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Energy efficiency in shipping

Review and evaluation of the state of knowledge

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Abstract

In total, shipping was responsible for emitting approximately 1,046 million tonnes of CO2 in 2007, which corresponds to 3.3 % of the global anthropogenic CO2 emissions in 2007. There is a direct correlation between CO2 emissions and energy consumption in the shipping business, since almost all energy consumed on-board is based on fossil oil. If just a fraction of that energy can be saved, it will have great benefits for the environment as well as the economy. Estimations from previous studies suggest that CO2 emissions from shipping can be reduced by 25-75 %, where the majority of reductions come from energy savings.

This study is aiming at giving an overview of the available knowledge on the potential for energy efficiency in shipping and identifying research needs. This report gives an overview of where and why the energy is consumed on-board, how some energy can be saved, the potential for several energy saving methods and how well developed those methods are. Several methods show potential for economically viable, simple and large energy savings – especially operational methods, concerning fleet management and logistics.

Since the different systems on-board are connected in different ways and influence each other, energy savings and changes in the energy system have been evaluated from a simplified systems perspective. Combinations of energy saving methods have been tried in thought experiments and the conclusion is that some methods might benefit from combinations while others might actually weaken each other. Further systems engineering for energy efficient shipping is needed to avoid sub-optimization.

Svensk sammanfattning

Världens samlade sjöfart släppte ut ungefär 1 046 miljoner ton koldioxid 2007, vilket motsvarar 3,3 % av världens antropogena CO_2-utsläpp 2007. Det är en direkt koppling mellan CO_2-utsläpp och energiförbrukning inom sjöfarten, eftersom nästan all energi som förbrukas ombord baseras på fossil olja. Om endast en bråkdel av denna energi kan sparas så kommer det att medföra goda effekter för såväl klimatet som ekonomin. Uppskattningar från tidigare studier tyder på att CO_2-utsläpp från sjöfarten kan minskas med 25-75 %, där majoriteten av minskningarna kommer från energibesparingar.

Denna studie ämnar ge en överblick av tillgänglig kunskap för potentiell energieffektivisering inom sjöfart och identifiera forskningsbehov. Denna rapport ger en överblick av var och varför energi förbrukas ombord, hur en del energibesparingar kan göras, potentialen för ett flertal energibesparande metoder och hur väl utvecklade dessa energibesparande metoder är. Flera metoder visar potential för ekonomiskt lönsamma, enkla och stora energibesparingar – speciellt operationella metoder, för hantering av flottan och logistik.

Eftersom de olika systemen ombord är sammankopplade på olika sätt och påverkar varandra, så har energibesparingar och förändringar i energisystemet utvärderats genom ett förenklat systemperspektiv. Kombinationer av energibesparande metoder har prövats i tankeexperiment och slutsatsen är att några metoder kan dra nytta av att kombineras, medan andra faktiskt kan försvaga varandra. Ytterligare utveckling av systemkonstruktion för energieffektiv sjöfart behövs för att undvika suboptimering.

Index

1 Introduction

The internationally growing energy turnover and quest for reduction of greenhouse gas emissions set the use of fossil energy into focus. In shipping the dominating source of energy is oil, thus making energy savings and energy efficiency measures one important way to decrease GHG emissions and will in the same time achieve economical advantage. This study is aiming at giving an overview of the available knowledge on the potential for energy efficiency in shipping and identifying research needs. This report will give an overview of where and why the energy is consumed on-board, how some energy can be saved, the potential for several energy saving methods and how well developed those methods are.

1.1 Energy turnover in shipping

When we look around the world, we see energy savings here and there, small as well as large. Three major reasons for energy savings are to reduce the CO_2 emissions, to reduce the consumption of finite resources and to save money – not necessarily in that order of priority. One way to save energy could be to use ships instead of trucks or airplanes for transports. In general, ships have a considerably better fuel economy than trucks and airplanes, based on amount of transported goods and distance. Figure 1 illustrates typical CO_2 efficiencies for various cargo ships, trains and trucks. Efficiencies are calculated as grams of CO_2 per transport work, where transport work is ton of cargo multiplied by kilometres travelled.

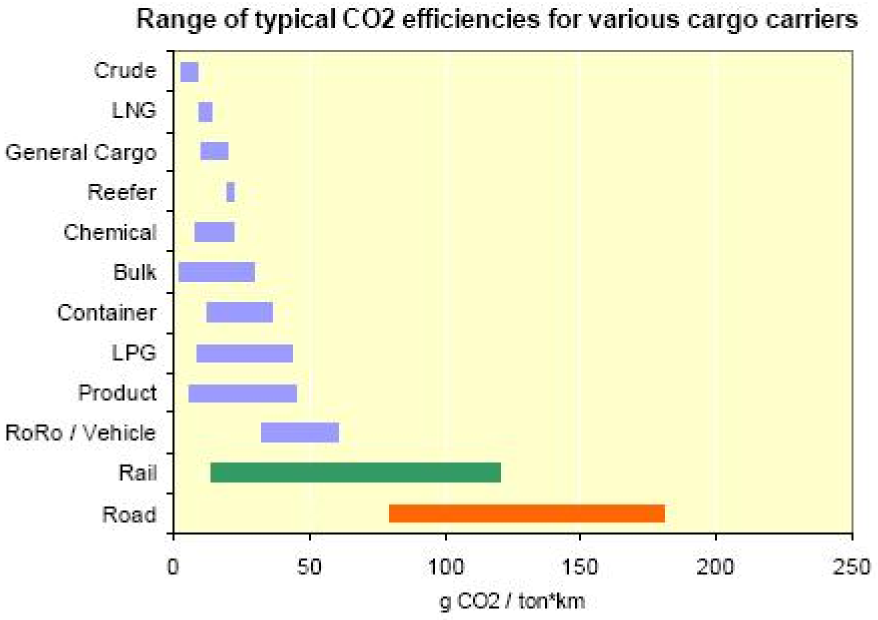

Figure 1: Range of typical CO_2 efficiencies for trucks, trains and ten different cargo ships. [1].

Today, around 90 % of all world trade is carried by ships [2]. So, even if shipping is an energy efficient way of transporting goods, it still consumes a large amount of total energy and almost all of that energy derives from fossil fuels. International shipping was in 2007 responsible for approximately 2.7 % of global anthropogenic CO_2 emissions. Domestic shipping and fishing was responsible for approximately 0.6 % of global anthropogenic CO_2 emissions in 2007. In total, shipping was responsible for emitting approximately 1,046 million tonnes of CO_2 in 2007, which corresponds to 3.3 % of the global emissions [1]. There is a direct correlation between CO_2 emissions and energy consumption in the shipping business, since almost all energy consumed on-board is based on fossil oil. As an example, a modern Ro/Ro vessel can use totally 25-75,000 MWh of propulsion power per year and 500-2,000 MW at quay during loading and unloading. That corresponds to 5-15,000 ton of oil per year, for one single Ro/Ro vessel, which corresponds to a residential district with 500-5 000 detached houses [3]. This study will illustrate the potential to save some of that energy.

From a theoretical point of view, it is possible to move an object from one point in space to another point without using any energy. Given that the sum of all the initial energies, e.g. kinetic and potential energy, are equal to the sum of all the final energies, then the net energy input will be equal to zero. In other words; if a ship starts in one port, at sea level with zero speed, and ends up in another port, at sea level with zero speed, then all the energy that was put into the ship must have left the ship again somehow. All the energy that is put in must come out again, unless it is stored. This study will illustrate some of the ways that energy can disappear from a ship, i.e. energy losses. If we can make sure that some of these energy losses do not occur, then the energy consumption will go down.

The fundamental laws of physics tell us that all energy that goes into a system must also leave the system, unless it can be stored somehow. The amount of energy that goes into the system equals the sum of the energy that goes out and the energy that goes to storage.

$E_{in} = E_{out} + E_{store}$

As an example, the system can represent a ship. Assume that before a voyage the bunkers are full, and before the next voyage the bunkers are refilled and full again, i.e. the amount of energy in storage has not changed and $E_{store}=0$. That means that all energy that was put into the ship as fuel oil has transformed into some other type of energy, e.g. kinetic energy (movement), electricity or heat. Since, none of these energies are stored in any way on a ship, they must be considered as energy losses. If any changes to the system can reduce the sum of all energy losses, then the total energy consumption will be reduced with the same amount.

2 The marine energy system

The main focus of this study is how to minimize the fuel consumption. As mentioned before, the amount of energy going in (fuel) equals to the amount of energy going out (energy losses). So, if the energy losses are identified and reduced, then the fuel consumption will also be reduced. It is also possible to use alternative energy sources, e.g. wind, solar or wave, which also will lead to a reduction in fuel consumption, since parts of the energy losses are then covered by free (non-fuel) energy.

As a part of identifying possible energy losses, a general energy flow diagram was constructed, illustrated in Figure 2. None of the energy flows are illustrated with a size of the flow, since the sizes differ greatly between ships. Some of the flows are small, or might be missing completely in some ships, but even small energy losses can make a difference – e.g. turning off the light when one leaves the toilet might not make a big difference on a large oil tanker, but it will not cost anything to do, so the payback time is more or less equivalent to zero.

