Chapter 2
Green Ship Technologies

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Abstract This chapter provides information on green ship technology measures. Included are background information, descriptions of the technologies, explanation of key issues, general pros and cons of each measure, and limits of applicability or effectiveness, as well as practical issues related to implementation. The technical measures described here include the design of energy-efficient ships using hull form optimization, efficient propellers, energy-saving devices, and other novel technologies; attention is paid also to air lubrication, wind-assisted propulsion, and solar power. A subsequent section on machinery systems covers key areas for machinery technology efficiency improvements including the main and auxiliary engines, waste heat recovery systems, auxiliary machinery, and hybrid power storage/production equipment. The last section on ballast water management addresses regulations and provides an overview of ballast water treatment systems and related issues.

Abbreviations

ABS	American Bureau of Shipping
AC	Alternating current
B	Ship beam
BMEP	Brake mean effective pressure
BWM	Ballast water management
BWMS	Ballast water management system
C_B	Block coefficient
CFD	Computational fluid dynamics

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CO_2	Carbon dioxide
Cp	Prismatic coefficient
CPP	Controllable pitch propeller
DC	Direct current
ECA	Emission control area
EGR	Exhaust gas recirculation
ESD	Energy-saving device
FOC	Fuel oil consumption per 24 h
FPP	Fixed pitch propeller
IMO	International Maritime Organization
L	Ship length
LCB	Longitudinal center of buoyancy
MCR	Maximum continuous rating
NOx	Nitrogen oxides
PM	Particulate matter
PTI/PTO	Power take in/power take out
PV	Photo voltaic
RANS	Reynolds-averaged Navier-Stokes
SCR	Selected catalytic reduction
SFOC	Specific fuel oil consumption
T	Ship draft
UV	Ultraviolet
VFD	Variable frequency drive
WHR	Waste heat recovery

1 Introduction

This chapter has been compiled to provide information on the current state of the art of green ship technology measures. Included are background information, descriptions of the technologies, explanation of key issues, general pros/cons of each measure, and limits of applicability or effectiveness, as well as practical issues related to implementation. Treatment does not include information and communication technologies, which are covered in Chap. 4 of this book.

The rest of this chapter comprises the following sections: Sect. 2 (“Design of Energy-Efficient Ships”) addresses issues related to the basic hull form design including selecting proper proportions and reducing resistance by optimizing the hull form and appendage design. Topics covered include hull optimization, efficient propellers, energy-saving devices, and other novel technologies, including air lubrication, wind-assisted propulsion, and solar power. Section 3 (“Machinery Systems”) covers the key areas for machinery technology efficiency improvements that can be applied to support sustainable shipping. The section is divided into four main subsections covering main and auxiliary engines, waste heat recovery systems, auxiliary machinery, and hybrid power storage/production equipment. Finally, Sect. 4 ("Ballast Water Management") addresses regulations and provides an overview of ballast water treatment systems and related issues. Ballast water is essential to the safe and efficient operation of shipping, but it also poses a serious ecological, economic, and health threat through the transfer of invasive aquatic species inadvertently carried in the ships. Living organisms can be eliminated from ballast water using a variety of technologies, which are summarized in this section. In addition, the section addresses some key issues associated with the installation and operation of these treatment systems.

2 Design of Energy-Efficient Ships

2.1 Hull Optimization: General Consideration

Hull form and propulsion optimization provide an effective means to improve the energy efficiency of ships. When assessing hull form optimization, the owner has several options available for consideration:

(a) Accept a standard, readily available hull form and propulsion system offered by the shipyard.
(b) Modify an existing and preferably well-optimized hull form to address the expected operating profile.
(c) Develop a new hull form design based on expected operational profile.

Option (a) involves the least capital expense – substantive savings in vessel construction costs are often realized by adopting the standard design offered by a shipyard. Due to the need to improve fuel efficiency, many of these standard ships have well-optimized hull forms and propulsors, albeit usually only optimized at the design condition and to a lesser extent at the normal ballast condition or other service conditions. Hydrodynamic performance varies significantly with changes in draft and ship speed; however these operating conditions may not be fully considered.

Option (b) enables optimization of the design for specific service conditions (e.g., a number of expected operating draft, trim, and speed combinations with their associated service durations). This optimization process generally involves modifications to the forebody design (the bulb and transition into the forward shoulder) but may also involve modifications to the propeller.

Option (c) enables optimization of vessel hull particulars to be in concert with the propeller and power plant for the relevant service conditions as mentioned under (b). This option is usually justified when a larger series of ships is being ordered, or when the shipyard under consideration does not offer a suitable standard design.

This section provides an overview of the key process elements that lead to an optimized hull design. Further details can be found in the American Bureau of Shipping (2013). Fathom Shipping (2013) provides another useful overview on ship efficiency features.

2.2 Main Considerations Prior to Detailed Optimization of Vessels

Before starting the optimization of a vessel design or retrofit, it is important to look at the vessel and its main parameters. It is recommended to evaluate the current trends of vessels in the same class. After the design evaluation against peers, it is important to take into consideration the operational profile, area of operation (trade route), principal dimensions, constraints, and hard points before embarking on the detailed optimization of the vessel. These elements are described below.

2.2.1 Vessel Operational Profile

Until recently all optimization for any vessel was done for a single design point, at service speed and design draught. After the rise in fuel prices, many owners found that the single design point rarely, if ever, occurred during service. Thus, vessels were overpowered and not operated at the design point for which hull and propeller had been designed.

Therefore, when embarking on a new vessel design project, it is important to take the anticipated operational profile into consideration. As a starting point, data from existing vessels (noon reports, AIS data or similar) can be used, or alternatively an operational profile can be determined based on the anticipated route network, vessel carrying capacity, etc. The operational profile is a matrix of speeds and draughts (and trim) where the vessel will operate with a percentage of time attached to each point.

The impact of optimizing the vessel over the operational profile is largest on ships with pronounced bulbous bows designed for higher speeds, but also tankers and bulk carriers can gain several percent points of efficiency over the operational profile when properly optimized.

2.2.2 Area of Operation

The vessel design/retrofit design can depend on the planned area of operation for the vessel, as design will affect the vessels motions and added resistance in waves. Whereas ship motions are related primarily to safety of ship and cargo and crew comfort, added resistance in waves can have a significant impact on the fuel consumption of the vessel.

The impact is more significant on routes with higher waves like the north Atlantic and less on routes in more calm weather conditions such as Indian Ocean or Mediterranean Sea.

Recent trends with slower speeds have resulted in vessel designs with vertical stems and no pronounced bulbous bows – these designs have shown merit in waves and in varying loading conditions for ships like container vessels and smaller tankers.

2.2.3 Principal Dimensions Study

Once the operational profile has been defined, the next step is to consider the principal dimensions. The main dimensions of the vessel are typically limited by numerous constraints. For a modern tanker or bulk carrier, typical constraints are:

- Beam may be restricted due to the port limitations.
- Draught may be restricted due to water depth at the berths or channels/seaways leading into the ports.
- Length may be restricted due to port constraints and/or lock constraints.

Typically, tankers and bulk carriers are built to fixed dimensions, but there is a relatively large savings potential in the selection of the main dimensions. For this reason, the option of altering the main dimensions should be considered in close dialogue with the ship yard/designer of the vessel at a very early design stage.

For container vessels and Ro-Ro or RoPax vessels, there are constraints such as:

- Beam variation is restricted due to number of rows of containers (both in hold and on deck) or lanes on trailer vessels.
- Draught may be restricted due to water depth at the berths or channels/seaways leading into the ports.
- Length variation is restricted due to number of bays of containers or number on trailers in trailer decks.

At this stage, semiempirical models/databases (possibly supported by computational fluid dynamics (CFD)) can be used to predict the preliminary powering requirements of the design variants.

