFO stood for 280 [mill TOE] and MDO 50 [mill TOE] (Chryssakis, Balland et al. 2014). Special areas such as The Baltic Sea have suffered from emissions as SO_x, NO_x and particle matters (PM) from shipping. Emission Control Areas (ECAs) have been established and shall act as an area where the amount of emission

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[1] TOE – Tonne of oil equivalent, 41,87 gigajoules

from burned fuel shall be within certain limits. There are one ECA in Europe and one in North America. For the European ECA the reduction of NO_x has been the target (NECA), but in the US both SO_x and NO_x are regulated (NECA/SECA). The limits are expressed in terms of % m/m – that is by weight percentage of sulphur content in exhaust released to the atmosphere (MEPC 2014).

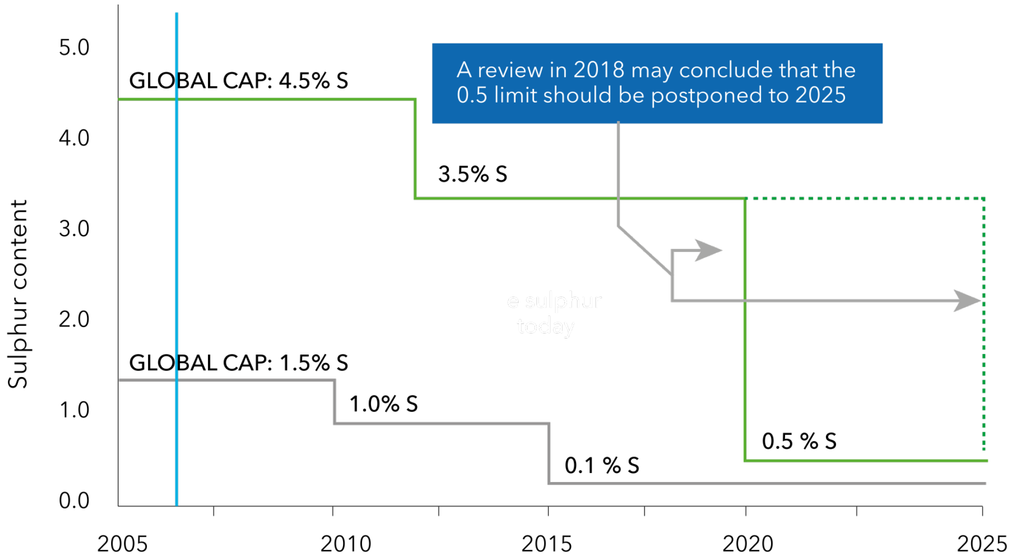


Figure 2 - Emission regulations to be put in action (DNV GL)

There are also some indications that a global price for CO_2-emissions from shipping will be implemented in the future (Ådland 2014). Further regulations that is approaching is the NO_x Tier 3 for newbuildings in ECAs from 2016 (IMO 2014). As seen from Figure 3 three phases of the EEDI (Energy Efficiency Design Index) shall be implemented in the years to come. It applies to all new ships above 400 GT, new ships which has undergone a major convention and new or existing ship which has undergone a major convention that is so extensive that the ship is regarded by the Administration as a newly constructed ship (MEPC 2011). The calculated EEDI for the abovementioned ships shall meet the requirements set by the Marine Environmental Protection Committee. Each ship must be better when it comes to energy efficiency than a given reference line. The main purpose of the EEDI is to drive the shipping industry towards ships with regulations that force the designers/owners/yards to build a more energy efficient ship than the comparable ships. The EEDI phase 1 will go into force from 2015, phase 2 in 2020 and phase 3 in 2025. The rising number of the phases implicates a higher reduction factor of the EEDI relative to the reference line.

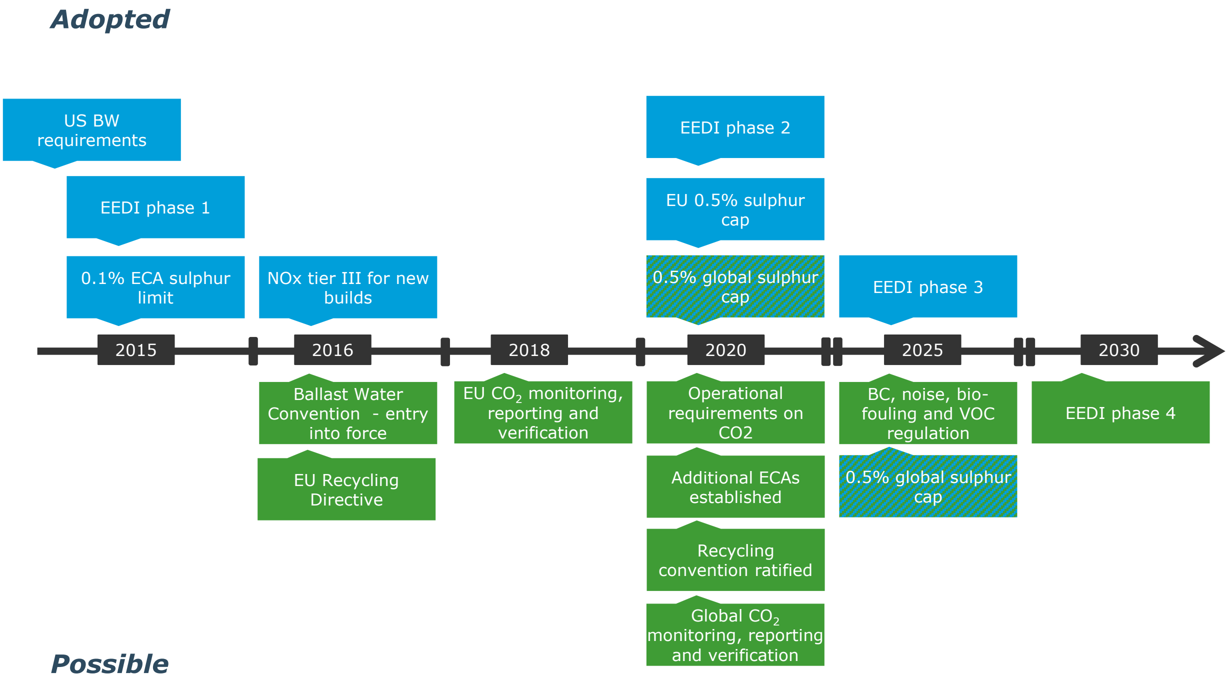


Figure 3 - Adopted and possible regulations (Balland 2014)

For existing ships the Regulation 22 of the MEPC 62, called Ship Energy Efficiency Management Plan (SEEMP), was made mandatory in July 2011. The regulation demands that every ship over 400 GT (covered by MARPOL annex VI) shall have a SEEMP onboard the ship (Balland 2014). The SEEMP shall contain a list of measures to make the particular ship operation more energy efficient (MEPC 2011).

2.3. Energy Efficiency Design Index (EEDI)

The energy efficiency design index (henceforth EEDI) was put into force on the 59th MEPC session from 13th-17th of July 2009. The mission is to stimulate innovation and technical development of everything that influences the energy efficiency of a ship in the design phase of a newbuild (IMO 2009). The EEDI regulation has been affecting ships that were built on a building contract placed on or after 1 January 2013 or the keel laid on or after 1 July 2013 or if the delivery date was on or after 1 July 2015 (MEPC 2011).

2.3.1. General

The EEDI is a power law relationship between the emissions of carbon dioxide, gCO_2/tonne nautical mile (t nm) and the capacity of the ship in deadweight (DWT). In the EEDI equation a lot of subsystems are taken into account including engine size, load and recovery systems for energy (Walsh and Bows 2012).

The index contains two values for the ship that must be seen in relation with the deadweight. During the design phase the value of the ships EEDI must be evaluated. It must be proven that the ships *attained* EEDI does not exceed the values set by the IMO, the *required* EEDI. The *attained* EEDI, which is a cost/benefit number, can be seen as a relation between the CO_2 discharge and the resulting transport work. It shows how much CO_2-emissions that is produced per transport work.

$$EEDI_{attained} = \frac{CO_2 - emission}{Benefit\ \ of\ \ ship} = \frac{\sum P \times C_F \times SFC}{CAPACITY \times SPEED}$$

Equation 1 - Simplified equation for the attained EEDI.

As seen from Equation 1 the carbon dioxide emissions from the ship at the design speed are divided by the benefit to the society that the ship has (MAN 2008). The benefit for the society is the capacity of transported goods, i.e. deadweight times the speed. The equation is very simplified and the actual equation given by the IMO contains a lot more information (explained in 2.4.2). But the main purpose of the EEDI can be read out of this equation: The amount of CO_2 per transported tonne mile shall be as little as reasonable possible. The lower the EEDI value is the more energy efficient is the ship.

2.4. Required and attained value

The *required* and *attained* values relationship is reflected by the formula:

$$\text{Attained EEDI} \le \text{Required EEDI} = (1 - X / 100) \times \text{Reference line value}$$

Equation 2 - Requirement of EEDI (IMO MEPC.203(62))

X is the reduction factor specified by MARPOL Annex VI of MEPC 66. The reduction factors for the ship type general cargo and the other main ship types (some intentionally left out) are listed in the Table 2-1. For the cases of which the deadweight (DWT) is between 3000 and 15000, the reduction factor shall be linearly interpolated between the two values dependent on the vessel size (MEPC 2011).

Ship type	**Size**	Phase 0 1. Jan 2013 – 31. Dec 2014	Phase 1 1. Jan 2015 – 31. Dec 2019	Phase 2 1. Jan 2020 – 31. Dec 2024	Phase 3 1. Jan 2025 and onwards
General cargo ships	15,000 DWT and above	0	10	15	30
	3,000 – 15,000 DWT	n/a	0 - 10	0 - 15	0 – 30
Bulk carrier	20,000 DWT and above	0	10	20	30
	10,000 – 20,000 DWT	n/a	0 - 10	0 – 20	0 – 30
Tanker	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0 - 10	0 – 20	0 – 30
Container ship	15,000 DWT and above	0	10	20	30
	10,000 – 15,000 DWT	n/a	0 - 10	0 – 20	0 – 30

Table 2-1 - Reduction factors (in percentage) relative to the EEDI reference line (MEPC 2011).

The ship types general cargo and refrigerated cargo holds a special position, as these types are the only two who has a reduction factor of 15 in phase 2. Bulk carriers, gas carriers, tankers, container ships and combination carriers have a reduction factor of 20 in phase 2. This will be a challenge to overcome for the general cargo ship segment. A doubling in the reduction factor from 2020 to 2025 can become hard to comply with.

2.4.1. Required EEDI value

To find the required EEDI value, Equation 3 is used. The reduction factor *X* is found in the resolution MEPC.203(62). Reduction factors for the general cargo ship type are listed in Table 2-1. If a ship shall fall in under several categories of the listed ones in the resolution the required EEDI for the ship shall be the most stringent. The reference line value shall be calculated as follows:

$$reference\ line\ value = a \cdot b^{-c}$$

Equation 3 - Reference line value

Ship type defined in regulation 2	a	b	c
Bulk carrier	961.79	DWT of the ship	0.477
Tanker	1218.80	DWT of the ship	0.488
Container ship	174.22	DWT of the ship	0.201
General cargo ship	107.48	DWT of the ship	0.216

Table 2-2 - Parameters for calculation of the reference line value for selected ship types (MEPC 2011).

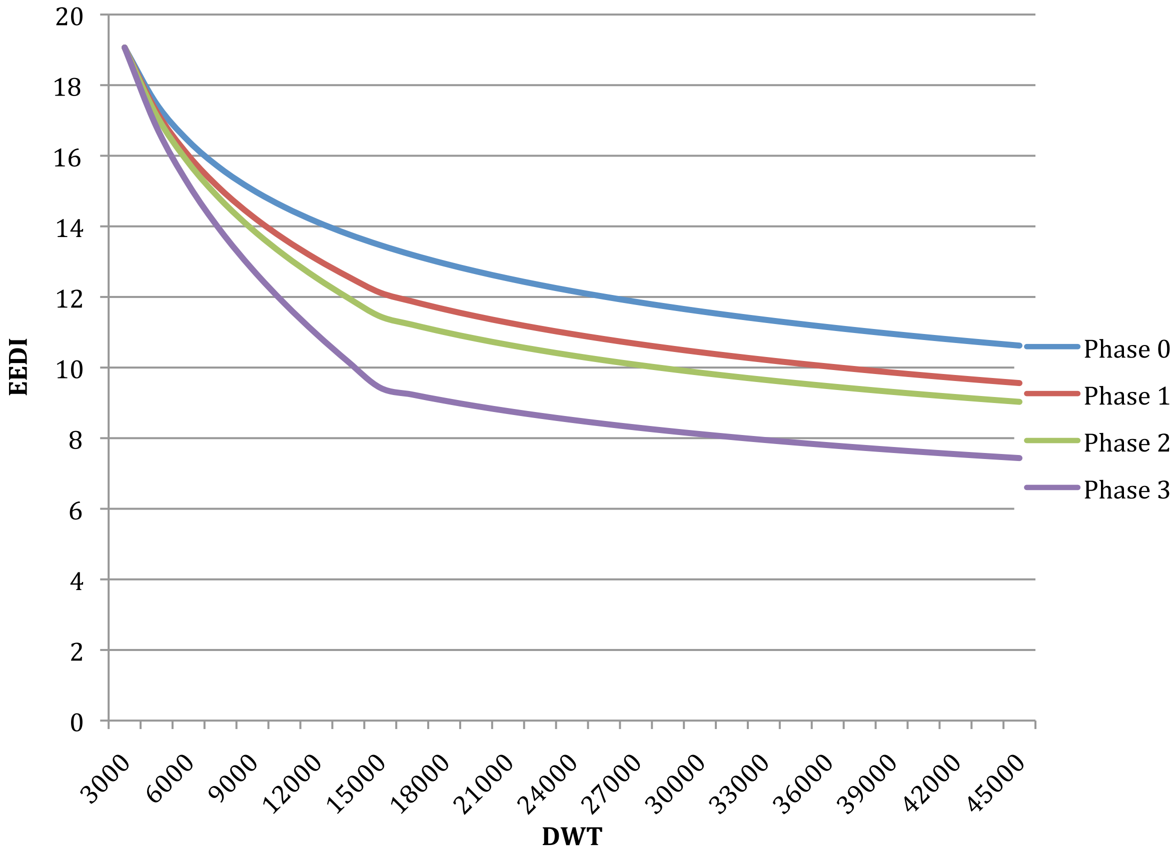
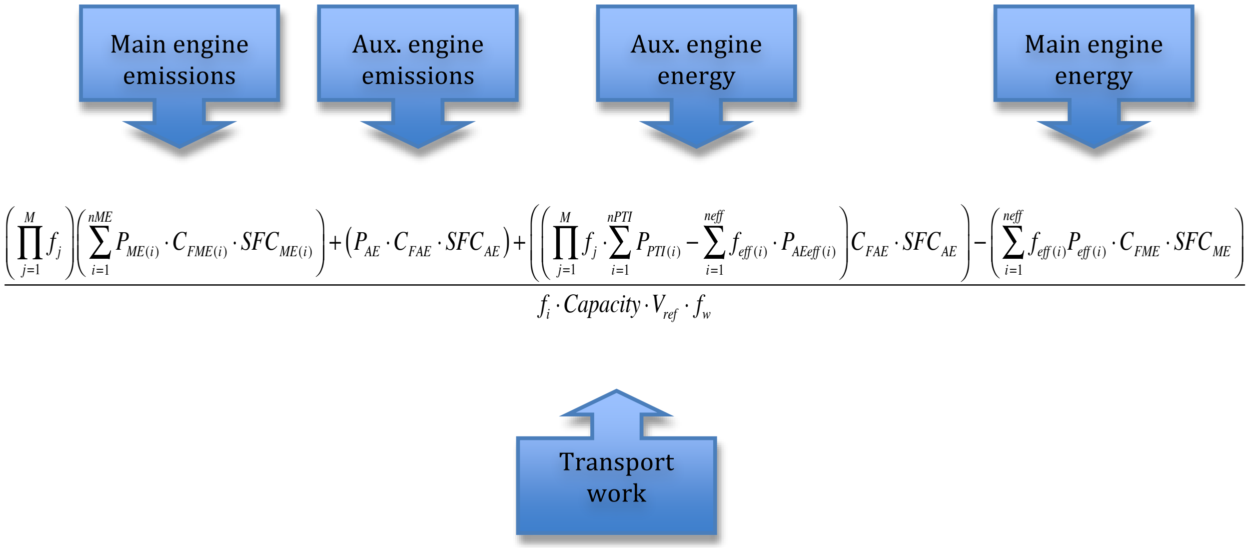


Figure 4 - Required EEDI for general cargo ships above 3000 DWT.

Plotting these parameters with the deadweight on the ship along the x-axis and the required EEDI vale on the y-axis, we get the plot in Figure 4. The amount of decease relative to the reference line is 10%, 15% and 30% for phase 1, 2 and 3 respectively.

Figure 4 shows the reference lines based on the reference line equation from the regulation with the particular parameters for *a* and *c* (as seen in Table 2-2). For the ships with deadweight between 3,000 and 15,000, the reduction factor shall be linearly interpolated between the two values based upon the vessel's size. For ships with deadweight just above 3000, the required EEDI stays almost the same.

2.4.2. Attained index value equation



$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}\right) + \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

Equation 4 - EEDI equation of attained value (IMO 2009)

C_F is a conversion factor between the amount of carbon dioxide (g CO_2) released and the specific fuel consumption for a type of marine fuel.

Type of fuel	Carbon content	C_F (t-CO_2/t-fuel)
Diesel/gas oil	0,878	3,206000
Light fuel (LFO)	0,86	3,151040
Heavy fuel oil (HFO)	0,85	3,114400
Liquefied natural gas (LNG)	0,75	2,750000

Table 2-3 - Conversion factors for different maritime fuels (IMO 2009).

We observe that the different fuels' carbon content have a large impact of the emission of CO_2. For later discussion we note that LNG releases 11,7% less CO_2 per tonne fuel. The heating value for LNG is 48,6 [MJ/kg] and 41,2 and 42,7 [MJ/kg] for HFO and MGO respectively (Balland 2013). A switch of fuel may also have a large impact on the EEDI value.

The following table contains explanations of the different parameters and constants in the EEDI equation. The information is withdrawn from the IMO MEPC circulation: "INTERIM GUIDELINES ON THE METHOD OF CALCULATION OF THE ENERGY EFFICIENCY DESIGN INDEX FOR NEW SHIPS" (IMO 2009).

	Constant	Explanation
Ship Design Parameters	V_{ref}	Ship speed in nautical miles per hour, design load condition.
	Capacity	For dry cargo carriers, tankers, container carriers, ro-ro cargo and general cargo ships deadweight is used.
Engine Power	P	Power of main and auxiliary engines. The subscripts $_{ME}$ and $_{AE}$ represents the main engine and auxiliary engine, respectively. Summation on *i* is for all engines with the number of engines ^{nME}. P_{ME} represents 75% of the installed power MCR, after deducing any possible shaft generator(s) – PTO/PTI.
	P_{PTO}	75% of the shaft generator(s) (Power Take Off) divided by the relevant efficiency.
	P_{PTI}	75% of the power consumption of each shaft motors (Power Take In) divided by the relevant efficiency.
	$P_{eff(i)}$	75% of the ME power reduction due to mechanical energy efficient technology.
	$P_{AEeff(i)}$	Auxiliary power reduction due to electrical energy efficient technology measured at $P_{ME(i)}$.
	P_{AE}	Required auxiliary power. Shall supply the main engine power at extra sea load and accommodation, pumps, cargo gear, ballast pumps etc. *
Specific fuel Consumption	*SFC*	Certified specific fuel consumption in g/kWh. As before, the subscript $_{AE}$ and $_{ME}$ represent the auxiliary and main engine respectively.
Correction and Adjustment Factors	f_j	Correction factor to account for ship specific design elements.
	f_w	Non-dimensional coefficient indicating the decrease of speed in representative sea conditions of wave height, wave frequency and wind speed. Can be determined as follows: 1. Ship-specific simulation of performance in at the representative sea conditions. 2. In case of no simulation, the f_w-value should be taken from a "Standard f_w"-table, which is contained in the Guildelines. 3. Should be taken as one (1.0) until further information is available.
	$f_{eff(i)}$	Availability factor of each innovative energy efficiency technology.
	f_i	Capacity factor for any technical/regulatory limitation on capacity (DWT), can be assumed one (1.0) if no necessity of the factor is granted. **

Table 2-4 - Equations constants explained.

*For cargo ships with $MCR_{ME} \geq 10\ 000$ kW we have that

$$P_{AE} = \left(0{,}025 \cdot \sum_{i=1}^{nME} MCR_{MEi}\right) + 250$$

Equation 5 - P_{AE} definition, large engine size.

For cargo ships with $MCR_{ME} < 10\ 000$ kW we have that

$$P_{AE} = 0{,}05 \cdot \sum_{i=1}^{nME} MCR_{MEi}$$

Equation 6 - P_{AE} definition, small engine size.

** The capacity factor for technical/regulatory limitation on capacity is for general cargo ships defined as in the following equation

$$f_i = \frac{0{,}000676 \cdot Lpp^{3{,}44}}{\text{capacity (DWT)}}$$

Equation 7 - capacity correction factor for general cargo ships.

There are present factors for correction when the ship is ice-classed, but this is not relevant for the shipping segment investigated in this thesis. For the purpose of the scope of the thesis we set al correction factors to 1,0.

2.4.3. Hybrid propulsion and EEDI

In the “INTERIM GUIDELINES ON THE METHOD OF CALCULATION OF THE ENERGY EFFICIENCY DESIGN INDEX FOR NEW SHIPS” (IMO 2009) says that the guidelines shall be used for

1) New ships with conventional propulsion system (main engine mechanical drive) and
2) To the extent possible, for ships with non-conventional propulsion systems (e.g diesel-electric propulsion, turbine propulsion or hybrid propulsion systems).

Later on in chapter 2 there is a note stating that the formula (i.e. the EEDI) *may* not be able to apply to diesel-electric propulsion turbine propulsion or hybrid propulsion systems. It may sound weird that these systems should be kept out of the attained EEDI regulations, as the diesel-electric propulsion system becomes more and more common within shipping. But as the guidelines in both MEPC.1/Circ.681 and MEPC.212(63) it *may* be reasonable to include it in the calculations.

In relation to the EEDI the hybrid system can be treated as a system to reduce the installed (prime mover) power, and hence have a positive influence on the index value. This has also been discussed per e-mail with Dr. Haakon Lindstad at MARINTEK and the same conclusion was drawn (Lindstad 2015).

