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GHG Emission-Mitigating Measures for Oil Tankers

Part A: Review of Reduction Potential

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The OCIMF mission is to be the foremost authority on the safe and environmentally responsible operation of oil tankers, terminals and offshore support vessels, promoting continuous improvement in standards of design and operation.

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29 Queen Anne's Gate
London
SW1H 9BU
United Kingdom

Tel +44 (0)20 7654 1200
FAX +44 (0)20 7654 1205
E-Mail enquiries@ocimf.com
Web www.ocimf.com

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Abbreviations

The following abbreviations are amongst those used within the text of this paper:

ACS	Air Cavity System
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
CSR	Common Structural Rules
ETA	Estimated Time of Arrival
HFO	Heavy Fuel Oil
HSVA	Hamburg Model Basin
HVAC	Heating, Ventilation, Air Conditioning
HVV	Hub Vortex Vane
ITTC	International Towing Tank Conference
LNG	Liquefied Natural Gas
LSE	Low Surface Energy
MGO	Medium Gas Oil
PBCF	Propeller Boss Cap Fin
SSPA	Swedish Model Basin
ULCC	Ultra Large Crude Carrier
VLCC	Very Large Crude Carrier
WED	Wake Equalising Duct

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Executive Summary

As part of the OCIMF CO_2 Trajectory Prediction project, 56 emission-mitigating measures affecting hull resistance, propulsion, machinery and operations were reviewed and their applicability to tankers assessed. This study included a review of the existing literature to provide a base estimate for the effectiveness of the measures. Consultation of recognised subject matter experts, of which a large proportion were directly involved in the development and testing of individual measures was then used to refine the base estimate. The final stage encompassed a face-to-face workshop held at OCIMF during July 28th to 30th 2010, where the estimates were scrutinised and discussed by an expert panel involving hydrodynamics, ship propulsion, machinery and operations.

The measures are separated into categories of ship resistance, propulsion, power generation and their effectiveness is then considered individually and in conjunction with other measures. The effectiveness of the emission mitigating measures is characterised with a minimum, maximum and most likely estimate of their ability to reduce overall CO_2 emissions from a baseline tanker.

It was found that publicised estimates of the effectiveness of numerous measures, including contra-rotating propellers and air lubrications, are overly optimistic and would not be realised on a tanker. Further, the effectiveness of emission-mitigating measures is dependent on ship size and operational pattern. Finally, particular combinations of emission-mitigating measures cannot be used and care must be taken to ensure that this is reflected when computing a fleet-wide reduction potential.

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1 Introduction

A prerequisite for the derivation of a realistic projection of CO_2 emissions from oil shipping is the assessment and critical review of the effectiveness of the plethora of available emission-mitigating measures. Further, owners and operators of crude carriers seek to identify means to reduce the CO_2 emissions from oil tankers.
Whilst a number of recent publications provide wide-ranging surveys of available measures, their suitability for crude carriers is not addressed.
This report provides a review of more than 50 emission mitigating measures, evaluating their suitability for VLCCs and expected emission reducing potential. These were obtained in a structured approach, involving:

- A comprehensive survey and critical review of available literature to arrive at a first estimate of the effectiveness of the measures.
- Review of these estimates by recognised subject matter experts.
- Discussion of refined estimates by industry experts and vessel operators.

1.1 Strategies for Emission Reduction

There are four principal strategies to reduce emissions from tankers:

1) Reducing ship resistance.
2) Improving propulsion efficiency.
3) Improving power generation (machinery).
4) Improving operation.

The traditional hydrodynamic approach is adopted to decompose the power requirements into resistance and propulsion aspects. While propulsor and ship hull should be regarded as a system, the decomposition aids understanding when savings are effectively cumulative and where different devices work on the same energy loss and are thus mutually exclusive. The decomposition in "resistance" and "propulsion" also reflects traditional expert focus.
In an initial review of published material it was deduced that the estimated potential for improvement appears to be overly optimistic and in most cases, the original source for the claimed improvement estimate is not given. There are various reasons for overestimated saving potentials:

- The emission savings achieved with a particular device used by promoters of a particular technology are normally for an ideal case. For example, formal hull optimization has improved the fuel efficiency of the hull of an offshore supply vessel by 16%. Subsequent literature then - correctly -states that up to 16% reductions in emissions may be gained. This is then quoted as "16% gains" in a subsequent survey or report.
- Numbers valid for one certain ship type (e.g. high-speed container vessels) are transposed to other ships (e.g. slower VLCCs), where they do not apply.
- Potential savings for particular devices are valid for initially bad designs, whereas hydrodynamically optimised designs would never achieve an analogous saving.
- Numbers are frequently taken for design speed and design draft and the frequently encountered off-design conditions (e.g. ballast condition, fixed ETA, etc) are ignored. Utilization of a fuel saving device is often incorrectly assumed to be 100% of the time at sea for a ship and 100% over fleets for global estimates.
- Saving potential refers to calm-water resistance, but is applied to total resistance or total fuel consumption (including the on-board energy consumption).

Thus, when assessing the impact of such improvements the actual operational profile of the vessel, including varying load cases, speeds, and environmental conditions must be taken into account

1.2 Baseline Vessel

For the evaluation of the emission mitigating options a baseline VLCC as defined in Table 1 is used. All savings are given as a fraction of the total CO_2 emissions[1] relative to the same ship without that particular device or strategy.

[1] Including emissions from main propulsion, auxiliary loads and other on-board power generation.

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Parameter	Value
Year of build	2009
Speed – full load	14 kts
Speed - ballast	16 kts
Installed power	24,000 kW
HFO consumption in full load condition	90 t/day
HFO consumption in ballast condition	90 t/day
Specific fuel consumption	0.184 kg/kWh
Days at sea/annum	280 days
Annual fuel consumption	25,200 t
HFO price	500 USD/t
MGO price	1,000 USD/t

Table 1: VLCC used for assessment of Emission Mitigating Measures

Savings should be accumulated by multiplying reduced power consumption. A saving of 4% for one option taken together with a saving of 6% for another option, which does not interact with the first option, does not give 10%, but (100%-4%)·(100%-6%) = 9.76%. For small percentages, the error in simple addition is negligible but when considering larger savings the use of correct mathematics is imperative. When devices interact (e.g. slow steaming and waste heat recovery), their net effect may be considerably less than when considered in isolation.

1.3 Plan of this Report

This report identifies, reviews and assesses the applicability of the emission reduction options available for ship resistance, propulsion, power generation and operations in Sections 2 to 5 respectively. Section 6 considers other aspects such as legislation and the report is concluded in Section 7.

2 Resistance

2.1 Introduction

Reducing the resistance of a vessel lowers the power required to propel it at a given speed, thus reducing fuel consumption and emissions. The resistance of a vessel is governed by:

- Mass including lightship weight.
- Design speed.
- Hull hydrodynamics.

Each of the above is now considered in detail and percentage estimates for emission savings are given.