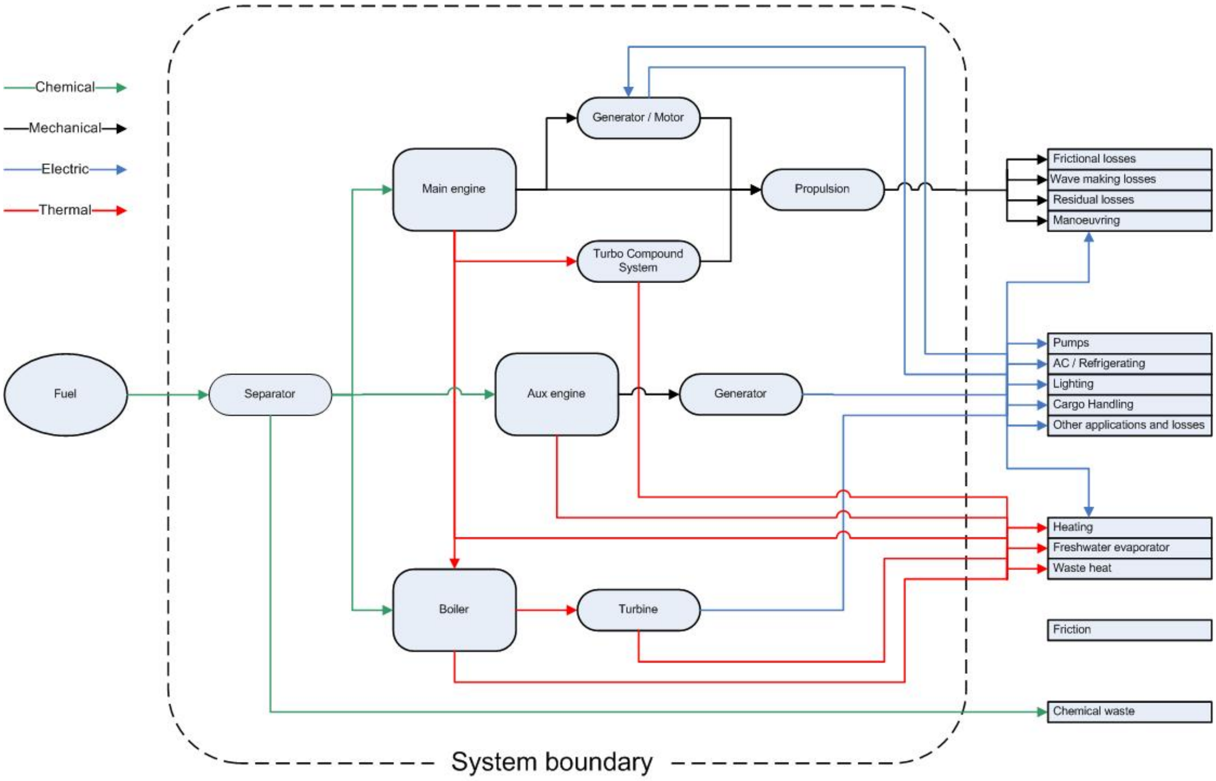

Figure 2: An illustration of how the energy can flow through a ship. Energy goes in as fuel on the left side of the system, gets processed in different ways and gets consumed as energy losses on the right side of the system. The system is here representing one ship, but it can also represent an entire fleet if several ships are influenced by a change, e.g. speed reduction.

This chapter will illustrate some of the ways that energy can disappear from a ship, i.e. the energy losses illustrated on the right side of Figure 2. If we can make sure that parts of these energy losses do not occur, the energy consumption will go down.

2.1 Propulsion

A significant part of the fuel is burned in the main engine to generate the mechanical energy needed to propel the ship. The proportion of fuel burnt in the main engine compared to auxiliary systems differs greatly between types of ships and cargo. The thermal efficiency will differ between engine types, illustrated in Table 1. The maximum thermal efficiency is only obtainable while the engine is working at optimal load, which is not always the case.

Table 1: Maximum thermal efficiency obtainable with current ship engine systems [1].

	Small (2 MW)	Medium (10 MW)	Large (30 MW)
Low-speed diesel	~47 %	~50 %	~53 %
Medium-speed diesel	~43 %	~47 %	~50 %
Gas turbine	-	~32 %	~35 %
Gas turbine combined cycle	-	-	~40 %
Steam turbine	-	-	~32 %

2.1.1 Viscous (frictional) losses

The viscosity of a fluid can be described as a friction between particles. When the ship moves through water, this friction will drag along those water molecules that are closest to the hull and those molecules will drag along the next ones and so on. This creates a “boundary layer”, which is a body of water that gets dragged along. A rough hull surface will create a thicker boundary layer, which results in a larger frictional resistance. A smooth hull will have less friction, but even a completely smooth surface will create a boundary layer. The boundary layer starts off as a relatively thin layer in the forward part of the ship and grows thicker as the flow develops along the hull. Roughness on the bow area will have a larger impact on the total frictional resistance than roughness in the aft areas.

2.1.2 Wave making losses

When a body moves through a fluid, particles will be pushed away from their equilibrium positions and thereby a pressure force will develop around the body. Since the ship moves on the surface of the water, this pressure force will counteract with the air pressure and gravity. If the pressure in the water is higher than the air pressure above, the water will be pushed upwards until gravity pulls it downwards with an equal force and thereby creating equilibrium. If the pressure in the water is lower than in the air above, the water will be sucked downwards instead. Since the difference in pressure moves away with the ship, the water will fall (or rise) back to its original level and thereby create a wave that dissipates outwards.

With a bulbous bow another wave system is created; a wave system that is designed to counteract with the wave system from the rest of the ship. The two wave systems can then neutralize each other.

2.1.3 Residual losses

When energy is transmitted from the engine to the propulsion system, there will be some energy loss depending on how the energy is transmitted. A direct mechanical drive (only possible for low speed engines) will have ~99 % efficiency, while a mechanical drive with speed-reduction gearbox will have ~95 % efficiency [1]. These *transmission losses* can either be categorized as residual losses or losses due to friction, explained further in section 2.3.4. With an electric propulsion system, there will be further transmission losses due to losses in, e.g., generator, cable, electric motor, explained further in section 2.2.4.

Most ships use propellers to generate thrust. The total *propulsion efficiency* of propellers varies between 50-70 %. Propeller losses can be categorized as rotational losses, frictional losses and axial losses. Rotational losses are due to rotational movement of the water behind the propeller. Frictional losses are due to friction between the propeller surface and the water, similar to what is explained in section 2.1.1. Axial losses are due to turbulence in the accelerated water behind the propeller [4, 5].

Air resistance from the superstructure is relatively small compared to resistance from the water. However, fast moving ships and ships with large superstructures, will have a potential for energy savings. The superstructure may also cause drift, and losses due to this drift, when the ship is operating in side wind.

Unlike the still-water conditions in a towing tank, for which many ships are optimized, the open sea will sometimes offer harsh weather with plenty of wind and waves. Unless the ship is designed to take advantage of the extra energy from wind and waves, those conditions will contribute to extra resistance. This extra resistance can be described as partly *wind resistance* and partly *added resistance in waves* (or *seakeeping*).

When a ship moves in restricted waters there will also be a *blockage effect* from the confining surface. The seabed in shallow waters or the banks of a canal will affect the flow around the ship and the wave making. It may have an influence on all other resistance components. [6]

2.1.4 Manoeuvring

Any type of manoeuvring, i.e. accelerating, braking and turning, will affect the total energy consumption. Accelerating will increase the thrust from the propeller and thereby increase the turbulence in the water behind the ship. A slow reduction in speed will occur naturally if the thrust is reduced, due to the natural forces acting upon the ship. Whenever a more rapid speed reduction is needed, it requires extra force in the form of increased resistance and/or reversed thrust. Use of the rudder for turning will increase the drag created by the rudder. A majority of merchant ships use transverse thrusters, for manoeuvring at low speeds, which requires a significant amount of extra (usually electric) energy, for short periods of time.

2.2 Electric applications

Generators, connected to auxiliary engines, are the common source of electricity on-board. Some ships are equipped with shaft generators, directly mounted on the main engine shaft, for extra electricity production when needed. It can also work as an electric help engine; delivering power back to the shaft if that is needed. Electricity can also come from a heat-recovery system, further described in section 2.3.

2.2.1 Pumps and fans

Pumps for cooling water and fans for ventilation consume a considerable amount of energy. The engine cooling system requires plenty of cooling water and also plenty of pumps for that water. In many cases, those pumps circulate a large amount of extra (unnecessary) water.

2.2.2 AC and Refrigeration

Occasionally, the cargo, crew and passengers require cooling. The amount of energy needed for air conditioning and refrigeration depends on what type of cargo and amount of cargo a ship is carrying and in what weather conditions it is travelling. On a Caribbean cruise ship, air conditioning will consume a similar amount of fuel as propulsion [7].

2.2.3 Cargo Handling

Some vessels have cranes for loading and unloading operations in ports, which require large amounts of power during such operations. Also electric/hydraulic operation of anchor windlasses, mooring winches, roro ramps and hoistable car decks are used. Similarly, on-board pumps for handling of liquid cargo will consume large amounts of power during operation.

2.2.4 Other electric applications and transmission losses

Almost any system on-board a ship can be operated with the help of some electricity, e.g. lighting, control and navigational systems. Transmission losses will occur in cables, transformers, switchboards, frequency converters and all other parts needed for transmitting electricity.

2.3 Heat

An easy estimate of a diesel engine, where e.g. 40-50 % of the energy leaves the engine onto the shaft, approximately 25-30 % will go out as heat in the exhaust and the rest (25-30 %) will go out as heat in cooling water, radiation and lubrication oil.

In theory, all heat energy created on-board can be utilized. Not all of it can be transformed to more useable forms of energy such as mechanical or electrical, but it can be used to increase the mechanical or electrical gain, or used for heating purposes. In practice – due to technical and economical reasons – only the heat from exhaust gases are used, and only to a limited amount.

A part of the engine exhaust flow can be fed into a turbine that, connected to the engine’s crankshaft, delivers some extra mechanical power. Alternatively the exhaust turbine can be connected to an electric generator. The exhaust gas can also be directed into a boiler. Steam from the boiler may be utilized in a steam turbine for generation of electricity, and it may also be utilized for other heating purposes (see sections 2.3.1 and 2.3.2). In some cases, an extra boiler is needed, which is fed by burning oil directly.