Once the main dimensions have been decided, the final powering prediction for the vessel can be calculated, and an initial selection of the propeller diameter and other characteristics can be made for use in the subsequent process. The final propeller design and diameter will be revisited once the lines have been optimized. The matching of the propeller and engine is very important to ensure that the necessary power is available with the lowest fuel consumption.

The potential for savings in a main dimensions study depends highly on the starting point, conditions, and constraints. But variation of main dimensions can easily decrease or increase the fuel consumption by 2–5% between the variants investigated.

Increasing the length/beam ratio and/or increasing length and reducing the block coefficient can provide reductions in propulsion fuel consumption up to 3–5%. Increasing the length while reducing the beam and maintaining the draft, displacement and block coefficient (C_B) constant normally yields improvements in hull efficiency, provided additional ballast is not needed to maintain adequate stability. A higher length/beam ratio tends to reduce wave-making resistance, while the reduced beam/draft ratio tends to reduce wetted surface and therefore the frictional resistance.

Increasing draft by reducing C_B and/or beam results in improvements to hull efficiency and may provide the additional advantage of allowing for a larger propeller to be fitted. Increasing length while reducing C_B reduces the required power. Reducing beam while increasing C_B also tends to reduce required power.

The longitudinal prismatic coefficient (Cp) is a commonly applied indicator of the longitudinal distribution of displacement. A lower Cp, favored for faster ships, implies a greater concentration of displacement amidships and a finer entrance angle. Tankers and bulk carriers with fuller (bluff) bow shapes will have a higher Cp.

Of course, main particulars and hull form coefficients cannot be selected based on hydrodynamic principles alone. The accommodation of the cargo block and main propulsion units, minimization of ballast, and restrictions from port and canal infrastructure are some of the factors that must be accounted for. Such design constraints are assessed against economic factors, including fuel consumption and construction cost. Other factors must be taken into consideration such as berth availability for the longer ships and structural reliability as the length/depth ratio increases. Nevertheless, driven by rising fuel costs, the longer-term trend will be toward increasing the length/beam ratio and reducing the block coefficient or reducing the design speed.

It is important that studies to determine optimal dimensions consider the effects of speed loss in waves. For early-stage analysis, a semiempirical approach such as Townsin and Kwon (1993) is adequate for estimating speed loss. As the design progresses, model tests in waves and numerical analysis provide a more accurate behavior of the specific hull form in waves.

2.2.4 Hard Points and Constraints Evaluation

Once the main dimensions have been determined, the detailed optimization of the hull form can begin. It is important to have a close and open dialogue between the ship yard/designers and the ship owner. Especially the discussion of the constraints/hard points on the vessel is critical, and it is important that the effect of these points is discussed on the basis of the preliminary general arrangement and preliminary lines plan. Constraints and hard points on tankers and bulk carriers are typically:

- Displacement and cargo intake
- Cargo holds/tanks layout

- Engine position in the hull in relation to the hull surface
- Rudder head box design
- Sea chest position and extension on the hull

For a container ship, it is also important to evaluate the container bay positions in relation to the hull surface. For Ro-Ro/Ro-Ro passenger vessels, equipment such as internal ramps and external doors and rams are often hard points that need to be included in the design process.

The following section describes the methods available to today's naval architect for optimizing hull form and propeller and outlines some of the issues that vessel owners should consider in the assessment of the hull form aiming to enhance vessel fuel efficiency.

2.3 Hull Form Optimization

Computational fluid dynamics (CFD) methods have reached the stage in which they can predict resistance and propulsion characteristics in calm water conditions with sufficiently high accuracy. With the advent of powerful computers, it is not necessary anymore to assume inviscid fluid conditions for hull flow calculations, and instead one can model viscous fluid effects using the Reynolds-averaged Navier-Stokes (RANS) equations. With CFD-RANS tools, it is possible to consider free surface effects in combination with fluid viscosity, including flow interaction with rudder and propeller. CFD-RANS is useful in assessing the influence of changes to the entrance angle, optimizing the location and shape of the fore and aft shoulders, as well as shape of fore and ship. CFD calculations are to be employed sequentially, allowing for refinement of shape and elimination of less favorable variations (see, e.g., Larsson et al. 2010).

There is substantive potential for fuel savings by optimizing for the off-design conditions where the expected operating profile differs from a single design draft and design speed. Changes in draft, trim, and speed can dramatically change the wave profile and overall resistance. Therefore, the owner and designer should prepare a clear specification of the different operating drafts and speeds on different legs of the expected voyages. Numerical analysis and model tests should then cover all operating conditions at which the vessel may spend a significant portion of its time at sea.

While designers are comfortable using CFD for quantitative assessment of required power, model tests are recommended for confirmation of the numerical results and for final power prediction. When developing lines, numerous trade-offs are considered. Although considerable progress has been made in numerical hull form shape optimization tools, the creation of lines remains part art and part science, and there is still no substitute for the experienced designer. There is considerable advantage in beginning with a good parent hull of similar proportions and in having an extensive database for benchmarking purposes. Therefore, many of the

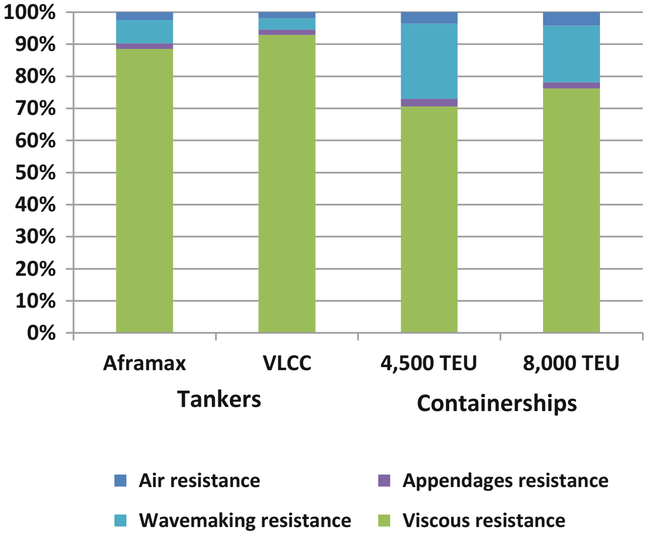

Fig. 2.1 Components of hull resistance in calm water conditions. (Source: ABS 2013)

best performing hull forms have been developed by the major model basins or yards with their own proven testing facilities, well validated through full-scale trial comparisons.

2.3.1 Approach to Improving Key Elements of Resistance

As shown in Fig. 2.1, viscous (frictional) resistance is the major component of overall resistance, accounting for between 70% and 93% of total resistance. The percentage of total resistance attributed to viscous (frictional) resistance is greatest for slower, larger ships. Wave-making resistance increases with ship speed and is a larger component of overall resistance for high-speed fine, form ships than it is for slower, full form ships.

When developing a full body hull form such as a tanker, emphasis is placed on reducing wetted surface as viscous resistance is a major component of overall resistance. Another important consideration is to provide a smooth and gradual transition to the propeller, to avoid separation of flow at the stern, and to provide for a uniform wake field (i.e., constant axial velocities at each radius). This encourages the LCB to be as far forward as practical, although care must be taken to avoid a harsh shoulder forward. Mitigating wave propagation at the forward shoulder is more important than reducing wave making by fining up the entrance angle, encouraging a blunter bow shape to accommodate smoother transitions through the forebody. The blunter bow shape allows a shift in volume from the midship region into the forebody region, resulting in better overall resistance performance for full body ships.