2.2 Lightship Weight

The lightship weight may be reduced by e.g. better structural design including formal optimisation[2]. The possible weight savings depend largely on the sophistication of the original design. Up to 2% may be saved in steel weight[3] and an average for typical steel weight saving of 0.4% is assumed, as the structural design of many tankers is already well regulated by classification society structural rules.

The steel weight of a VLCC is assumed to be 10% of the displacement in fully loaded condition and 50% in ballast condition. The fuel consumption scales with displacement to the power 2/3. Thus a 0.4% reduction in steel weight gives a 0.03% improvement in the fully loaded condition and a 0.13% improvement in ballast. For simplicity 0.1% is used as the average fuel saving potential.

Ballast water adds to the overall displacement (size) of the ship. Ballast-free ships have been proposed, but often at the expense of increased width which in turn increases resistance and fuel consumption. No net fuel reduction has been demonstrated and the option is therefore not further discussed.

Other measures to reduce power consumption lead to smaller engines (and associated periphery like

[2] Note the difference between "optimisation" (generation of 10-20 designs and picking the best) and "formal optimisation" (generation of thousands of designs typically following some optimisation strategy

[3] Consultant's experience in reduction of structural weight.

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power trains and fuel tanks), leading to secondary savings due to smaller ship size in new designs.

2.3 Vessel Speed

Speed reduction is a very effective way to reduce fuel consumption and emissions. The standard assumption is a cubic relationship between power and speed which is widely used for small speed changes. Real speed-power curves may exhibit local deviations from this assumption and it is applicable for the bare-hull, calm-water condition.

Thus a 10% speed reduction (i.e. 90% of the initial speed) yields a 27% reduction in required power (0.93 = 0.73) or, using a corresponding calculation, a 14% reduction in power for a 5% speed reduction. For comparison, HSVA report fuel savings of typically 13% for tankers, for a speed reduction by 5%, *(Mewis and Hollenbach, 2007)*. The corresponding cubic law estimate gives 14%, possibly because it refers to existing ships where hull, propeller and engine are designed for one speed and operate at lower efficiency at off-design conditions.

In addition, slower design speeds allow higher propeller efficiency, adding another 2% savings potential[4]. For new buildings, design for slower speed is a very effective means to reduce fuel consumption. The smaller required power means that a smaller engine can be employed. In addition, the smaller engine plant decreases the lightship weight and displacement of the ship. This leads to secondary savings. On the other hand, sea keeping and added resistance are largely unaffected. The total savings per ship are then estimated to be 29%. Considering time in port and dock (not affected by ship speed), we estimate an increase in 7% in fleet size to keep the delivery capacity. The net reduction in CO_2 emissions is therefore 24%, with a 7% larger fleet and 29% savings per ship steaming at a slower speed (71%·107% = 76%).

However, there are several drawbacks for lower speeds:

- Lower speed attracts less cargo and market reality may imply that higher freight rates will bring back higher speeds.
- Safety aspects pose lower limits for very low speeds. Designing tankers for much lower speeds, e.g. 20-50% of current design speeds, poses some risks for ensuring directional stability at the design speed. Rudders can be designed to be more effective, e.g. by increasing size and using flaps, but also by using active propeller-rudders like podded drives. However, the reduction of available power will affect manoeuvrability in confined waters and the execution of emergency manoeuvres.
- Transitional costs for logistics pose barriers in intermodal transport chains. These costs occur once for adapting existing schedules, but can be considerable in large transport networks.
- Slower ships transport less and to maintain a transport capacity additional ships are needed. Thus an increase in crew costs is expected.
- Parts of the auxiliary power requirements are proportional to the size of the main engine. However the requirements for crew (hotel-load), navigation and (if applicable) cargo care are independent of speed.
- Capital costs of cargo depend on transport time and cargo value. Slower transport increases then the capital cost on the cargo and reduces freight rates accordingly.

Slow steaming i.e. adopting a lower speed for an already built ship is deemed an operational measure and discussed in Section 5. There are commercial considerations which complicate the matter further, but these are beyond the scope of this report.

2.4 Hydrodynamic Resistance

The typical decomposition of the calm-water resistance of the baseline VLCC is

- 72% frictional resistance,
- 20% viscous pressure resistance and
- 8% wave resistance.

With a further 2% accounting for wind resistance, 4% for appendages (including rudder) and 15% margin (for sea keeping and increased roughness), the following is a breakdown of allocation of effective power delivered by the propeller

- 59.5% frictional resistance,
- 16.5% viscous pressure resistance,
- 6.6% wave resistance,
- 1.7% air resistance,
- 3.3% appendages and
- 12.4% margin (seakeeping and roughness).

[4] MARIN, private communication.

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The frictional resistance[5] is governed by the wetted surface (main dimensions and trim) and the surface roughness of the hull (average hull roughness of coating, added roughness due to fouling and coating degradation). Ships with severe fouling may require twice the power as those with a smooth surface. More exotic options, such as sheathing, electro-conductive or biological coatings are not considered here *(Bertram, 2000b).*

2.4.1 Hull Coatings

Advanced hull coatings can reduce frictional resistance. Such low-surface energy (LSE) coatings create non-stick surfaces similar to those known in Teflon coated pans. By reducing the hull roughness and inhibiting marine fouling, LSE coatings reduce fuel consumption and consequently emissions. Figures of up to 6% have been quoted in the public domain by shipping companies and some publications claim improvements in excess of 10%.

These reductions may be valid directly after coating, with the prerequisite hull cleaning, blasting and likely propeller cleaning. However, an appropriate assessment should consider the period between dry dockings. A high-performance coating may save 8% in the first year, then 6% in the second year and 2% in the following 3 years (i.e. an average of 4% over 5 years) compared to a conventional self-polishing coating. For smaller tankers, the first-year gain is estimated to be 6%, with a 5-year average of 3%.

This study estimates a typical value of 3.5% for a VLCC. Some operators report lower figures which may be attributable to inappropriate workmanship. Problems with ensuring the appropriate level of quality in during coating are expected to decrease with time, partly through progress in "user-friendliness" of coatings and partly through better training and more experience.

Coatings based on nanotechnologies have been on the market for several years. It is difficult to judge claims concerning their fuel saving potential. *Buhaug et al. (2009)* rate the claims as "largely unsubstantiated" and this review does not treat them separately from LSE coatings.

2.4.2 Air Lubrication

Air lubrication has attracted some attention in recent years. The principle of operation is that a film of air on part of the hull reduces friction and in turn fuel consumption. The basic concepts include:

- Air bubbles (injection of air bubbles along the hull).
- Air cavity (recesses underneath the hull are filled with air).
- Air films *(Foeth et al., 2008; Cecchio, 2010).*

In 2008, sea trials were conducted with the "ACS Demonstrator", a 2,550 DWT cargo ship *(NN, 2009a).* The considerable technical effort is most attractive for large, slow ships. The promoters claim savings of up to 15% extrapolated for VLCCs. At present, there is no consensus on the saving potential and no reliable, third-party evaluation.