2.3.1 Heating

The most common fuel used today is heavy fuel oil (HFO), a residual fuel with high viscosity. To lower the viscosity to an acceptable level, the HFO needs to be pre-heated before combustion. Sometimes the cargo consists of HFO, bitumen, some special crude oil, or other cargo that requires heating. Passenger ships will also require extra heat, for passenger comfort.

2.3.2 Freshwater evaporation

By using heat in a freshwater evaporator, a ship is able to produce its own freshwater. By doing so, there will be more room for cargo and passengers, since no large extra tanks for freshwater is needed.

2.3.3 Waste heat

Whenever energy gets transformed, the total quality (exergy) will be lowered and in the end all energy will end up as low temperature thermal energy. The basic principle of a combustion engine is to transform chemical energy (fuel) into high temperature thermal energy (heat) which partly transforms into mechanical energy. Not all of the thermal energy can transform into mechanical energy, since thermal energy has lower quality than mechanical energy. Hence, some of the thermal energy needs to transform into a lower form of energy, i.e. low temperature thermal energy. The low temperature thermal energy will be transported away as exhaust gas, radiation, heated cooling water or warm lubrication oil.

Any of these with high enough temperature, e.g. the exhaust gas, can be used for another transformation, where a smaller part becomes mechanical energy while the major part becomes thermal energy with lower temperature. This is usually called waste heat recovery.

Some of the low temperature thermal energy can be utilized for heating purposes, as described in sections 2.3.1 and 2.3.2. All thermal energy that does not transform into higher forms of energy, e.g. mechanical, electrical or chemical, or gets utilized for on-board heating, is a waste of energy. It is waste heat.

2.3.4 Friction

Friction creates losses among all moving parts. All steps within the system boundary of Figure 2 contain moving parts. Since it would be too messy with one red arrow from each and every step pointing at “friction”, those are left out.

2.4 Chemical waste

Heavy fuel oil (HFO) is a residual fuel, with relatively high content of impurities. To avoid damage to the engines or burners, the oil is treated in separators before use, where the impurities are separated as waste. A large vessel can produce up to a tonne, or more, of this chemical waste (sludge) every day [8]. The separated sludge contains a fraction of oil that never gets used in the way it was supposed to. Consequently, some energy will be lost.

2.5 Optional energy input

In addition to reducing the fuel consumption by reducing the energy consumptions mentioned above, it is possible to reduce the fuel consumption by adding another energy input. A ship is surrounded by energy from wind, waves and the sun. While at berth, it is also possible to bring on energy from shore, e.g. electricity, district heating and district cooling.

3 Methods for energy savings

To give an overview of the available knowledge on the potential for energy efficiency in shipping, this study has focused on energy saving methods that are available today or in a nearby future. An overview of a large number of these methods is gathered in this chapter. All methods are divided into five groups, depending on what parts of the energy system that are influenced. *Hull and superstructure* focuses on design issues that change the body of a ship. *Power* focuses on design issues that change the power production on-board a ship. *Propulsion* focuses on design issues that change the propulsion system on a ship, i.e. the interaction between propellers and water flow. *Optional energy input* focuses on alternative, non-combustible, energy sources, that can lower the fuel consumption. *Operational* focuses on the handling of a ship or fleet.

This overview explains how the different methods for energy savings work and how they manage to be more energy efficient. Examples of potentials for energy savings are given for a majority of these methods. All potentials are provided by suppliers or other studies concerning similar subjects.

An overall assessment of potential reduction of CO_2 emissions was presented in [1], shown in Table 2. This gives an indication of overall potential reduction of fuel consumption, since all figures in Table 2, except “low-carbon fuels” and “exhaust gas CO_2 reduction”, are directly related to fuel savings.

Table 2: Assessment of potential reduction of CO_2 emissions from shipping by using known technology and practices [1].

DESIGN (New ships)	Saving (%) of CO_2/tonne-mile	Combined	Combined
Concept, speed & capability	2-50*	10-50 %*	25-75 %*
Hull and superstructure	2-20		
Power and propulsion systems	5-15		
Low-carbon fuels	5-15**		
Renewable energy	1-10		
Exhaust gas CO_2 reduction	0		
OPERATION (All ships)			
Fleet management, logistics & incentives	5-50*	10-50*	
Voyage optimization	1-10		
Energy management	1-10		

* Reduction at this level would require reductions of speed.
** CO_2 equivalent based on the use of LNG.

The largest energy savings will require reduction of speed, which will affect the entire fleet if the total amount of cargo transported by ships shall remain unchanged. That brings a new dimension to the energy system illustrated in Figure 2. A dimension where the energy system of all influenced ships need to be included. Otherwise, sub optimizations might occur, where an energy save on one ship leads to an energy loss on another ship.

Basically, the most important part of designing an energy efficient ship is to optimize it for those conditions it will be working under, e.g. speed, weather, type of cargo, amount of cargo etc. Make sure that all parts of the ship are optimized for the same conditions, e.g. do not optimize the hull for 10 knots, the propeller for 15 knots and the main engine for 20 knots. Remember that some parts of the ship affect each other, e.g. optimizing propeller and engine separately might not give the optimum result due to vibrations from resonance frequencies. Consider the whole ship as a system and avoid sub optimization. If the working conditions for a ship changes, e.g. the standard route gets changed, then the ship should be re-optimized for the new working conditions.

One good example is offshore supply vessels, which can often be a special case, especially when their time in dynamic positioning (DP) mode is proportional to their time in free running mode. DP mode requires excellent manoeuvring, while low resistance, high propulsion efficiency and low transmission losses are beneficial in free running mode. A combination of electric propulsion from retractable thrusters for DP mode and single screw mechanical propulsion for free running mode, on a single skeg hull will give all of these benefits. This design can *"reduce the annual fuel consumption of a typical supply vessel by 35 % compared to a conventional vessel"* [9].

3.1 Hull and superstructure

The hull and superstructure is basically the shell of a ship, a contact surface to the surrounding environment. This contact results in drag from friction (from water and air), wave making losses and residual losses; described in sections 2.1.1 to 2.1.3. All these losses lead to increased need for propulsion power. This section will mainly focus on options that can decrease the required propulsion power through different design of the hull and superstructure.

3.1.1 Size

Larger ships are generally more energy efficient as they can transport more cargo, at the same speed as smaller ships, with less power per cargo unit. Estimations say that a 10 % larger ship will have 4-5 % higher transport efficiency [9]. The utilization factor might however be higher on a smaller ship, which will result in a higher overall efficiency for the smaller ship. Requirements to enter harbours and canals put a restrain on the size of a ship. A larger ship will only be more efficient than a smaller ship if it can utilize the extra size for extra cargo [1].

Looking upon the entire transport system, a lowering of total energy consumption by using larger ships can work between harbours that are able to handle the extra size. By using these larger ports as transport nodes, transports to and from smaller ports (and through canals etc.) can also decrease energy consumption for the entire transport system if the smaller ships are primarily used between the smaller ports and the transport nodes. Efficient cargo handling in the transport nodes is required.

3.1.2 Weight

By reducing the weight, the displacement will decrease or the loading capacity will increase. Principally, a decrease in displacement will result in a decrease in resistance with a similar ratio. However, factors like stability, slamming and full immersion of the propeller must be considered as well. Utilization of a higher loading capacity, with the same resistance, will result in higher energy efficiency per transported unit.

Weight reductions might be possible through lightweight structures, e.g. high tensile steel, aluminium and composite materials. A lightweight structure might have affect on fatigue margins and composite materials might be a fire hazard. Reducing ballast is another option, which might have an effect on stability and thereby require an increased beam.

Example 1: *"Removing 3000 tons of permanent ballast from a PCTC and increasing the beam with 0.25 m to achieve the same stability will reduce the propulsion power demand by 8.5 %"* [9]

Example 2: *"A 20% reduction in steel weight will give a reduction of ~9 % in propulsion power requirements. However, a 5 % saving is more realistic, since high tensile steel has already been used to some extent in many cases."* [9]

3.1.3 Dimensions

A long slender hull will in most cases have a lower resistance than a short bulky one. A higher L/B ratio will have a negative effect on stability, which can be compensated by e.g. outriggers. Several designs of superslender monohulls with outriggers exist world-wide. However, many ships are still built with non-optimal hull dimensions simply because they are easier, and cheaper, to build. Harbours and canals might have requirements for the length of a ship. *“Adding 10-15 % extra length to a typical product tanker can reduce the power demand by more than 10 %.”* [9]

3.1.4 Aft-body

Modifications to the aft-body of a ship are mostly relevant if the design was non-optimal to begin with. A “ducktail” is an extension of the waterline, and thereby a modification of the dimensions of the ship with increased L/B ratio. It might also reduce the drag behind the ship with a more slender stern. An “interceptor” is a vertical flap fitted onto the transom of the ship, pushing the flow of water downwards. This creates a lift effect on the aft-body, in a similar way as a conventional trim wedge, and a more favourable trim is obtained at higher speeds. Both these technologies are combinable, but the total potential is less than the separate potentials added together. They are both relatively cheap and easy to retrofit. The resulting energy savings depend on the original design. Even negative results are possible.

Example Ducktail: *”4-10 % lower propulsion power demand. Corresponding improvement of 3-7 % in total energy consumption for a typical ferry.”* [9]

Example Ducktail: *“typical potential 5-10 %”* [7]

Example Interceptor: *“1-5% lower propulsion power demand. Corresponding improvement of up to 4% in total energy demand for a typical ferry.”* [9]

Example Interceptor: *“typical potential 5-10 %”* [7]

Example Ducktail+Interceptor: *“Can be a good combination, but it is not possible to sum the potentials”* [10]

Example Ducktail+Interceptor: *“typical outcome 10-15 %”* [7]

3.1.5 Appendages

Appendages are not always included in the small scale tests in the towing tank, but they do add extra (usually viscous) resistance. CFD (computational fluid dynamics) can be a helpful tool to find better solutions for the appendages.