For higher speed and therefore finer hull forms typical for larger containerships, wave making is more significant (18% of total resistance for a standard 8000 TEU containership shown above). Such a vessel will have more slender proportions as compared with a tanker, with a higher L/B ratio. In this case, the more slender and finer hull allows the LCB to be moved aft while still maintaining good flow into the propeller. This enables a reduced entrance angle and softer forward shoulders. The bulb on a containership will be elongated with finer shape to reduce wave-making resistance.

2.3.2 Forebody Optimization

Forebody optimization includes consideration of the bulb design, waterline entrance, forward shoulder, and transition to the turn of the bilge. A properly designed bulbous bow reduces wave-making resistance by producing its own wave system that is out of phase with the bow wave from the hull, creating a canceling effect and overall reduction in wave-making resistance. Physical factors considered in bulb optimization include volume, vertical extension of the center of volume, longitudinal extension, and shape. Further details on bulbous bow and forebody design can be found in Larsen et al. (2010).

The characteristics of the bulbous bow must be carefully balanced with the shape of the entrance and the transition toward the forward shoulder and bilge. Bulbs are most effective at certain Froude number (speed-length ratio) and draft. Changes in speed and draft significantly change the wave created, such that reductions in draft or speed can lead to increases in wave-making resistance. As few commercial vessels operate solely at one design draft, compromises in the bulb design are needed to provide good performance over the expected range of operating drafts and speeds. For a container vessel fuel savings of over 5% were reported by modifying the bulbous bow of a shipyard design that was optimized to the design draft, so that it provided more favorable performance over the anticipated operating profile of drafts and ship speeds (De Kat et al. 2009).

2.3.3 Aftbody Optimization

Aftbody optimization includes efforts to mitigate stern waves, improve flow into the propeller, and avoid eddy effects. A properly designed stern can reduce the aft shoulder crest wave as well as the deep wave trough and stern waves. Improving the nature of the stern flow can lead to improved propulsive efficiency. Viscous flow calculations are needed to evaluate aftbody flow through the propeller and wetted transom flows in way of a submerged transom because these are dominated by viscous effects.

Single screw sterns forward of the propeller may be V-shaped, U-shaped, or bulb types. The tendency is toward the bulb shape, as the improved wake reduces cavitation and vibration. Asymmetrical sterns can be designed to improve propulsive efficiency through pre-rotation of the flow to the propeller and to some extent by reducing the thrust deduction. The pre-rotation of the flow into the propeller helps reduce the separation of flow in the stern aft of the propeller. To date, these enhancements have not been proven to be sufficiently effective to offset the extra complexity involved in construction, apart from some twin-skeg designs.

Twin-screw propulsion arrangements offer enhanced maneuverability and redundancy and are also adopted when the power required for a single propeller is excessive. Propulsion power may exceed what can be handled reasonably by a single propeller if, for example, the vessel design is draft limited, and the propeller diameter is correspondingly reduced. For a twin-screw design, there is the choice of open shafts with struts or twin skegs (or gondolas).

For twin-screw propulsion with open shafts, efficiency is generally compromised when compared to a single screw design, in part due to the high appendage resistance from struts and bearings. The introduction of the twin gondola-type skeg design eliminates the need for these appendages and can provide favorable hydrodynamic performance, especially for full-bodied ships and those with wide beams and/or shallow drafts. For slender, higher-powered ships, the open shaft twin-screw design may be more favorable when two propellers are required because the open stern shape provides lower wake variation, resulting in less cavitation and vibration.

For full hull form ships, it has been found that twin skegs may provide a 2–3% efficiency improvement over well-optimized single screw designs with corresponding characteristics (SSPA 2009). If the propeller diameter on a single screw design is suboptimal due to draft restrictions, unloading of the propellers in twin-skeg arrangements can lead to significant propulsion efficiency improvements. While there may be improvements in the overall efficiency of the vessel, in relation to fuel consumption, the fitting of twin skegs does have disadvantages that should be evaluated, including:

- The wetted surface is typically about 4–5% higher for a twin skeg vs. a single screw design. The lower the C_B, the more pronounced the effect on wetted surface.
- The hull steel weight is increased (by roughly 4–5% for tankers).
- Twin skeg arrangements are more expensive to build.

As there are numerous design and installation arrangements for twin skegs, each unique to the specific vessel design, it is essential that an optimization effort consisting of CFD and model testing be employed to achieve the desired results.

2.3.4 Appendage Resistance

For cargo vessels in calm water conditions, appendage resistance is about 2–3%. Roughly half of the appendage resistance is attributable to the rudder and half to bilge keels. Rudder resistance can increase substantially in severe wind/weather conditions or for directionally unstable ships as noted below.

Added resistance from a bow thruster tunnel can be significant (in the range of 1–2% of calm water resistance). Grid bars are frequently placed over the opening perpendicular to the flow direction. They serve to break up laminar flow and reduce vortices. Anti-suction tunnels can be used to reduce the pressure variation across the bow thruster tunnel.

2.3.5 Maneuvering and Course-Keeping Considerations

A high block coefficient, forward LCB, lower length to beam ratio, and open stern are factors that can lead to reduced directional stability. Accordingly, performance should be assessed through CFD or by model tests, either through captive tests in a towing tank or by free running models testing in an open basin. Where the vessel's mission requirements necessitate the use of a hull form with reduced directional stability, effective course keeping can be provided by larger rudders, high-performance rudders, or skegs, which will induce a penalty in overall efficiency when compared to vessels not provided with such rudders or skegs. In such cases, viscous flow CFD assessment and model tests are recommended as the drag and added resistance resulting from the larger, high-performance rudders and skegs can vary substantially.

2.4 Propulsion Arrangement and Propeller Selection

Once the resistance and propulsion characteristics of the hull have been optimized, the propeller designers can start their work and optimize the final propeller(s) for the vessel. This should be done in close dialogue with the engine manufacturer to ensure the best possible match. It is well known that a larger diameter propeller in general gives better efficiency, but when the propeller diameter is limited by other factors, advanced propeller design can still help to increase the propulsive efficiency.

Important aspects to consider during the design process of the propeller include:

- Engine layout
- Sea margin
- Light running margin

A range of independent propeller vendors are offering a variety of modern propeller designs for commercial vessels, which have the potential of increasing the propulsive efficiency.

Often the designs from different vendors are tested in a model basin for the same range of speed and draughts used in the tests with stock propellers. To ensure best possible relative comparison, all propellers should be tested during the same test session, including a retest of stock propeller. It is important to note that the operational profile might also affect the selection of final propeller design, as some of the design variants will be less efficient under certain operational conditions.

Differences between new propeller designs can be as high as 2–5% on a modern tanker or bulk carrier, so there is potential for significant savings with minimum extra new building costs. The value of savings naturally depends on the constraints put on the design space for the propeller (operating RPM, maximum propeller diameter, minimum pressure pulses, etc.).

2.4.1 Single Screw Vessels

For single screw vessels such as tankers, bulk carriers, container vessels, and some Ro-Ro vessels, a fixed pitch propeller (FPP) tends to be most appropriate. Commonly used FPP vendors include:

- Stone Marine Group Ltd., UK
- MAN Kappel Propellers, Denmark
- Wärtsilä Propellers, The Netherlands
- MMG, Germany

Figure 2.2 shows an example.

2.4.2 Twin-Screw Open Shaft

For Ro-Ro vessels, Ro-Ro passenger vessels, and cruise vessels, the most common solution is controllable pitch propellers (CPP) fitted on open shafts supported by bossings and brackets. This solution is also used on smaller container vessels and smaller tanker vessels. Commonly used vendors include:

- Rolls Royce (KaMeWa), Sweden
- MAN Propellers, Denmark
- Wärtsilä Propellers, The Netherlands
- Nakashima Propellers, Japan

The CP propellers allow the ship crew to optimize the pitch setting through the combinatory to match pitch to the present speed and loading of the vessel, resulting in minimum fuel consumption.