Reported gains in field trials are not corrected for replacing old plates with high surface roughness by new plates, polishing hull or propeller during refit in dry-dock, more favourable environmental conditions during sea trials, etc. Gains are frequently given for shaft power savings at design speed, without consideration of required power creating and maintaining the air lubrication. Net savings (considering also the power needed to maintain air lubrication) may well be negative, i.e. increasing resistance. A well designed air lubrication system may have a saving potential of approximately 2% but a poorly designed system may well result in a net increase in emissions. Additional operational expenditures come mainly in the form of increased maintenance and repair costs for a complex piping system.

2.4.3 Wave and Viscous Pressure Resistance

For given main dimensions, wave resistance offers large design potential for many ship types but for VLCCs, wave resistance is a comparatively small part of the overall resistance. The main aspect is the optimum design of the bulbous bow for full and ballast draft, possibly also a speed range rather than one design speed. Bulbous bows should be designed based on CFD *(Bertram, 2000a)* and formal optimization *(Abt and Harries, 2007)* can be used to identify global optima. The wave resistance should be considered together with the viscous pressure resistance and main dimensions.

Flow separation occurs when the velocity gradients become too large in a flow. Large curvature (= large changes) in flow direction should then be avoided. Flow separation in the aft body is delayed by the flow acceleration due to the propeller and different in model scale and full scale. Various constraints from the machinery arrangement limit the potential. Current

[5] For a given speed.

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claims are up to 5% reduction in emissions using formal lines optimisation using CFD solvers[6]. Proper selection of main dimensions and ship lines offers an interesting lever for cost effective improvements of fuel efficiency. Aspects of hydrodynamics, structural weight and production should be considered in an optimization of main dimensions and lines. It is important to consider not only resistance, but also propulsion (hull and propeller) interaction. CFD computations coupled to formal optimization are at present still subject to research, but expected to mature sufficiently for commercial applications. The cost for such applications is expected to drop as computing expenses generally decrease and processes are expected to be automated to a large extent. Up to 5% appear feasible in some designs, but 2.5% appears a realistic potential for hull design optimization.

2.4.4 Appendage Resistance

Appendages make a disproportionately large contribution to the resistance of a ship. The term appendages includes negative appendages such as recesses for side thrusters, sea chests, etc. Hydrodynamic analysis can determine proper alignment of appendages. However, for VLCCs, the resistance due to appendages is relatively small, and most of the appendages are already designed to be streamlined (e.g. the bilge keel). The savings potential is estimated at effectively zero

Improving the profile or changing to a highly efficient flap rudder allows reducing rudder size, thus weight and resistance. Due to the rotational component of the propeller, conventional straight rudders (at zero degree rudder angle) encounter oblique flow angles to one side at the upper part and to the other side in the lower part. This creates for most rudder profiles a slight additional thrust by recuperating part of the rotational losses and improves propulsion. Some experts recommend therefore straight rudders. Others (e.g. HSVA) argue in favour of twisted rudders. *Hollenbach and Friesch (2007)* claim that a twisted rudder with Costa bulb may lead up to a 4% lower power consumption for large container vessels.

High-efficiency rudders combine various approaches to save fuel: twisted rudders are combined with a bulb on the rudder as a streamlined continuation of the propeller hub *(NN, 2004; Beek, 2004; Lehmann, 2007)*. Savings of 2-8% are claimed by manufacturers; the saving potential of appendage design is estimated at 1% for VLCCs.

2.4.5 Added (Wave) Resistance

The added resistance in long waves is influenced by the ship motions, the added resistance in short waves mainly by wave reflection/diffraction of the ship. The expected motions of VLCCs are already comparatively small due to the ship size. The reflection component in full hull shapes can be reduced by different bow forms. Such proposals appear to be academic and not attractive in a holistic view. Ideally, total power requirements should be minimized, considering also added resistance in waves in design (or even formal optimization). This has been proposed, but requires reliable prediction of the added resistance in waves. This in turn is difficult to measure and compute. Nevertheless, future improved design procedures combining calm-water resistance and added resistance in waves may give improvements of typically 0.3%.

Wind adds power requirements in two ways: (a) direct aerodynamic resistance on the ship and (b) indirect power demand due to drift in side winds. The effect can be evaluated in wind tunnel tests and CFD simulations. Savings of 1 to 1.5% on the overall power of container vessels have been estimated by *Hollenbach et al. (2007)*. For VLCCs, 0.2% fuel savings appear more likely at the expense of increased construction costs.

Ships are usually optimised for the trial or design speed in calm water, but later operated most of the time at lower speeds, even when they are not slow-steaming. A reduction in emissions is anticipated if a vessel is designed for a more realistic mix of operational speeds, load conditions and environmental conditions. VLCCs operate at a more even speed profile than many other ship types. The fuel savings gained are estimated to be 0.5% at the expense of a higher design effort.

2.5 Summary

Not all savings are cumulative, but with state-of-the-art technology, emission form VLCCs could be reduced by an estimated 30% in terms of resistance, using the most attractive options:

- Speed reduction.

[6] Advanced CFD software that allows capturing wave resistance, viscous pressure and frictional resistance as well as the effect of the propeller. The main improvement potential lies in the bow and aftbody. Formal hull optimisation using free-surface viscous flow solver is frontier technology and not yet state of the art.

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- Optimizing main dimensions and lines for life-cycle cost.
- Using top-range low-friction coating.

However, this figure is dependent on the adoption of a lower design speed and if that is excluded, the emission reduction potential for resistance is estimated at 6%. This saving is however theoretical and may not be realised uniformly across a fleet of tankers.

3 Propulsion

The propeller transforms the power delivered from the main engine via the shaft into thrust to propel the ship. Typically, only two thirds of the delivered power is converted into thrust power. A specialist committee of the International Towing Tank Conference *(ITTC, 1999)* reviewed various unconventional options to improve propulsion of ships. Model tests for these devices suffer from scaling errors, making any resulting quantification of savings for the full-scale ship questionable.
The aft hull form, rotating propeller and rudder interact yielding an overall propulsion performance (and resulting power requirement). Power-saving devices are designed to reduce flow losses around the working propeller. The main losses and corresponding options are discussed in this section.

3.1 Propeller Efficiency

Modern design methods may facilitate improvements in propeller design, especially if design methods progress to reliable prediction of full-scale wake fields and hull-propeller interaction, considering speed and load case ranges instead of just a single operation point. Such improved propeller design procedures may be in place within the next 10 years. Potential savings of 0-4% were reported in a survey among experts from ship model basins.
This report estimates an average saving of 2.5% via the improvements in propeller efficiency due to better design methods. However, the variability of propeller design and the high level of interaction with the hull make it difficult to predict the fuel saving potential. Note that other measures discussed further below will improve the wake field, decreasing the additional improvement potential of better design approaches.
One well-known class of high-efficiency propellers consists of propellers with tip-modified blades. Tip fins on propellers can lead to more efficient propeller blades without increasing diameter, similar to the tip fins often seen on aircraft wings. There are several variations on the theme (ITTC, 1999):

- Contracted and loaded tip (CLT) propellers with blade tips bent sharply towards the rudder *(Hollstein et al.,1997).*
- Sparenberg-DeJong propellers with two-sided shifted end plates *(Sparenberg and De Vries, 1987; Jong et al.,1992).*
- Kappel propellers with smoothly curved winglets *(Andersen, 1996; Andersen et al., 2002).*

For the CLT propeller, 16% fuel savings were reported for refitted tankers and bulkers. However, in interviews, propeller experts unanimously voiced doubts about these claims. For Kappel propellers, 4-6% fuel savings have been claimed for a 35,000 DWT product tanker. Savings of approximately 4% appear feasible for VLCCs.