2.5. General cargo ships

In the MEPC.1/Circ.681 the general cargo ship is defined as follows: "A ship with multi-deck or single-deck designed primarily for the carriage of general cargo" (IMO 2009). From the annual Equasis report of 2013 we have that the general cargo fleet constitute 19,9% (16,201 ships) of the worlds merchant fleet, in total number of ships. In gross tonnage the general cargo ship segments makes out 5,3%. The percentage of general cargo ships that are between 15-25 and above 25 years is 23,2 and 43,5% respectively. The rather large fraction of ships above 15 years (66,7%) requires a considerable amount of newbuilds in the period of the EEDI implementation (Equasis 2013).

Small GT<500		**Medium 500≤GT<25 000**		**Large 25 000≤GT<60 000**		**Total**	
Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
4 330	14,6%	11 670	31,8%	201	1,9%	16 201	19,9%

Table 2-5 - General cargo ships in the world fleet (Equasis 2013).

The ship segment of general cargo carriers is a workhorse of the sea. They may not travel the longest with the most cargo tonnage, but they carry a lot of diversified goods around the world. As seen in the picture below the diversity in the cargo can be large: From homogenous bulk freight, to containers and miscellaneous cargo, such as yachts. We can also observe the rather large cargo handling system – with three cargo cranes on the upper deck. These can operate the cargo all over the ship and serves as one of the main criterions for the characteristic flexibility of the general cargo ships.

Figure 5 - General cargo ship with yachts on the weather deck (Yachtpath 2015).

A lot of programs have been started to increase the amount of goods carried by ships. “The Marco Polo programme” and “Motorways of the sea” are European Commission programmes that shall make the transport chains in Europe more sustainable and more commercially efficient than road-only transport (European Commision 2015). As previously discussed the most energy efficient way of transporting goods is by sea. The EEDI may harm the competitiveness of the general cargo freight, versus road transport, if the solution of new builds will be to slow down speed. The speed of the transport chain is one of the key features to a smooth cargo logistic distribution. If the general cargo ships must slow down shipping speed, this may be seen as a weakness in the transport chain.

2.5.1. National incentives

In Norway the Government have granted 3 billion NOK to goods transference and some of this shall be used to stimulate sea transport instead of road-only transportation (Godsfergen 2015). In the Governments maritime strategy it was stated that transferring goods from road to sea should be stimulated (Nærings- og fiskeridepartementet 2015) The organization SPC Norway (Shortsea Shipping Norway) is a special interest organization working for the promotion of short sea shipping. The promotion is mostly nationwide, but also directed to Europe, throughout cooperation with the European Short Sea Network and other shortsea promotion centres (Shortsea Shipping Norway 2015). Statistisk sentralbyrå (Norway’s central institution for producing official statistics) reported in 2015 that over half of the general cargo fleet in Norway was older than 30 years. With such an old fleet and heavy incentives of more cargo off the roads, there must be a turnover in the building of new ships for the cargo transportation along the coast and between our neighbours.

Reletively large ship with a variety of cargo handling gear – cranes and sideloaders

Designed for container trade, specialized

No cargo handling gear, designed for short sea shipping trade

Designed and optimized for carriage of bulk cargo, no cargo handling system.

High speed, heavy load cranes.

Low speed, optimized for sea-river trade.

2.6. The influence of EEDI on the general cargo ships

The general cargo fleet will be especially influenced by the new EEDI restrictions. The ship type often has a design that favours to a high flexibility, due to the diversity in cargo, instead of optimized deadweight. The EEDI does not take the positive aspects of flexibility into account, but award the ship types with high deadweight.

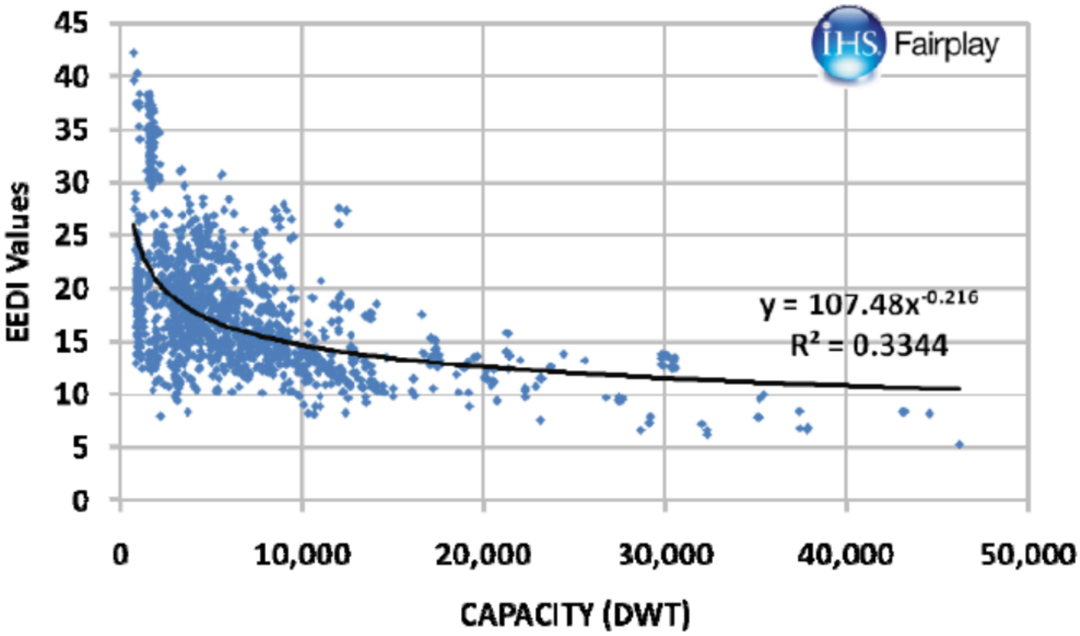


Figure 6 - Scatter of ships above 400 GT from the IHS Fairplay against the reference line (Verhulst, Nieuwenhuis et al. 2012). The R^2 of 0,3344 represents a high scatter from the y-graph line.

A project group consisting of CMTI, CONOSHIP and MARIN has investigated measures to improve the correlation of the attained EEDI with the reference line of required EEDI. The group proposed three additional factors for the smaller general cargo ships to account for difference in minimum required speed, cargo handling equipment and lightweight differences (Verhulst, Nieuwenhuis et al. 2012). We will not discuss these factors more in this thesis, but have chosen to mention them as they say something about the situation for the general cargo segment. Especially the small ships will face difficulties complying with the required EEDI, as can be seen in the high amount of ships with too high attained EEDI-value. Here are some reasons why the differences in EEDI are so big between vessels in the same deadweight class (from the Conoship/MARIN/CMTI report)

- The required minimal operational speed from sea route, resulting in a diversity in installed power and main dimensions (this will also influence the lightweight/deadweight ratio)
- Sailing area will influence the outer main dimensions, amongst others due to the restrictions of ports, canals, locks etc.
- Cargo handling equipment: Crane, side ramp, excavator, RoRo ramp and combinations of these. The weight and displacement of the loading equipment results in a decrease for cargo space. The mounting and strengthening of the ship structure will also increase the lightship weight.
- Main engine type, main engine speed, fuel types and fuel consumption. The choice of main engine has a large impact of the CO_2 emissions from the engine. Many engines were installed during a period when fuel prices were at a low and not a large concern for the ship owners/operators.
- Additional class notations can lead to an unfavorable ratio in lightweight/displacement.
- The diversity in hold volume results in large differences in gross tonnage and lightweight.
- Relation between the ships optimal design condition and the ship's maximum capability. Some ships are optimized for operation in design draught that corresponds with the maximum scantling draught. Whilst others are optimized for a partially loaded draft – i.e. much lower than the maximum scantling draft.

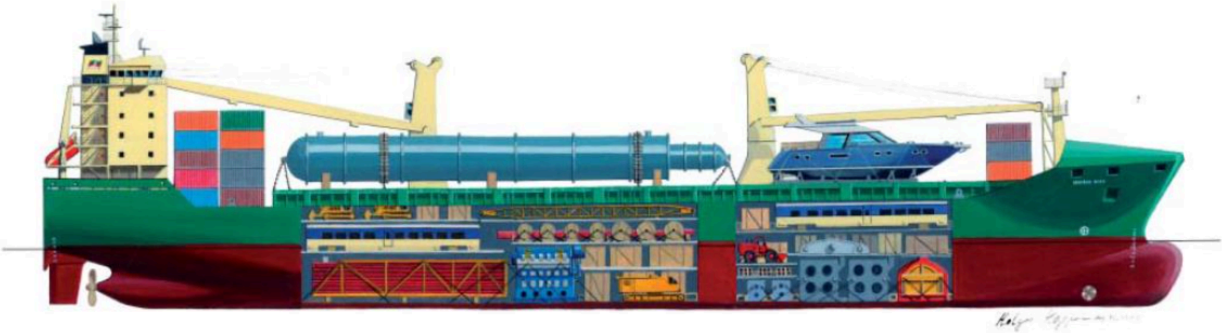


Figure 7 - The Rickmers Superflex combining general cargo and containers (Verhulst, Nieuwenhuis et al. 2012).

2.6.1. Improving the EEDI in general

There are many ways to solve an equation and the EEDI can be lowered with many types of energy efficiency measures. The main focus will be on lowering the EEDI by installing a hybrid system, but there are very many technologies to reduce the amount of CO_2 released per tonne mile. First of all the power demand can be reduced by:

- Optimizing main dimension while holding the DWT constant.
- Classical hydro dynamical optimization.
- Reducing the sea margin of the main engine.

Energy saving devices for hydrodynamic efficiency in the aft ship are numerous: post swirl fins, rudder bulb, Kappel propeller, AHT nozzle, Mewis duct, pre swirl fins, efficiency rudders, etc. Exploiting the residual energy from the engines is also a smart way to lower the EEDI. Waste heat recovery can raise the energy efficiency with several percents.

Several articles have reported that the easiest way of reducing the EEDI may be to lower the ship's operational speed. We will discuss the impacts of speed reduction in the following chapter and will not address it further in this section.

3. Assessment of hybrid propulsion system operation

3.1. Ship operating conditions

All ships operate in more or less varying conditions. Currents and waves make the day-to-day sailing different in means of ship resistance and ship motions. As a result of the varying resistance on the ship, the engine load also varies throughout the day. Depending on the ship type, the ship will have different timeslots in different operational modes. The major operating modes are (Patel 2012):

- In-port loading the cargo
- Manoeuvring in and out of port
- At sea in transit, cruising speed
- In-port unloading the cargo
- Anchor and standby
- Emergency operation

Most ships carrying cargo will spend most time at sea. When using the term “at sea” it is meant that the ship can operate in more or less constant speed for longer periods at time. The ship operator will try to reach the most sensible speed to deliver within the time schedule and at the same time minimizing the fuel consumption. The typical small general cargo ship will however spend a lot of time in port, loading and discharging. The loading/discharging rates are very dependent on the cargo handling system and what type of cargo the ship is carrying.

In the following sections we will try to take a closer look to how a real life ship operation of ships are, especially with the general cargo ship in mind. The way external forces influence the daily operation of the ship is important to understand one of the main advantages of a hybrid propulsion system.

3.2. Impact of power reduction on operational performance and reliability

Two of the conference papers from the RINA conference “Influence of EEDI on Ship Design” discuss the possibilities of reducing installed power and sea margin (as a result of total power reduction). The papers from Deltamarine in Finland states that “it has been demonstrated through examples that EEDI would practically mean power limitation for new ships” (Quach 2014). The result of the EEDI may be that a lot of new ships have installed less effect than similar ships build before the restrictions were adopted. This will have effects on the shipping trade.

Following the International Towing Tank Conference (ITTC) *sea margin* or *power margin* can be defined as: “The margin which should be added to the estimation of the speed power relationship of a newly built ship in *ideal* weather conditions to allow for the ship in *realistic* conditions. In practice this does not mean that the ship must meet full speed in all weather conditions, but that it can sustain its service (design) speed over a *realistic percentage of conditions*” (ITTC 2005). The sea margin cannot be reduced without taking some precautions in relation to safety and operability. In adverse weather the ship needs a certain power reserve to keep the manoeuvrability and control over the ship. The added resistance in waves consists of contributions from (among others):

- The wind
- The wave induced relative wave elevation along the waterline
- The wave induced changes of the mean pressure over the submerged part of the hull
- A wind and wave drift angle in oblique and transverse waves
- Course keeping and steering

(Dallinga, Grin et al. 2014)

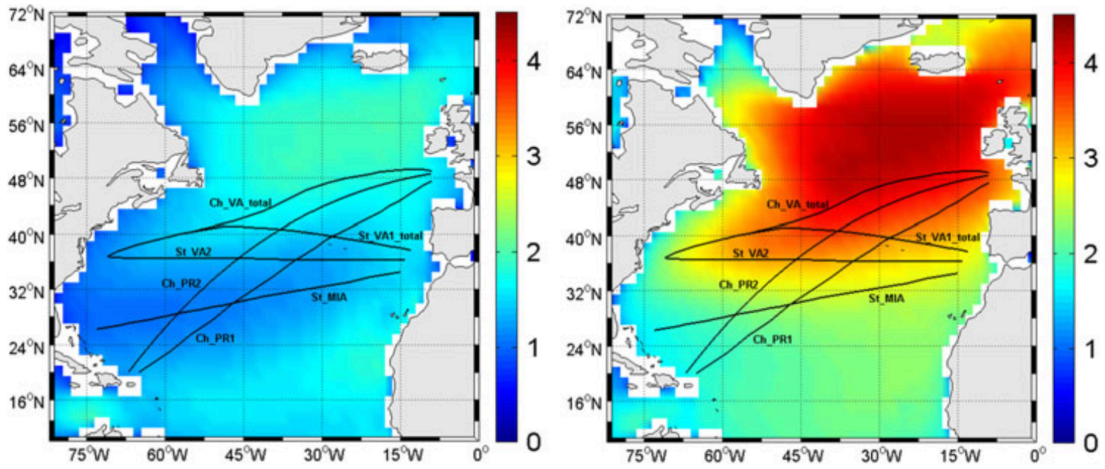


Figure 8 - Summer (a) and winter (b) mean significant wave height in the North Atlantic (Vettor and Guedes Soares 2015).

From Figure 8 one can observe that the differences in RAW will vary severely depending on the time of the year and the trading route. These maps only show the significant wave height, which is just one of the parameters influencing the resistance in waves, but draws a good picture of the differences at sea. The route of the ship must be optimized for lowest RAW, but in most areas the RAW will always be a large part of the ship resistance. The coast of Norway is famous for harsh winds and rapidly changing weather. Ship designers will encounter challenges designing ships for these areas compared to an inland waterway cargo vessel or a general cargo vessel for the Baltic Sea. Possible consequences of the decrease in ship speed due to less installed power can be; increase in trip duration and reduced reliability (Dallinga, Grin et al. 2014). This is an unwanted consequence for a shipping segment that is very reliant on delivering on time.

The EEDI regulations can cause a lower operating margin for the shipping companies. In a tight race with land-based transport as trailers and railways, a reduction in trustworthiness on delivery time can be fatal. A hybrid system can be a part of the solution when it comes to replacing the “lost” sea margin and keeping up the reliability as seaborne trade can provide.

3.2.1. Minimum installed power

The potential slow steaming in the general cargo fleet may save CO_2 emissions, but the total transportation efficiency is reduced. Transportation efficiency relies on fuel consumption, time and capacity. Certain vessels need to have a high speed to perform their specialized tasks. To reduce the speed in this segment will mean to reduce the competitiveness of the sea transport (Quach 2014). The oil price is an important transport efficiency driver, but we now see a shifting from economical to regulatory drivers – with the EEDI and ECAs in leading roles.

The problems with the possible power reduction that may come in the wake of the EEDI regulations has lead IMO to take actions. In 2013 the INTERIM GUIDELINES FOR DETERMINING MINIMUM PROPULSION POWER TO MAINTAIN THE MANOEUVRABILITY OF SHIPS IN ADVERSE CONDITIONS was adopted by the MEPC. The purpose of the guidelines is to assist the companies and organizations in verifying that the ships have sufficient installed propulsion power. This is to ensure the safety and to guarantee that the ships will be able to handle the described adverse conditions. For ships less than 200 [m] the following describes adverse conditions at sea: Significant wave height h_s = 4,0 [m], peak wave period T_p = 7,0 to 15,0 [s] and mean wind speed V_w = 15,7 [m/s] (MEPC 2013).

From the MEPC 64/4/13 we have that the minimum power value for general cargo ships is defined by the equation (MEPC 2012):

$$\text{Minimum power line value} = a \times (DWT) + b$$
$$a = 0{,}1520$$
$$b = 2399{,}5$$

Equation 8 - Minimum installed power.

3.3. Engine running profile

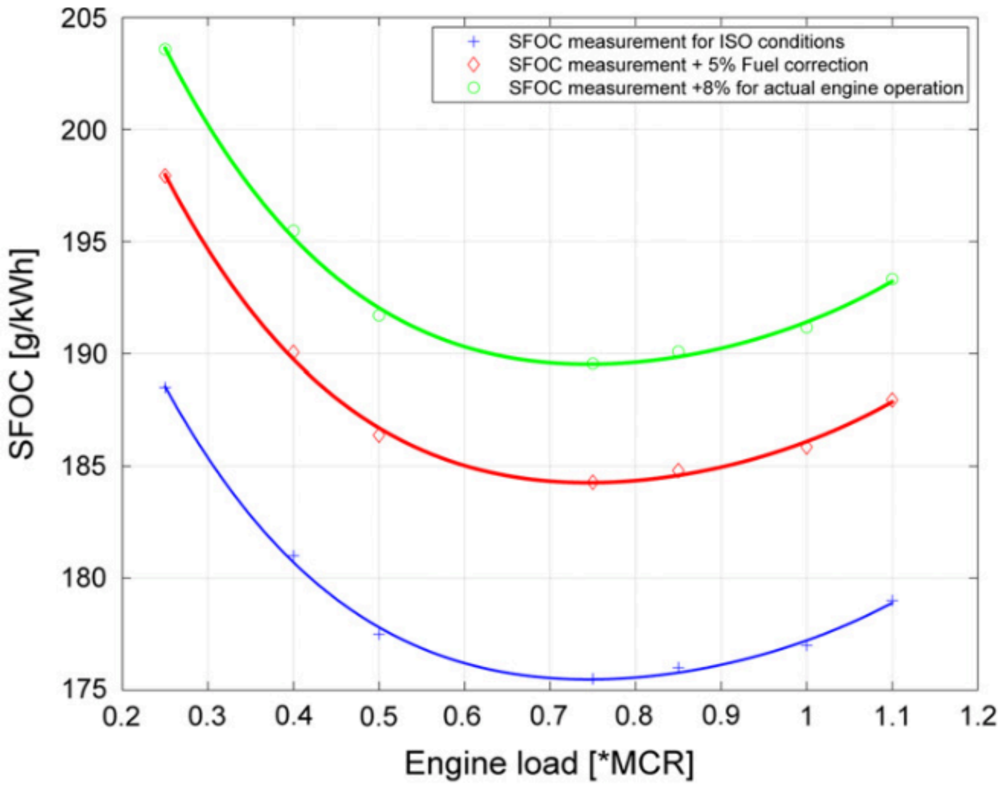


Figure 9 - SFOC vs Engine load from a MAN 7S60MC-C8 (Dedes, Hudson et al. 2011)

Figure 9 represents the relation between the specific fuel oil consumption (SFOC) for a typical marine engine. The graphs represent the span of measured fuel consumption and what the engine can perform under ISO conditions (which is merely realistic at sea). It shows the logical relations between engine loading and how much fuel is used. A typical “sweet spot” for operation of a maritime engine is in the range 70-85% of maximum continuous rating (MCR). This means that the engine is tuned to use minimum fuel per kWh produced a certain percentage below the maximum power the engine can produce. In moderate or rough sea the wave resistance is higher than in calm water. The trust is increased, the propeller is not working at design point and more fuel is injected in the engine to maintain the torque on the shaft to drive the propeller (Dedes, Hudson et al. 2011). The gap between the “sweet spot” and the maximum power outtake is called the sea margin. In case of adverse conditions the ship must have a certain margin to maintain the desired speed and maneuverability. The sea margin is a power reserve to overcome the resistance added in waves (RAW). When the engine(s) work outside the “sweet spot”, the operation is not optimal in respect to efficiency and emissions. This problem is attempted to solve through innovative engine systems, such as the multiple engine diesel-electric system. A diesel-electric system will give more flexibility and ability to control the engine power production through a power management system. One of the thoughts behind a hybrid system is that this flexibility is taken to another level and gives the ship operator even more choices in power output to the propulsors.

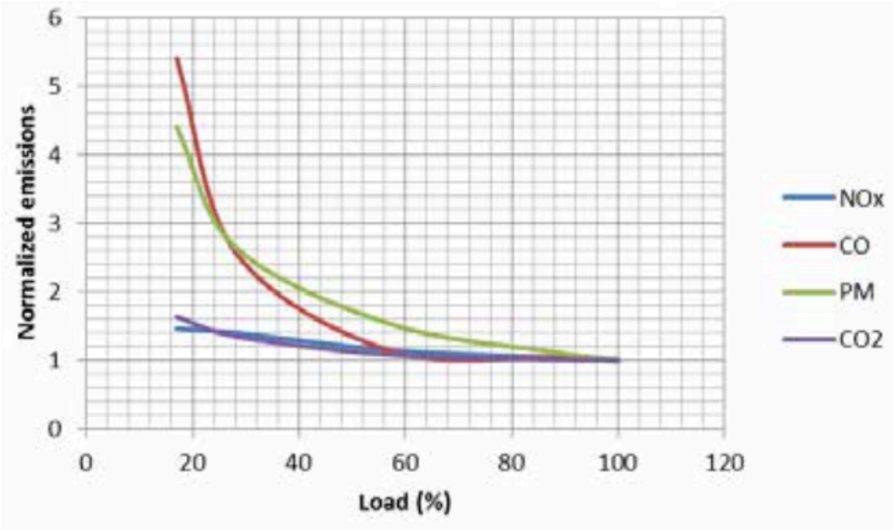


Figure 10 - Emission product during the power range of a diesel engine (DNV GL)

We can observe from Figure 10 that the particulate matter and the carbon monoxide emissions drastically rise when the engine load decreases. The same can be seen with the CO_2 and NO_x, but in a minor scale compared to PM and CO. A conventional maritime diesel engine should be run close to the design “sweet spot”. This will optimise the fuel consumption per kW produced and bring the emissions per kWh to a minimum. This is a problem for diesel engines with direct mechanical propulsion: The nominal efficiency may be higher, but it is lowered when the engine is out of its “comfort zone”. A well-proven solution to this problem has been to install diesel electrical propulsion where main engine(s) and auxiliary engine(s) could be turned on and off depending on the power demand. To call the technology for a solution may be to take it a bit too far, but the higher number of engines gives the propulsion system a higher probability of engines working close to their sweet spot. The electrical energy is sent to a switchboard and distributed to where it is needed (Ådnanes 2003).