Fig. 2.2 Three-bladed Kappel propeller. (Courtesy MAN)

Fig. 2.3 Rolls Royce CPP. (Courtesy Rolls Royce – Commercial Marine)

The open shaft systems require attention to the design and optimization of the appendages, as the bracket systems can contribute largely to the resistance of the vessel. Figure 2.3 shows an example of CPP.

2.4.3 Azimuthing Propulsion and Pod Propulsion

For offshore vessels the twin open shaft propulsion system is often replaced with twin azimuthing thruster units to ensure high maneuverability and DP capability. This arrangement can also give less resistance and better propulsion efficiency. Commonly used vendors include:

- Rolls Royce (KaMeWa), Sweden
- Wärtsilä Propellers, The Netherlands
- Nakashima Propellers, Japan

On offshore vessels many of the azimuthing thruster units are fitted with ducts to ensure high bollard pull for towing operation and DP application.

For larger passenger vessels and cruise vessels with diesel electric configuration, POD units are often seen as an alternative to open shaft arrangements. The POD units are typically configured with electrical motor in the gondola, but some smaller units are equipped with mechanical connections of the propeller shafts. Commonly used vendors include:

- ABB, Finland (Azipods)
- Rolls Royce (KaMeWa), Sweden

2.5 Energy-Saving Devices

2.5.1 Overview

During the years, many different devices have been studied to either correct the energy performance of suboptimal ship designs or to improve an already optimized design by exploiting physical phenomena usually regarded as secondary in the normal design process. The final objective is to reduce fuel consumption related to propulsion. It should be noted the devices described here are not necessarily compatible, and their combined effects could be less than the sum of the savings of the individual components.

This section explores a range of energy-saving devices (ESDs), most of which historically concentrate on the improvement of propeller propulsion effectiveness. However, the industry has also seen the recent development of a series of devices aimed at either reducing the hull frictional resistance or exploiting readily available natural resources, such as solar and wind energy. Energy-saving technologies such as air lubrication are examined in Sect. 2.6.

The following propulsion efficiency related ESDs are described in this section:

(a) Wake Equalizing and Flow Separation Alleviating Devices

  (i) Wake Equalizing Ducts
  (ii) Vortex Generators of fins

(b) Pre-swirl Devices
    (i) Pre-swirl Fins and Stators
    (ii) Pre-swirl Stators with Wake Equalizing Ducts

(c) Post-swirl Devices
    (i) Asymmetric Rudders
    (ii) Rudder Bulbs
    (iii) Propeller Boss Cap Fin types
    (iv) Rudder Thrust Fins
    (v) Post-swirl Stators

It is important to note that the operational profile might also affect the selection of ESDs, as some of them may be less efficient under certain operational conditions.

2.5.2 Evaluation and Analysis of Energy-Saving Devices (ESDs)

Once the design (hull, propeller and engine) of the base vessel has been finalized, an analysis of feasible ESDs for a modern vessel can be initiated. But before starting to delve into the details of which ESDs are feasible for full form vessels, it is instructive to review the different types of propulsion losses that ESDs are supposed to help reduce and/or recover.

In the quest to maximize fuel efficiency, it is important to understand the origins of the energy consumption of the vessel in question.

In the process of converting the shaft rotation to a longitudinal force that can propel the vessel forward, energy can be saved by:

(a) Reducing the required propulsion power (i.e., *optimize hull* for resistance)
(b) Reducing energy losses (*optimize wake field* and *optimize propeller*)
(c) Recovering energy losses

Item (a) has already been discussed in Sect. 2.3, so the following section is focused on how the flow into the propeller can be further improved and how some of the energy losses can be recovered.

The total propulsion efficiency of a propeller varies typically between 50% and 70%. The losses for an average propeller (with an efficiency of 60%) can be attributed to three primary physical phenomena:

Axial losses – A propeller generates thrust, due to the acceleration of the incoming water. Behind the vessel, the outcoming flow mixes with the surrounding flow. Due to this turbulence, energy will be lost. Typically, the axial loss amounts to approximately 20%.

Frictional losses – When the propeller rotates, water in contact with the propeller blade surface causes friction and thus losses. The total blade surface, speed of rotation, and surface roughness are the primary factors affecting frictional losses of a propeller. The frictional losses can primarily be reduced by reducing the number of blades and reducing the blade area ratio within the limitation of risk of cavitation. Typically, the frictional losses amount to approximately 13%.

Rotational losses – Rotation of the propeller blades causes not only the generation of a longitudinal acceleration of the water, which generates thrust, but also an unwanted rotational acceleration, which generates swirl. The energy that goes into swirl is a loss. Typically, the rotational loss amounts to approximately 7%. This is an important number to remember because this means that if we were able to remove all rotational losses, then we would save at most 7%. Some ESDs introduce a pre-swirl that also improves the propeller inflow (wake field), and by combining these effects, they can thus result in higher savings.

The rotational losses can be approached in two ways:

- In front of the propeller (Pre-swirl – MEWIS ducts or similar, Schneekluth ducts with Grothues spoilers, vortex generators, stator fins, and similar)
- Behind the propeller (Post-swirl – Rudder position, rudder bulb, Propeller Boss Cap Fin (PBCF), thrust fins, post stator, and similar).

2.5.3 Wake Equalizing Duct and/or Flow Guide Fins

For many full form ships, the wake field is not very even, and the flow into the propeller is retarded in the upper half of the propeller disk. In general, wake equalization and flow separation alleviating devices are features to improve the flow around the hull that were developed to obviate propeller problems and/or added ship resistance caused by suboptimal aft hull forms. As such, they are less effective when the ship geometry has been designed correctly, with an eye at optimizing the flow to the propeller and avoiding the generation of detrimental hydrodynamic effects such as bilge vortices.

An example solution is a wake equalizing duct (WED) or to install flow guiding fins (also referred to as vortex generators). The concept for both solutions is to condition the flow in front of the propeller. This is done by guiding water from regions with high flow velocity into regions of low velocity and thus making the wake field more even. Some examples of such systems include, with applicability to tankers, bulk carriers and containerships:

- Schneekluth Duct – savings potential 2–4%, and additional 1–2% in combination with Grothues spoilers
- Vortex generators from SHI (SAVER fins) – savings potential 1–2%

2.5.4 Pre-swirl Devices

To further improve the propeller inflow, a contrarotation in the flow can be introduced in front of the propeller – this has the effect of reducing the rotational losses behind the propeller. For full form, low-speed ships, there are several vendors, but the main supplier is Becker Marine System with their MEWIS duct, where a

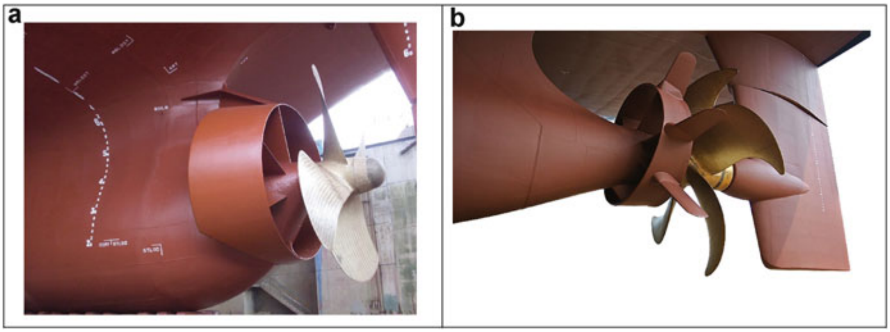

Fig. 2.4 Example of MEWIS duct and Becker Twisted Fin. (**a**) MEWIS Pre-Swirl duct on a tanker vessel. (**b**) Becker Twisted fin on a large container vessel. The vessel is also fitted with a twisted rudder and integrated rudder bulb. (Courtesy Becker Marine Systems)

wake equalizing duct and pre-swirl stators are combined in one ESD and pre-swirl stators system (PSS) developed by DSME.