3.2 Recovery of Rotational Energy

Most ships lose a substantial amount of energy through the rotation of the propeller, imparting rotational rather than axial momentum on the water. A large number of devices have been proposed to recover some of this energy. These can be categorized into pre-swirl (upstream of the propeller) and post-swirl (downstream of the propeller) devices. Typically 3-8% fuel savings are claimed for all these devices, which appear unlikely for VLCCs. *Buhaug et al. (2009)* give the rotational losses for a VLCC as 3.9%. As such losses can only be recovered in part; a 2.5% fuel saving improvement is taken as an upper limit for propulsion improving devices that recovers rotational losses. This upper limit is seen by some experts as overly optimistic. As all these devices target at the same energy loss, only one of them should be considered and gains are certainly not cumulative. Rudders behind the propeller already recover some of the rotational energy. Many of the optimistic estimates are apparently based on considering the propeller in open-water condition without rudder. Potential gains should always be considered with rudder behind the propeller to avoid overly optimistic estimates. The prerequisite hydrodynamic analysis should not rely on any one method (e.g. CFD or physical model test).

5) Pre-swirl devices are generally easier to integrate with the hull structure. Pre-swirl devices include pre-swirl fins and pre-swirl stator blades *(Liljenberg, 2006).* Based on interviews with experts, possible savings range from 0-3.5%, with 1.5% as a likely estimate. Pre-swirl fins can be combined with a wake-equalizing nozzle in a so-called Mewis Duct, discussed further below.

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6) Asymmetric aft bodies *(Schneekluth and Bertram 1998)* are a very robust way to generate swirl, but involve major changes in design and are not a refit option. The added costs in ship construction for an asymmetric aft body may be prohibitively high. Typical savings are estimated as 2%.
7) The vane wheel *(Grim, 1980; Schneekluth and Bertram, 1998; Carlton, 2007)* is a freely rotating device installed behind the propeller (on the tail shaft or the rudder horn). Its function is to extract energy from the propeller slipstream which would otherwise be lost. The vane wheel is composed of a turbine section inside the propeller slipstream and a propeller section (vane tips) outside the propeller slipstream. The vane wheel became unpopular after several reports of mechanical failures. Operators remain hesitant to use this device, as it appears mechanically delicate. There are concerns that collision with wood, ice floes, or even ropes may damage the vane wheel. Improvements of 7-10% are reported by *Breslin and Andersen (1994),* where higher values are possible for higher propeller loading. For tankers, 4% improvement appears realistic, as the device exploits not just the rotational energy of the propeller wash.
8) Rudder thrust fins are foils attached at the rudder. Both x-shaped thrust configurations and configurations with only two blades have been proposed. The blades are designed to generate thrust in the rotating propeller slipstream. Full hull forms (like tankers) are expected to benefit more from such fins than slender container vessels. Fuels saving potentials of up to 9% have been claimed *(Buhaug et al., 2009).* However, numerical simulations by third-party experts have not been able to demonstrate any performance improvements for full-scale conditions. Until conclusive evidence is available, this class of device is considered to be rather ineffective with 0.05% saving potential.
9) Stator fins are fixed on the rudder and intended for slender, high-speed ships such as car carriers, *(Hoshino et al., 2004).* Thus they appear not suitable for VLCCs and are not discussed further in this report.
10) Contra-rotating propellers combine recuperation of rotational energy losses with better propeller loading *(Schneekluth and Bertram, 1998).* Reported claims range from 6-20% in fuel efficiency improvement. *Buhaug et al. (2009)* give much lower estimates of 3-6% based on the estimates of rotational energy losses. However, contra-rotating propellers also have larger surface, more losses in bearing and recuperate rotational energy that otherwise would be recuperated by the rudder. For VLCCs, fuel savings of 3% appear feasible, but the mechanical complexity associated with frequent failure and downtime problems make the adoption of contra-rotating propellers very unlikely.[7] More recently, podded drives and conventional propellers have been combined to hybrid CRP-POD propulsion *(Ueda and Numaguchi, 2006),* claiming 13% fuel savings. These appear attractive for vessels that require redundant propulsion.

Opinions on propulsion improving devices scatter widely, from negative effects (increasing fuel consumption) to more than 10% improvements. Full scale CFD simulation or in-service measurements may reduce the present uncertainty. With considerable doubts remaining amongst both industry and academic experts, the above options are less likely to be adopted.

Devices may be added to the propeller hub to suppress the hub vortex. Propeller boss cap fins (PBCF) were developed in Japan *(Gearhart and McBride, 1989; ITTC, 1999).* Publications by the patent holders report 3-7% gains in propeller efficiency in model test and 4% for the power output of a full-scale vessel *(Ouchi, 1988, 1989; Ouchi and Tamashima, 1989; Ouchi et al., 1988, 1989, 1992).* The Hub Vortex Vane (HVV) offers an alternative to PBCF *(Schulze, 1995).* The HVV is a small vane propeller fixed to the tip of a cone shaped boss cap. It may have more blades than the propeller and an increase of 3% in propeller efficiency is claimed. However, the presence of the rudder significantly reduces the strength of the hub vortex and hence the gain in propeller efficiency due to PBCF can be reduced by 10-30%" *(Junglewitz, 1996; ITTC, 1999)* Independent investigations by a large model basin reported (in personal communication) savings in the order of measuring accuracy, namely 0.1-0.2%. This estimate is adopted here and a 0.2% saving potential is assumed for hub vortex-suppressing devices.

3.3 Propeller Flow Field

The propeller operates in an inhomogeneous wake behind the ship. This induces pressure fluctuations on the propeller and the ship hull above the propeller, which in turn excite vibrations. The magnitude of these vibrations poses constraints for the propeller design. Discontinuities such as inlets and cooling water outlets introduce further discontinuities usually not considered in design. Subsequent cavitation and vibration problems may be solved using vortex generators, albeit at the expense of added resistance. A more homogeneous wake translates into better propeller efficiency. Ideally, the hull lines (including discontinuities such as appendages and inlets) should be optimised to have good hull-propeller interaction already in the design stage.