3.4. Hybrid concept

A hybrid system seeks to even out the power fluctuations in the engines. When the power demand is higher the power source is discharged and when it is lower the source is charged. *This concept is called load levelling*. The concept is based on energy production and storage, where the peaks in energy demand use the stored energy to supplement the main power production (Dedes, Hudson et al. 2012).

If the engine loading fluctuations exceed 5%, the potential associated fuel saving could be up to 15% (Dedes, Hudson et al. 2012). The possible reduction must be seen as a function of how much the engine fluctuations are over time. This will depend both on weather on short term and the sailing route pattern in a long term. To illustrate the loading fluctuation, Figure 11 shows the loading of three post-panamax sister ships in laden voyage day-by-day. The y-axis shows the fraction and not the percentage as indicated in the graph from the article in "Energy Policy". The energy demand for the three ships, in ballast and laden voyage, ranges from 71 to 80 %MCR for the current period.

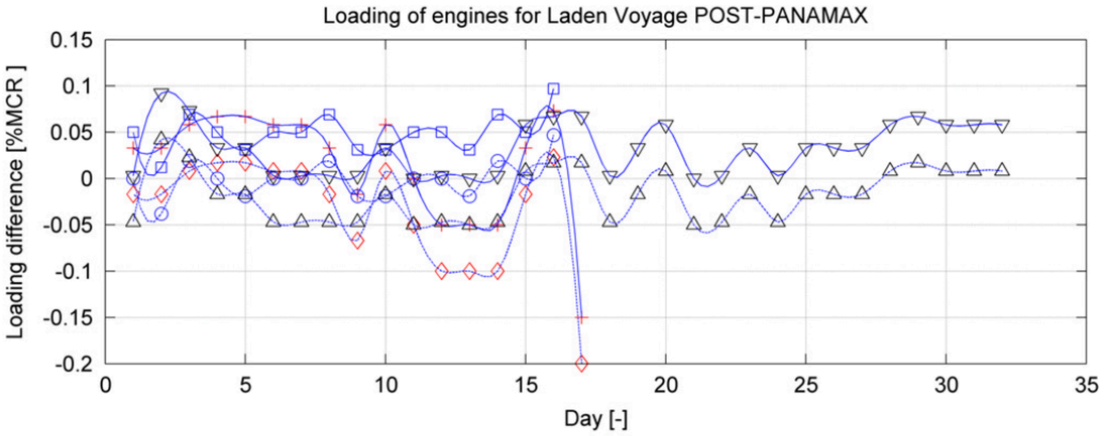


Figure 11 - Loading difference in %MCR from normal continuous rate day-by-day (Dedes, Hudson et al. 2011).

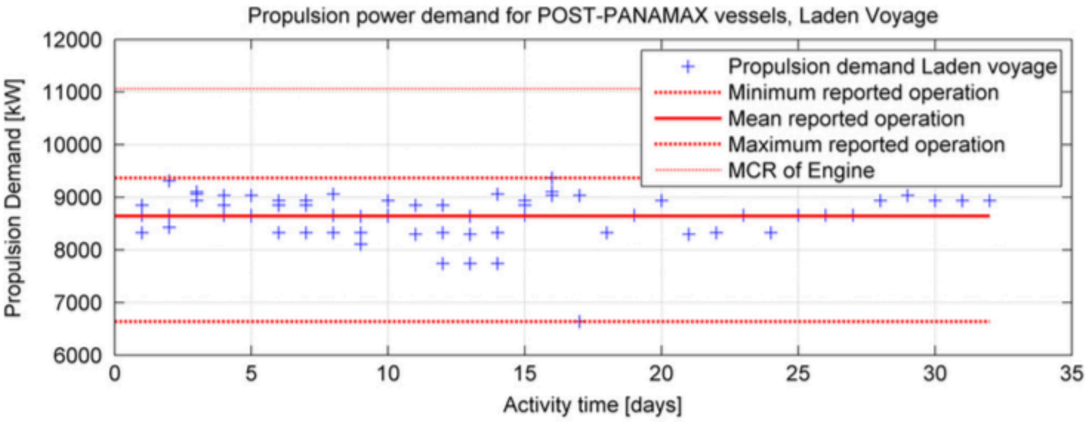


Figure 12 - Daily loading difference in kW (Dedes, Hudson et al. 2011).

The ship is sailing in waters where the resistance is changing due to extern forces such as waves and current. Fluctuations from the NCR can be logged and the power demand to smooth the oscillations can be found. In Figure 12 we see that the energy demand is always differing on a day-to-day basis.

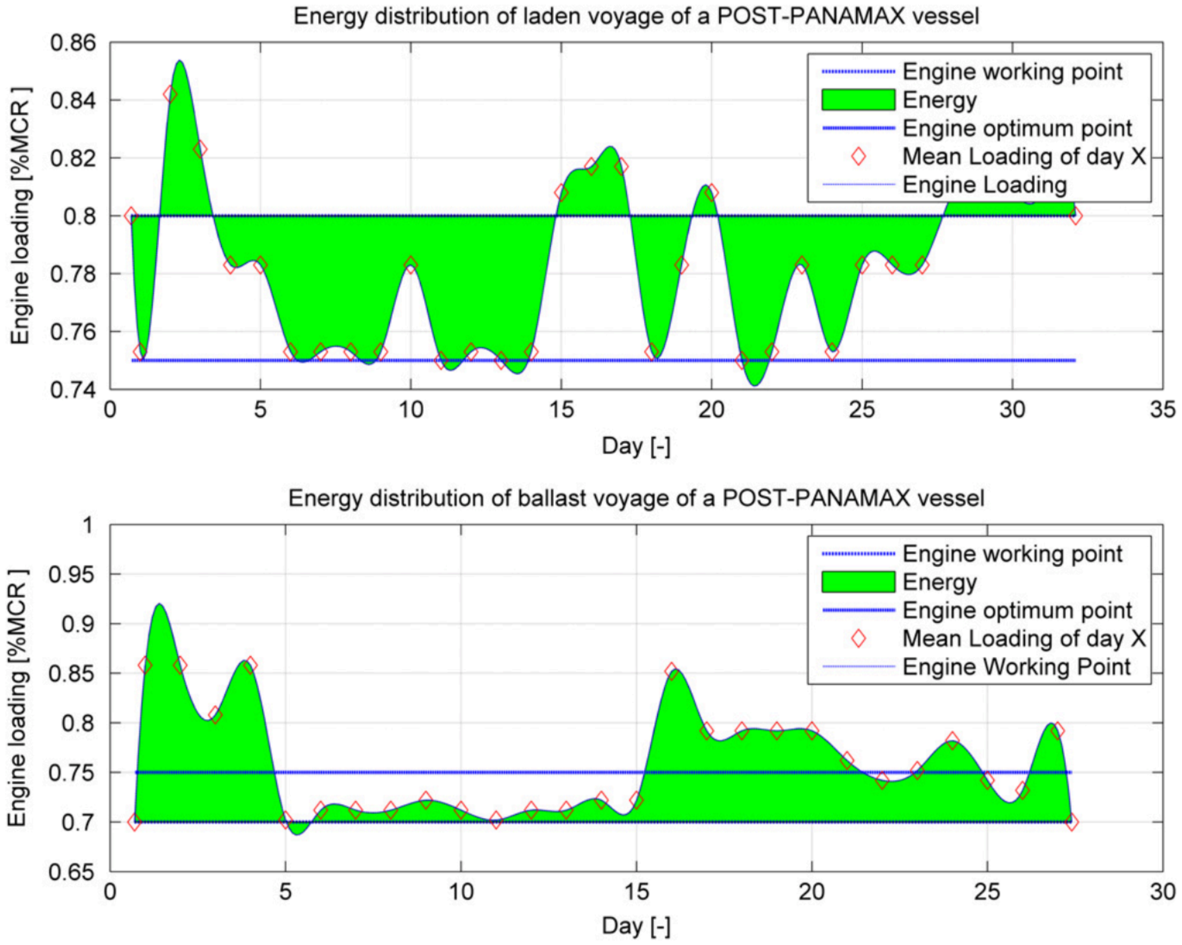
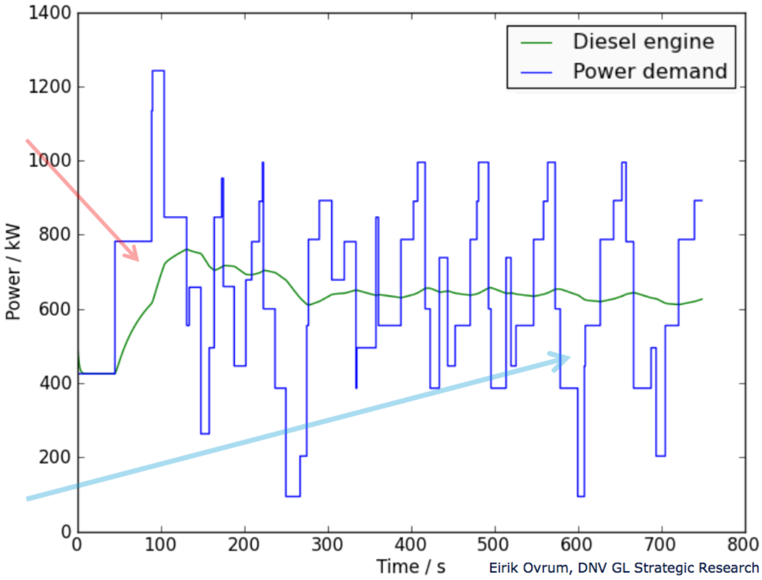


Figure 13 - Energy distribution for a POST-PANAMAX in laden and ballast voyage (Dedes, Hudson et al. 2011).

In these particular graphs (Figure 13) the amount of energy over and under the engine optimum point of MCR is constantly changing. The engine's optimum working point is at 75 %MCR and can be seen as a blue dotted line. In the laden voyage the engine working point is over the optimum point and the engine is working outside its sweet spot. What is interesting to observe here is the difference in laden and ballast condition. In laden voyage the engine is working 5% over the NCR and in ballast 5% under NCR. So in neither of the two conditions the ship's engine is operating at the optimum point. We see that the engine must face both under- and overproduction of power. The sea state forces the engine out of its "sweet spot", where it was made to perform at its best. This is not optimal in both in relation to fuel emissions and efficiency.

Battery **discharges** when power demand is greater than the Diesel engine output:

Battery **charges** when power demand is less than the Diesel engine output:



Eirik Ovrum, DNV GL Strategic Research & Innovation

Figure 14 - Hybrid system mission.

In Figure 14 (Tronstad 2013) the mission of a hybrid system is sketched. The engine runs on almost a constant output, i.e. optimal load, and the hybrid system can serve the fluctuating power demand.

We will look at the possibility to avoid these fluctuating curves on the main engine by implementation of energy storage, first and foremost a battery. The technical details around such a system will be discussed in the following section.

4. Hybrid propulsion system

In shipbuilding hybrid can mean two things: 1) A system containing a diesel-electric and diesel-mechanic system or 2) A system of a power producer and a storage device (Tronstad 2013). This thesis will focus on a hybrid system with a battery energy storage device. We have just seen a start of the hybrid technology within the shipping industry. Submarines and other naval ships have previous used the technology for unlike reasons of improving some function, such as going under the radar and near to silence operations. The improvements we have seen in the car industry have made it easier to implement batteries in ships. The batteries are getting better and better and most important – cheaper. The economical feasibility is changing day by day due to the vast expansion in the battery industry growing around the car industry. We have not seen the same growth of hybrid technology in the shipbuilding industry, but some ships have implemented the system with success. One is the PSV *Viking Lady* and the FellowSHIP project. The PSV have successfully been operated in the North Sea since 2009 and have both a fuel cell and batteries installed as energy sources.

4.1. System boundaries and energy terminology

In any energy system there will be different components that store, contain, convert or transmit energy. The terminology for the system that lay between the potential energy and the resulting thrust are presented here in Table 4-1.

	Description
Energy carrier	The energy carrier is a “consumer article” that is onboard the ship as potential energy. It can be diesel, LNG, electricity or hydrogen for instance.
Energy Converter	The unit that converts potential stored energy to electrical or mechanical energy. Can typically be a combustion engine (gas/diesel), but also include the storage unit as in the case of a battery or fuel cell.
Energy transmission	The system that transmits the energy from the energy converter and transform this energy to thrust in the water. Examples can be propeller, axis, gear, generator and electromotor.

Table 4-1 - Energy terminology (Wold, Gundersen et al. 2011).

4.2. Potential benefits of a hybrid powertrain system

Offshore supply vessels, fishing vessels and harbour tugboats; they have in common that all spend a large amount of time in frequent load variations. The same cannot be said about general cargo vessels, as they have not the same need for positioning as these vessels. The power used to hold the ship in place and for the execution of their operations are the main drivers for hybrid propulsion in the three mentioned ship types. The operational modes lay the basis for a hybrid system that can be economically feasible to install. The *Viking Lady* and the *Viking Queen* have reported a fuel reduction between 15-18%. In the example of *Viking Queen* this gives a payback period of under five years (Larsen Hirth 2015). For the general cargo ship type, the operational profile is not the main driver for the economical fairness of choosing a hybrid system. The regulatory changes in the industry with the EEDI (and ECA if relevant) are the main driver. But this does not mean that the general cargo cannot improve the operations at sea and in harbour with a hybrid system (as we shall see later in the thesis). An installed battery can lead to a more energy efficient operation of the ship and the ship's systems. For instance would it be mote convenient to install electrical cargo handling equipment on an AES with an energy storage unit.

4.2.1. Cold ironing

Cold ironing is the term for connecting the ship to a shore-side power shore when in harbour so the ship's machinery can be shut down. This causes the machinery space and hull iron to turn cold, thereby the name (Patel 2012). General Cargo ships often have their own cargo handling equipment and are therefore depending on a reliable power source when loading and unloading in harbour. The AES easily connect with a so-called fast plug connection and the whole ship's sub systems can be driven by electrical power from shore. In a hybrid ship the plug-in will also be an opportunity to charge the batteries and can therefore be seen as an economical benefit with annual fuel savings (Vartdal and Chryssakis 2011). The environmentally profit is also present, as the down shutting of the auxiliary and main engines eliminated the human injurious emissions as NO_x and SO_x. It is expected that cols ironing will be implemented in more ports in the years to come.

4.2.2. Eliminate frequent load variations/Engine load optimization

This theme has been discussed previously in 3.3. As mentioned in the introduction to this chapter *Potential benefits of a hybrid powertrain system* there are some vessel types that have an operational profile that form a solid basis for reducing fuel consumption through load levelling and optimization. If the load variations can be served by a secondary power source (battery/fuel cell), the main engine can run on constant rpm – which of course can be the design continuous running, i.e. the optimal engine load. The energy of ICE depends on the loads; the lower range is far worse in respect to both efficiency and emissions (Ovrum and Bergh 2015).

ICEs are also less efficient while changing its loads and the emissions of SO_x, NO_X and particulate matter rise. The energy storage can handle the transient loads while the engines run on the most optimal rpm.

4.2.3. Power redundancy

For many ship types power redundancy is of the essence. For a PSV in DP beside a platform, redundancy is necessary to reduce the possibility of loss of power and control. In many cases this mean that several generators run at low loads or an additional generator running at idling. If the energy accumulator can provide power to the ship within the time it takes to start an engine, it could possibly provide the required redundancy (Vartdal and Chryssakis 2011). For passenger ships the term "safe return to port" has been implemented. The term comes from the SOLAS convention and refers to that ships are it's own best lifeboat. In case of fire in the engine room the ship shall be able to return to port. With extern power source as a battery the chances of returning safely to port increases.

4.2.4. Local emissions

The emissions from shipping are both a global and local challenge. If the energy storage device is big enough, it could be use to reduce the harmful emissions in more sensitive areas such as harbours, coastal areas and rivers/channels. The reduction of injurious emissions in more dens areas can also pay off, when the local legislatives often favour the less emitting ships (Vartdal and Chryssakis 2011). For instance in the ECAs the amount of SO_x or NO_x emitted are strictly regulated by upper threshold values.

4.2.5. Noise and vibrations

Noise and vibration are pollutants that have been more focused on lately. With a hybrid system, the noise can be reduced locally and ensure a more convenient working environment aboard the ship. For some ships as naval and research a low level of noise is crucial for good data harvesting. Running only on battery and electromotor will assure a quiet operation.

4.2.6. Energy harvesting

With the growth in electrical ships the possibility of energy harvesting has become more relevant. But harvesting energy from different sources merely makes sense without an integrated storage medium. A hybrid system facilitates such harvesting. Possible sources are solar, waves, wind and harvesting from the ship's systems. The regenerative energy harvesting from crane operations on an offshore construction that lowers a module to several thousand meters is a way of exploiting the potential energy that can lay in an operation. This could also be done on a general cargo vessel with onboard cranes, but in much smaller scale. The energy harvested from lowering cargo to the quay can make the unloading more energy efficient.

4.3. System Description

The hybrid system discussed in this thesis will consist of a power system with two main subsystems: 1) energy production or prime mover and 2) an energy storage device, which could be a battery or a fuel cell. To utilize the energy in the energy storage unit (ESU) the engine system must have a diesel/gas electric system as in the figure above, or a diesel/gas mechanical system with power take-in (PTI) on the reduction gear. There are also a lot of additional systems that must be installed for the hybrid system to work optimally – as we shall discuss later.

4.4. Type of ship drives

Ships can have different forms of drives for the propulsion and other energy consumers on board. From the mechanical and electrical point of view we will present the four main categories from the book "Shipboard Power Electrical Systems" by M. R. Patel (Patel 2012).

Mechanical-drive (conventional) ship*:* The propeller is driven by a shaft that runs directly to from the engine or through a gear (reduction gear). The service loads of the ship (pumps, HVAC, lightning, cargo handling, deck machinery etc…) are typically served by auxiliary engines coupled with a generator.

Electrical-drive ship: More and more implemented in ships. The main propulsors are driven by electrical motors, which are supplied with energy from generators coupled with an engine (diesel/gas). The ship service power if served by separate ship service gensets.

Integrated-electric ship: This type of system has both the ship service power and propulsion power demand served by the main engines' generators. To supply the ship service power demand a transformer is needed for step-down transforming of the electricity. This type of system gives the freedom to send all produced power to the propulsion system, for a boost operation mode.

All-electric ship: When all the subsystems of the ship are converted to electric-powered the ship is all-electric. These systems could typically be compressed gas-powered, hydraulically powered or steam-powered in a more conventional ship.

4.4.1. Electrical-drive/Integrated/All-electric ships

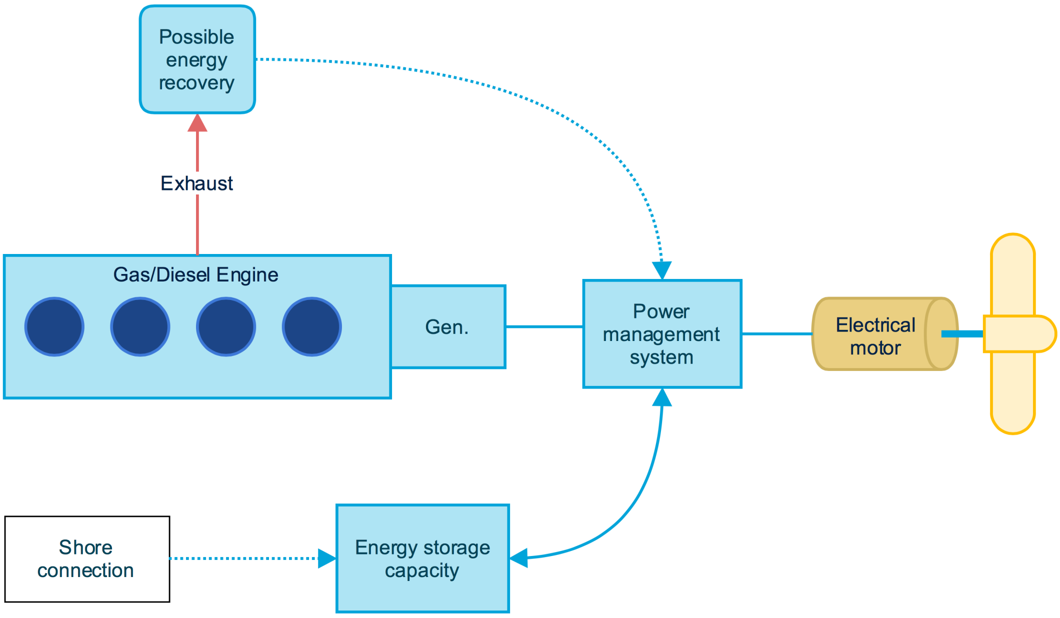


Figure 15 - Layout of a very simplified hybrid system.

Figure 15 shows a very simplified illustration of a hybrid system in a ship with diesel-electric propulsion. If it is an electrical drive/integrated/all-electric depends on the systems around, whether or not the service power is supplied by the main generators and the extent of electrification of the subsystems. The energy from the diesel engine is converted to AC electricity by a shaft generator. Normally a diesel-electric engine system will have more than one engine (as generically illustrated here) and the possibility to choose how many engines that shall be running at the given time. This is one of the benefits with a partly or all-electric ship – the energy production can be more adjusted to the energy demand by shutting down or staring engines. The produced electrical power is easily distributed to the energy consumers. The power train in this sketch does not include the energy consumption on the rest of the ship, typically called ship service power. This can be cargo handling, deck machinery, shop loads, electronics, communication, hotel loads and HVAC.