Savings for MEWIS duct lie typically in the range of 3–6% for a tanker or bulk carrier application (Mewis and Guiard 2011), whereas savings with PSS typically are in the range from 2% to 4% for a typical tanker or bulk carrier application (Simonsen et al. 2011). Savings will vary depending on the actual vessel design and its characteristics (hull form, propeller loading, rudder design, etc.).

Pre-swirl systems have been developed for medium-/high-speed vessels with slender hull forms by Becker Marine Systems with the Becker Twisted Fin, where a pre-swirl stators and a structural ring/duct are combined, and by DSME with the pre-swirl stators system (PSS). Initially the Becker Twisted Fin systems included a full ring, but the newest designs include a partial ring. Savings for Becker Twisted Fin lie typically in the range of 2.5–3.5% for container vessel applications and similar numbers apply for pre-swirl stators systems. Savings may vary depending on the actual vessel design and its characteristics (hull form, propeller loading, rudder design, etc.). Figure 2.4 shows an example of two pre-swirl devices.

2.5.5 Rudder Position

In the optimization of the vessels propulsion, it is important to investigate the longitudinal position of the rudder as this has an impact on the recovery of the rotational losses. Several studies have been performed on this topic and presented at conferences worldwide. There are obviously some limitations to the position of the rudder in relation to the hull, which must be considered in an early stage of the design.

Potential savings may be in the order of 1–2% on tankers and bulk carriers from best to worst position (relatively small range of variation in position). More information can be found in Reichel (2009) and in Minchev et al. (2013).

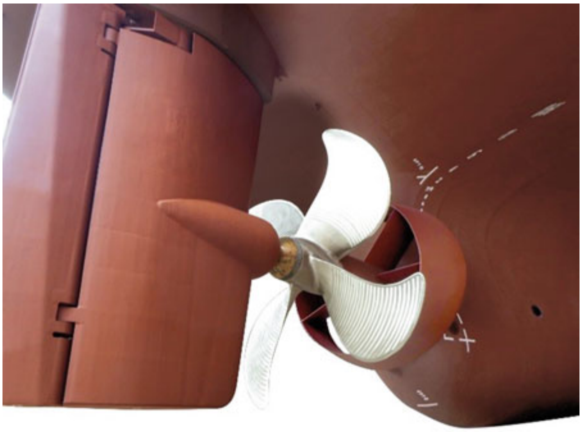

Fig. 2.5 Rudder bulb mounted on twisted flap rudder. (Courtesy Becker Marine Systems)

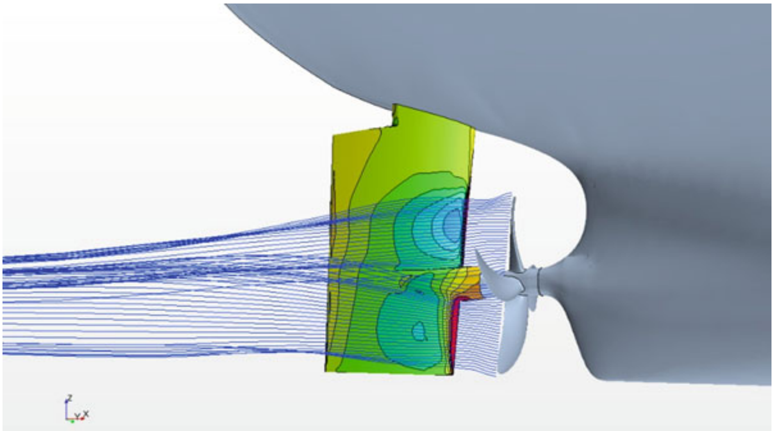

Fig. 2.6 CFD flow simulation of rudder bulb. (Source: ABS graphics)

2.5.6 Rudder Bulb

Once the rudder position is fixed, the implementation of a rudder bulb on the rudder can be addressed. The aim is to remove the hub vortex (high radial distribution in the flow near the propeller hub) and thus recover some of the rotational losses resulting in reduced fuel consumption.

Several designs exist from a range of vendors. The concept has been widely used and has been implemented on to all types of vessels including full form tankers and bulk carriers (see Fig. 2.5).

Potential savings are in the order of 1–2% for full form tankers and bulk carriers. The final rudder bulb can be optimized using advanced CFD analysis taking the actual flow behind the vessel and operational profile into account (see Fig. 2.6).

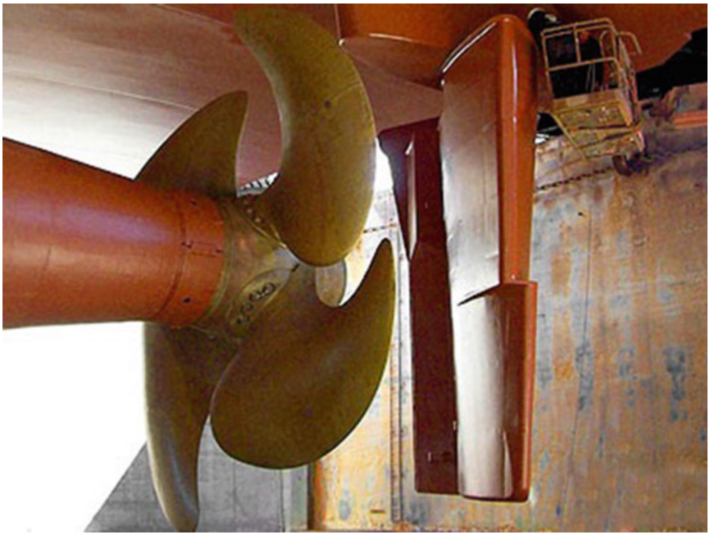

Fig. 2.7 Twisted flap rudder. (Courtesy Becker Marine Systems)

Savings may vary depending on the actual design, propeller loading, propeller hub diameter, distance between propeller hub, and rudder leading edge.

2.5.7 Twisted Rudder

A twisted rudder (twisted above and below the propeller center line) can also reduce the fuel consumption. The effect from the twisted rudder is not to regain loss but to reduce the drag on the rudder due to angled flow (due to propeller rotation) over the rudder (see Fig. 2.7).

Several designs exist from a range of vendors with some variation in designs. The concept has been widely used and implemented on all types of vessels; the biggest gains have been observed on faster vessels. Potential saving is a reduction of power in the order of 1–2%. A twisted rudder is also often seen in a combination with a rudder bulb where the gains can be compounded.

2.6 Novel Technologies

2.6.1 Air Lubrication

In ship resistance, the three main components are friction resistance, form resistance, and wave resistance. The dominant component is the skin friction resistance, which can make up 60% or more of the total resistance. In the past three decades, there has been continuous interest in air lubrication as a method to reduce the skin friction drag of the ship's hull.

Three categories of air lubrication methods can be distinguished:

- Bubble drag reduction
- Air layer drag reduction
- Air cavity drag reduction

In bubble drag reduction, small bubbles are generated by compressor or blower and injected into the turbulent boundary layer of the ship's hull. When very small bubbles are generated, this drag reduction method is referred to microbubble drag reduction. The size of such microbubbles is generally less than 0.1 mm and in the order of microns. Typically, bubbles are injected at the forward end of the flat part of the ship's bottom.