[7] There are also noise considerations when comparing CRP to conventional propellers

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Wake equalizing devices such as Schneekluth nozzles *(Schneekluth, 1986; Schneekluth and Bertram, 1998)*, the Sumitomo Integrated Lammeren Duct or the Hitachi Zosen nozzle may improve propulsion in suboptimal tanker designs. Independent analyses came to contradicting evaluations of the effectiveness of WEDs *(Celik, 2007). ITTC (1999)* states cautiously: "In conclusion, partial ducts [like WED] may result in energy saving at full scale, but this was not, and probably cannot be proven by model tests …". *OK (2004, 2005)* considers the WED as ineffective or even counterproductive at full scale based on detailed insight in the flow in full-scale CFD simulations for one tanker. At present, there is no third-party confirmation of this pessimistic claim.
The effectiveness may depend on local flow details like the strength and position of the bilge vortex in the propeller plane, making the WED effective in some cases and ineffective in another. Based on estimates from experts from various model basins and universities, the effectiveness may then vary between -1 to 5% compared to the optimistic estimates of up to 6-7%. WEDs should be designed using CFD (and possibly additional model tests) and effectiveness should then be assessed on an individual case basis. For VLCCs an emission saving potential of 1.5% appears likely.
Grothues spoilers and vortex generators have been employed to resolve design flaws leading to vibration problems. They are expected to increase fuel consumption rather than lead to any fuel savings.
Mewis (2008, 2009) combines a wake equalizing duct with a pre-swirl fin, claiming 7-9% gains for bulkers and tankers. Hydrodynamics experts gave averages for tankers ranging from 0-3.5%, staying again well below the above claims and an average effectiveness of 2.5 % is estimated here.
Ducted propellers have been proposed as propulsion improving device, claiming up to 20% fuel saving potential *(Buhaug et al. 2010)*. Ducted propellers have been used for many decades and a small number of tankers were fitted with them in the 1970s. The use of ducts did not increase due to reported problems with vibration and cavitation. Modern tugs, offshore supply vessels and fishing vessels frequently feature ducted propellers. Problems with cavitation and vibrations may be overcome by simulation guided design (CFD and finite element analyses). Saving potential was estimated by hydrodynamics experts at 0-3.5%. A savings potential of 2% appears likely, following an older SSPA estimate.

3.4 Summary

Not all devices presented in this section are cumulative, but with state-of-the-art technology, a new VLCC design could be improved by an estimated 6.5% in terms of propulsion using:

- Improved propeller designs due to better design procedures (including hull-propeller-rudder interaction and operational profiles) and wider choice of propeller geometries (including tip-modified propellers).
- Possibly a propulsion improving device for existing sub-optimal ship designs.
- Improved propulsion through best-practice duct or vane wheel.

Again, it must be emphasised that these savings may not be realised uniformly across a fleet of tankers.

4 Machinery

There are various options to save power in the main and auxiliary engines as well as the assorted energy consuming equipment onboard ships. The saving potential depends on the ship type.

4.1 Main Engine

Approximately 25% of the energy in main engines is lost in the exhaust heat. *Buhaug et al. (2009)* estimate that fuel savings of 10% can be obtained by energy recovery from exhaust gas. The amount that may be recovered depends on the engines used, the exhaust gas temperature and the sulphur content in the fuel (dew point of acid restricts allowable outlet temperature of exhaust gas heat exchanger). For VLCCs without power take-in (PTI) the saving potential is estimated to be 2-7%, typically 4.5%. For ships with PTI, the saving potential is estimated at 5-12%, typically 10% *(Krapp, Watter 2008,)*. Most VLCCs use already simple heat recovery without PTI, but few VLCCs so far use the option of heat recovery with PTI.
Better engine control may come in various forms, using the potentials of e.g. common rail injection and two stage turbo charging to improve engine efficiency in the whole range of operation. However, the engine development is currently dominated by the upcoming requirements to reduce NOX-emissions. This by tendency will reduce fuel efficiency, because of lower combustion temperatures and increased back pressure as a result of exhaust gas cleaning systems. Part of– if not all- potential improvements may be consumed to compensate the influences of NOX-emission control. Whilst a saving of 3% may be possible through further development of diesel engine technology, impending legislation suggests that no overall contribution of the engine sector to reduce fuel consumption and CO_2 emissions from shipping is possible.

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4.2 LNG as a fuel

LNG as a fuel may be an attractive solution, not only because of the lower emissions (22% lower CO_2 emissions, 16-20% lower net greenhouse gas emissions due to methane slip depending on employed technology; no sulphur emissions), but also due to (presently) lower equivalent fuel price. For the same energy content, LNG was in April 2010 approximately half the price of HFO. Long-term predictions for LNG prices vary widely. Gas engines (Diesel cycle engines using gas as fuel) are already available and a wider range is expected to develop in the wake of stricter emission regulations after 2015. Current obstacles for engines and networks of LNG bunker stations are expected to be overcome first in short sea shipping in Europe. Long-term, also VLCC operation with LNG can be envisioned, as required LNG tanks could be arranged on deck. The savings in greenhouse emissions are estimated to be 18-20% (for global emission reduction). The savings potential for switching to LNG as fuel is estimated as 19%.

4.3 Fuel Cells

Fuel cells offer larger thermal efficiencies than diesel engines. However, they require particular fuels, typically LNG. At present, the available units are too small, but larger units up to required main propulsion power are expected to evolve in the next four decades. By 2020, fuel cells may be a cost competitive alternative for auxiliary power generation. It will take probably several decades before fuel cells are used as the sole source of propulsion. The efficiency of fuel cells is expected to be considerably greater than that of diesel engines, possibly as high as 65-70%. As the widespread use of fuel cells is several decades away, they are not discussed further at this stage.

4.4 Wind Power

Wind has been the predominant power source for ships until the late 19th century. Wind-assistance has recently enjoyed a renaissance. Wind-assisted ships use predominantly other means of power (typically diesel engines) and wind power plays only a secondary role. Generally, the systems may be attractive for ship speeds below 15 knots. For modern cargo vessels, automatic systems are the only viable option and the additional structural effort for mast support on ships with sails can be considerable.
Kites and Flettner rotors are generally more efficient than sails per surface area, but smaller in overall size. Optimum solutions depend on many parameters, most notably ship type, route and speed. *Schenzle (2010)* analysed various advanced sail-assistance options (sail wing, wing sail, Flettner rotor, kite) for a bulk carrier (75,000 DWT) and various routes.

- Modern sails can be controlled automatically. They may be reefable cloth type (sail wings) or rigid profile type such as wing sails *(Schenzle, 2010).*
- Wind kites have been brought to commercial maturity. Kites harness wind power at larger heights without the stability penalties of high masts. They move with much higher speeds than wind speed through the air, exploiting lifting forces similar to foils. By 2010, 4 ships were equipped with kites, 3 years after the first installation. *(NN, 2008*). Kites are claimed to be 25 times as effective (per given surface area) than regular sails.
  For VLCCs, one problem is that the largest available size was (as of 2010) a 16 t pull (160 kN) kite[8]. Kites with a 32 t pull are under development and kites with a 130 t pull are envisioned. Savings of 10-35% are claimed for smaller ships and transatlantic routes.
- Flettner rotors are another technology harnessing wind energy for ship propulsion *(Ragheb, 2010).* After 80 years of obscurity, they have resurfaced in 2010 with the delivery of the E-Ship 1, a freighter equipped with Flettner rotors. These four cylinders, each 27 m tall and 4 m in diameter, are claimed to save 30% of the conventional fuel needed by the ship (10,000 DWT at 17.5 kts design speed, 7,000 kW installed power). Flettner rotors have the disadvantage that they create additional wind resistance for head winds and increased air draft (unless they are retractable, which requires additional system effort and complexity). For large tankers, slightly larger units may be used than for *Schenzle's (2010)* bulker study.
- Solar-power and wind-power can be combined, using fixed sails equipped with solar panels. This option is employed successfully on the SolarSailor ferry operated in Sydney. SolarSailor wings have been designed for a large bulker, but the project was abandoned with the global financial crisis. The potential should be comparable for best-practice sails. Sufficiently large units are yet to be developed and the technology including high-performance solar panels is still expensive.