4.5. Mechanical drive

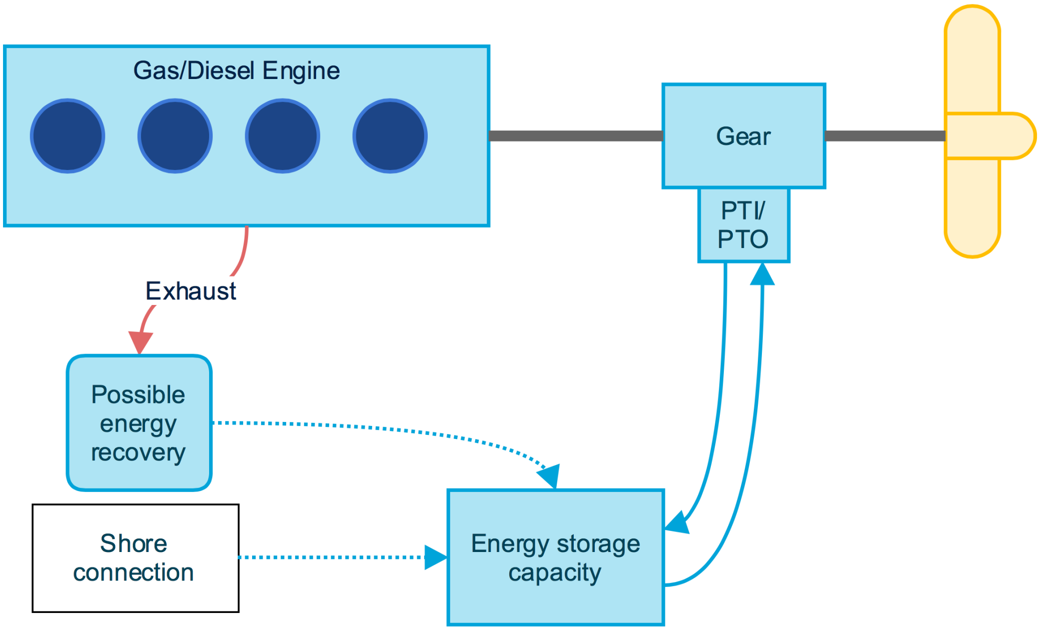


Figure 16 - Hybrid system with diesel-mechanical drive.

The power from the energy storage capacity can also be directly coupled to the mechanical drive through a power take-off (PTO)/power take-in unit (PTI). The PTI is connected to an electrical motor that gets the electricity from the energy storage unit. Due to the direct coupling of engine and propeller shaft, the power flexibility is not as high as in the more electrified systems. The possibility of shutting down engines when not needed is not an option with a mechanical drive solution. On the other hand can one take advantage of both the high diesel-mechanical efficiency and the flexibility that lays in the PTI. This can be a attractive solution for a cargo ships where the battery take the load variations, can provide boost mode and increase the redundancy of the system (Tronstad 2013).

4.6. Hybrid propulsion system efficiency

For an engineer and a ship builder the efficiency is of the essence when installing a power producing and consuming system. Different propulsion systems come with different efficiency and choosing should be based on efficient energy transformation. Sometime high efficiency is traded against other factors that are more crucial for the ship owner and the operation of the ship – such as low CAPEX and OPEX. To tailor the efficiency at the point where the ship shall perform is crucial, as discussed in previous sections with optimum loading of the engines. For the hybrid systems the efficiency will vary from system to system. In the following we shall investigate the difference between the efficiency from a conventional diesel system to a hybrid and between hybrid systems.

4.6.1. Diesel-electrical and battery-drive efficiency

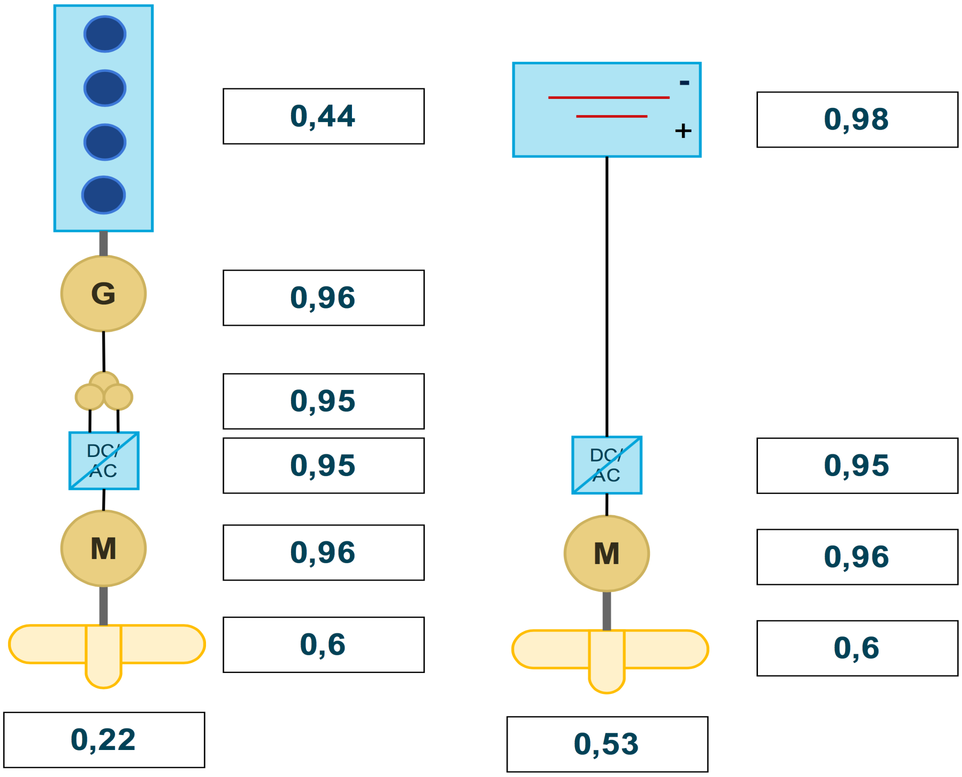


Figure 17 - Schematic presentation of the differences in efficiency.

The numbers for the components' efficiency are taken from a DNV GL presentation on the theme *hybrid power solutions of tomorrow* (Tronstad 2013). The numbers does not perfectly correlate with the efficiency intervals in the coming section, but the figure is more of a presentation on where the energy is lost in conversion and transmission and gives a brief intro to this.

We can observe that the thermal efficiency of the engine is relatively low, but can be higher if an energy recovery system (boiler) is mounted in the exhaust chimney – this is not taken into account here. An energy recovery system is briefly sketched in Figure 15 and Figure 16 as *possible energy recovery*. In the figures the energy is lead to the energy storage capacity, this is possible if the energy recovery can be utilized for electricity production. Exhaust gas boilers (smoke tube boilers) can be mounted on the chimney and the steam can be used to produce electricity in a steam turbine combined with a generator (Valland 2012).

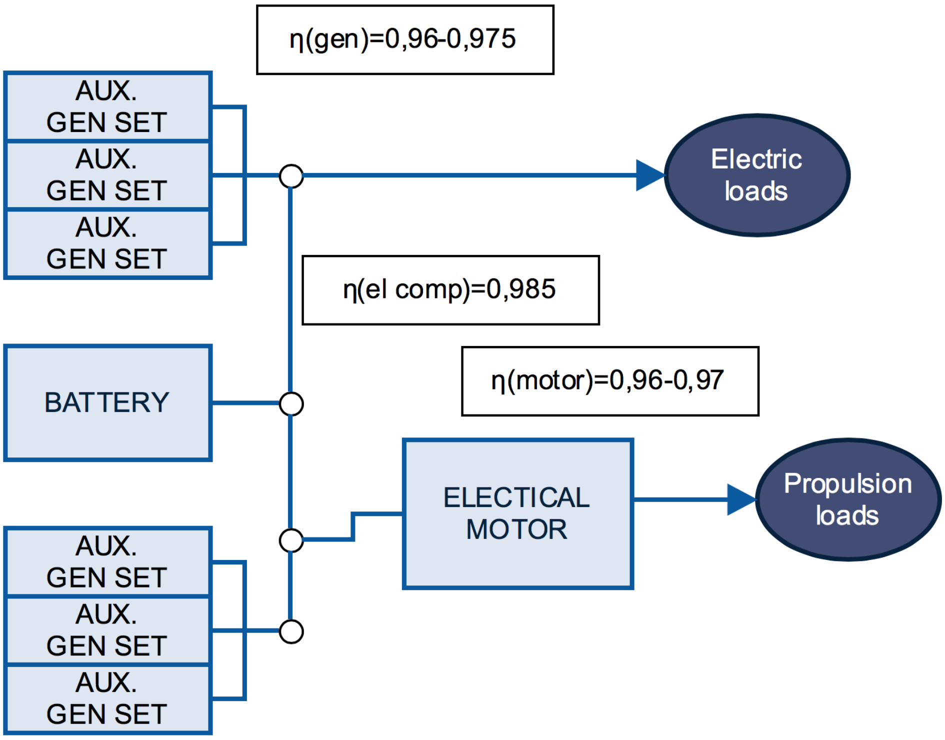


Figure 18 - Approximately efficiency of components in AES system (Dedes, Hudson et al. 2011).

The efficiency for the generator is not for the whole genset. A genset will have much lower efficiency due to the relative low efficiency of an ICE. Figure 18 and Figure 19 does not take into account whether or not the battery is charged from a shore connection (plug-in hybrid), only from the gensets superfluous energy production or combination of both (which is to prefer). If the hybrid system has a plug-in solution and can exploit the superfluous power production rather than “wasting” it in a braking resistor – the efficiency will be much higher.

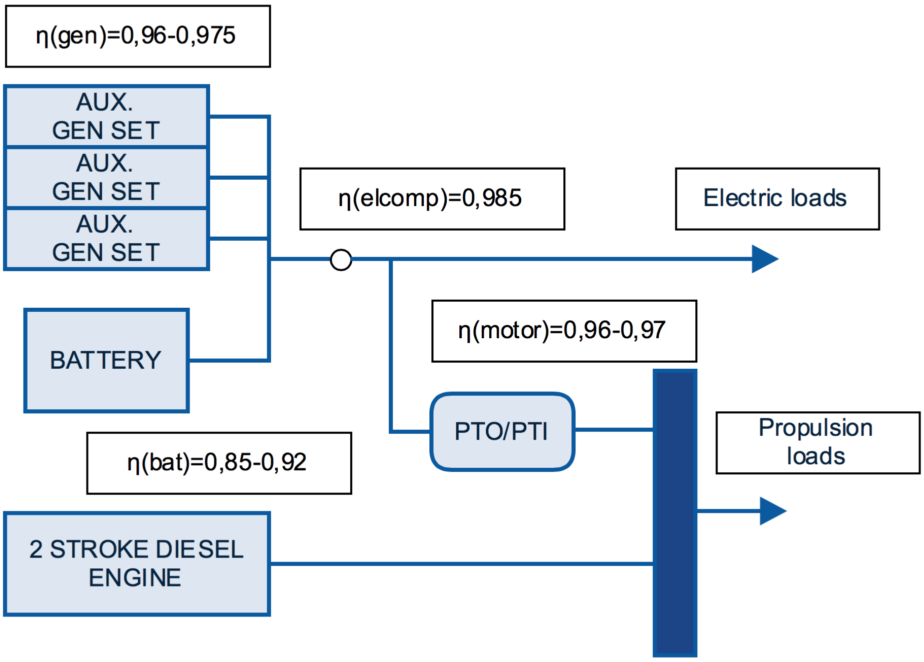


Figure 19 - Approximately efficiency of the components in a diesel-mechanical system with PTI (Dedes, Hudson et al. 2011).

The well to propeller efficiency is interesting when looking into the environmental benefits of installing a hybrid system. Not only focusing on the lowering the EEDI, but also shine a light on the source of the power and how it is transferred to the propeller. From the Revolt report from DNV GL we have the following well to propeller efficiency for a pure battery system (Tvete 2015):

Process	Efficiency
Hydro power	0,95
Transmission and distribution	0,94
Charging	0,95
Transmission losses (el-motor)	0,95
Thrust	0,79
Well to propeller efficiency	0,63

Table 4-2 - Battery well to propeller efficiency.

This well to propeller efficiency is very high for a propulsion system. In comparison a diesel electric propulsion with the following fuels MGO and LNG (ECA compliant fuels) have η=0,235 and η=0,239 respectively (Tvete 2015).

The high efficiency of the well to propeller rely much on the high battery and hydropower efficiency. In addition to be a non-emitting way of producing energy, hydropower is also considered being on of the most efficient ways of converting kinetic energy to electricity.

5. Hybrid system components

Installing a hybrid system is not only inserting an energy storage device and couple it up with the propulsion system. There are a lot a systems and components that are needed around the storage device to make the system work. After the commercialization of the diesel-electric system, power management systems have become more normal. Kongsberg Maritime has for instance developed several systems to automate the power production in the engines (Kongsberg Maritime AS 2015). We will in this chapter look into the different parts of a hybrid system and how the system is controlled.

Arrangements Components	**Conventional 2-stroke Diesel**	**Hybrid Diesel-Electric system – All Electric Ship (AES)**
Prime Mover	2-stroke Marine Diesel Engine	4-stroke marine diesel generator sets
Auxiliary Power	4-stroke generator sets, 1 emergency	Covered by the main propulsion unit (fully electrified vessel)
Components	Shaft generator (if applicable), shafts and bearings	Marine type electric cables, transformers, converters/inverters (motor speed control), rectifiers (storage system existence), Electric motors
Propulsor and maneuverability	Large diameter fixed pitch propeller, steering gear	FP propeller(s), CP propeller(s) with steering gear OR podded propulsion (no stearing gear)

Table 5-1 - Differences between a conventional and a hybrid propulsion system.

Table 5-1 shows some main differences between a conventional 2-stroke diesel engine, which have been the main supplier of power at sea for decades, and a hybrid diesel-electric system.

5.1. AC and DC grid systems

Types of hybrid systems can be divided into several groups. On way of defining the system is by what kind of current most of the system has. We have two types of current: Alternating current (AC) and direct current (DC). The overweight of existing AES are using AC distribution systems, but it might make sense to use a DC distribution in combination with a hybrid system (Zahedi, Norum et al. 2014). The incentives for this change lays in the challenges associated with an AC power distribution system and the possibilities the power sources with DC output (batteries) bring.

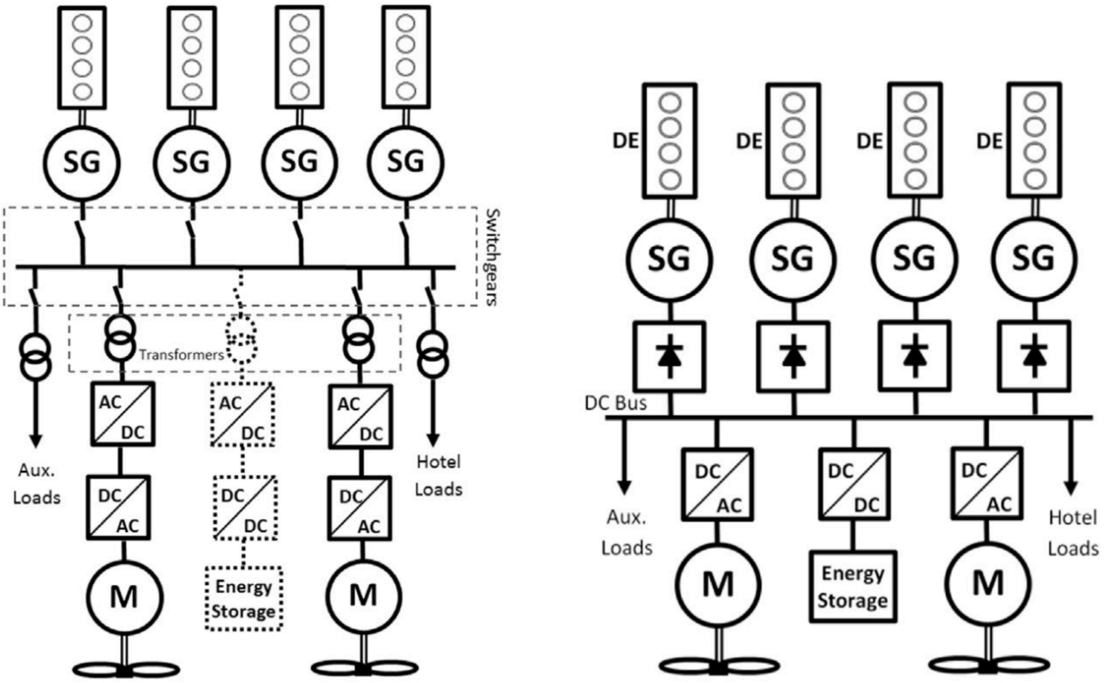


Figure 20 - Single-line diagram of AC-network (left) and DC-network (right) (Zahedi, Norum et al. 2014)

The DC-network provides advantages as space and weight savings. The AC-grid uses more space due to the larger number of switchgears and converters. In addition the DC power system can permit the prime movers run on their optimal speed, as the DC does not require synchronization of generator units (Zahedi, Norum et al. 2014). We also see that the DC system has eliminated some of the stages of transformation that are necessary in the AC-network. In Figure 20 we see some of the components that we find in the hybrid system, we will look further into these in the following.

5.1.1. Switchboard

The switchboard (often more than one) is the component in the ship's electrical system that shall distribute the electrical power to the propulsion and ship. The switches can be circuit breakers or simple contractors (Kwasieckyj 2013). It is normally split in two, three or four to comply with the redundancy requirements (Ådnanes 2003). The switchboard has an important role in the hybrid power system as distributer together with the ship's power management system.

5.1.2. Transformer

Transformers are used to divide the electrical system and make partitions with different voltage. Phase shifting transformers can be used before frequency converters, used for variable speed propulsion, to reduce the distorted currents. There are numerous types of transformers; air insulated, resin insulated and oil/fluid insulated (Ådnanes 2003). We will not go further in on the manner of operations of the transformers.

5.1.3. Inverter (DC to AC)

Most used variable speed drives for ships are AC motors. In most electrical ship systems one has to convert a DC to an AC – this is done by an inverter. The type of inverters installed depends on the electrical layout of the system, whether it is AC or DC based.

5.1.4. Rectifier (AC to DC)

A rectifier converts an AC to a DC. A "conventional" hybrid system (if the term could be used about such a young ship technology) will have multiple stages of conversion due to its integration with DC devices such as batteries (Zahedi, Norum et al. 2014).

5.1.5. Bidirectional converter (DC to DC)

In a DC hybrid power system a bidirectional DC-DC converter is used to incorporate the energy storage device in the power system (Zahedi, Norum et al. 2014).

5.1.6. Electrical bus

The term electrical bus is often used when discussing the power system architecture. An electrical bus means the parallel conductor bars of heavy cross section to which the generators and loads are connected. Generators feed the bus with power and the loads draw power from the bus (Patel 2012).

5.1.7. Breaking resistor

When an electrical propulsion system produce more power than needed in thrust (propeller partially out of water in adverse conditions) the excess power can be sent to a breaking resistor. In the breaking resistor the excess power is made into energy and overloading is avoided.

5.2. Charging technology

If the battery pack in the hybrid system shall be charged through a shore connection when in port, there are several technologies available. The infrastructure of so-called alternative marine power (AMP) is not yet widely installed in harbours around the world. National incentives such as the maritime strategy from the Norwegian Ministry of Trade, Industry and Fisheries, aimed to stimulate the extension of land electricity stations in harbours (Nærings- og fiskeridepartementet 2015). It is expected that more harbours around the world will prepare for the possibility to connect with land electricity. This is an easy way to eliminate local emissions from ships that usually would run the main or auxiliary engines when in port.

For hybrid ships there are three main technologies for charging in port: inductive charging, pantograph charging and plug-in charging. Inductive charging is a little viable solution due to very high CAPEX, low extensiveness and low efficiency. Plug-in is on the other hand installed in many ports and have been a proven technology for connecting ships to shore electricity. Pantographs are usually used for trains, trams and busses, but can be used for connecting ships to shore electricity. The first pantograph for maritime application has been installed on the full-electric ferry *"Ampere"* (Tvete 2015).

5.3. Battery system

For the systems discussed in this thesis the energy storage system consists of a battery pack. The thesis will not carry out a feasibility study on a fuel cell; this is due to the small amount of information available on the field and a natural limitation of the thesis problem.

As discussed in section 5.1 the configuration of the current in the hybrid system can differ. ABB has stated in the paper "Future trends of electrical propulsion and implications to ship design" that a DC distribution in the ships power supply may be a smart arrangement (Pestana 2014). This should be taken with a pinch of salt, as it comes from a company selling DC grid systems. Nevertheless it leaves the designer more freedom also on how the electricity between the battery and the ships power load system can interact.

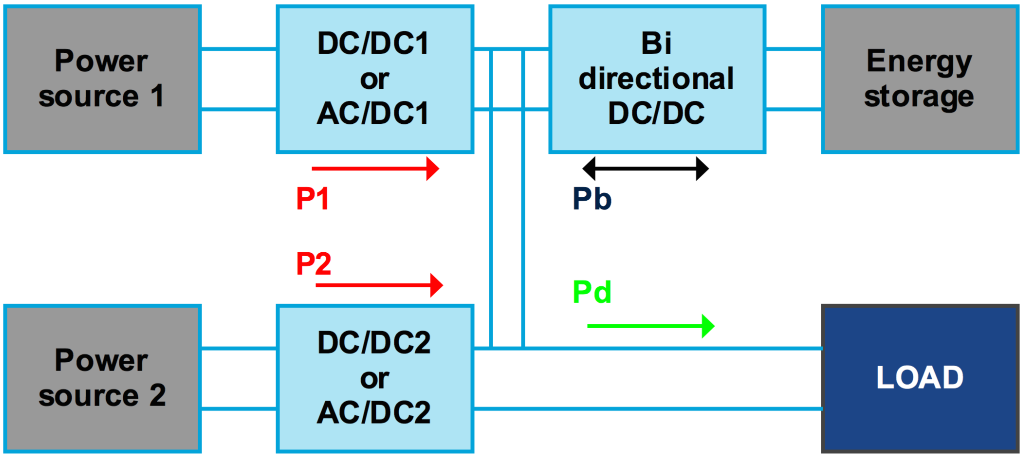


Figure 21 - Type of converters (AC/DC-grid) in a ship with electrical propulsion and a battery.

Figure 21 show how the energy storage, in our case a battery, can be implemented in a shipboard electrical system. We can observe the different options in type of current – DC or AC distribution. The energy flow is indicated with arrows. The bi-directional DC/DC converter makes recharging and discharging of the battery a seamless process.