In the UK, Silverstream Technologies has developed a technology to reduce the frictional resistance of a vessel by injecting air into cavities on the bottom of the ship. Conceivably the interface between the air cavities and water creates microbubbles that follow the streamlines beyond the injection point. The system has been installed and tested on a 40 k DWT product tanker in cooperation with Shell (Silberschmidt et al. 2016). It has been reported that the net amount of power saving from the air lubrication system was measured to be about 4%, as mentioned in below press release statements:

http://www.shell.com/business-customers/trading-and-supply/trading/news-and-media-releases/silverstream-air-lubrication-technology.html
https://www.marineinsight.com/shipping-news/silverstream-air-lubrication-technology-proven-to-deliver-significant-long-term-energy-savings/

The system has been installed on some recently built cruise vessels, but no performance results have been reported yet.

In air lubrication, with sufficient air injected into a turbulent boundary layer, air layer drag reduction occurs when the injected air bubbles coalesce into a continuous or nearly continuous layer (film) of air separating the solid surface from the water flow and subsequently result in a skin friction drag reduction.

The following applications use the air layer drag reduction concept:

- Mitsubishi Air Lubrication System (MALS)
- Samsung Heavy Industries SAVER system

The Mitsubishi Air Lubrication System (MALS) is a patented air lubrication system using the drag reduction method developed by the Japanese shipbuilder Mitsubishi Heavy Industries Ltd. (MHI). Frictional drag reduction is achieved using an air injector device to deliver air through injection holes at the ship's bottom to generate air bubbles and form a layer to separate the surrounding water from the hull surface (Mizokami et al. 2011). The locations of the air injection outlets are designed to allow the air bubbles to cover the ship bottom as widely as possible. It is understood that the MALS can be applied to different types and sizes of seagoing vessels. Typically, for low-speed full form ships such as tankers and bulk carriers that have a large, flat bottom, one spanwise air injection outlet at the bottom forward near the bow might be adequate. For fine form ships such as ferries and containerships with the flat bottom being narrow near the bow and at stern, a triple outlet scheme (e.g., one centerline and two side injection outlets) at the forward of the flat bottom might be more appropriate. Calm water trials resulted in net power savings of around 10%, but the performance in waves during regular service conditions has not been publicized.

Samsung Heavy Industries (SHI) has been developing an air lubrication system, referred to as the SAVER system (Lee et al. 2017; Jang et al. 2014). Model tests and full-scale trials have been carried out on several vessels. In 2014, SHI designed an air lubrication system for a Heavy Cargo Carrier (HCC, $L = 165$ m, $B = 42$ m, $T = 5.25$ m), which was retrofitted, and conducted sea trials to measure fuel-saving effects. Subsequently in 2015, a joint development project to develop an air lubrication system for an LNG carrier retrofit was set up and conducted in cooperation with BG Group (now Shell), Gaslog, and ABS. The LNGC has a cargo capacity of 170,000 m^3 and a length of 290 m. Lee et al. (2017) describe the design and testing of the SHI system for the two full-scale ships, along with model test results. The power savings of the systems have been evaluated through sea trials and in-service voyages, and the full-scale results have been compared with model tests. Generally it was observed that the model test would overestimate the propulsion power savings when compared with the sea trial results. The full-scale performance data suggest that for the HCC, the system can lead to an average power saving of 8.8% on actual voyages; for the LNG carrier net savings of about 4–5% saving were observed on the basis of the full-scale measurements (Lee et al. 2017).

The air cavity concept is based on the usage of a recess (or several recesses) in the bottom of a ship, where air is supplied to it so that an artificially inflated air cavity is formed and separates a part of the bottom from the contact with the water, therefore reducing the frictional resistance. Here, the air layer in the cavitating flow is much thicker than the turbulent boundary layer on the ship hull. Air is continuously injected into the cavity to make up for air dissipation into the surrounding fluid.

For ocean-going ships either the bubble drag or air layer drag reduction technology seems to be most suited. To date net savings have been documented to be in the order of 5%, which typically applies at the higher operational speed range for the vessels fitted with the systems.

2.6.2 Renewable Energy

The utilization of renewable energy sources is currently benefiting from a vast international attention in all industrial fields, including shipping. In our industry, attempts in this direction are naturally concentrating on wind power, since this is readily available at sea and has a long history of successful exploitation. However, photovoltaic (PV) solar panels are also being considered in specific fields such as the generation of auxiliary power.

Wind Propulsion

Wind has been used to propel ships for millennia, but the vast practical benefits of modern propulsion systems have meant the progressive decline and disappearance of sails from all merchant vessels. In many ways, it is hard to imagine a return to sails and the complexity of operation imposed by this type of propulsion. However, the large fuel-saving benefits that wind power can provide should not be underestimated. Even if the need to compromise between optimization of shipping operations and minimization of fuel consumption will imply only a partial reduction of the latter, it is reasonable to expect this to be easier to achieve and to offer a greater potential with the use of wind power, than with the adoption of most other energy-saving measures.

In recent decades we have seen the application of Flettner rotors, sails, kites, and wing foils on different ship types. Flettner rotors are vertical cylinders spinning around their axis. A propulsive force is generated in the direction perpendicular to that of the wind hitting the rotor as a result of the Magnus effect. For this reason, rotor sails offer maximum efficiency near apparent beam wind conditions. The rotors need to be driven by an electrical motor to achieve the necessary RPM; this power needs to be added to the propulsive power. In the applications presented so far, the Flettner rotor shall be considered as a supplement to the normal propulsion system.

Applications are still limited, but there has been some success for the Flettner rotors, especially from the Finnish Company Norsepower.[1] An issue of the Flettner rotor is the negative drag when heading into the wind; there have been designers proposing a version that can be folded away or telescopically collapsed to minimize aerodynamic drag (and air height in port) when they are not in use.

Towing kites are currently the only wind power exploitation technology commercially available to ships. The principle behind it is relatively simple, although the technology necessary to deploy, control, and recover the kite is complex. In practice, extra power is provided to propel the ship by flying a kite tethered to her bow. The kite speed through the air increases its efficiency compared to standard sails, but the setup requires a computer to control the kite. Naaijen et al. (2006) estimate that significant fuel savings are possible using these systems for slower ships (typically bulk carriers and tankers); however the envelope of operability of kites is limited to a relatively narrow range of wind conditions (essentially quartering winds), which further limits the usefulness of these systems. To evaluate the actual cost-benefit of kites, it is necessary to estimate their potential when deployed on specific routes, where wind patterns can be predicted.

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[1] https://www.norsepower.com/ Accessed Oct. 2, 2018

A concern regarding towing kites is the complexity of its operation and the risk associated with the system behavior in rough weather. As the largest gains provided by towing kites are when strong tail winds are present, it is paramount that the system can be operated safely, reliably, and with no additional strain of the already limited crew resources available onboard.

Solar Power

There have been attempts to use photovoltaic (PV) panels to power small craft, such as the 30-m-long catamaran Planet Solar, designed to circumnavigate the world on a 500 m^2 array. However, because of the low electrical output per unit surface, PV solar panels are better suited as an additional source of auxiliary power. In this role they have already been utilized on commercial vessels such as the NYK car carrier Auriga Leader, equipped with 328 solar panels. The energy generated by the 40 kW solar arrays on this ship is used to power lighting and other applications in the crew's living quarters.

The drawback of PV solar power is the high capital cost and required surface area.

3 Machinery Technology

This section covers the key areas for machinery technology efficiency improvements that can be applied to support sustainable shipping. The section is divided into four main subsections covering main and auxiliary engines, waste heat recovery systems, auxiliary machinery, and hybrid power storage/production equipment.

While there is efficiency improvements that can be applied individually to each type of installed equipment or system, the biggest efficiency gains may be achieved where installed machinery is considered in a more holistic approach for the entire ship and ship operating profiles. With this approach it may be possible, for example, to make the best use of emerging advanced medium and high-speed engine designs coupled with electric drive, high-voltage or direct current (DC) power distribution systems, and energy storage devices such as battery packs or capacitors. While these techniques may be best suited to ship applications with high transient power demands and short mission profiles, the principles are equally applicable to all ship types.