There are few wind-assisted modern cargo ships. Kites are most mature with four installations (July 2010). The potential of other wind assistance options may be similar in magnitude. A negligible savings

[8] Less than 5% of the resistance of a typical VLCC.

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potential is given for a VLCC trading Europe-Persian Gulf via Suez, 2% for the same tanker via the Cape of Good Hope, 3% for a Suezmax tanker on the same route and 18% for a product tanker trading in the North Atlantic. Wind-assistance installation and maturity of technology are expected to grow in the next decade, but the technology is judged to be borderline mature at present and less attractive for VLCCs than for other ships. Given the dependence on environmental conditions, ship size and speed, a potential saving of 1.0% is estimated in this instance.

4.5 Others

Solar energy may supply only a very small part to the total energy balance of a ship. For VLCCs, solar energy does not appear to be a reasonable option for the foreseeable future. In 2009, a Japanese car carrier was equipped with solar panels covering around one quarter of the ship's open deck, but producing just 40 kW of the power compared to 13,240 kW of the main engines *(NN, 2009b).* Even considering progress in solar panel technology, the saving potential is virtually 0% and not further considered here.
Wave energy thrusters are also not a reasonable option for ship propulsion. Due to low energy density and high transmission losses, the attainable thrust is very small. The saving potential is effectively zero.
Bio fuels were not discussed as these fuels appear to be best used on land to substitute fossil fuels there. Further, bio fuel content in marine fuels may cause problems due to acid content of bio fuels.

4.6 Auxiliary Systems

Frequency controlled (or speed controlled) pumps instead of fixed rpm pumps (for cooling water and other systems with high utilization rate) may decrease energy consumption for the pumps by 25%. Matching cooling system flows to engine loads and ideal engine operating temperatures will also improve the performance of the engine itself. For VLCCs trading often in hot regions, savings will be smaller as pumps operate more frequently near design conditions of 32°C sea water temperature but savings of 15-20% may be achievable. Electrical power needed for pumps is estimated to be 2% of the total power. In addition, redundancy in pumps and coolers can be used to adapt to different cooling requirements. A 0.5% saving of the total emissions is assumed.
HVAC (heat, ventilation and air conditioning) systems contribute less than 1% to the total fuel consumption. HVAC related fuel consumption may be improved using proper coatings, insulation, and system design. The fuel savings potential is estimated as effectively zero for VLCCs.

4.7 Summary

With state-of-the-art technology, a new VLCC design could be improved by an estimated 7% via the following:

- Exhaust heat recovery using PTI.
- Improved engine control.
- Wind assistance.
- Frequency controlled pumps.

With future technology, employing LNG as fuel for fuel cells, additional CO_2 reductions of 30% appear possible. However, these savings may not be realised uniformly across a fleet of tankers.

5 Resistance

5.1 Shipping in the Transport Chain

Transport efficiency can be increased by various modifications to the use of ships in the crude oil transport chain.

- Better cargo capacity utilization. Ships with larger capacity utilization (ratio of actual cargo load to maximum cargo load) have a better energy efficiency operational indicator (EEOI). VLCCs trading fully loaded in one direction and in ballast back have little room for improvement in this respect, unless a return to the Oil-Bulk-Ore carrier can be achieved.
- Concentration of cargo in larger ships *(Buhaug et al., 2009).* VLCCs are unlikely to grow in size. ULCCs, with twice the size of currently operating VLCCs, were built and operated in the 1970s. ULCCs were subsequently abandoned due to port facility restrictions and logistical aspects as well as the amount of capital tied up in a single cargo. It is not expected that larger tankers will (re-)appear in the future. The cargo is already concentrated in the largest ships in the world fleet.
- Reduced time in port: If time in port is reduced, the ship can sail at a reduced speed without sacrificing transport capacity and earnings. As reduced speed is a very attractive option as discussed

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above, reducing time in port is also an attractive option. The multitude of stakeholders in port operations makes it often difficult to reduce port time, but a reduction by several hours per port call was deemed realistic through faster processing of documents and test procedures. The savings would translate into typically 1% in the fuel consumption. Pressure on ports to reduce time in port for ships may come from environmental aspects, avoiding unnecessary pollution in port or from port capacity problems motivating faster through-put. However, more efficient turn-around in ports is likely to result in a vessel performing more journeys (and earning more money) rather than performing the same number of journeys at a slower speed.

- Reduced speed for existing ships (slow steaming). The option is less attractive than designing for lower speed which was discussed previously as there are no secondary savings for smaller machinery plant and thus reduced ship weight. Moreover, ship, propeller and engine operate in an off-design condition and thus at a lower efficiency. The option will be adopted only when there is a slump in demand for shipping transport. Extended operation in off-design conditions leads to increased maintenance and down-time costs. In addition to technical obstacles, non-technical obstacles like existing delivery contracts and logistics chains pose obstacles to fleet-wide adoption. A fuel saving of 13% has been reported for a 5% reduction in speed on an in-service vessel *(Mewis and Hollenbach, 2007).*

5.2 Voyage Optimisation

- Trim optimisation: For each draft and speed, there is a fuel-optimum trim. For ships with large transom sterns and bulbous bows, the power requirements for the best and worst trim may differ by more than 10% *(Mewis and Hollenbach, 2007).* Systematic model tests or CFD simulations are recommended to assess the best trim and the effect of different trim conditions. Decision support systems for fuel-optimum trim have been proven to result in considerable fuel savings for relatively low investment *(Hansen and Freund, 2010).* For VLCCs, there is more potential in ballast draft than in full draft. The potential is smaller than for containerships, as a significant part of the trim optimization concerns the wave resistance (thus a relatively small part of the total resistance for VLCCs) and the achievable trim is more limited than for e.g. containerships. For fully loaded condition, there is virtually no room for trim variation. The overall potential is estimated to be 0.25% on average.
- Ballast optimization: Avoiding unnecessary ballast reduces displacement and thus typically also fuel cost. However, for VLCCs, ballast is already planned professionally, and driven by prevailing market forces, and there does not appear to be further potential for improvement.
- Weather routing (i.e. optimization of a ship's course and speed) may reduce the average added resistance in seaways. Weather routing systems widely differ in performance and price. Claims of up to 10% are reported and *Buhaug et al. (2009)* give 1-5%. Some experts estimate the saving potential to even less than 1% for most realistic scenarios. The saving potential largely depends on which routes are traded (for example Mediterranean or Atlantic). We estimate the saving potential beyond what is already widely done today to 0.1%.
- An even engine load profile *(Söding, 1992)* in operation has an emission reduction potential of 1%. Enabling an even load profile during an entire voyage requires accurate ship models and accurate prediction/assessment at the beginning of the voyage of weather, currents and possible other constraints during the voyage, making accurate weather forecasting a prerequisite.
- The adjustment of the autopilot course keeping function, avoiding the use of rudder wherever possible, is another option to reduce consumption and emissions. Up to 2.5% fuel savings have been reported, but no reliable source is known. A likely fuel savings potential is estimated at 0.5%.