5.4. Battery system definition

In the following a generic battery system will be presented. There are many different types of batteries that are useable for maritime vessels. The two Norwegian suppliers of batteries for maritime use, Grenland Energy AS and ZEM energy, both specialize in Li-ion batteries. This technology is very well proven in through the automotive industry and is the preferred option for traction batteries (Ellingsen, Majeau-Bettez et al. 2013). The following illustration and information on the generic battery system in 5.4 is more or less based on the "DNV GL guideline for large maritime battery systems" (DNV-GL, Grenland Energy et al. 2013)

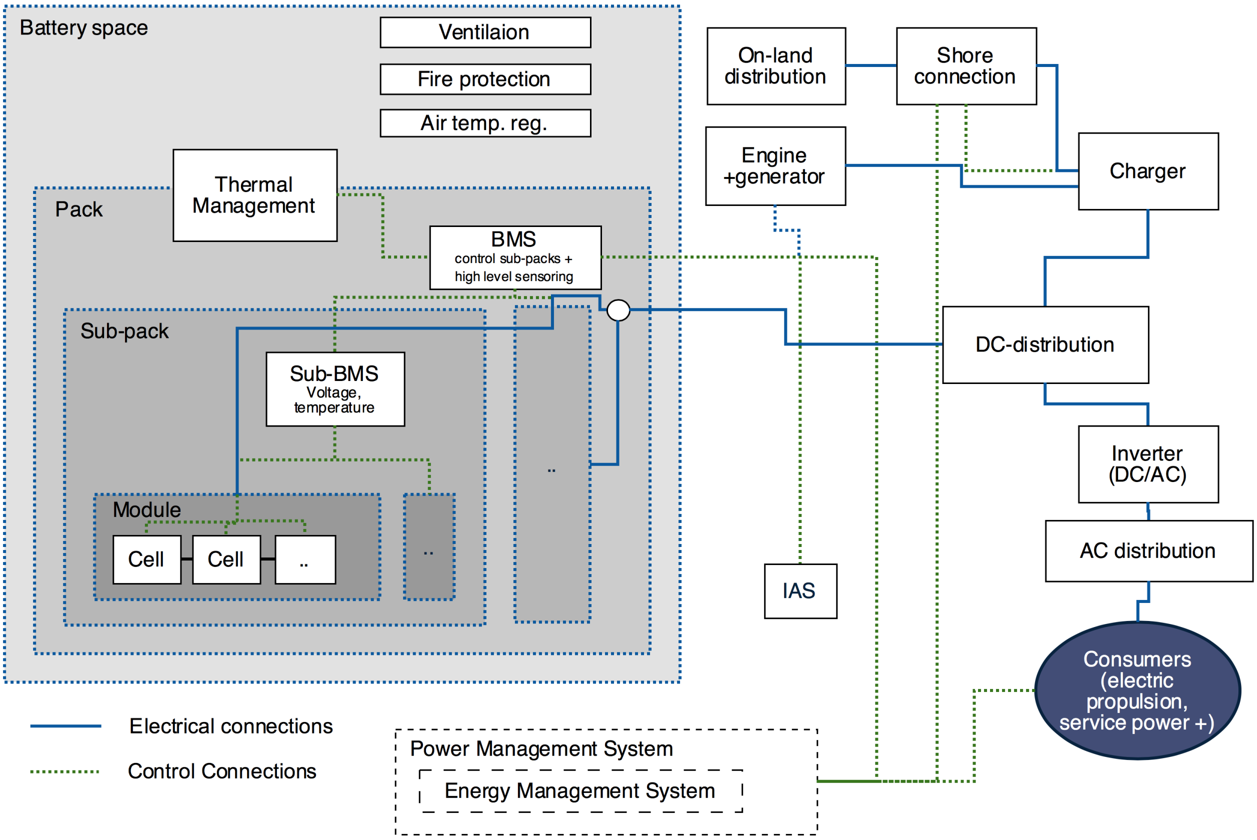


Figure 22 - Generic battery system from the DNV GL guidelines on maritime batteries.

The figure shows the parts that will be present in a battery system in a hybrid ship with a state of the art system. The blue line and the stippled green line represent the electrical and the control signals' pathway respectively.

5.4.1. Cell

The cell is the smallest electro chemical unit in a battery. It is here that the energy is stored. For the cells delivered to the *Viking Queen* from ZEM energy the strategy was to base the system on *quality* cells from the automotive industry. These are produces in large quantities and gives the best price/performance ratio (Mollestad 2015). Such Li-ion cells can have an energy density of 152 Wh/kg and a power density of 2400 W/kg, but the Temperature is an essential part of ensuring optimal operation of the battery cells. Different battery technologies demands different temperatures, but all require a adequate thermal management system (as seen in the figure). The cells are further stacked in modules and the modules are the first level of electrical control (DNV-GL, Grenland Energy et al. 2013).

5.4.2. Sub-pack and pack

The battery pack consists of one or more sub-packs. It can work as a standalone unit, serving the ship's loads throughout the DC-distribution. The sub-packs are on the other hand an assembly of modules and is the smallest unit that can be electrically isolated (DNV-GL, Grenland Energy et al. 2013)

5.4.3. Battery space

The battery space is the room that houses the battery system at a specified set of environmental conditions. Moisture and temperature are two conditions that must be monitored constantly. Sufficient ventilation is demanded as accumulation of flammable gasses can occur during the charging/discharging process. Fire protection (detection and extinguishing) should be installed. A relevant example of lacking of temperature control is the *Dreamliner's* Li-ion batteries that had a trend of catching fire.

5.4.4. Battery management system (BMS)

The battery system is often referred to as BMS. Surveillance of different parameters is crucial for optimal and safe operation of batteries. Sensor input and feedback on voltage, temperature, current and gases are typical data from a battery system. In addition to the sub-BMS there will usually be a "Master-BMS" that control the battery and communicates with the ship's power management system. From the “Tentative rules for Battery Power” we have that the following shall be controlled by the BMS (Det Norske Veritas 2012):

- Internal charging/discharging of the battery
- Battery temperature – air and liquid cooling initiation possible
- Cell balancing

5.4.5. Energy management system

The Energy management system is installed to estimate the remaining energy in the batteries. Figure 23 shows the control system installed in the hybrid PSV *Viking Lady*. The modules are controlled and monitored by a “Battery Pack Control Module” which communicated with the different systems around the battery pack, i.e. physical display, diagnostic tool coupled with a PC, charger control and the general loads controller (array controller or customer equipment) (FellowSHIP 2015). This system was installed with the purpose to deliver a lot of energy over a short period of time and not to deliver a constant flow of energy to supplement the main engines. For such a system the energy management system and battery management system play important roles. The energy management system must rapidly serve the different power consumers and the battery management system must monitor several parameters in the battery in real-time. Especially temperature has been a concern in regard with fast discharging and charging of lithium-ion battery cells.

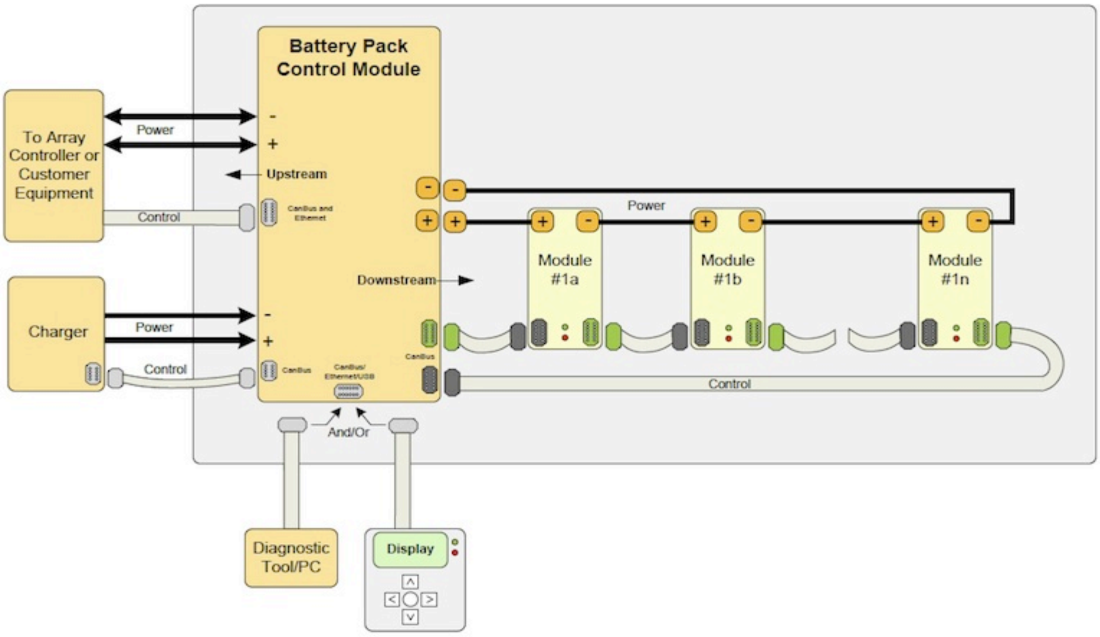


Figure 23 - Control system delivered by Corvus for the *Viking Lady*.

5.5. Battery performance and energy-to-power ratio

The ships operational profiles demand different battery performances. A ship that operated most in DP will have the need for a high power type of battery. A high power battery will be able to charge and, more important, discharge very fast (high C-rate). This quality makes the battery pack suitable for quick response to load variations. A ferry that has minor load variations will be more suited for a high energy battery pack. Such packs contains more energy in kWh, but have a lower C-rate and can not handle the same quick load variations. But let it be said that a high energy system also will have the opportunity to smooth the load variations out, just in a smaller scale.

5.6. Type of battery

For marine applications many types of batteries can be applicable to use. We have already narrowed the paper to include battery based hybrid system and not energy storage in fuel cells. The chemistry behind the electrochemical batteries will not be discussed in this thesis.

There are two types of electrochemical batteries: *primary* and *secondary* batteries. Primary batteries convert chemical energy to electrical energy, but the reaction is non-reversible. A secondary battery is known as the rechargeable battery, meaning that the chemical reaction is reversible (Patel 2012). We will exclusively look into secondary batteries in this thesis.

The major rechargeable (secondary) battery types are:

- Lead-Acid
- Nickel-Cadmium (NiCd)
- Nickel-metal hydride (NiMH)
- ZEBRA
- Lithium-ion (Li-ion)
- Lithium-polymer (Li-poly)
- Sodium battery

5.7. Lithium-ion

This thesis will consider the Li-ion battery technology as the best option and most mature battery technology for marine applications. The hybrid ships and all electric battery ships build lately have all preferred a lithium-ion (Li-ion) type of battery. Ships like the *Viking Lady, Viking Queen, Edda Ferd* and *Ampere* all have Li-ion batteries installed. In Norway we have suppliers like Grenland Energy and

ZEM and Corvus is a Canadian company that have delivered to several projects. The popularity of Li-ion technology for maritime use can be blamed on the automotive industry. Electrical cars like *Toyota Prius, Nissan LEAF, Think city, Smart* and *Tesla Model S* all has Li-ion batteries installed. The research done on making electrical cars commercial feasible has put the Li-ion batteries in a leading position both on land and at sea. The rapid growth in the automotive industry has also pushed down the price on lithium ion batteries. A report published by McKinsey suggests that large Li-ion battery packs could drop to 200 US$/kWh by 2020 and 160 US$/kWh by 2015 (Amsterdam Roundtables Foundation and McKinsey & Company 2014). In the master thesis "Batteries for Marine Applications" the author states that the *"Li-ion battery is an ideal candidate for marine applications"* (Abelleira 2013).

There are many types of lithium-ion batteries on the market. The difference in the elements in the name and main difference between the batteries is mostly variations in the cathode materials. We will not discuss these in dept, but list them without further explanation.

- Lithium cobalt oxide
- Lithium manganese oxide
- Lithium nickel manganese cobalt oxide (NMC)
- Lithium iron phosphate (LFP)
- Lithium nickel cobalt aluminium oxide (NCA)
- Lithium titanate (LTO)
- Lithium ion polymer (LIP)

What kind of type of Li-ion battery that is chosen is based on weighting different qualities and making compromises. As Figure 24 shows some main properties to consider in choosing a Li-ion battery technology (Dinger, Martin et al. 2010). The further the coloured shape extends along the given axis, the better the performance along that property. The figure is from the BCG report "Batteries for Electric Cars" (Dinger, Martin et al. 2010).

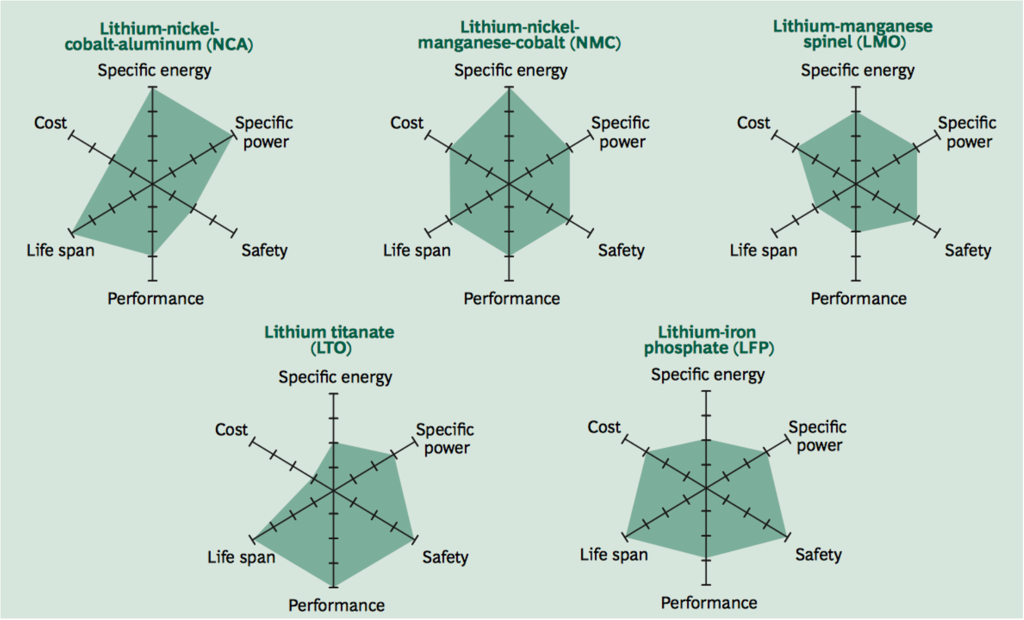


Figure 24 - Tradeoffs among five principal lithium-ion technologies.

5.7.1. Li-ion batteries in PSV

Edda Ferd is a PSV delivered to Østensjø Rederi AS I 2013. The battery hybrid system delivered was from Siemens in cooperation with Corvus energy. The ship was the first to get the Corvus energy and Siemens' "Blue Point C Drive" system installed (2013). The battery pack consists of 52 x 6,5 kWh and has a total capacity of 338 kWh. The bus voltage is 700 and is a DC system. The Figure 25 shows the hybrid system of the ship which shall reduce the fuel consumption with 25-30% compared to similar vessels (The Motorship 2013). Østensjø now has a new order in on a hybrid ship; the *Edda Freya* shall be delivered in the Q1 2016. This ship will have a DC grid of 1050V, a battery pack of 546 kWh consisting of 84 Corvus advanced lithium polymer batteries (PR Newswire 2015).

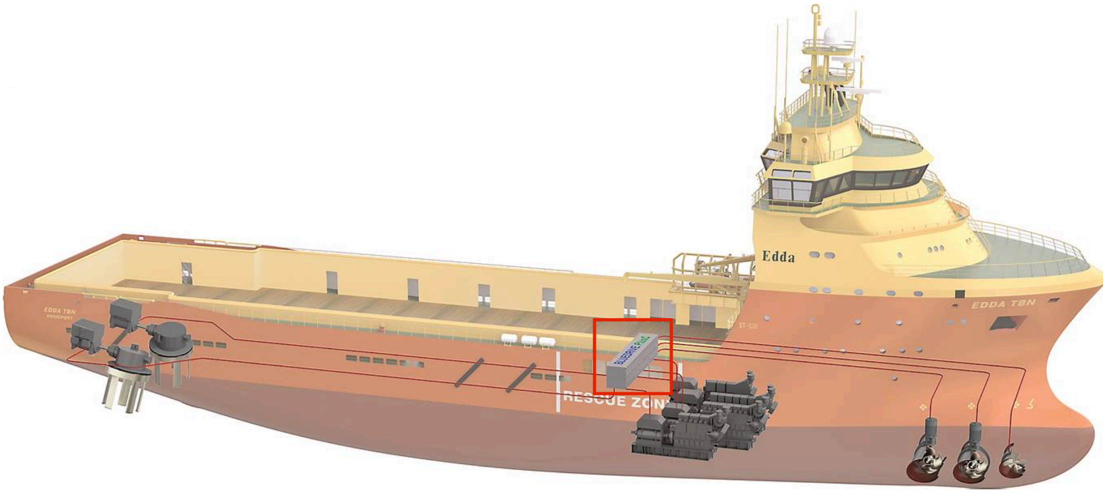


Figure 25 - Edda Ferd with the innovative propulsion system. Battery pack outlined.

The Canadian company Corvus is positioned as one of the leading suppliers of powerful lithium-ion batteries to the maritime industry. The company has presented one block diagram of a hybrid propulsion arrangement for an offshore supply vessel. The modules consist of 24 lithium-ion cells with 0,27 kWh. The total energy in the module is 6,5 kWh. The modules are arranged in serial in packs, each pack made up of 21 modules and contains a total energy of 137 kWh. The packs are placed in arrays of 11 packs in parallel. Each of the packs have pack controllers that manages the modules (Corvus 2015).

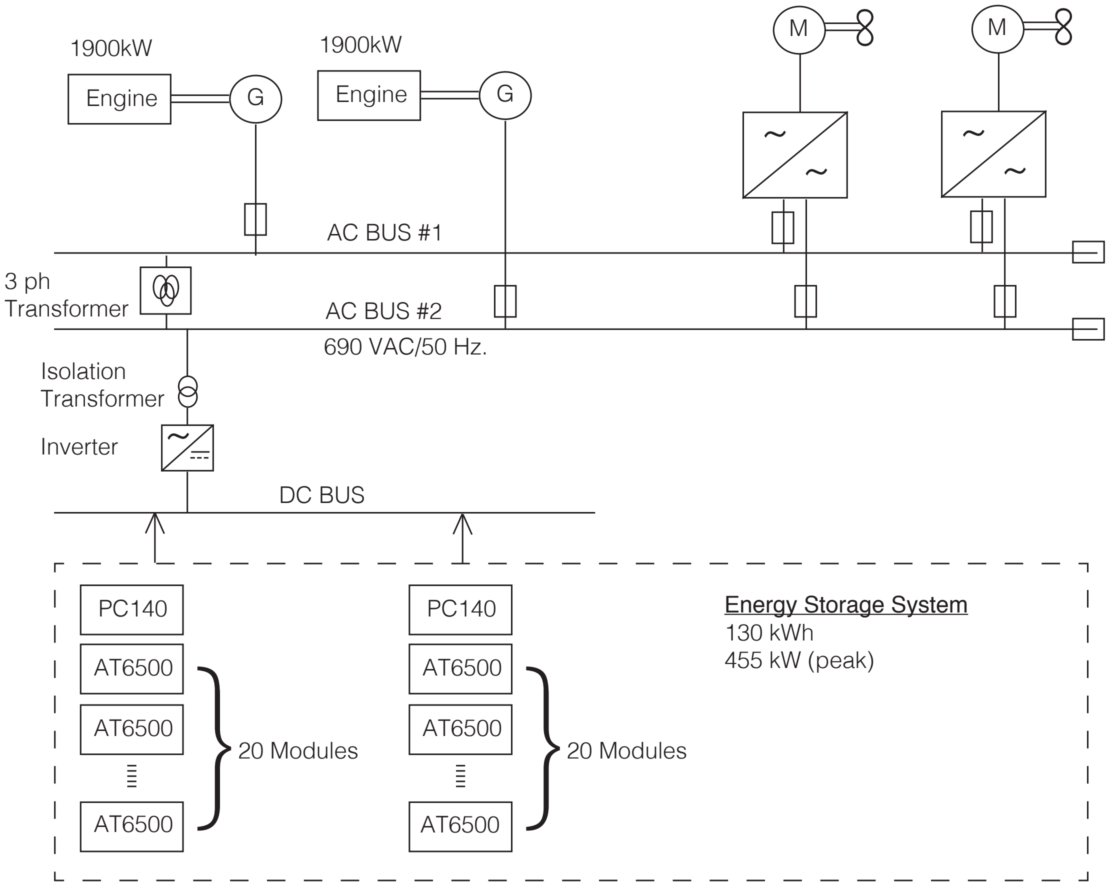


Figure 26 - Example system arrangement for an OSV.

The block diagram (Corvus 2015) shows a AC hybrid system with 40 modules in two packs. The packs are connected to a DC bus that is linked to the AC bus via a DC/AC inverter and a transformer. The gensets deliver power directly to the AC bus and can serve the electrical engines. The switchboard is not present here in this block diagram, but is a crucial part of the power management system.

From the Corvus company the following information is given on the batteries they deliver. As commercial information this should be taken with a pinch of salt, but can give an indicator of the state of the art battery pack qualities.

Type	**Commercial 8D8M Lead acid**	**Competitor Lithium-ion MLi 24/160**	**Corvus Energy AT6500-250-48/96**
Cell	Lead acid AGM	LiFePO4	Lithium NMC
Nominal voltage DC	12V	26,5V	44,4V/88,8V
Energy density	24 (Wh/kg)	86 (Wh/kg)	93 (Wh/kg)
Power density	41 (W/kg)	685 (W/kg)	951 (W/kg)
Cycle life (80% discharge)	300	<2000	>5000
Self discharge	10 %/month	<6 %/month	<2 %/month

Table 5-2 - Battery comparison from Corvus Energy.

5.7.2. Environmental footprint of Li-ion batteries

The EEDI regulation from IMO aims to reduce the cargo footprint per tonne mile transported goods. We will therefore present a small insight of a life cycle assessment of a lithium-ion battery pack. An article by Ellingesen and colleagues with the title "Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack" calculated the impact Li-ion batteries have on global warming. The study came to the conclusion that a 26,6 kWh automotive battery pack (253 kg) caused emissions corresponding to 4,6 tonnes carbon dioxide-equivalents (Ellingsen, Majeau-Bettez et al. 2013). The study was based on a NCM traction battery and cannot directly be transferred to marine, due to different cradle-to-gate of the two transporting methods. The study can on the other hand tell us something important about where the emissions is made: If the energy source used during the lifetime of the battery is renewable, the production stands for most of the CO_2-emissions.

The potential carbon dioxide-emission savings for on a ship is so high with a lithium-ion battery that the production emissions are negligible in the long run, this was stated by the DNV GL researchers Vartdal and Ovrum in an article in Teknisk Ukeblad (Dalløkken 2013). The distribution can be seen in Figure 27 and states how little the battery production fraction is (Mollestad 2015).