To fully realize this efficiency potential will of course require bold challenges to established machinery and propulsion arrangements in what is traditionally a very conservative market. The use of modern simulation and modeling techniques can help support this process at the concept and detail design stages. The knowledge base can be further improved through the life of the ship by comprehensive data collection, analytics, and machinery optimization.

The decoupling of machinery and vessel speeds by the use of the electric propulsion systems mentioned above therefore suggests the advent of electric drive, energy storage, and hybrid propulsion systems may sound the demise of the direct-drive slow-speed diesel engine. However, the additional system losses associated with these propulsion systems may negate the advantages; at present we see no significant emerging trend away from direct-drive slow-speed propulsion systems for the bulk of the commercial deep sea fleet. Determining the most fuel-efficient ship design and operational practices remains a very ship-specific process.

The slow-speed two-stroke engine has long had the highest thermal efficiency of any prime mover and hence by selection alone provides a fuel-efficient solution. Although fuel prices are notoriously volatile, there has always been an operational incentive to operate engines as fuel efficiently as possible and hence reduce operational costs. Some quirks of the marine industry with regard to who actually pays for the fuel of course can obscure this objective in certain cases, but when combined with the IMO statutory design and operational energy efficiency regulations that are now in place, the general trend is clearly to continue to minimize fuel consumption in the years ahead. The marine efforts to reduce CO_2 emissions are consistent with the regulatory regimes in other transport sectors.

In support of these objectives, the long-term predominant marine fuel and prime mover choice will likely emerge in the 2025–2030 time frame through a combination of market success with technologies currently being trialed and other market and political forces. Liquefied natural gas (LNG) is one of those emerging for non-gas carriers since around 2000. In the meantime traditional marine fuels and diesel engines will dominate the shipping sector with a wide variety of other potential solutions, which may be very ship type, size and trading route specific, emerging in increasing quantities. Gas turbines are expected to continue to find niche marine propulsion and power generation applications, and fuel cells may play an increasing role in ship power generation in the next 15 years. However, the internal combustion engine will continue to be the dominant marine prime mover in years to come, and the main steps to be taken for sustainable shipping, from the efficiency and emissions viewpoint, will continue to be reducing fuel consumption and improving overall ship efficiency. In view of the 2018 IMO decision to work toward a 50% reduction in GHG emissions by 2050 from the shipping industry, the emphasis will shift to the additional benefits that can be gained from replacing traditional fossil fuels with bio or carbon neutral fuels, such as hydrogen and ammonia. Such fuels can be burned in internal combustion engines without drastic engine modifications. For a discussion on alternative fuels, see Chap. 13 of the book.

This section presents the most practical and widely available energy efficiency measures that may be applied to ship machinery and a brief look at emerging technologies.

3.1 Main and Auxiliary Internal Combustion Engines

3.1.1 Propulsion and Power Generation Arrangements

The traditional propulsion and power generation arrangement for large deep sea commercial shipping has generally been a single slow-speed two-stroke main propulsion engine direct coupled to a fixed pitch propeller with three medium-speed four-stroke auxiliary engines driving generator sets. A simple, reliable, and cost-effective solution with minimum system losses has been the de facto propulsion solution since the marine industry made the transition from coal to oil as the primary energy source.

The slow-speed two-stroke engine is typically defined as one with a rated speed of less than 400 rpm and which includes a long-stroke design with the piston rod connected to the connecting rod using a crosshead construction, as illustrated in Fig. 2.8. This crosshead construction supports very long-stroke designs and enables the cylinder lubrication to be separated from the bearing lubrication systems. This feature supports the use of specialized alkaline oil lubrication of the piston/liner interface and enables accurate control of corrosion caused by high sulfur fuels. More information on the two-stroke slow-speed cylinder lubrication systems is given further below. The suitability to burn high-sulfur residual fuel oils has long been one of the key features of the slow-speed engines and has enabled the supply of cheap refinery residue fuels to the marine market. The slow-speed design has evolved to ever larger piston strokes, and stroke/bore ratios in excess of 4.5 are now common. There has also been a trend for improved fuel consumption through

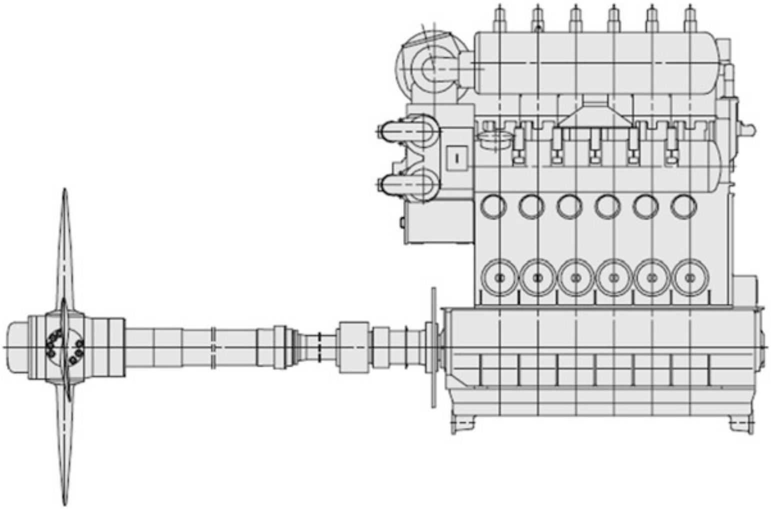


Fig. 2.8 Direct-coupled slow-speed two-stroke propulsion arrangement with CPP. (Courtesy MAN)

increased brake mean effective pressure (BMEP). Typical BMEPs have risen from 18 to 22 bar and typical firing pressures increased from 140 to 180 bar since 2005. This has supported the trend in reducing rated engine speed and the use of ever larger diameter propellers for increased propulsion efficiency.

The medium-speed four-stroke diesel engines are of a trunk piston design and are defined as engines with a rated speed between 400 and 1400 rpm. These are the predominant auxiliary engine design used for power generation on deep sea fleets and usually have higher specific fuel oil consumption (SFOC) characteristics than the slow-speed two-strokes. However, sophisticated modern medium-speed engine designs that incorporate, for example, two-stage turbocharging systems with intercooling and aftercooling, electronic fuel injection, common rail fuel supply, miller timing, etc. are now achieving SFOC values as low as the two-stroke slow-speed designs under certain conditions.

High-speed diesel engines are defined as engines with rated speeds over 1400 rpm and are also of a trunk piston design. These may be utilized as auxiliary or emergency generator sets on larger vessels and as propulsion and auxiliary engines on smaller vessels such as ferries or patrol craft where the high power to weight and power to volume metrics are a requisite. These engines have long been closer to large automotive and off-road engines and hence have included the advanced design features mentioned above for medium-speed engines for many years.

An example of a typical main and auxiliary engine arrangement is shown in Fig. 2.9. The advent of electric propulsion and hybrid systems means there are many potential variants now emerging.