The propeller shaft and its attachments must be streamlined and should run parallel to the flow of water under the vessel. Thereby, resistance is lowered and it creates less disturbance of water flow into the propeller. *“Up to 3 % difference in power demand between poor and good design. A corresponding improvement of up to 2 % in total energy consumption for a typical ferry.”* [9]

Openings in the hull create disturbances in the flow. These disturbances can be reduced by putting "scallops" behind an opening and/or putting a grill, perpendicular to the flow, over an opening. It is also important to install the openings in the right location of the hull. Another option is to avoid the openings completely, e.g. through the use of tugboats instead of installing bow-thrusters. *“Designing all openings properly and locating them correctly can give up to 5 % lower power demand than with poor designs. For a container vessel, the corresponding improvement in total energy consumption is almost 5 %.”* [9]

Bilge keels can be removed, resized and/or get a better alignment. Zinc anodes should be removed from high-speed areas (e.g. rudders) and get aligned with the direction of the local flow. Welding seams should be grinded off to give a smooth hull. *"Potential savings with all (hull openings, zinc anodes, bilge keels) together is up to several percentages."* [7]

The propeller, and appendages designed to change the flow to and from the propeller, are further mentioned in section 3.3 with subsections.

3.1.6 Superstructure

Air resistance is usually just a small part of the total resistance. However, fast moving ships and ships with large superstructures will have a potential for energy savings. With a bit more streamlining, unnecessary losses may be reduced, not only from wind that flows from bow to stern, but also losses due to drift caused by side wind. *"For these ships it is estimated that there is potential for reduction in power consumption of 2-5 % depending on the size of the superstructure and area of operation. Also for other ships there is expected to be a certain potential for reduction by keeping the topsides as uncluttered and streamlined as possible, perhaps in the order of 1-2 %."* [11]

3.1.7 Bulb and bow

A bulbous bow creates a wave system that counteracts with the wave system from the rest of the ship. New and better bulb designs develop all the time. *"A so-called surface piercing bulb with soft stem; typical gain 3-7 %"* [7].

Increased resistance from rough weather and irregular wave patterns have just recently become an issue for ship designers, as ships have generally primarily been designed for making contract speed in still water conditions. A sharper, wave piercing, bow can decrease the wave-added resistance. [1]

3.1.8 Air lubrication

A large part of the resistance during shipping derives from friction between hull and water. By pumping air into cavities under the hull, and thereby letting the ship float on top of an air cushion, the frictional resistance may be lowered. The hull-water friction is much larger than the hull-air-water friction. The pumps will consume some extra power, but there is potential for reduced net consumption. Predictions say that low speed vessels with large flat bottoms can reduce fuel consumptions with up to 15 %.

One technology, called Air Cavity System (ACS) has been developed by the DK Group. A successful full-scale sea-trial was conducted on board the ACS Demonstrator in the Oslo Fiord, as well as operational tests in Skagerrak and Kattegat. Stena has developed their own air cavity concept, to be used on a 15,000 dwt tanker called E-MAXair – when it gets built.

Predictions for savings in fuel consumption are: *"Tanker ~15 %, Container ~7.5 %, PCTC ~8.5 %, Ferry ~3.5 %."* [9]

3.2 Power

This section will mainly focus on methods that can increase the efficiency of engines and power transmission, through better design of the power system on-board a ship.

Engines are expensive parts of a ship and more efficient engine designs are developed all the time. It is better to put in a good engine to begin with, than it is to upgrade after a while. Just as other parts of the ship, the engines should also be optimized for workloads which best suit the ship's standard operating pattern. One large low-speed main engine, directly connected to the propeller, is the most common option for ships that usually work at high engine load, e.g. tankers, bulk carriers, container ships and general cargo ships. Transmission losses are low, since it requires no gearbox, and the engine can have a high thermal efficiency (given that it is optimized correctly). Multiple engines, connected to two or more propellers through a gearbox, are more common on RoPax and cruise vessels. These ships also have a tendency to require a relatively large amount of power for auxiliary systems, e.g. HVAC and lighting. This opens up a possibility for energy savings through smarter designs that can handle variations in power demand.

3.2.1 Diesel electric machinery

A smart design might include diesel-electric propulsion, which generally has higher transmission losses than mechanical propulsion, but can work at higher total efficiency when changes in load profiles are part of the normal operation. Diesel-electric propulsion is basically a larger set of auxiliary engines, all connected to electric generators, and electric motors connected to the propellers.

Electric propulsion will usually be less space consuming and have a more flexible utilization of the on-board space, which increase the payload of the vessel. With an increased payload, and unchanged power consumption, the energy consumption per unit of cargo will be reduced.

3.2.2 CODED (combined diesel-electric and diesel-mechanical) machinery

A combined diesel-electric and diesel-mechanical system might improve the total efficiency even more. The low transmission losses from the mechanical part are utilized at high load, while in part load the electric power plant will be optimized by using an appropriate number of engines.

3.2.3 Hybrid auxiliary power generation

Hybrid power systems can consist of fuel cell, diesel generators and batteries. With or without electric propulsion, parts of the electricity can be generated by fuel cells – powered by e.g. hydrogen, methanol or natural gas. The maximum theoretical efficiency is higher for fuel cells than for engines. In an intelligent hybrid design – with diesel or gas engines, combined with fuel cells and/or batteries – the loading of each component can be balanced and the system efficiency maximized.

The Viking Lady is the first merchant vessel to test fuel cell technology for on-board electricity production. The fuel cell was installed in September 2009. [12-15]

3.2.4 Common rail

Common rail is a tool for direct fuel injection for diesel engines. With electronic control of the injection valves, the fuel injection can be controlled in regard to time and quantity. This allows optimization, and lower fuel consumption, over a larger operation field. If the engine spends a majority of its time running at a different load than it is originally optimized for, it can relatively easy be tuned for that load range which is most commonly used.

3.2.5 Fans, pumps and compressors

As the system design point normally is based on maximum ambient air and sea water temperatures, fans and pumps constantly running at full speed will usually result in large amounts of extra water and air being circulated. With frequency control, fans and pumps can operate at variable speed and the flow can be optimized for the actual need.

Just as any other part of the ship, it is important that compressors are optimized for those conditions they will work under. AC-compressors are dominated by screw and centrifugal compressors, which are similar in efficiency but have totally different loading curves. Running one compressor type as if it was the other type can increase the energy consumption remarkably. Running the system at part load can also increase the energy consumption dramatically if it is only optimized for full load. An additional small compressor might be recommendable for ships running in cold waters.

3.2.6 Waste heat recovery

Thermal energy from exhaust gas can be partly recovered as electric energy or in some cases as mechanical energy. The energy can be recovered through an exhaust turbine, a boiler and a steam turbine. Non-converted thermal energy can be used for on-board heating and/or freshwater production.

Example 1: *"Exhaust waste heat recovery can provide up to 15 % of the engine power. The potential with new designs is up to 20 %."* [9]

Example 2: *"The corresponding increase in engine power is estimated to be in the range of 9 to 11 %, which, in terms of shaft efficiency, increases to about 55 % (from about 49.5 %)."* [1, 16].

Due to deposits and corrosion by sulphur oxide, the temperature of the exhaust stack should be above a minimum recommended temperature of 180 °C, which limits the efficiency of the steam cycle. Today, as far as this study has found, no heat-recovery system will utilize the thermal energy from anything else than exhaust gas, and usually only from the main engine. The exhaust gas contains approximately 50 % of the thermal energy from a normal diesel engine, corresponding to approximately 25 % of the total energy from a diesel engine working at optimal load.

3.2.7 Liquid Natural Gas (LNG)

LNG has received an increased interest as a fuel for marine applications due to increased oil prices and restrictions in SO_X, NO_X and PM emissions. Gas-fuelled engines available for ship propulsion today, with 25-50 cm bore diameter, have similar or slightly higher shaft efficiency compared to similar diesel engines [1]. The higher exhaust temperatures (400-430 °C) from gas fuelled engines, combined with a possibility to run with lower temperature in the exhaust stack (below 100 °C), gives a higher potential for energy recovery. This is possible since the gas contains no sulphur and the combustion produces very little particles. *"A simplified calculation [...] means that the actual shaft efficiency increases from 45 % to 50.9 %"* [1].

With LNG there is no need for separation and heating of HFO. Instead, the cooling effect from LNG (-162 °C) can be utilized for cooling on-board, e.g. refrigeration and air conditioning. LNG carriers can utilize the boil-off gas and thereby reduce the need for reliquification. *"Saving in total energy < 4 % for a typical ferry. In 22 kn cruise mode, the difference in electrical load is approx. 380 kW. This has a major impact on emissions."* [9]

3.2.8 Power management and automation

Running engines with low rpm at low load results in higher efficiency than with a high rpm at low load. With an electrical system based on DC distribution and frequency controlled consumers, it will be possible to have generating sets working in variable rpm mode. The rpm can be adjusted to the work load and thereby maximizing the efficiency.

Running engines at any load other than what they are optimized for results in loss of efficiency. The optimized load is usually set quite high. With a proper power management system, a correct number of generators are running at all times. Instead of e.g. having two generating sets working at 45 % there should only be one working at 90 %. With an advanced power management, the fuel economy can be fully automated and always running at maximized total efficiency. This is achieved by running engines at their most efficient level, only running the minimum number of engines for the required load and paralleling different sized generating sets. The system will decide which generators that can provide the best total fuel efficiency to meet the demand, automatically starting and stopping engines when needed. Most engines are left running at their optimized load, while one engine is left to handle the remaining load. Not like standard load share systems that use an equal load sharing.

All processes on-board can be automated, e.g. engines, power generation, power distribution, thrust control and ballast. A system that monitors all parameters can operate the vessel at the best fuel performance available.