5.3 Maintenance

Optimal (condition based) hull, propeller and engine maintenance can contribute to fuel savings:

- Hull cleaning can be optimised based on employed coatings and trade patterns. Cleaning can be performed by divers (and in future possibly also underwater robots). However, frequent cleaning may deteriorate the coating requiring pre-mature re-coating or leading to decreased vessel performance. Based on operational experience for VLCCs, the saving potential for optimizing hull cleaning is estimated to be 2%.
- Propeller polishing is already widely carried out. Additional saving potential is small, estimated to be effectively zero. Propeller coating has been suggested. However, propellers are polished to a very smooth state. The additional gains for VLCCs are estimated to be virtually 0%.
- Condition-based engine maintenance, involving intelligent monitoring schemes, has proven to be effective. The systems are expected to develop further and gain wider acceptance. A savings potential of 2% is estimated.

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Better overall energy management systems may balance the energy demand of the consumers on board reducing peak demands allowing in turn a reduction of the generator capacity *(Krapp, 2009)*. One example is combining auxiliary and main engines, which provides options for a more flexible propulsion management, where auxiliary engines are used for slow speeds, classical mechanical drive for regular operation and mechanical drive with added electrical drive for rare peak loads. Fuel monitoring systems, possibly combined with simulations of the overall machinery system, allow detailed assessment and guidance for better balanced energy profiles *(Freund et al., 2009; Hansen and Freund, 2010)*. The saving potential is estimated as 0.8%.

5.4 Human Factors

The human factor plays an important role in fuel saving. It drives how much of the potential technical or procedural improvement is exploited. There are basically two separate aspects that require different approaches to exploit existing saving potential:

- Awareness, i.e. educating the operator. Potential savings may be determined looking at actual logs of routes or on-board measurement campaigns. Savings then depend on training and/or displayed information. Certified fuel consumption, e.g. in the form of an energy efficiency index, can raise awareness when deciding on charter contracts. Onboard monitoring systems furnish valuable data for a posteriori analyses and are known to affect crew behaviour.
- Care, i.e. incentivising the operator. This includes e.g. willingness of the crew. Incentive systems can lead to shared benefits and thus motivation to save fuel.

In a similar way, contractual frameworks between owners and charterers can be amended to motivate both stakeholders to save fuel. It is inherently wasteful for a vessel to steam at high speed to a port where known delays to cargo handling have been identified. By reducing speed to a mutually agreed arrival time, the vessel avoids spending time at anchor awaiting a berth, tank space or cargo availability. Emissions and fuel consumption can thus be reduced. This procedure is advocated under the term "virtual arrival". Savings from Virtual Arrival are estimated to be 1-6%, with an average of 4% if such flexibility is included in the contracts[9].

5.5 Summary

With state-of-the-art technology, a new VLCC design could be improved by an estimated 5% in terms of machinery, using the most attractive measures:

- Voyage optimisation, including virtual arrival.
- Optimise maintenance of hull, propeller and machinery.

Considerably greater gains are possible by reverting to a liner mode of operation for tankers, with observed differences in efficiency in excess of 30%. Given the nature of this change in operational mode it is not considered as an option here.

6 Others

6.1 Legislation

Some expected changes in international legislation will lead to higher fuel consumption and CO_2 emission as a necessary side effect of improving other environmental aspects:

The formation of NOX depends on the temperatures in the combustion process and sufficient time for the chemical reaction. As a rule of thumb lower and evenly distributed temperatures during combustion will reduce NOX generation. On the other hand, high efficiencies and corresponding low CO_2 emissions require high combustion temperatures. This so-called Diesel dilemma will result in reduced efficiency with restricted NOX emissions. Future engines complying with "Tier 3" NOX requirements shall use advanced technologies to keep the fuel consumption at present levels. To date, it is not certain that the NOX emission goal can be reached without losses in efficiency (e.g. due to power required for exhaust gas cleaning and recirculation, production of fuel water emulsions or exhaust gas catalysts and their corresponding effects on engine performance). Effects may be different for two-stroke and four-stroke engines. Development work is still in progress and therefore any information by engine manufacturers is politically influenced and preliminary. Therefore a conservative estimate is an increase in fuel consumption by 1-5%, with a most likely estimate at 3%, for the future main engines.

Ballast water treatment systems will become mandatory and depending on what technology is used and how much ballast water needs to be treated, may increase emissions by 0-1%. A conservative estimate is a 0.3% increase in emissions.

[9] Virtual Arrival is expected to apply to at most 20% of all VLCC voyages and a typical saving of 15-20% has been reported in trials.

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6.2 Retrofit

The discussion so far has focussed on newbuildings. With typically 30 years of operation, it takes decades before new technology replaces old technology on fleet-wide or global scale. The options for fleet in service are more limited, but still significant reductions in fuel consumption and emissions can be expected. Some of the newbuilding options can also be applied as refits to fleet in service. Others, e.g. changing main dimensions or lines, are generally prohibitively expensive once a ship has been built. Refit options are marked in Table 2 in the appendix.
Ships are often operated at considerably lower speeds than the design speed. Tuning of engines for actual operational conditions (optimizing for lower speeds) has been mentioned by various consultants and vendors. If the ship shall be operated at lower speeds for a longer period the engine may be adapted to the mean effective pressure by changing the fuel injection system or installing an exhaust turbocharger.

7 Conclusion

7.1 Summary of Results

The effectiveness of the various measures considered in this report is summarised in Table 2 below. The key indicates whether measures are compatible: for measures with an identical second digit, only one can be selected. The effectiveness is quantified using:

- Minimum (min), which is the smallest gain anticipated from the technology (may be negative is a deterioration in performance is expected),
- Maximum (max), which is the upper limit of any gain.
- Most likely (ml), what is considered the most probable reduction in emissions achieved by the use of the technology.

The refit column indicates whether a technology is suitable for refit to existing ships.