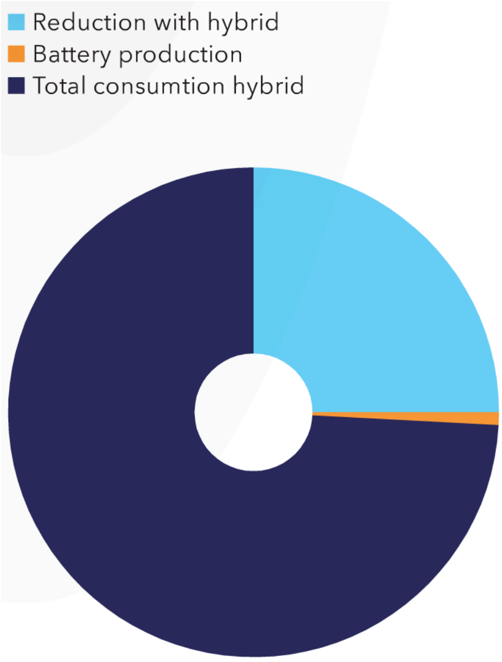


Figure 27 - CO2 emissions for a hybrid ship.

The emissions from production of the hybrid battery pack parts are not included in any of the EEDI calculations. Only the emissions from burning the fuels diesel, LFO, HFO, LPG and LNG contribute in the attained EEDI value. The source of the electricity used to recharge a plug-in battery pack will not be assessed when the hybrid system is not taken into the EEDI calculation (IMO 2009).

In a LCA the afterlife of the cells are also of importance. Most countries importing batteries has to sign up to an agreement that the batteries shall be recycled. The valuable materials in the batteries more or less pays for the cost of the recycling process (Mollestad 2015).

5.7.3. Lifetime estimation

A problem with energy storage is the lifetime of the battery pack. It is normal to operate with a life span of 10-15 years or lithium ion batteries (Tvete 2015). We separate between two types of capacity fade: cycle and calendar. One is dependant on how many cycles the battery has been trough and the other on the age of the battery pack. The life span of the battery depends on a lot of parameters like temperature, dept of discharge (DOD), cycles, cycle characteristics and age (DNV-GL, Grenland Energy et al. 2013). The BMS is crucial in monitoring the condition of the cells and securing that the operation is optimal in respect to securing maximal lifetime. DNV have earlier launched a battery prediction tool, “Battery XT”, to simulate the lifetime of a battery from the mentioned parameter.

5.8. Pricing of the Li-ion battery

One of the biggest disadvantages with lithium-ion battery packs is the price of the cells. Compared to older battery technologies the lithium-ion battery cells have a much higher cost per kWh. The present price for one kWh of installed battery power is not the only interesting parameter. As with fuel prices the forecast of the cost of batteries are of high significance for the development of the technology. The companies selling lithium-ion batteries for the maritime industry mostly deliver tenders and the price per kWh can differ from project to project depending on subsystems and solutions installed. The automotive industry seems more transparent when it comes to expose their US$/kWh-ratios.

McKinsey analysis have pointed out that improved manufacturing and technology will be the two main drivers in the foreseen cost drop. The report "Evolution. Electric vehicles in Europe: gearing up for new phase" proposes a drop to US$197 in 2020 and US$163 by 2025 (Amsterdam Roundtables Foundation and McKinsey & Company 2014). This is a very low estimate, but gives an indication of a very promising market situation for lithium ion batteries.

A recent study has reviewed the historic development in the costs of battery packs electric vehicles and made a model for predicting the future evolution of costs. The article was published in *Nature Climate Change* by Nykvist and Nilsson under the name "Rapidly falling costs of battery packs for electric vehicles". It can sound illogical to use a model based on battery packs for electric vehicles, but it is in fact in the automotive industry the maritime battery application suppliers have extracted knowledge and technology. It is fair to assume that the batteries in use for maritime vehicles will follow the same development in price as the traction batteries. The paper presents a systematic view of 80 estimates of lithium-in batteries for the automotive industry published between 2007 and 2014. Results from the paper shows that the industry-wide cost has declined around 14% annually, from over US$1000 in 2007 to US$410 in 2014 (2014 US$). The market leading manufacturers have a lower decline in costs per year, but are at a historic US$300 per kWh (Nykvist and Nilsson 2015).

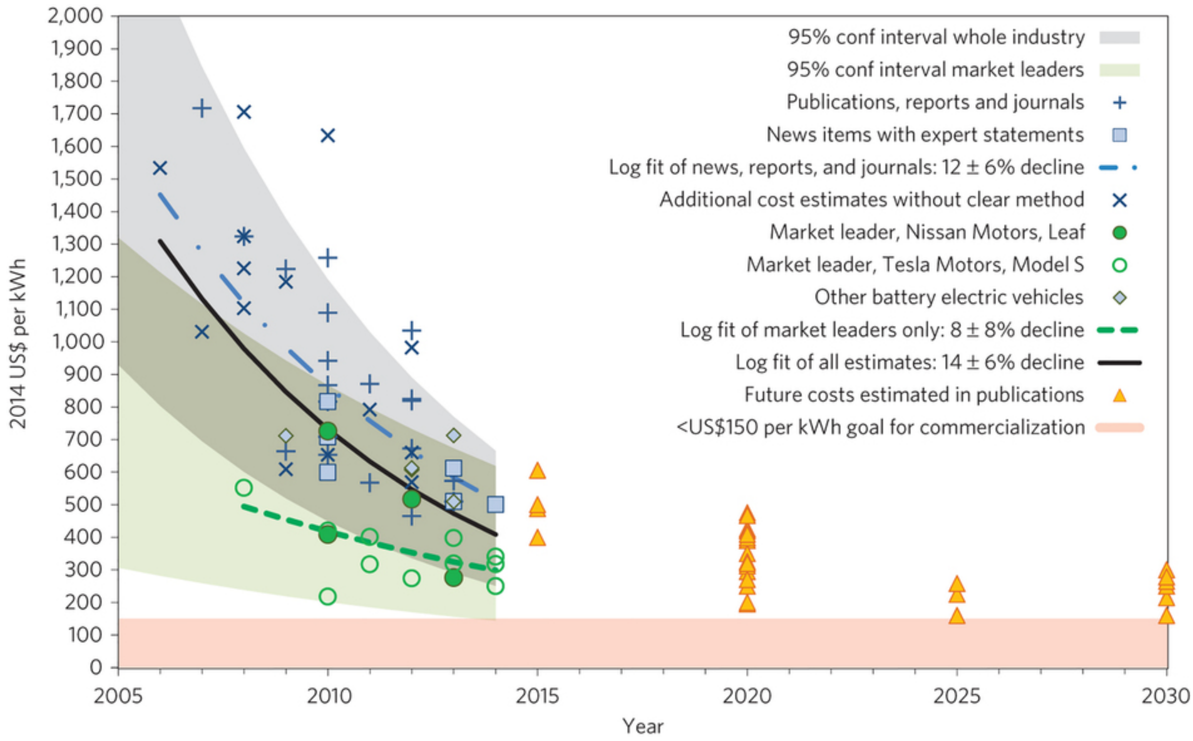


Figure 28 - Cost of lithium-ion battery packs for electric vehicles.

Figure 28 (Nykvist and Nilsson 2015) shows the results of the method of assembling the information from 80 estimates. The uncertainty of the exact costs in the future is uncertain, but the trend is clear – the market price for lithium ion battery pack will decrease. As the price for batteries decrease the EEDI phases makes it more challenging to build ships that comply with the regulations.

For the maritime industry the estimates on installed battery effect can be a bit higher. This is due to more subsystems and adjustments for maritime usage. The DNV GL have however stated that optimized maritime battery systems will drop to US$500 in near future (Mollestad, Valøen et al. 2015).

It is commonly agreed upon that the price of a battery pack must down to US$150 per kWh if battery electric vehicles shall be cost-competitive with internal combustion engines (Nykvist and Nilsson 2015). In the figure this is the bottom pink area – namely a goal for commercialization without subsidies. An industrial goal will drive the industry against more optimized and larger production.

5.9. Alternative hybrid ship applications

A hybrid system invites to a more flexible operation of many ship types. Depending on the subsystems on the ship, the hybrid can be a really smart way of making ship operation more efficient. Not only in respect to propulsion, but on all electrical integrated system aboard. These advantages have previously been mentioned in the chapter "Potential benefits of a hybrid powertrain system", but here we will look more into the details of crane operations and photovoltaic energy harvesting.

5.9.1. Hybrid ship crane operation

Figure 29 shows one of the ship concepts developed by Rolls-Royce for the short sea shipping project "Godsfergen" (Roald 2015). On this particular concept a Ro-Lo ship with two cranes and a stern ramp, which all can be electrically powered. The cranes shall have power recovery and Rolls-Royce claim an energy reduction of 30% compared to conventional systems (Savvides 2015). The power recovery happens through a utilization of the potential energy from hanging goods, that is the kinetic energy released when the goods are lowered to the quay or into the hold.

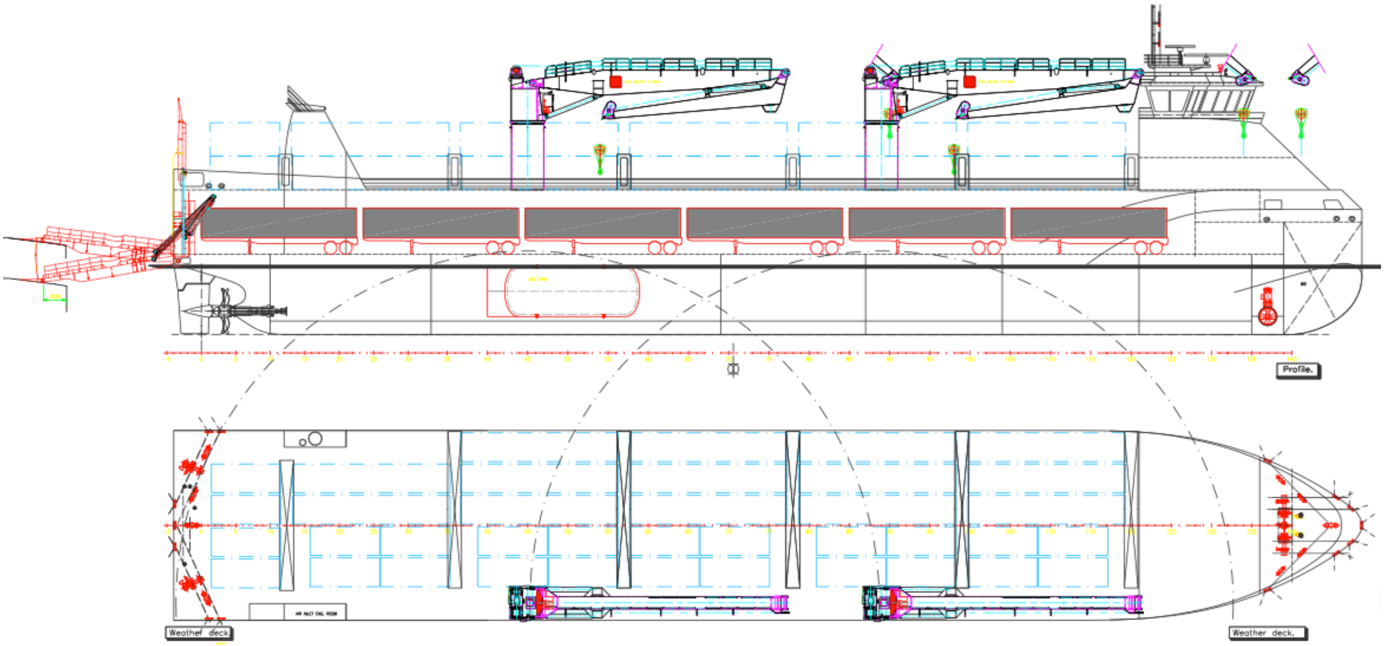


Figure 29 - Cargo handling arrangement of a concept Lo-Ro.

In the paper "Modelling lithium-ion battery hybrid ship crane operation", Ovrum and Berg model the ship fuel consumption for crane operation on a 50 000 dwt dry bulk, open hatch vessel. The modelled system has three slewing type cranes that are powered by electric motors. The fully electric cranes enable so-called *regenerative braking.* By using the electrical motors in the crane as a generator under the lowering and breaking of the cargo the generated power could be sent into the ships grid. If the power demand of the crane operation and the service loads are net negative, the power could be used to recharge the batteries.

In the particular simulation study performed on a Grieg Star 50.000 DWT open hatch vessel, DNV GL and Grieg Star assessed the benefit of hybrid crane operation. The conclusion was that the lithium-ion battery installation had a payback time of less than one year and annual savings of $110.000 (Ovrum and Bergh 2015). The savings and the CAPEX of the system rely on the power demand in harbour and the sixe of the system. The paper does not say that much about the fuel savings for a general cargo ship, but tells that there is a large opportunity of making the ships operation more energy efficient. Many studies do not include the systems around the main focused system and important technical benefits can be lost in the dept in specialization of one system. The hybrid system on a ship will communicate with many other systems and it is therefore important to map out the systems that can make the installation even more advantageous.

5.9.2. Hybrid photovoltaic

One of the mentioned benefits of a hybrid system is the easy-made incorporation of a power harvesting system. For a general cargo shop that runs in the Baltic sea and North Sea will not be able to harvest that much energy from a photovoltaic system. There are a lot of trading routes where energy harvesting from the sun is more suitable.

Figure 30 shows a block diagram from a photovoltaic hybrid system proposed installed on a ferry operating around Geoje Island in South Korea. The specific ship was equipped with two 200 W PV arrays (Lee, Shin et al. 2013).

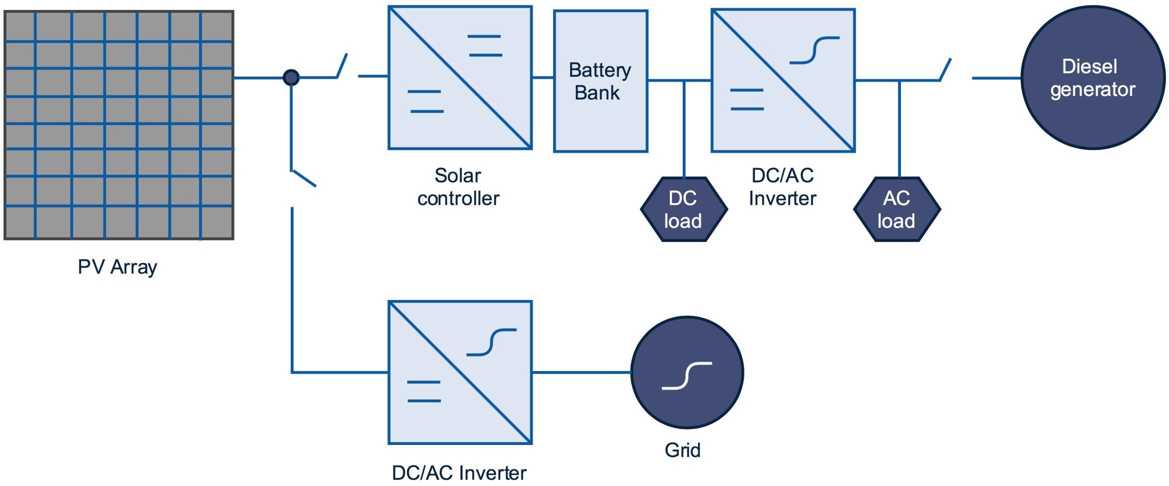


Figure 30 – Block diagram of photovoltaic interaction with the hybrid system.

The economical and environmental benefits were analysed in the case study. The payback period and environmental goodness are very much dependent on the emission regulations in the area and weather. But the conclusion were that hybrid PV/diesel ship has a commercial and environmental potential in many countries were location favours a photovoltaic energy harvesting system (Lee, Shin et al. 2013). We will not assess a photovoltaic energy harvesting hybrid system further in this thesis.

5.10. Influence on ship design

5.10.1. Design implications

We know from several projects that it is possible to successfully install a hybrid system to propel a ship. The FellowSHIP project with the PSV *Viking Lady* was a door opener for both battery and fuel cell hybrid technology on ships. It has been proven that it is not a problem to retrofit ships with battery systems, but it is preferred to install it in a newbuid for optimized space usage. Even though it is technically feasible to install a battery based hybrid system, it will influence the design. We will in the following investigate some of the design implications.

5.10.2. Cost of space and cargo loss

When installing a hybrid system the designers bring one more element into a (typically) space sensitive area of the ship – engine room department. A hybrid system will be more spacious than a conventional diesel-mechanical or diesel-electrical propulsion system. How much more volume that is needed is depending on the type of battery system. A DC system can be smaller, as the system has fewer components than an AC system and does not necessarily require a "main switchboard" (Pestana 2014). The other sub-systems described earlier must also be taken into consideration if space is a critical design parameter.

Cargo carrying ships are very sensitive to changes in the cargo capacity. The required freight rate will rise if the there is a loss of cargo space and the operational expenses remain the same. The impact will be different in newbuilds and retrofits. The design process of installing a hybrid system with battery storage will be easier for a newbuild, but there might be acceptable interference with the cargo holds even in a retrofit. The reason is that most of the general cargo ships have the wheelhouse in the aft of the ship, behind the cargo holds, and therefore *can* a hybrid system be installed without confliction with the cargo space. The potential loss of cargo must be brought into consideration in the economic feasibility in installing a hybrid system.

Generally the combination of a diesel electric and energy storage devices can say to have flexible arrangement options. When connecting the systems electrically the need for alignment on the same deck plane, as with diesel-mechanical systems, is eliminated. For instance can the void space (often situated above the engine room) be exploited for energy storage. The cable loss in a electrical system onboard is estimated to be up to 6%, but this is a worst case situation (Dedes, Hudson et al. 2012).

5.10.3. Hydrostatics

Weight estimation in shipbuilding is always a delicate matter. The weight and placement of the hybrid battery system, with the battery pack as main weight component, has to be added in the stability calculations. We will later look into typical weights for a hybrid system, but for a newbuild there should be no problem placing the weight in a safe manner. When retrofitting a general cargo ship with a battery pack the arrangement can be more complicated. Trim shall be assessed, as the trim values are important for optimal hydrodynamic efficiency. Compromising between changing trim values and the hybrid systems interactions with the cargo space must be considered necessary. The weight of the battery pack can be considerable, depending on the effect installed. The cells delivered by ZEM Energy have an energy density of 152 Wh/kg, so a typical PSV with 650 kWh installed capacity will have a battery pack weighing approximately 4,2 tonnes (Mollestad 2015).

5.10.4. Risk based design

In the beginning of implementing lithium-ion battery packs in EVs and HEVs the safety issue was a hindrance for commercialization. Under abusive operating conditions (e.g. overcharge, impact, heat shock) the battery can produce high temperature, smoke, fire and explosion (Yoshio, Brodd et al. 2009). The system must therefore be continuously monitored and external safety devices must be installed. Non-flammable electrolyte technology has been on of the factors in the successful scale-up of the lithium-ion production (Yoshio, Brodd et al. 2009).

In the DNV rules for classification “Tentative Rules for Battery Power” the general design principle 102 is:

“The arrangement of the battery spaces must be so that a hazardous situation that may be caused by a break down of the batteries (e.g. gassing, explosion, fire) can not lead to loss of propulsion or auxiliary power for essential or important users.” (Det Norske Veritas 2012).

This means that a safety assessment must be carried out with the following steps: Hazard identification (HAZID), risk assessment, risk control options and proposed implemented measures (Det Norske Veritas 2012). Also securing the system with barriers of risk reduction, both proactive and reactive. For pure electric propulsion ship the rules for redundancy is much stricter than for hybrid ships. Generally a hybrid system will bring higher redundancy to a ship’s propulsion system (Vartdal 2013).

6. Cases

6.1. Focus area

We will in the following look into a general cargo ship and assess the feasibility of installing a hybrid system with the mission of complying with the required EEDI. Figure 31 is a plot with general cargo ships in the IHS Fairplay Database (Verhulst, Nieuwenhuis et al. 2012). The red rectangles in the plot highlight the capacity areas where the scatter is the highest, i.e. where the correlation between the EEDI reference line and the attained EEDI is at its lowest. The EEDI reference line is based on the RESOLUTION MEPC.203(62) and represents the base line for the further EEDI reductions; three phases of stricter demands on energy efficiency. The situation for general cargo ships with low DWT (3.000-20.000) will be worse when phase 1, 2 and 3 is put into force in 2015, 2020 and 2025, respectively. We will focus on the general cargo ships in the lower deadweight ranges, from 3.000 to 20.000 DWT, due to the challenges this capacity-range faces in the EEDI regulation.

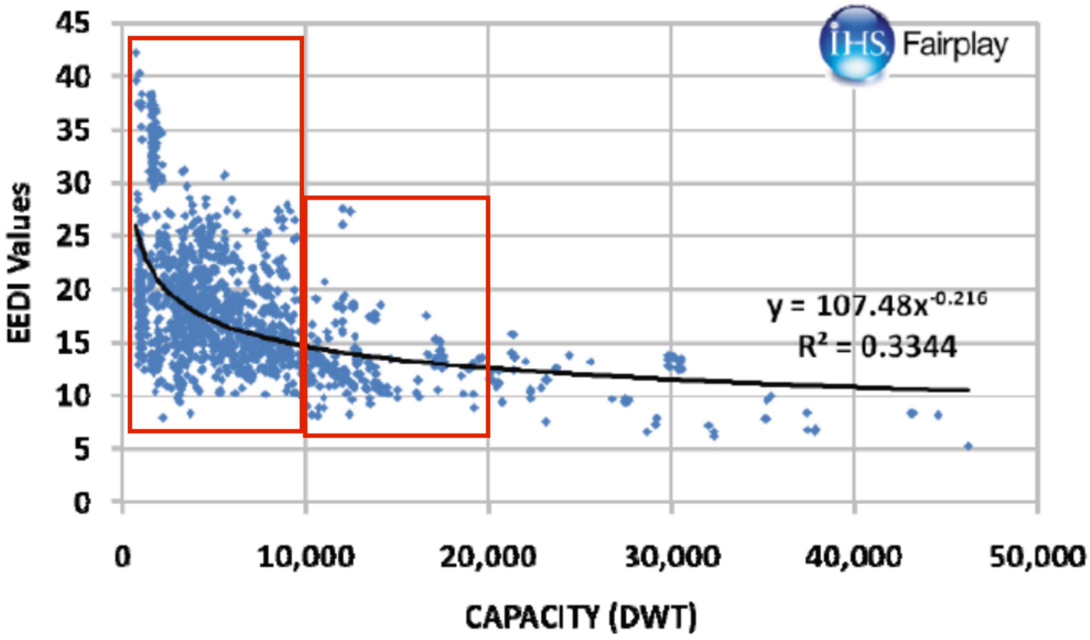


Figure 31 - EEDI values of general cargo ships from the IHS Fairplay database.