3.2.9 Low loss electric network

A modern electric network can reduce transmission losses, especially for ships with diesel-electric propulsion. As an example, Wärtsilä has developed a patented power distribution system, called Low Loss Concept (LLC). A 95 m passenger/vehicle/container vessel will be the first passenger vessel with the LLC, ordered by the Canadian ship-owner Transport Desgagnés. [17]

Example 1: *"Transmission losses reduced by 15-20 %", correspond to up to 2 % of total energy consumption.* [9]

Example 2: *"LLC can reduce electrical losses by 3 %."* [17]

3.3 Propulsion

This section will mainly focus on options that can increase the propulsion efficiency and thereby decrease a part of the residual losses described in section 2.1.3. Since screw propellers are the most common alternative for ship propulsion today, this section will focus on such systems. Other options for propulsion can be sailing, which is discussed in section 3.4.1, or other more complicated mechanical devises, sometimes referred to as e.g. whale tail, fish tail, duck feet or goose feet. Such complicated devices are costlier to build and maintain, due to more complicated structures and not viable today [1].

3.3.1 Propeller design

Propellers with advanced blade sections are available today, which can result in up to 2 % energy savings compared to conventional propellers [9]. A basic idea of improving a propeller's efficiency is to increase the diameter and/or decrease the number of revolutions per minute (rpm). A ship with controllable pitch propeller(s), operating at constant rpm, can reduce its fuel consumption by reducing the rpm at reduced speed. If there is limited room for the propeller, it might be beneficial with propeller tip winglets. Ships with heavy propeller loadings might benefit from ducted propellers.

3.3.2 Optimization of propeller, rudder and hull interaction

The skeg makes the water flow more slowly just before the propeller. It creates a wake. A good skeg design creates a flow that is evenly distributed over the entire propeller angle. This provides an effective medium for the propeller to work in. A good skeg design can result in 2 % lower propulsion power demand [9]. The rudder and other appendages cause extra drag that can be influenced by the acceleration of water from the propeller. The aim is to have an even flow into the propeller, as well as out from the propeller. Just optimizing the propeller, rudder and hull separately does not guarantee an optimal solution in total. The interaction between them must be optimized as well. A few hours of CFD simulations can improve performance by up to 4 % for the design of a new ship, without any large increases in cost [9].

The Wärtsilä Energopac® is a result from similar optimization projects. This and other propeller-rudder combinations can be a part of a total optimization for new ships or a simpler solution for retrofitting older ships, where redesigning the hull is not recommended. This solution can improve the fuel efficiency with 2-6 %, but it costs more than a regular rudder and propeller [9].

Solutions for ships with poor original design includes guide vanes in front of the propeller and wake-equalising ducts. The guide vanes reduce cross-flow, by straightening the boundary layer, in front of the propeller. The wake-equalising duct gives a more homogeneous wake flow, by accelerating the water flow to the upper parts of the propeller and retarding the flow to the lower parts of the propeller. The average wake field is more or less unchanged. [1]

3.3.3 Pre- and post-swirl devices

Many devices are designed to take benefit from the rotational energy created by the propeller, i.e. to reduce the rotational losses. Radial reaction fins or an asymmetric stern can provide a favourable pre-rotation of the water flow in front of the propeller, which will increase the boost from the propeller. By applying a ”twin-skeg” design consisting of two mirroring assymetric sterns with counter rotating propellers a propulsion efficient yet course stable design can be obtained. Some examples of post-swirl devices are additional thrusting fins at the rudder, rudder bulb systems with fins, fins on the propeller fairwater (boss cap fins) and an asymmetric rudder. Reductions in power consumption can be in the range of 1-9 % [1]. Some of the solutions mentioned in section 3.3.2 include some form of reduction of rotational losses, i.e. the percentages for energy savings should not be added.

3.3.4 Contra rotating propellers (CRP)

Another device designed to recover rotational energy is the CRP, which consist of two coaxial propellers rotating in opposite directions. The forward propeller creates a rotational flow which is recovered by the aft propeller. The CRP will also have lower propeller loading than a single propeller, which results in higher propeller efficiency. Compared with double non-coaxial propellers, the CRP will have less resistance from the shaft line(s) plus a better wake factor behind the skeg. *“The power reduction for a single screw vessel is 10 % to 15 %.”* [9]

3.3.5 Pulling thrusters

Compared with regular propellers (located behind the shaft), pulling thrusters can have a clean inflow of water, free from turbulence. A concept with two thrusters and a centre line propeller can reduce fuel consumption with 8-10 %, compared to a twin shaft line arrangement on a single skeg hull [9]. The lower propeller loading from the three propellers (instead of two) and the clean inflow to the thrusters contributes to parts of the energy saving. Another contribution comes from the wake factor behind the skeg for the centre line propeller. The largest contribution to the energy saving is however due to less resistance from hull appendages (the two long shaft lines). These potential energy savings are based on model testing, not full scale.

3.4 Optional energy input

Using some other energy than fuel (e.g. oil or gas) is not really a way to reduce energy consumption, but it is a way to reduce fuel consumption, so it will be mentioned here. Besides, renewable energy in the form of wind, wave and solar radiation is surrounding the ship anyway, so not using it could be considered a waste of energy. Anyway, these options can reduce emissions and costs.

3.4.1 Wind

People have used wind for ship propulsion for centuries, but it was abandoned due to e.g. its intermittency in power supply and high demand for manpower. Today’s solutions are more often based on wind as a supply for a smaller proportion of the total power demand, together with engines that are still capable of providing power for the full demand. Options for recovering wind energy for propulsion are; classic soft sails, solid wing sails on top of the superstructure, wings on the outside of the superstructure, kites and Flettner rotors. Different predictions for fuel savings exist for different technologies and ships, [18-21], where the most optimistic is SkySails own prediction of 10-35 % on average. SkySails have successfully tested their towing-kite system on two commercial vessels, the 132 m long multipurpose heavy lift carrier MS “Beluga Skysails” and the 88 m long cargo vessel MV “Michael A”. *Beluga SkySails* is a new ship and had her maiden voyage in January 2008. *Michael A* is an older ship that was retrofitted with the SkySails technology at the end of 2007. [21]

3.4.2 Wave

Utilizing wave energy for propulsion is mainly used by surfers, not large cargo ships. It is still an undeveloped area for large ships and no commercial methods for wave energy conversion are available today. However, the potential fuel savings are large and research is conducted. A recent case study for a bachelor’s thesis [22] says that the available effect, from wave energy, for a ship travelling on the north Atlantic is approximately 50 kW/m on average during a year. That responds to approximately the same effect as the main engine on the ship in the study. Just like wind energy, wave energy is intermittent. Theoretically, all available wave energy can be utilized for propulsion. Practically, we are still waiting for a commercially viable method.

A few studies and experiments have been made. A recent example is the 10 m long catamaran “Suntory Mermaid II” that travelled from Hawaii to Japan, merely propelled by wave power. [23]

3.4.3 Solar

Many ships have large naked surface areas, where solar cells or panels can be applied. Solar cells can convert solar radiation to electricity which can be used in the ships electricity system. Solar panels can convert solar radiation to heat, which can be used for on-board heating purposes.

3.4.4 Land connections (electricity, heat, cooling and water)

Cold ironing, the process of providing shore-side electrical power to a ship at berth while the ships main and auxiliary engines are turned off, is growing around the world. It still needs a proper international standard to become a viable solution for ships travelling world-wide. Whether this solution actually saves energy or not will not be discussed in this report. However, cold ironing will reduce diesel consumption and it will reduce emissions.

Other possibilities for land connections are district heating and cooling. Many ships still have a need for heating and/or cooling while at berth. If these ships would get their heating/cooling from a land based source instead, the total energy consumption (ship + land) would most likely be reduced. This is still not commercially available, but it has good potential for the future.

Fresh water is possible to produce on-board, but doing so while at berth would be a waste of energy. There is most likely not much energy to save by supplying more fresh water from land connections, since most ships probably already do so.

3.5 Operational

This section focuses on energy efficient ways of handling ships and fleets. Large energy savings can be achieved quite rapidly compared to energy savings through design (sections 3.1 to 3.4), due to e.g. the long life time of a vessel. Many operational measures require almost nothing more than some decision making and education.

3.5.1 Speed reduction

Basically, the simplest and most effective way to reduce energy consumption on-board one ship is to reduce the speed. Reducing the speed with one knot will result in approximately 11 % reduction in energy consumption, with an equal distance travelled [9]. However, reducing speed will result in longer periods at sea, which in turn results in a reduced amount of transported cargo per time period. Unless the extra time at sea is compensated by less time doing something else, some cargo needs to be transported by some other means. Consequently, the entire transport system needs to be included into the analysis to find the optimal reduction of total energy consumption from transports. Suddenly it is not so simple anymore.

If the reduced speed on one ship is compensated by increased speed on another identical ship, the result will be increased total energy consumption. It is also not recommended to use trucks, trains or planes to compensate for the decrease in transported cargo per time unit. However, compensating with an increased number of ships can reduce the total energy consumption. It is possible to calculate the optimal amount of ships and their speeds, with respect to total energy consumption and economic yield. A reduced demand for shipping, with reduced shipping rates, will reduce the average speed on the world fleet, which was last seen during the present (2009) economic crisis.

Other ways to reduce the speed, without increasing transports in other parts of the transport system, would be to reduce the time spent in harbour as well as the time spent in queue, waiting to enter a harbour, canal or similar. More effective cargo handling, berthing and mooring, and a queue system that does not discourage a just-in-time arrival, are recommended. Ships on short routes will have a greater benefit from measures like these.

Voyage optimization, with weather routing, can find the optimal routes with respect to waves, winds, currents and shallow waters, which all affect the energy consumption. By minimizing speed variations and the average speed, the energy consumption for propulsion will be reduced.