Key	Item	Effectiveness			Refit
		min	ml	max	y/n
100	Resistance		30.0 %		
110	Structural optimization	0 %	0.1 %	0.3 %	n
120	Design for 10 % lower speed	20 %	24.0 %	27.0 %	n
131	Low-friction coatings	0.0 %	3.5 %	5.0 %	y
132	Air lubrication	-5.0 %	2.0 %	4.0 %	y
140	Bare hull optimisation	1.0 %	2.5 %	5.0 %	n
161	Resistance of appendages	0.0 %	0.0 %	0.2 %	y
162	Rudder resistance	0.2 %	1.0 %	1.8 %	y
171	Reduced resistance in seaway (design)	0.0 %	0.3 %	1.5 %	n
180	Wind resistance	0.0 %	0.2 %	0.8 %	n
190	Design for operational profile	0.0 %	0.5 %	1.5 %	n
200	Propulsion		6.5 %		
210	Optimise propeller efficiency	0.0 %	2.5 %	4.0 %	y
211	Tip-fin propeller (CLT, Kappel, etc)	0.0 %	4.0 %	6.0 %	y
221	Preswirl devices	0.0 %	1.5 %	3.0 %	y
223	Asymmetric aftbody	1.0 %	2.0 %	3.5 %	n
224	Grim vane wheel	1.0 %	4.0 %	5.5 %	y
225	Rudder thrust fins	0.0 %	0.05 %	1.3 %	y
226	Contra-rotating propellers	1.5 %	3.0 %	9.0 %	n
227	PBCF or HVV	0.0 %	0.2 %	0.9 %	y
228	Wake Equalizing Ducts	0,0 %	1,5 %	3,0 %	y

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Key	Item	Effectiveness			Refit
229	Combined duct + fins	0.0 %	2.5 %	3.5 %	y
230	Ducted propellers	0.0 %	2.0 %	3.0 %	y
300	Machinery		7.0 %		
310	Waste heat recovery for e-generation	2.0 %	4.5 %	7.0 %	n
311	Waste heat recovery with PTI	5.0 %	10.0 %	12.0 %	n
312	Avoid oversizing main engine	0.1 %	0.3 %	0.5 %	n
313	Better engine control	0.0 %	0.8 %	1.3 %	
314	Shaft generator	0.5 %	1.0 %	1.5 %	n
216	Auxiliary boiler optimization	0.0 %	0.5 %	1.0 %	n
320	LNG as a fuel	18.0 %	19.0 %	20.0 %	n
321	Fuel cells as prime mover	n/a	n/a	n/a	n
330	Wind assistance	0.0 %	1.0 %	3.5 %	y
331	Solar panels	0.0 %	0.0 %	0.5 %	n
332	Wave energy thrusters	0.0 %	0.0 %	0.0 %	n
340	Frequency controlled pumps	0.3 %	0.5 %	0.7 %	y
350	Reduce HVAC energy	0.0 %	0.1 %	0.2 %	n
400	Operations		4.5%		
411	Better cargo utilization	0 %	0.0 %	0.0 %	y
412	Concentrate cargo in larger ships	0 %	0.0 %	0.0 %	y
413	Reduce time in port	0.0 %	1.0 %	3.0 %	y
421	Trim assistant and ballast optimization	0.1 %	0.3 %	1.5 %	y
423	Weather routing	0.0 %	0.1 %	0.2 %	y
424	Even main engine / e-load operation	0.0 %	1.0 %	1.5 %	y
425	Autopilot adjustment/upgrade	0.0 %	0.5 %	1.0 %	y
431	Virtual arrival	1.0 %	4.0 %	6.0 %	y
441	CBM hull	1.0 %	2.0 %	4.0 %	y
451	Propeller polishing		0.0 %		y
452	Propeller coating		0.0 %		y
453	Improved machinery maintenance	0.0 %	2.0 %	4.0 %	y
454	Energy management	0.0 %	0.8 %	1.0 %	y
500	Legislation				
501	NOX code (tier 3)	-1.0 %	-3.0 %	-5.0 %	n
502	Ballast water treatment	0.0 %	-0.3 %	-1.0 %	y

Table 2: Effectiveness of Various Emission Mitigating Measures

7.2 Concluding Remarks

There are a number of measures available to save fuel and thus emissions for ships. Unfortunately, there is large scatter in saving potential and quoted saving potential is unreliable for various reasons as discussed in the introduction. The estimated saving potential for the various options discussed was derived in good faith by the experts participating in the workshop and with remarkable consensus. However, they are not cast in stone and are subject to re-evaluation in the light of new facts. Despite these uncertainties, the compiled information may serve for a first assessment, identification of most promising options and realistic targets for the industry. To the best of the authors' knowledge, this is the only such survey involving high-level expertise in hydrodynamics, machinery and operation, reflecting also operational realities. Note that the potential savings given apply for the case-study tanker and should not be applied fleet wide (i.e. one cannot assume that 100% of the fleet will adopt them).

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1. Fred R. Adolfen (Statoil)
2. Prof. Dr.Ing.habil. Volker Bertram (FutureShip GmbH)
3. Stephen Collins (Shell Shipping Technology)
4. David Connolly (Shell Shipping Technology)
5. Ian Falconer (Shell Shipping Technology)
6. Bernhard Godderidge, PhD (Shell Shipping Technology)
7. Dr.Ing. Reinhard Krapp (Germanischer Lloyd)
8. Bertrand Minguet (Total)
9. Tony Moran (Shell Shipping Technology)
10. Hans-Georg Payer, PhD (--)
11. Jakob Buus Petersen, PhD (AP Moller - Maersk)
12. Clifford Proctor (OCIMF)
13. Dragos Rauta (Intertanko)
14. Ken Reid (Shell Shipping Technology) and
15. Peter F. Weber (SeaRiver Maritime)

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2 External Expertise

External expertise was added by many experts. However, the views within this document reflect the consensus of the workshop participants. The comments of the external experts were considered, but not necessarily adopted. We thank our colleagues who shared their expertise with us, in alphabetical order:

1. Poul Andersen (Danish Technical University)
2. Chris Barras (Shell Shipping Technology)
3. John Buckingham (BMT DSL)
4. Malcolm Burke (Shell Shipping Technology)
5. Robert Dane (Solar Sailor)
6. Johan H. de Jong (MARIN)
7. Ould El Moctar (University of Duisburg-Essen)
8. Jürgen Friesch (HSVA)
9. Jürgen Isensee (Die Grünen)
10. Fabian Jürs (SkySails)
11. Jens Julius Kappel (--)
12. Ernst-Christoph Krackhardt (Siemens)
13. Hans Otto Kristensen (Danish Technical University)
14. Jean-Marc Laurens (ENSIETA)
15. Friedrich Mewis (Mewis Ship Hydrodynamics)
16. Anthony F. Molland (Southampton University)
17. Ingo-Roger von Pereira (Von Pereira Maritime Services)
18. Alan Plumb (Shell - STASCO)
19. Eckhard Praefke (ISA Propulsion)
20. Torben Rasmussen (Hempel)
21. Peter Schenzle (--)
22. Campbell Scott (Shell Shipping Technology)
23. Heinrich Söding (TU Hamburg-Harburg)
24. Gerd-Michael Würsig (Germanischer Lloyd)
25. Hironori Yasukawa (University of Hiroshima)

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