6.2. Operational profile effect on EEDI

The general cargo ships below 20.000 DWT are optimized for a large variety of niche markets. Even though a ship is specialised for a specific trade the vessel is also designed to be capable of carrying grain, coal or other bulk cargoes as a return freight or when the main cargo is not available for freight. The variety of trade routes and cargo will have an influence on the operational profiles of the general cargo vessel. The minimum required speed is one of the parameters that are affected by the range of operating profiles. As a presentation of the variety in ship speed, the V_{ref} of some vessels in the Conoship, MARIN and CMTI study (Verhulst, Nieuwenhuis et al. 2012) are plotted in Figure 32.In the lower regions we have the highest spread of speeds, from 9 to 15 knots – the same spread we find in Figure 33.

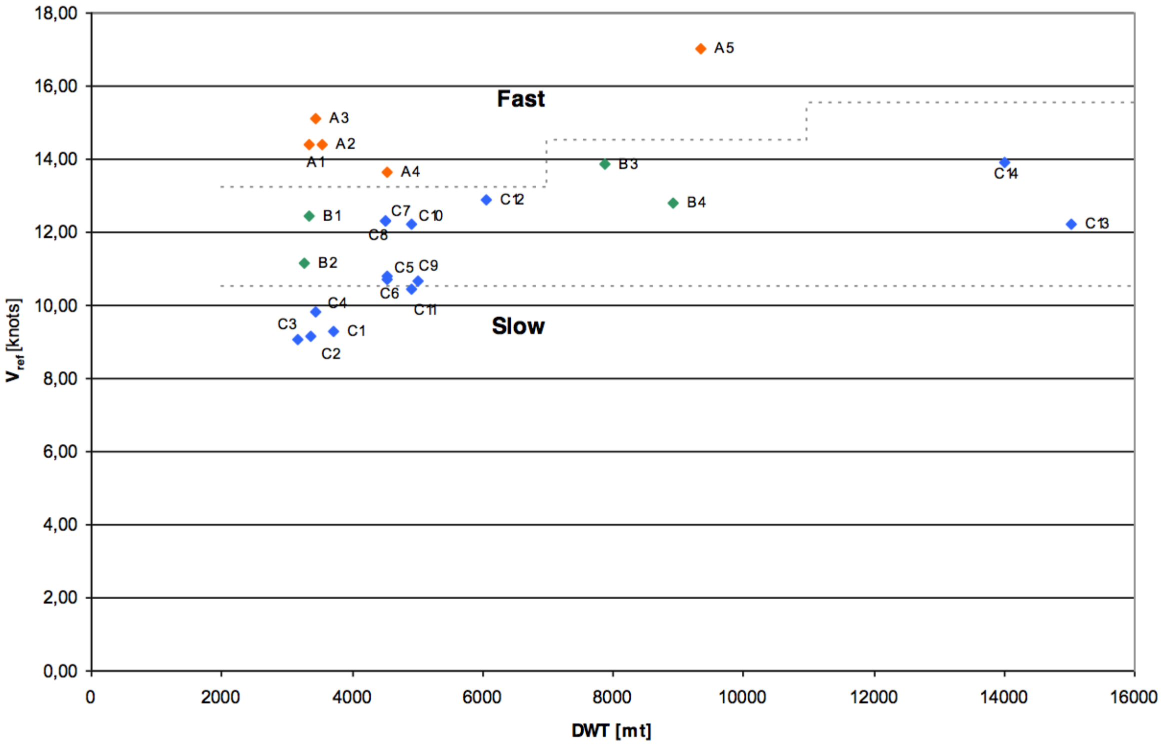


Figure 32 - Plotting of ships speed in respect to capacity (DWT).

The Figure 32 also displays boundaries of what are common speeds of general cargo vessels. The report contributors have defined the boundaries in this plot and these are not commonly recognized, but fair estimations based on the data set.

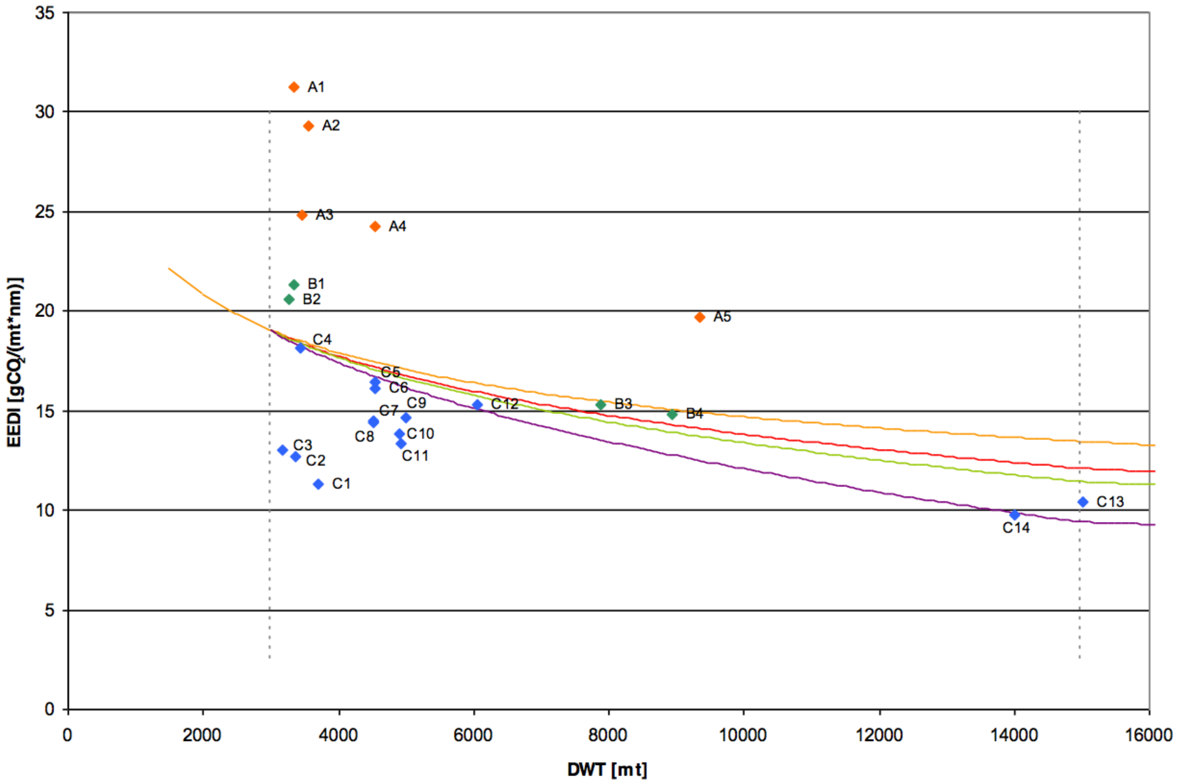


Figure 33 - The sample ships' attained EEDI plotted against the required EEDI lines.

Not surprisingly are the ships with highest V_{ref} (A1-A5) way above all of the plotted lines for required EEDI in Figure 33 (Verhulst, Nieuwenhuis et al. 2012). Also the ships that are in the "normal" speed range (B1-B4) have problems with too high attained EEDI. The V_{ref} is submitted below the fraction line in the attained EEDI formula and is a reducing factor of the EEDI value when increasing. This does not compensate for the needed main engine power (P_{ME}) to attain the speed. A look at the resistance curve for any given ship can give an explanation to this discrepancy. The resistance of common mono hulls will increase approximately exponentially with speed. A high V_{ref} will lead to an unfavourable EEDI value. The challenge is to maintain a high operating flexibility with high speed and at the same time attain a low EEDI value – this challenge can be solved with a hybrid system.

6.3. EEDI values

Some general cargo ships have been assessed to find out whether or not there are possibilities to reduce the EEDI of fast vessels. Some case ships have been studied from the *Royal Institute of Naval Architecture's* (RINA) publications "Significant Ships of the year" 1994-2004 (RINA 1994-2003). These ships shall represent some of the best within ship design and can be seen as a benchmark for the industry's standard. The case ships have deadweight between 4500 and 16000 tonnes.

Ship particulars	*Arklow Rally*	*Arcadian Faith*	*Celtic Monarch*	*Flinterzee*	*Happy River*
Main engine power (P_{ME})	1800	3520	4900	3280	8775
Capacity (DWT)	4500	5273	6250	5820	15634
Speed (V_{ref})	11,5	16	15,5	14,5	16
Attained EEDI	16,42	19,29	23,27	17,51	15,55
Required EEDI	17,47	16,88	16,27	16,52	13,35
Percentage deviation	-6,00 %	14,31 %	43,02 %	5,95 %	16,49 %

Table 6-1 - EEDI calculation results for general cargo case ships.

As presented in 6.2 the correlation between high service speed and high EEDI can be observed in Table 6-1. The ships assessed are built between 1994 and 2002 – which is a representative age for most of the general cargo ships sailing today. The smallest ship, *Arklow Rally* with its 4500 DWT, actually complies with the required EEDI reference line. The EEDI reference line is however the line that represents phase 0 and is already outdated due to the beginning of phase 1 from 1 January 2015.

The numbers presented can only make good estimations of the EEDI value of the ships. To calculate the exact value of the EEDI one must have very specific values of engine and generator specifics, such as efficiencies. Such information has not been available in this study and the values remain estimations, but gives good enough insight for the scope of the thesis. The intention of the above estimates is not to calculate the EEDI of the vessels in a very accurate way, but to give examples of discrepancy between attained and required EEDI for small general cargo vessels. The results from the calculations will be used as a guideline in suggesting a solution to the design index regulatory challenge.

Figure 34 presents the index values for the five ships assessed against the four lines of required EED value. The ships with lower deadweight have the advantage that the reduction factor is linearly interpolated between 3000 and 15000 DWT. Meaning that the leaps between the phases will not be that big as for ships over 15000 DWT. On the other hand it is harder to change the index value when the ships particulars (main/auxiliary engine power, capacity, regenerative systems) are much smaller.

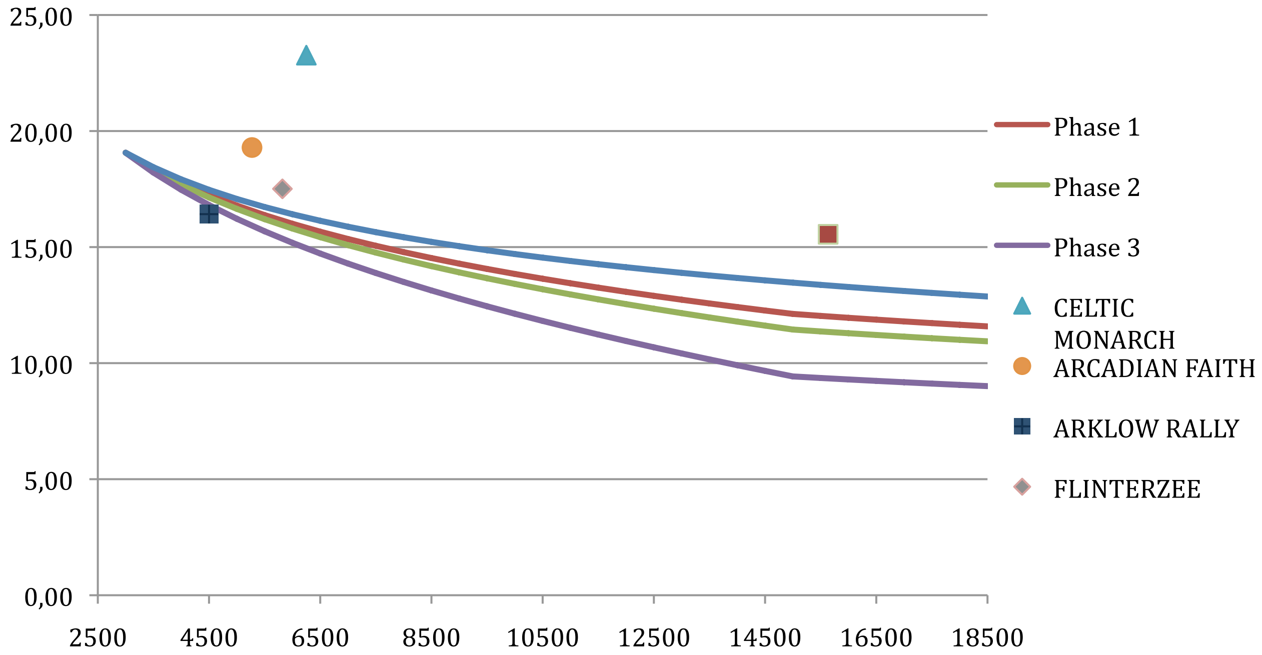


Figure 34 - The attained EEDI values of the five case ships plotted against the EEDI phases.

6.4. Hybrid system proposal

To make the ships compliant with the current and coming phases of the EEDI regulations – the design parameters that have influence in the EEDI equation must the changed. Previously we have presented the idea of reducing the main engine power to bring the P_{ME} with installing a hybrid system with a battery pack. We will in the following look at the feasibility of doing such. When installing a battery pack, the installed power in the battery cells are not taken into account in the EEDI equation and will lower the EEDI value.

6.4.1. Lowering the EEDI

To lower the EEDI value for the five case vessels, we must see how much the installed effect of the main engine must be reduced. The calculation done is just approximations due to the lack of highly detailed information on the ships. We will not assess the phase 0 of the EEDI since this phase was superseded by phase 1 in Jan 2015.

Engine power reduction (Δ_{PME} kW)	*Arcadian Faith*	*Flinterzee*	*Celtic Monarch*	*Happy River*
Phase 1 (1 Jan 2015 – 31 Dec 2019)	550	300	1700	2200
Phase 2 (1 Jan 2020 – 31 Dec 2024)	570	320	1800	2600
Phase 3 (1 Jan 2025 and onwards)	700	450	1900	3800

Table 6-2 - Reduction of main engine in kW to comply with the EEDI.

In table Table 6-2 the results of the attained EEDI calculation is presented. The calculation of the value for the ship *Arklow Rally* was left out because the attained value complies with all the phases and is not a suitable ship for hybridization (that is in respect to EEDI – hybridization can still be favourable). From the table we have that *Celtic Monarch* and *Happy River* both demand a lot of power reduction to comply with the required value in the three phases. Due to the large amount of power reduction we consider these unfitted for hybrid installation. We will discuss the general cargo vessels *Arcadian Faith* and *Flinterzee* further, since these are most fitted for hybrid propulsion.

6.4.2. Trade routes and operation

The economical feasibility will rely much upon the operational pattern of the ship and it’s trading routes. We will look into the nearby coastal areas. The area around Norway is favourable in many ways for a hybrid general cargo ship. The Baltic Sea and the North Sea are both ECAs, meaning that sulphur content in the exhaust cannot exceed 0,10% from 1 January 2015. A hybrid system can reduce the fuel consumption of the expensive low sulphur fuel oil. A fuel reduction will therefore be more profitable within an ECA. In IMO it has been suggested that a NECA should be established in the Baltic Sea and the North Sea (Baltic Ports Organization 2014). The Nordic countries have plans for building out the shore-to-ship infrastructure and making cold ironing more accessible. This will make the technical feasibility of plug-in hybrid very good. The sea state of the oceans in this area is quite changing and can be very adverse. This favours a hybrid propulsion system that can handle load variations and maintain the speed of the ship.

Figure 35 shows a map over the container and cargo transporting routes in the Baltic and North Sea (Baltic Transport Journal 2015). The first advantage of the routes is that all is within the limits of the ECA. Rotterdam, Antwerp, Bergen, Oslo, Gothenburg, Stockholm, Helsinki and Tallinn have installed or have plans on installing alternative marine power (Papoutsogolou 2012). Shipping between those harbours will supply the ship with a reliable and foresighted electrical power.

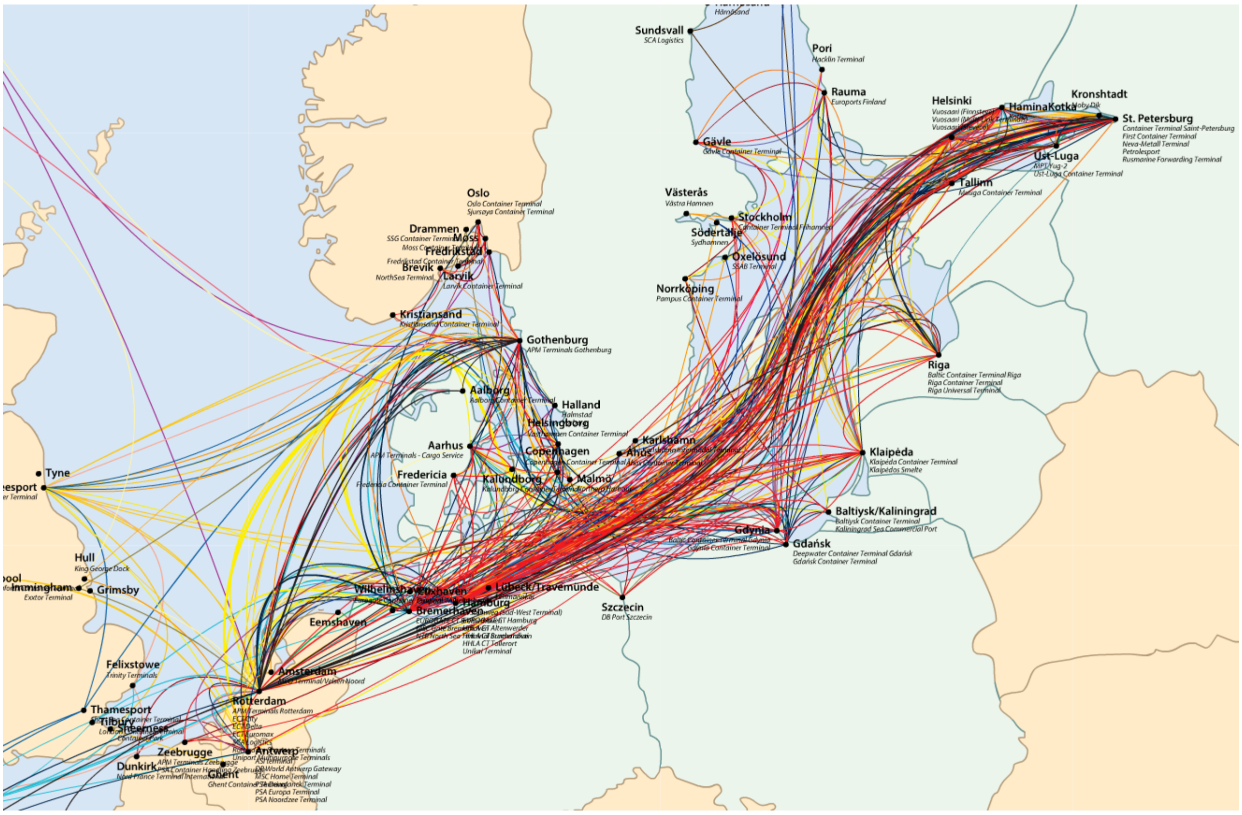


Figure 35 - Cargo routes in the Baltic and North Sea.

6.4.3. Battery

Aiming to reduce get the attained EEDI under the required EEDI line, we need to establish an estimate of how much electrical power is needed. The installed effect of the battery has to compensate for the reduced installed main engine power. Finding the needed effect of the battery pack is not straightforward. The amount of reduced power in the main engine (kW) cannot easily be traded with kW in a battery pack. Installing a battery pack that would run constantly to serve the lost engine effect would not be a feasible solution in most cases. The installed battery pack must be optimized for the operation of the ship: Trading routes (weather and current), duration of voyage between ports (time between plug-in charging, if installed), minimum speed (manoeuvrability in adverse conditions) and speed flexibility.

For the purpose of optimizing operational efficiency for the general cargo vessel, the battery pack must both supply the ship in need for extra energy and power. The cells must have high energy content to endure longer discharging periods and enough power to supply the load variations.

6.4.4. Price and payback

The price of installing the battery pack will be the most significant decision factor. For the Revolt ship the DNV GL project group used a kWh-price of US$1000. As we have discussed earlier the price is projected to fall constant in the years to come and the kWh-price will be lower when the different phases of EEDI go into power. For the purposes in this thesis we will use US$1000 per kWh, which is seen as a conservative estimate.

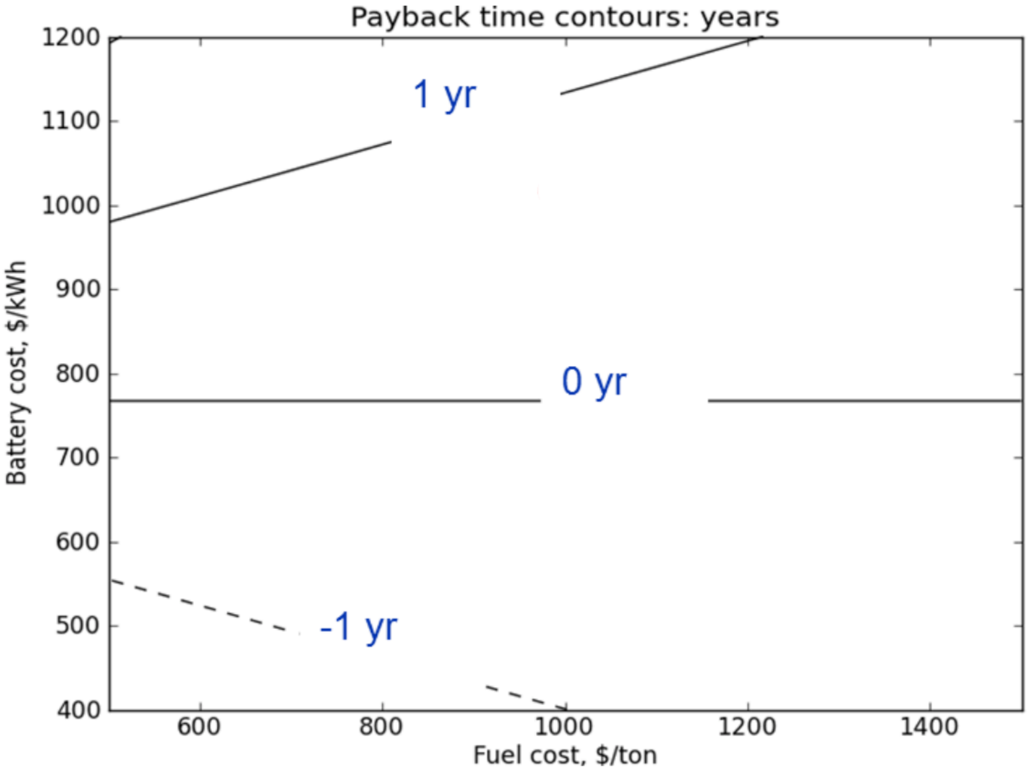


Figure 36 - Contour plot of the payback time.