A reduction in scheduled speed will save energy, but it will save even more energy if the ship is adapted for the speed reduction, e.g. through de-rating of the engines. Operating at part load creates unnecessary losses in every part of the ship that is not already designed for the changed speed. An ideal situation would be a ship that is actually designed for lower speeds.

3.5.2 Maintenance

Roughing and bio fouling of the hull and propeller will increase the resistance. A good hull coating will result in a smoother surface and less fouling. Hull cleaning and propeller polishing in regular, more frequent, intervals can result in substantial energy savings. Optimal maintenance and tuning of the engine can also contribute to a better fuel economy. With a system for condition-based maintenance, all maintenance is planned through on-board measurements and communication between the ship and experts. Maintenance will be correctly timed and ensure optimal performance.

3.5.3 Energy saving operation awareness

All methods mentioned in this report have some potential for energy savings, but only if they are used properly. Many other energy saving methods can be found with a higher energy saving awareness within a shipping company. With proper training and education, the crew will better know what to look for to find new options for energy savings and they will know how to use the ship/fleet in a more energy economic way. With proper on-board measuring, it will be easier to find leaks, low efficiencies and unnecessary energy use, i.e. it will be easier to know where to look for potential energy savings. Measuring can also illustrate the result. Incentives and/or bonuses will achieve a higher willingness to participate in an energy saving operation. Historical data show that incentives can reduce energy usage by up to 10 % [9].

Continuous measuring and analysis of the system can result in many methods for better fuel economy. The vessel trim can have a large impact on fuel consumption; up to 15-20 % between best and worst case, with 1-5 % as a probable energy reduction for an average ship. The vessel trim can be optimized through continuous logging of required power for various conditions. Better autopilot control, with better adaptation for prevailing conditions, will reduce the use of the rudder and thereby reduce the drag; with an anticipated benefit of 1-5 %. Better autopilot control has good potential for podded ships. Accurate measurement of propeller data, e.g. speed through the water, propeller torque and propeller thrust, can enable fuel savings of up to 2 % in general or up to as much as 4 % in special cases. Leaks of e.g. heat, cooling and pressurised air can also have a big impact on the energy consumption. Fixing leaks can be an easy way to save energy and they are much easier to find with continuous measuring of the system. Proper isolation is important for preservation of heat and cooling. [7, 9]

Proper instructions and a higher energy saving awareness can reduce any unnecessary use of apparatus that increases the energy consumption. The use of fin stabilisers, for example, creates extra resistance. Hence, idle use of fin stabilisers is unwanted and should be kept to a minimum. Lighting is another good example where idle use is unwanted. Smart lighting, with motion detectors and timers, or some simple instructions to the crew to switch off the lighting when they leave a room, can reduce the idle use. Better planning of where the lighting is located and the use of reflectors will reduce the total amount of light needed by lighting up necessary parts of the room, e.g. the work area, instead of unnecessary parts of the room, e.g. the ceiling. Using energy efficient light sources, with more light per watt, will of course also lower the energy cost.

It is also important to remember that energy can never disappear. It can only be transformed or transported and all energy will in the end be transformed into thermal energy (heat). As an example, a 100 watt light bulb in a confined room (without windows where the light can escape) will not only light up the room but also heat up the room with 100 watts. In an air-conditioned space that will result in a double cost for any idle use of energy consuming apparatus, first the energy consumed by the apparatus itself and secondly the energy consumed by the air-conditioning to remove the extra heat. It is also important to remember to view the ship as a system. One thing leads to another. No energy will be saved if the temperature in one area is raised slightly to save cooling but the heat is transferred to an adjacent area and treated there. One large heat source, the sun, can easily be avoided at a low cost, with sun screens.

4 Existing systems studies and systems tools

There are very few evaluations of the entire energy system, similar to what is described in section 2. It seems like some consulting businesses have tools for this purpose, or something similar, but they are not open for public viewing.

One article [24], published in scientific literature, is focused on synthesis, design and operation optimization of a marine energy system. In this case, “the marine energy system” is concentrated to those parts of the ship that converts the fuel into useable forms of energy, i.e. mechanical, electric and thermal energy. It is focused on how to set up and use e.g. engines, turbines and waste-heat-recovery systems, i.e. it can be categorised under section 3.2 of this study. The article describes an optimization tool that is primarily designed for cost effectiveness, but it can also be used for pure fuel effectiveness by assuming really high fuel prices. It does not consider the final energy consumers on-board, described in section 2, or how different energy saving measures can affect each other, positively or negatively.

A previous research project [3] developed a computer tool, *LCA-ship* – a life cycle analysis program for ships. The computer program is designed to calculate all environmental impacts from a ships entire life cycle, from data that is normally found in a shipping company concerning vessel data and vessel movements. It has an application for propulsion power modelling that can estimate the needed propulsion power, with a standard ship performance prediction method referred to as ITTC-78. Input data for the propulsion power modelling are ship type, length, beam, bulb type and many others. Default values are used for several input data. The computer program also has a, somewhat simplified, tool for onboard energy system modelling. In this application it is possible to define the fuel consumption from four systems – main engine, aux engine, burner and shore power – and the internal flows of these systems, including to and from e.g. gear, generator, exhaust gas economiser, turbine and high/low temp exchanger. The energy flow into any of the systems is in one single form, e.g. tonnes of oil per hour, but the output flow might contain several different energy forms, e.g. mechanical, electrical or several different forms of thermal energy. It is also possible to define all energy consumers and how much energy they consume of different forms, one by one or in larger units. One option is to use only one unit, *the ship*, as a single energy consumer. From this it is possible to make an energy balance, where all flows with a surplus of energy (i.e. waste energy) or a lack of energy are highlighted. Analyses of this kind are mainly based on trial and error, where it is necessary to try one option, document the results, try another option and finally compare the results.

LCA-ship, and especially its application for energy system modelling, can probably be a suitable tool, or starting point, for contingent further research in e.g. systems engineering for sustainable and energy efficient shipping. However, some further development might be necessary. As *LCA-ship* is described in the report [3] and manual [25], it seems difficult to (in the program) combine different energy converters for similar purposes, e.g. diesel generators and fuel cells for electricity production. For a full energy system model it should be possible to define more than one type of energy entering a component and it should also be possible to define energy loops/feedbacks. It should also be possible to analyse the exergy (energy that is available for use) in different steps of the process. There are no published assessments of energy systems, from *LCA-ship*.

5 Analysis

This study is meant to give an overview of the situation within energy savings for the shipping business. Available information is mostly data from manufacturers and not so often from independent sources. As an overview, no deeper assessments have been made during this study. Instead, this analysis is based on available information, personal estimations and knowledge gained during this study. The information presented in this analysis should not be regarded as definitive, rather as guidance.

Important issues that appeared before and during this study are; maturity, simplicity, potential and payback for different energy saving methods. *Maturity* is an estimation of how well developed a technology is and how well tested it is. *Simplicity* is an estimation of how easy it is to implement a new technology. *Potential* is an estimation of the potential for energy savings through a certain technology. *Payback* is an estimation of how quick the investment cost of a new technology can be repaid through fuel savings, with running costs included. All of these issues are graded and presented in Table 3 to Table 7 with an average grade presented as *Total.* The grades are; "+" for "good", "++" for "better" and "+++" for "best". Options that are not recommended are simply left blank.

5.1 Hull and superstructure

The primary energy savings for methods applied to the hull and superstructure (presented in section 3.1 and Table 3) are mainly categorised as less required propulsion power, i.e. mechanical energy from the main engine. Energy savings in propulsion power leads to reduced fuel consumption in the main engine and thereby less heat from the main engine. This will, most likely, mean that a secondary energy saving will be in the form of reduced waste heat. It will, however, depend on how the power from auxiliary engine(s) depends on the power from the main engine(s) and whether there will be sufficient heat for heating purposes or not. Decreased fuel consumption in the main engine might very well result in increased fuel consumption in the burner/boiler if there is not sufficient heat from the main engine for heating purposes on-board. Reduced energy consumption among the engines might also reduce electricity consumption for fans, pumps and compressors, especially with frequency control. If the engines are running on HFO, secondary energy savings will occur in separation and heating of bunker fuel.

Table 3: An estimation of *maturity, simplicity, potential, payback* and *total score* for energy saving meassures concerning the hull and super structure for new-built ships and retrofitted ships.

HULL & S.S.	Maturity	Simplicity		Potential		Payback		Total score	
		new	retrofit	new	retrofit	new	retrofit	new	retrofit
Size	+++	++	+	++	+	+++	n/a	+++	++
Weight	++	++	+	+++	+	+++	+++	+++	++
Dimensions	+++	++		+++		++		+++	
Aft-body	+++		+++		+++		+++		+++
Appendages	+++	+++	+	++	+	+++	++	+++	++
Superstructure	++	++	+	+	+	n/a	n/a	++	+
Bulb and bow	+++	+++		++		n/a		+++	
Air lubrication	+	+		+++		++		++	

Payback for size (retrofit) is marked with "n/a" since it depends more on the cargo market than actual fuel savings. Paybacks for superstructure and bulb and bow are marked with "n/a" due to lack of sufficient information about price.

5.2 Power

The primary energy savings for methods applied to the power system (presented in section 3.2 and Table 4) are mainly categorised as less waste heat, due to increased efficiency in the power system. The fans-pumps-and-compressors method and power management and automation will, however, primarily result in energy savings categorised as electric energy, which secondarily leads to e.g. less waste heat from electricity production. The use of LNG can affect the energy system in many ways and it is therefore treated as a special example, described in section 5.7.

Table 4: An estimation of *maturity*, *simplicity*, *potential*, *payback* and *total score* for energy saving methods concerning the power generation for new-built ships and retrofitted ships.

POWER	Maturity	Simplicity		Potential		Payback		Total score	
		new	retrofit	new	retrofit	new	retrofit	new	retrofit
Diesel-electric	+++	++		+++		++		+++	
CODED	++	++		+++		++		++	
Hybrid aux.	+	+		+		+++		++	
Common rail	+++	++	+	+	+	++	+	++	++
Fans, pumps, compressors	+++	+++	++	++	++	+++	+++	+++	+++
Waste heat recovery	+++	++	+	+++	+++	++	++	+++	++
LNG	++	++	+	++	++	++	++	++	++
Power manage & auto	++	+++	++	+++	+++	+++	+++	+++	+++
Low loss electric network	+	+++		+		+++		++	

Using common rail for retrofit is only recommended if the engine needs to be changed anyway. The fans-pumps-and-compressors method is especially useful for ships that are adapted for warm waters but running in cold waters. There are many technologies to choose between for power management and automation, so the outcome might vary widely.

5.3 Propulsion

The primary energy savings for methods applied to the propulsion system (presented in section 3.3 and Table 5) are mainly categorised as less required propulsion power, mainly due to increased propulsion efficiency. As it is described in section 5.1, this will most likely lead to secondary energy savings in the form of reduced waste heat, reduced electricity consumption for fans, pumps and compressors and reduced need for energy in separation and heating of HFO.

Table 5: An estimation of maturity, simplicity, potential, payback and total score for energy saving methods concerning the propulsion system for new-built ships and retrofitted ships.

PROPULSION	Maturity	Simplicity		Potential		Payback		Total score	
		new	retrofit	new	retrofit	new	retrofit	new	retrofit
Propeller design	+++	+++	+++	+	+	+++	++	+++	++
Optimization of p, h & r	+++	+++	++	++	++	+++	++	+++	++
Pre- & post-swirl devices	+++	++	++	++	++	++	++	++	++
CRP	++	++		+++		++		++	
Wing thrusters	+	+++		+++		++		++	

Some ships might have greater potential energy savings with propeller design than what is presented in Table 5. The wing-thrusters concept will increase manoeuvrability and increase flexibility in the engine arrangement. Many energy saving technologies in the propulsion sector will have influence on cavitations and/or pressure pulses. Higher energy savings might be obtainable with higher margin for pressure pulses.

5.4 Optional energy input

Optional energy input will not actually lower the energy consumption. It will only lower the fuel consumption. However, if the optional energy is renewable (and free), e.g. wind, wave and solar, then it could be considered a waste of energy *not* to use it. While in use, the shore provided energy will, hopefully, be enough to shut down all on-board engines completely. The wind, wave and solar are, on the other hand, intermittent and will require backup power. While the optional energy is in use, the required backup power for propulsion, electricity and/or heating will be reduced, which will lead to similar effects as described in section 5.1, with less heat from the engines, reduced need for fans, pumps and compressors and less fuel that needs separation and heating. Intermittent use of optional energy can reduce engine efficiency if they run on part load.

Table 6: An estimation of maturity, simplicity, potential, payback and total score for energy saving methods concerning optional energy input for new-built ships and retrofitted ships.

OPT. ENERGY INPUT	Maturity	Simplicity		Potential		Payback		Total score	
		new	retrofit	new	retrofit	new	retrofit	new	retrofit
Wind	++	+++	+++	+++	+++	++	++	++	++
Wave	+	+	+	n/a	n/a	n/a	n/a	n/a	n/a
Solar	+	++	++	++	++	++	++	++	++
Shore provided electricity	++	+++	+++	n/a	n/a	n/a	n/a	n/a	n/a
Shore provided heating	+	++	++	n/a	n/a	n/a	n/a	n/a	n/a
Shore provided cooling	+	++	++	n/a	n/a	n/a	n/a	n/a	n/a

Energy extraction from waves is still an undeveloped technology for merchant ships. Potential and payback from wave energy are marked with “n/a” due to lack of information about future developments. Potential and payback from shore provided electricity, heating and cooling are marked with “n/a” since they mainly depend on availability, standards, prices and how the electricity, heating and cooling are produced.

5.5 Operation

Energy reductions from operational methods will occur in all fields, mainly in the form of reduced unnecessary energy consumption. Secondary energy savings will occur here as well, similar to what is described in sections 5.1 to 5.4. Speed reduction can affect other ships if the total amount of transport needs to be maintained, i.e. the marine energy system (illustrated in Figure 2) will no longer be just one ship but needs to include all other ships that are influenced by the speed reduction.

Table 7: An estimation of maturity, simplicity, potential, payback and total score for energy saving methods concerning the operation of ships.

OPERATION	Maturity	Simplicity		Potential		Payback		Total score	
		new	retrofit	new	retrofit	new	retrofit	new	retrofit
Speed reduction	++	n/a	n/a	+++	+++	n/a	n/a	+++	+++
Maintenance	+++	+++	+++	+++	+++	n/a	n/a	+++	+++
En. saving op. awareness	+++	+++	+++	+++	+++	+++	+++	+++	+++

It is simple to reduce speed, but difficult to make it work. Payback from speed reduction depends on cargo rates. Payback for maintenance depends on how well maintained the ship was to begin with. It is a running cost. The economically best option is to find the lowest cost for maintenance plus fuel.

5.6 Combinations

Some methods for energy savings are easier to combine than others. Some methods might strengthen each other, while others might actually weaken each other. Those combinations that occurred in examples and thought experiments during the process of this study are presented in the following two sections, as good combinations and as bad combinations.

5.6.1 Good combinations

As a first example is a remodelling of the *superstructure* combined with *wind* and/or *solar* energy input. Since the superstructure is being remodelled for less air resistance anyway, why not put in some smooth and slender wings and solar cells at the same time. This will mostly save some extra effort from not needing to rebuild any parts of the superstructure or recalculate the air resistance.

If *air lubrication* is considered, then it would be recommended to design a new *bulb*. A properly designed bulb will decrease turbulence under the hull and keep the air under the ship for a longer time.

Any of the electric propulsion methods, i.e. *diesel electric* or *CODED machinery*, could benefit from *hybrid auxiliary power generation* and *low loss electric network*. With electric propulsion systems there are higher electricity consumption/production than with mechanical systems. The hybrid auxiliary power generation can produce that electricity with higher efficiency and the low loss electric network can deliver the electricity with less transmission losses. If the hybrid auxiliary power generation has a proper *power management*, the losses can be even smaller.

The *fans-pumps-and-compressors* method can be a good combination with any other energy saving method that will influence an engine to run on part load more often. If the engine runs on part load, it will not need full cooling capacity, i.e. the pumps for cooling water will not need to run at full capacity. The more often this happens, the more energy can be saved. The fans-pump-and-compressors method is a part of designing a ship for those conditions it actually will work under.

Using *LNG* can increase the benefits of a *waste heat recovery system* since the exhaust from a gas engine is hotter than from a diesel engine and it is possible to have a cooler exhaust stack with a gas fuelled engine. It is possible to run *fuel cells* in a hybrid auxiliary system on methane which will be much simpler if that methane is already on-board in the form of LNG.

The *optimization of propeller, hull and rudder interactions* is also a part of designing a ship for those conditions it will work under. It can be a relatively easy way to save extra energy whenever it is considered to alter any design feature that will influence the water flow around the propeller, hull or rudder.

The *wing-thrusters* concept can be completely mechanical, completely electrical, or a combination of both. The *CODED* system has potential for energy savings and it is easy to implement on the wing-thrusters concept. The increased manoeuvrability from the wing thrusters can also decrease turnaround time in port and thereby make it easier to *decrease speed* during transit.

Wind, wave and solar energy are, to some degree, surrounding the ship at all times. The longer time a ship spends surrounded by these renewable energies, the more energy can be absorbed by the ship.

Speed reduction will prolong the time at sea and thereby increase the potential uptake of renewable energy.

A *speed reduction* will increase the benefit of a good design, optimized for the new speed. Even better would be to have the ship designed for a low speed to begin with. A new ship, designed for low speed and running at low speed, is more optimal than an old ship, designed for high speed and running at low speed.

5.6.2 Not so good combinations

Almost all energy savings will have a direct or secondary effect on the thermal output from the engines. If the mechanical output from an engine is lowered, the thermal output will also be lowered. Additionally, the exhaust temperature is lower from an engine working at part load than from an engine working at full load. This will have a negative impact on the *waste heat recovery system*. Less thermal energy to recover means less energy savings from the WHR system and lower temperature in the exhaust results in lower efficiency in the WHR system. A few things that need to be considered are on-board heating, size of the WHR and payback for the WHR. Will there be enough heat for on-board heating, without burning extra fuel just for heating purposes? One measure for saving energy, that results in extra burning of fuel just for heating, might in the end result in unaltered total energy consumption. Is the size of the WHR good? If all other measures for saving energy results in a smaller main engine, maybe the WHR should be smaller as well. What will the payback for the WHR be? If the total fuel save from the WHR is lowered, due to other energy savings, the payback for the WHR will become longer.

Pre- and post-swirl devices are designed to increase the propulsive efficiency by utilizing some of the rotational energy from the propeller. C*ontra rotating propellers* are also designed to utilize the rotational energy, plus some other benefits. By using both these technologies, one of them will cancel the other. The same thing can happen with any two methods for energy savings that reduce the same energy loss.

5.7 LNG, an example of how the system can be affected

LNG is still a relatively new type of fuel, compared to diesel, and it shows good potential for development. The waste heat recovery process has higher potential with gas-fuelled engines, due to the higher exhaust temperature and the possibility to run with a lower temperature in the exhaust stack. It is possible to use LNG in certain fuel cells. The cooling effect from the liquid gas can be utilized for cooling purposes. No need for heating and separation of HFO is needed. LNG is a clean fossil fuel with low carbon content, which results in less emission of CO_2, NO_X, SO_X and PM, which leads to less need for resources and energy for cleaning of exhaust gases. It is also possible to liquefy biogas, instead of natural gas, and thereby reducing emission of fossil CO_2 even more. Knowledge obtained from developing technologies for LNG might be transferrable to developing similar technologies for hydrogen, which is sometimes seen as the fuel of the future. However, it is not as simple as that, since more components are affected. It requires a large amount of energy to liquefy the natural gas. LNG might not be possible to use in engines that are similar to the diesel engines that are already designed for similar ships. The energy density is only 60 % of that of diesel fuel, which results in more space required for storage of fuel and maybe less space available for cargo. Many things need to be considered when assessing a fuel change from diesel to LNG.