The contour plot in Figure 36 (DNV-GL, Grenland Energy et al. 2013) shows the lines for constant payback time depending on the battery- and fuel cost for a given vessel (not our case vessels). We have earlier discussed the anticipated price decrease of installed kWh in batteries, it is more uncertain how the price of bunkers will develop in the coming years. High fuel prices have always been a driver for alternative fuels and energy efficient measures. Now (May 2015) the prices for Rotterdam is US$570 for MGO (ca same for LSMGO) and US$380 for HFO (IFO180) (Ship & Bunker 2015).

6.4.5. Payback scenarios

The uncertainty in the economical equation of whether or not a hybrid system will pay of is large and relies on many parameters. We do not have any information engine loading to base the scale of the battery pack on. What we can do is to assess how much can be saved by reducing the main engine power. For the *Arcadian Faith* and *Fliterzee* to reach the required EEDI phase 1 and 3 they must reduce their main engine power between 550-700 kW and 300-450 kW, respectively. The SFOC is set very low for the two case ships – the values are from the engine manufacturer and represents consumption under ISO conditions. This does not represent operation reality, but gives an understanding of how it would be if these ships were to be built today. From the ReVolt report we have that the "at sea-ratio" is 0,77 (Tvete 2015) and this is used to represent the time the ship is in transit. Transit time: 365*24*0,77=6745 h/year.

	Arcadian Faith	*Flinterzee*
SFOC	179 g/kWh	174 g/kWh
Engine reduction	550 – 700 kW	300 – 450 kW
Potential fuel reduction	98,5 – 125,3 kg/h	52,2 – 78,3 kg/h
MGO price low – high	575 - 1050 US$/MT	
Potential savings low	56,6 – 72 US$/h	30 – 45 US$/h
Annual savings low	**383 – 486 (1000US$)**	**202 – 303 (1000US$)**
Potential savings high	103,4 – 131,6 UDS/h	54,8 – 82,2 US$/h
Annual savings high	**697 – 888 (1000US$)**	**370 – 554 (1000US$)**

Table 6-3 - Potential savings of reducing installed engine size.

If the payback period of an installed battery should be one year the reduced fuel cost also represents the battery pack size when presuming cost per installed kWh is US$1000.

Return on investment	*Arcadian Faith*	*Flinterzee*
Battery pack 1 year payback period	Low: 383 - 486 kWh High: 679 - 888 kWh	Low: 202- 303 kWh High: 370 – 554 kWh
Battery pack 2 year payback period	Low: 776 – 971 kWh High: 1352 – 1776 kWh	Low: 404 – 606 kWh High: 780 – 1108 kWh

Table 6-4 - Equivalent battery size to potential savings.

6.4.6. Newbuild CAPEX

The newly delivered general cargo ship *M/S Kvitbjørn* is a 5000 DWT with a CAPEX of US$32,5 million. This gives a US$/DWT-ratio of 6500 (Tvete 2015). For the *Arcadian Faith* and the *Flinterzee* this means a CAPEX of 34,3 and 37,8 million US$. The proposed installed battery packs will for the *Arcadian Faith* and the *Flinterzee* only amount between 1,1 - 2.6% and 0,6 – 1,5% of the total CAPEX, correspondingly. The CAPEX of the *MS Kvitbjørn* must be said to be high for a general cargo ship, due to an adequate hull form, complex cargo handling gear and LNG propulsion. The ship has innovative design elements, but represents the modern general cargo ship with more environmentally friendly operation.

6.4.7. Crane operations

When installing a hybrid system it would make sense to install a full electric cargo handling system. Regardless of the ship is shore connected or not, this will reduce both the fuel consumption and the emissions in port areas. Ovrum and Bergh modelled crane operations for a 50 000 DWT open hatch dry bulk ship from Grieg Star to run on a hybrid crane system. Their results were extraordinary and show that it is possible to use a hybrid propulsion system together with other shipboard systems. The challenge of intercommunication between different shipboard systems can be the difference in energy and power demands.

The reduction of using a hybrid crane operation was 30% in fuel, corresponding to US$110.000 annually (Ovrum and Bergh 2015). These numbers are not possible to achieve with a general cargo vessel between 3000 and 15 000 DWT, but shows the potential of the technology. With a plug-in system in the port, the crane operations can be close to zero-emission.

6.4.8. Other aspects of economy

Another reason for that the North Sea and Baltic Sea region is interesting regarding innovative designs is the possibility of funding by governmental and international incentives. In Norway the NO_X-fund has been driving innovative ship designs trough supporting projects of ships that emits less than the conventional ship types. Enova is also a provider of funding for project that can prove to be environmentally friendly. The EU has also been suggesting some funds that have the same structure as the NO_X-fund. Start capital for technologies aiming to make shipping more energy efficient is important due to the fact that it is a risk to install a young technology with high CAPEX.

It has been anticipated that some kind of global emission tax on CO_2-emissions from ships will be adopted. Norway has a national taxation on the CO_2, but an agreement on a global system has not yet been reached. Ships with more energy efficient design will however be favoured in some ports and can reduce the OPEX of general cargo ships that has typically have several port visits every day. World Ports Climate Initiative (WPCI) has developed the Environmental Ship Index (ESI). The ESI value depends on scores from the three emission contributions NO_X, SO_X and CO_2. The higher ESI score the less will the port cost be for the ship charterer/owner. For our case area there are several ports that has adopted the system and gives beneficial prices for environmentally friendly ships (World Ports Climate Initiative 2015).

7. Conclusion

The overall aim for this thesis was to assess the possibility of lowering the Energy Efficiency Design Index (EEDI) value with a hybrid propulsion system in a general cargo ship. The ship type investigated was small (<15 000 DWT) and fast (>13 kn) general cargo vessels. It was found that it is possible to lower the EEDI of a general cargo ship by installing a hybrid propulsion system. The hybrid system can optimize the ship's operational efficiency and engine load. The system has many advantages like enabling cold ironing, eliminating frequent load variations, power redundancy, reduction of local and global emissions, less noise/vibrations, facilitate energy harvesting/sub-system integration and has overall higher efficiency than conventional systems.

The report states that a lithium ion battery with high energy-ratio and the possibility of serving load variations will be the best technical solution. A DC grid will take up less space than an AC system and can easily integrate other shipboard systems, like cargo handling equipment. It was established that

The results from the systems study were tested in a case study. The study proposed that the two ships investigated could have been built with a hybrid propulsion system with the result of complying with the strictest EEDI phase. The size of the battery pack was calculated by how much the cost of the system could be justified by the fuel savings of installing the hybrid system. The potential fuel savings for the two ships were 383 – 888 (1000US$) and 202 – 554 (1000US$) for the 5273 and 5820 DWT ships, respectively.

My personal opinion after working with this theme is that battery hybrid ships will become more popular in the years to come. I think that the general cargo segment will need innovative technologies to keep up the competitiveness against land transport – hybrid propulsion can be this technology.

8. Further work

The thesis is not based on real life ship data and this is a clear weakness in my opinion. For possible further work it would have been good to have an industry partner that could provide very accurate loading data of the engines for a larger period of time. On the basis of real life data, good decision on battery pack type and size could be made. The study could include the precise fuel consumption of the vessel and analyse how much potential fuel savings that can be achieved due to use of hybrid propulsion. Simulations of how the hybrid system works together with the rest of the propulsion system could be carried out as a verification method.

It is not only the transit period that is interesting to investigate in the light of hybrid propulsion. With a battery system onboard it would be natural to study all of the ships operational modes. For this ship segment in particular the crane operation and cargo gear could be assessed to see how much could be saved in fuel, costs and emissions.

The infrastructure of alternative marine power (AMP) in ports has not yet been widely developed. A study on how to optimize the route of a plug-in hybrid vessel between ports with charging facilities could be interesting. A large simulation model that implements route, speed, heading, weather, cargo handling, manoeuvring and charging possibilities could be a valuable tool in a decision-making process.

I personally think that the batteries are just on the brink of commercial breakthrough in the maritime industry. Analysis on how the market (quantum/price/recycling) for batteries would develop vs. the need for lowering the EEDI would be interesting. The cost predictions in this thesis insinuate that the price will drop parallel with the strictness of the EEDI regulations.

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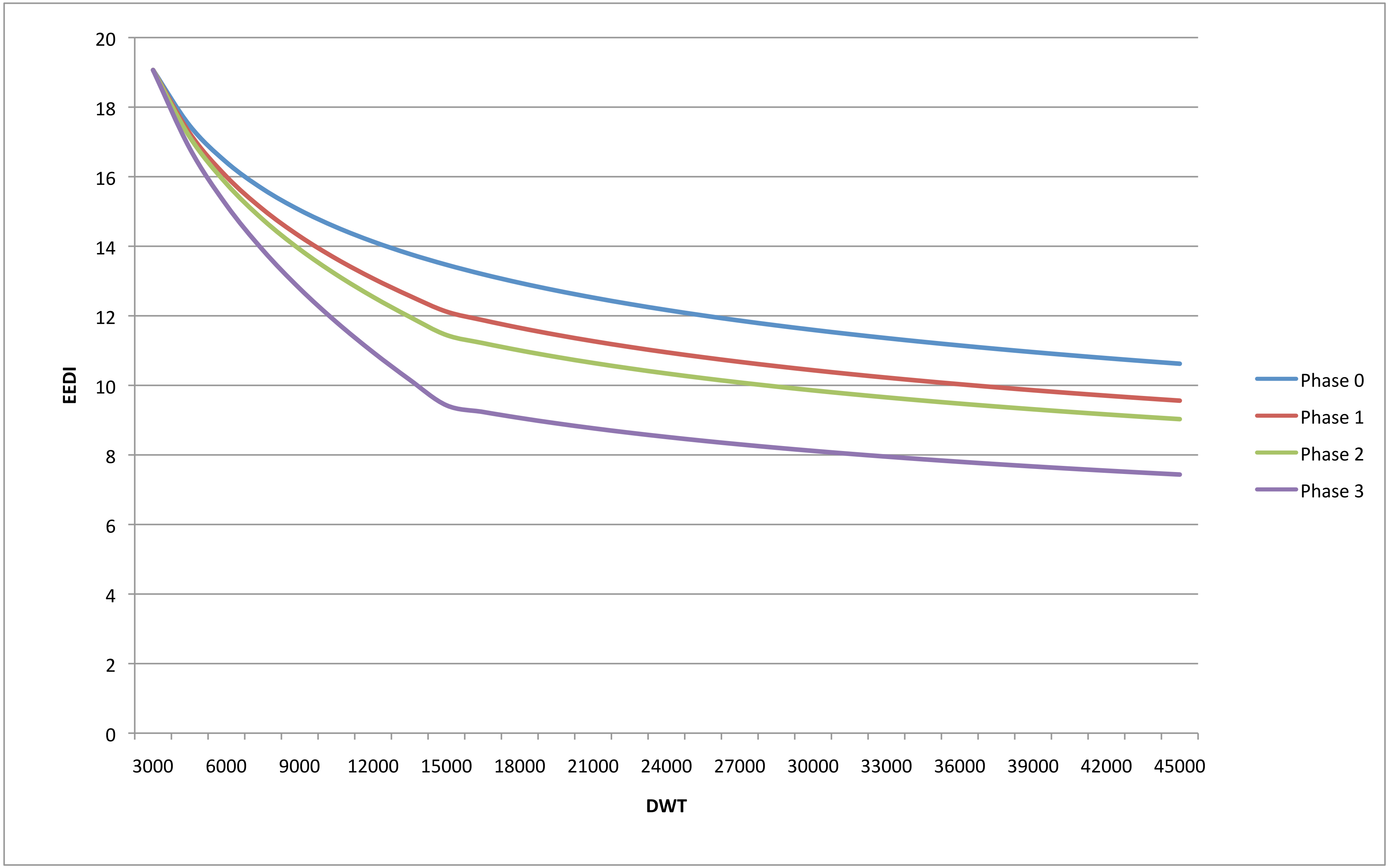
Appendix A - EEDI calculations

EEDI calculation for general cargo ships.
Phase 0, phase 1, phase 2 and phase 3.

					Phase 0	Phase 1	Phase 2	Phase 3
a	c	b (DWT)	Reference line		0	10	15	30
		1500		1500				
107,48	0,216	3000	19,07	3000	19,07	19,07	19,07	19,07
		4500	17,47	4500	17,47	17,25	17,14	16,81
		6000	16,42	6000	16,42	16,00	15,80	15,18
		7500	15,64	7500	15,64	15,06	14,76	13,88
		9000	15,04	9000	15,04	14,29	13,91	12,78
		10500	14,55	10500	14,55	13,64	13,18	11,82
		12000	14,13	12000	14,13	13,07	12,54	10,95
		13500	13,78	13500	13,78	12,57	11,97	10,16
		15000	13,47	15000	13,47	12,12	11,45	9,43
		16500	13,19	16500	13,19	11,87	11,21	9,24
		18000	12,95	18000	12,95	11,65	11,01	9,06
		19500	12,73	19500	12,73	11,45	10,82	8,91
		21000	12,52	21000	12,52	11,27	10,65	8,77
		22500	12,34	22500	12,34	11,10	10,49	8,64
		24000	12,17	24000	12,17	10,95	10,34	8,52
		25500	12,01	25500	12,01	10,81	10,21	8,41
		27000	11,86	27000	11,86	10,68	10,08	8,30
		28500	11,72	28500	11,72	10,55	9,97	8,21
		30000	11,59	30000	11,59	10,44	9,86	8,12
		31500	11,47	31500	11,47	10,33	9,75	8,03
		33000	11,36	33000	11,36	10,22	9,65	7,95
		34500	11,25	34500	11,25	10,13	9,56	7,88
		36000	11,15	36000	11,15	10,03	9,48	7,80
		37500	11,05	37500	11,05	9,94	9,39	7,73
		39000	10,96	39000	10,96	9,86	9,31	7,67
		40500	10,87	40500	10,87	9,78	9,24	7,61
		42000	10,78	42000	10,78	9,70	9,16	7,55
		43500	10,70	43500	10,70	9,63	9,10	7,49
		45000	10,62	45000	10,62	9,56	9,03	7,44

EEDI calculation for general cargo ships.
Phase 0, phase 1, phase 2 and phase 3.



EEDI calculation for general cargo ships.

Phase 0, phase 1, phase 2 and phase 3.

	Attained EEDI without hybrid system				
Capacity	6250	5273	4500	5820	15634
EEDI value	23,27	19,29	16,42	17,51	15,55

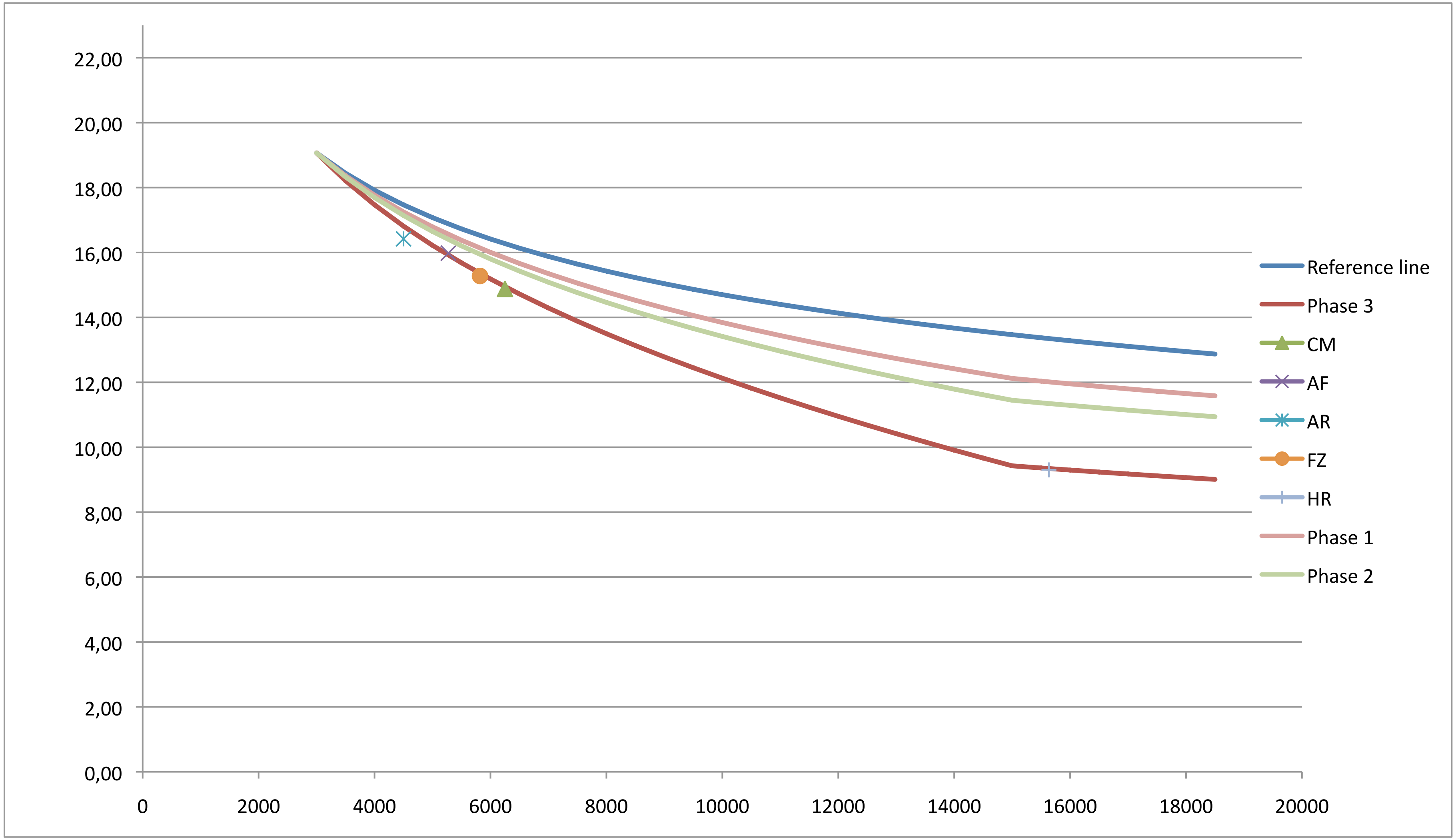
Carbon content coefficient MGO C_F	3,206

Ship particulars	CELTIC MONARCH (97)	ARCADIAN FAITH (94)	ARKLOW RALLY (02)	FLINTERZEE (97)	HAPPY RIVER (97)	
P_{ME}	4900	3520	1800	3280	8775	
SFC_{ME}	178	179	183	174	171	
P_{AE}	245	176	90	164	438,75	
SFC_{AE}	200	200	200	200	200	
Battery reduction	1900	650	0	450	3800	
Capacity	6250	5273	4500	5820	15634	
V_{ref}	15,5	16	11,5	14,5	16	
Attained EEDI	14,88	15,98	16,42	15,28	9,30	
Required EEDI	14,95	15,92	16,81	15,36	9,34	Phase 3 ref.
Required EEDI	15,61	16,40	17,14	15,94	11,35	Phase 2 ref.
Required EEDI	15,83	16,56	17,25	16,14	12,01	Phase 2 ref.
Difference	-0,49 %	0,37 %	-2,33 %	-0,54 %	-0,44 %	Phase 3
Difference	-4,70 %	-2,57 %	-4,20 %	-4,17 %	-18,01 %	Phase 2
Difference	-6,03 %	-3,51 %	-4,81 %	-5,32 %	-22,57 %	Phase 1

a	107,48
c	0,216

EEDI calculation for general cargo ships.
Phase 0, phase 1, phase 2 and phase 3.

Attained EEDI value for the case ships with hybrid system correction



EEDI calculation for general cargo ships.
Phase 0, phase 1, phase 2 and phase 3.

DWT	Interpolation factor
3000	0
4500	0,125
6000	0,25
7500	0,375
9000	0,5
10500	0,625
12000	0,75
13500	0,875
15000	1

DWT	Interpolation factor
3000	0,00
3500	0,04
4000	0,08
4500	0,13
5000	0,17
5500	0,21
6000	0,25
6500	0,29
7000	0,33
7500	0,38
8000	0,42
8500	0,46
9000	0,50
9500	0,54
10000	0,58
10500	0,63
11000	0,67
11500	0,71
12000	0,75
12500	0,79
13000	0,83
13500	0,88
14000	0,92
14500	0,96
15000	1,00

EEDI calculation for general cargo ships.
Phase 0, phase 1, phase 2 and phase 3.

a	c	b (DWT)	Reference line	phase 1	phase 2	phase 3
				10	15	30
107,48	0,216	3000	19,07	19,07	19,07	19,07
		3500	18,44	18,37	18,33	18,21
		4000	17,92	17,77	17,69	17,47
		4500	17,47	17,25	17,14	16,81
		5000	17,07	16,79	16,65	16,22
		5500	16,73	16,38	16,20	15,68
		6000	16,42	16,00	15,80	15,18
		6500	16,13	15,66	15,43	14,72
		7000	15,88	15,35	15,08	14,29
		7500	15,64	15,06	14,76	13,88
		8000	15,43	14,78	14,46	13,50
		8500	15,23	14,53	14,18	13,13
		9000	15,04	14,29	13,91	12,78
		9500	14,86	14,06	13,66	12,45
		10000	14,70	13,84	13,41	12,13
		10500	14,55	13,64	13,18	11,82
		11000	14,40	13,44	12,96	11,52
		11500	14,26	13,25	12,75	11,23
		12000	14,13	13,07	12,54	10,95
		12500	14,01	12,90	12,35	10,68
		13000	13,89	12,73	12,15	10,42
		13500	13,78	12,57	11,97	10,16
		14000	13,67	12,42	11,79	9,91
		14500	13,57	12,27	11,62	9,67
		15000	13,47	12,12	11,45	9,43
		15500	13,37	12,04	11,37	9,36
		16000	13,28	11,95	11,29	9,30
		16500	13,19	11,87	11,21	9,24
		17000	13,11	11,80	11,14	9,18
		17500	13,03	11,72	11,07	9,12
		18000	12,95	11,65	11,01	9,06
		18500	12,87	11,58	10,94	9,01

EEDI calculation for general cargo ships.
Phase 0, phase 1, phase 2 and phase 3.

Attained EEDI values for the case ships - without hybrid correction