6 Conclusions

Basically, the most important part of designing an energy efficient ship is to optimize it for those conditions it will be working under, i e the intended operational profile. Make sure that all parts of the ship are optimized for the same conditions. If the working conditions for a ship changes, the ship should be re-optimized for the new working conditions or be replaced.

Plenty of energy (5-50 %) can be saved through speed reduction [1], especially if the ships are adapted to (or designed for) lower speeds. This will, however, require further development in logistics and some economical incentives that motivates the reduced speed. Development in logistics can also enable higher energy savings through the possibility to use larger ships between large ports, supported by small ships between the large ports and smaller ports located nearby.

When it comes to hull, engine and propeller design, development and improvements occur constantly. Plenty of options are available to choose between. Choose something that fits the predicted working profile!

A prediction of the future would be that we will soon see more of some technologies, e.g. air lubrication, (diesel) electric propulsion, fuel cells, LNG dual fuel engines, wind energy and shore provided electricity. All of these seem to be well accepted in a few parts of the shipping industry and are therefore being developed properly. However, they will not be accepted throughout the majority of the shipping industry without proper proofing, which might happen sooner for some (e.g. electric propulsion and shore provided electricity) and later for others (e.g. air lubrication and fuel cells).

Wave energy still needs more development before it can be utilized in full scale. Shore provided district heating and cooling is already possible, but it requires more promotion. LNG shows some good potential and might be possible to develop further. Waste heat recovery is already utilized quite often, but it might have a potential of much higher energy savings than it has today. That will, however, require a deeper analysis of the entire engine system to evaluate if it is feasible with today’s diesel engines. Speed reduction is an efficient solution, but it requires more development in logistics and economical incentives before it can be utilized to its full potential.

7 Suggestions for further research within the area

The energy savings may be achieved within different areas. These set requirements on different efforts and with different implications at a system level. Some examples:

1) Technical measures that are easy to perform, will require an effort to start, but no surveillance or work load later. An example in this category is the exchange of “traditional” lamps bulbs with low energy lamps.

2) Technical measures that involves “more intelligent” use of existing equipment. Examples are regulating pumps, turning off equipment when not in use etc

3) Organisational measures, involving changes in incentives and organisation in order to save energy. A responsibility and reward system for low fuel use at the level where this can be affected, ie on board, may be an example.

4) Changes that are performed in a complex system. Surplus heat may be used for heating of cargo or preheating of fuel. A saving may cause a need for producing this heat in another way.

For number 1, the question is why it has not already happened, ie not a central issue for technical research, possibly within behavioural research.

Number 2 and 3 are parts of an energy management system that is under development. However, the organizational means to implement changes and also the effect of organising in the logistic chain is an area where there is a opportunity to increase the understanding by research. The outcome in energy use and efficiency is related to where in the chain decisions are taken. Similar studies have been performed within the building sector, where a picture with many different actors and decision makers far from the activities also is found. The energy turnover for similar buildings with similar use has been shown to be very different due to management issues. This is probably also true for shipping. *Further research related to organisation with focus on shipping is recommended.*

Number 4 addresses issues within systems engineering, systems modelling and environmental systems analysis. There is a need for further developing the understanding of the complex energy system on board in order to avoid sub optimizations and increased energy use and environmental impact. This can be performed by systems modelling, where also environmental impact and sustainability issues are taken into account, thus achieving a sustainability assessment. Research within this area related to ships and shipping systems is not large at present, but should be developed in order to give ground for decision making in when working with energy efficiency in refurbishing and new construction. *Further research within systems modelling with a sustainability focus within shipping is recommended.*

In addition research on specific technical solutions to support energy efficient shipping is needed. In the area of wave energy there have been some demonstrations of energy saving systems, but the opportunities and theoretical background needs more developing before the technology is ready for implementing. *Further research on the opportunities for wave energy use in shipping is recommended*.

Explanation of some terms and abbreviations used in the report

cold ironing = the process of providing shore-side electrical power to a ship at berth while its main and auxiliary engines are turned off.

CRP = (coaxial) Contra Rotating Propellers.

DP = Dynamic Positioning.

exergy = amount of energy available for use.

HVAC = Heat, Ventilation and Air Conditioning.

LNG = Liquid Natural Gas.

reefer = ship for refrigerated cargo.

rpm = rotations per minute.

superstructure = all parts of the ship situated above the waterline.

References

1. **Buhaug, Ø.; Corbett, J.J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D.S.; Lee, D.; Lindstad, H.; Markowska, A.Z.; Mjelde, A.; Nelissen, D.; Nilsen, J.; Pålsson, C.; Winebrake, J.J.; Wu, W.–Q.; Yoshida, K.** *Second IMO GHG study 2009*, London, UK : International Maritime Organization (IMO), 2009.
2. **Eyring, V., Köhler, H. W., van Aardenne, J. and Lauer, A.** *Emissions from international shipping: 1. The last 50 years, J.* Geophys. Res., 110, D17305, doi:10.1029/2004JD005619: 2005.
3. **Jivén, K., Sjöbris, A., Nilsson, M., Ellis, J., Trägårdh, P. and Nordström, M.** *LCA-ship, Design tool for energy efficient ships - A Life Cycle Analysis Program for Ships, Final Report.* MariTerm, TEM, SSPA: 2004.
4. **Voermans, A.** *Propulsion improvement – fuel saving by means of upgrading ship propulsion.* Scandinavian Shipping Gazette No. 18 2006.
5. **Wärtsilä.** *Propulsion improvement. Do you want to save 15% on fuel?* < http://www.wartsila-nsd.com/Wartsila/global/docs/en/about_us/Sustainability/Serevices-Case-W-Propulsion-improvement.pdf > (Accessed on 2009-09-21).
6. **Larsson, L. and Raven, H.C.** *Ship resistance and flow.* Gothenburg and Wageningen, 2004.
7. **Kanerva, M.** *Energy Savings in Ships.* Presentation: Meriliikenne ja Ympäristö, 8-9 Dec. 2005, Hanasaari, Espoo, Finland : Deltamarin Ltd. 2005.
8. **Ahlbom, J., Duus, U.** *Rent skepp kommer lastat.* Projekt Grön Kemi. 2003. ISSN 1403-168X
9. **Wärtsilä.** *Boosting Energy Efficiency.* Presentation: Energy Efficiency Catalogue / Ship Power R&D, 3 February 2009. < http://www.wartsila.com/Wartsila/global/docs/en/ship_power/energy-efficiency/boosting-energy-efficiency-presentation.pdf >
10. **Levander, O.** Wärtsilä. [phone interviews] May-June 2009. Phone number: +358-10 709 3412.
11. **Kollamthodi, S. et al.** *Greenhouse gas emissions from shipping: trends, projections and abatement potential: Final Report.* AEA Energy & Environment, 2008. ED43808 – R02 (Issue 4).
12. **FellowSHIP. <** www.fuelcellship.com > (Accessed on 2009-09-23).
13. **Stensvold, T.** *Testing a fuel cell on a ship.* DNV Forum No. 1 2009. pp. 32-33.
14. **Eidesvik.** *Banebrytende teknologi løftet ombord.* < www.eidesvik.no (Nyhetsarkiv og media) > (Accessed on 2009-09-23).
15. **Witsø, J.E.** *Milestone for maritime environmental project.* DNV, < www.dnv.com (News & press releases) > (Published on 2009-09-14).
16. **MAN B&W.** *Thermo Efficiency System (TES) for Reduction of Fuel Consumption and CO_2 emissions.* MAN B&W Diesel A/S, Copenhagen, Denmark
17. **Wärtsilä.** *Wärtsilä secures first ferry reference for its Low Loss Concept – saves fuel and costs.* < www.wartsila.com > Wärtsilä Corporation, Press Release (Published on 2008-10-23)
18. **Clauss, G., Siekmann, H. and Tampier B., G.** *Betriebssimulation von Frachtschiffen mit Windzusatzantrieb (Simulation of the Operation of Wind-Assisted Cargo Ships).* 102. Hauptversammlung der Schiffbautechnischen Gesellschaft, Berlin : 21-23 Nov. 2007.
19. **Johansson, E. and Kjellberg, M.** *Energy savings potential of auxiliary sails on a transoceanic panamax tanker.* Chalmers University of Technology, Gothenburg : Master's thesis X-07/215, 2007.
20. **Silvanius, M.** *Wind assisted propulsion for pure car and truck carriers.* KTH Centre for Naval Architecture, Stockholm : Master's thesis, 2009.
21. **SkySails.** < www.skysails.info > (Accessed on 2009-09-27)

22. **Dotevall, J., Magnusson, R., Olsson, J., Skoglund, L., and Tunander, H.** *Analys av vind/våg/solenergi för fartygs energiförsörjning.* Chalmers University of Technology, Gothenburg : Bachelor’s thesis, SJOX02-09-06, 2009.
23. **Horie, K.** *Kenichi Horie official site.* < www1.suntory-mermaid2.com/english/ > (Accessed on 2009-09-28)
24. **Dimopoulos, GG, Kougioufas, A V., Frangopoulos, C A.** *Synthesis, design and operation optimization of a marine energy system.* Energy 33 (2008) pp. 180–188.
25. **MariTerm AB, SSPA and TEM**. *Computer application manual: LCA-ship – A Life Cycle Analysis Tool for Ships. Prototype version 1.0*. 2004.