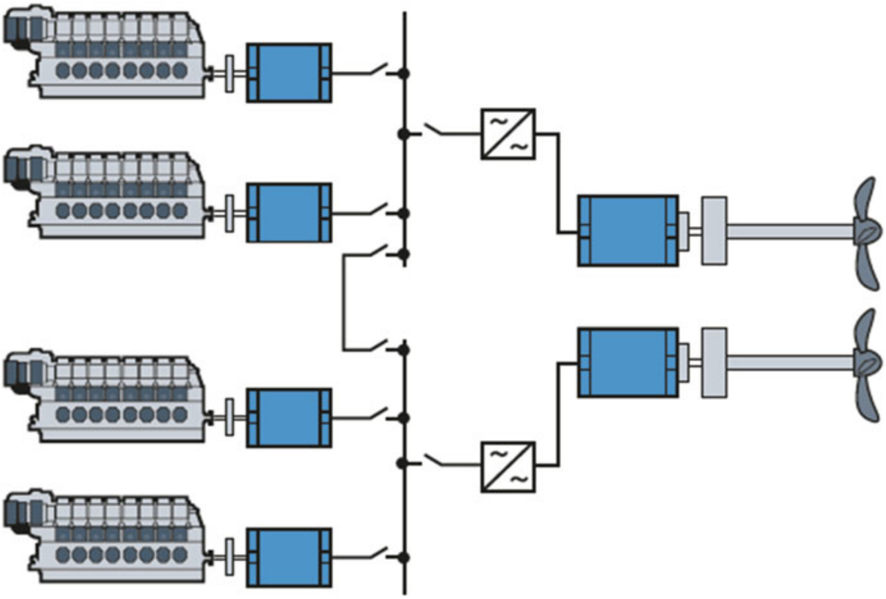


Fig. 2.9 Twin-screw medium-speed diesel electric drive and power generation. (Courtesy MAN)

3.1.2 Propulsion Engines

The slow-speed two-stroke engine is the most efficient prime mover available and can achieve fuel efficiency in excess of 52% from the base engine. This compares, for example, to an efficiency of approximately 42% from an advanced road car diesel engine. With minimal losses from the direct-coupled engine to propeller configuration, the two-stroke slow-speed propulsion arrangement, particularly with a fixed pitch propeller (FPP), provides the simplest and most fuel-efficient propulsion option.

Medium-speed two-stroke diesel engines have slightly higher SFOC, typically 3–4% higher than a two-stroke slow-speed design at similar power levels. Similarly, high-speed four-stroke engines may have SFOC levels 4–5% higher than the medium-speed designs. Since the propulsion shaft speed of medium- and high-speed engines needs to be reduced significantly to match an efficient propeller speed, these engines must be connected to the propeller through a speed reduction transmission system. This can be either through a mechanical reduction gear unit or an electric drive system. These transmission systems introduce additional losses, approximately 2–4% from gear units and 10% from an electric drive system. Hence there can be significant fuel penalties for medium- and high-speed installations compared to slow speed. Figure 2.10 shows a comparison on typical SFOC curves for slow-, medium-, and high-speed engines.

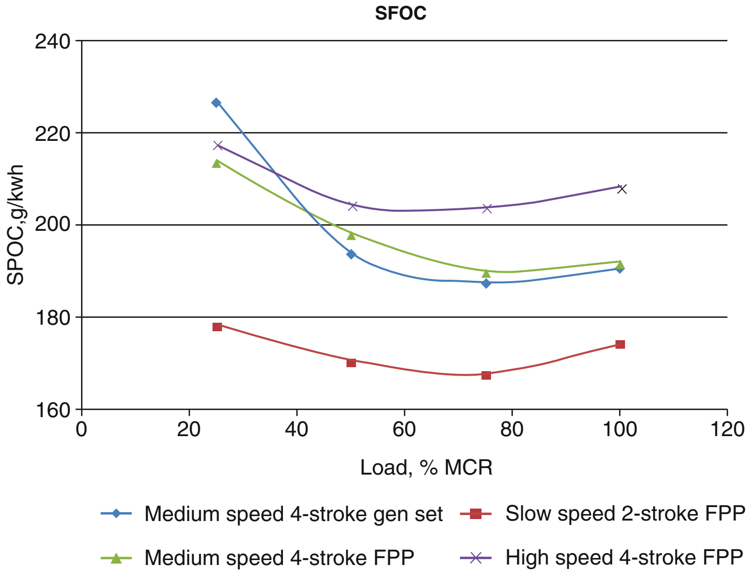


Fig. 2.10 Comparison of SFOC curves

The use of controllable pitch propellers (CPP) with constant speed engine operation and the potential for engine operation in the fuel efficiency “sweet spot” that electric drive provides are ways that some of these penalties can be reduced. The potential to apply even slower propeller speeds, or operate the propeller at its most efficient operating point by changing gear ratios, and through the delinked engine and propeller speed feature of electric drive arrangements are further ways these penalties can be reduced. This perhaps can best be demonstrated by the emerging use of high-torque, high-speed engines in variable speed and variable load electric drive arrangements, particularly in combination with hybrid features, to give potential overall ship fuel oil consumption (FOC) reductions of up to 20%.

3.1.3 Power Generation Engines

The main electrical power onboard ship is generated by the auxiliary diesel generators, which may also be supplemented by a shaft generator driven from the two-stroke slow-speed main propulsion engine. This shaft generator provides the opportunity to provide electrical power at the lower SFOC applicable to the two-stroke slow-speed engine. Ship electrical systems typically utilize alternating current (AC) architectures at a frequency of 50 or 60 Hz. This require the generators to be driven at a constant synchronous speed, which can be determined by dividing 7200 (for 60 Hz) or 6000 (for 50 Hz) by the number of generator poles (only an even number of poles are used). The larger the number of poles, the slower the generator speed, and generally the higher its cost. Medium-speed generator engines typically operate at 720, 750, 900, and 1000 rpm with high-speed engines running at 1500 or 1800 rpm, depending on the AC frequency selected and generator design.

Where engines are arranged in a diesel electric drive arrangement, the power generation engines provide power for both propulsion and ship electrical loads.

3.2 Engine Design Trends and Trade Offs

3.2.1 Design Trends

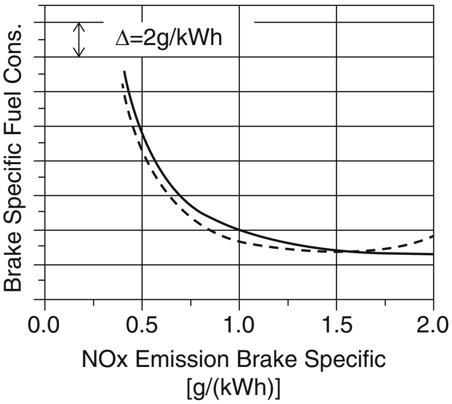
Overall engine efficiency, or brake thermal efficiency, is made up of a number of individual engine efficiencies, notably volumetric and mechanical. There are some potential significant efficiency gains from waste heat recovery systems (see below for more information) and some gains from improving mechanical efficiency by reducing friction, but the biggest improvements have generally been made by improving volumetric efficiency. The last 60 years has seen significant developments in internal combustion engine power density, BMEP, cylinder firing pressures, and efficiency. Much of this has been enabled by the increasing use and level of turbocharging technologies. A downside of the high BMEP, highly turbocharged, modern internal combustion engines is a reduction in transient response. This can be improved by the use of turbocharging and air management techniques such as exhaust waste gates/bypass, variable geometry turbochargers, and air bypass features, but as with all adjustable engine parameters, it is a compromise to achieve optimum performance. The increasing trend in required charge air boost pressures has until now largely been accommodated by single-stage turbocharging systems. Future engine designs will see an increase in the use of two-stage and sequential turbocharging systems to support high BMEP, low-emission designs incorporating features such as Miller timing.

3.2.2 Trade-Offs

An expansive discussion of engine design fundamentals and features is beyond the scope of this publication, but it is worth noting that for any particular engine design, there are a number of significant trade-offs to be reconciled between design features and settings to achieve low fuel consumption together with low exhaust emissions. Achieving lower CO_2 emissions by reducing fuel consumption often directly conflicts with achieving low emissions of other emissions species that may be regulated, for example, the nitrogen oxides (NOx) versus SFOC trade-off, the particulate matter (PM) versus SFOC trade-off, and the NOx versus PM trade-off. Figure 2.11 shows an example of these trade-off curves. Balancing these conflicting characteristics result in a compromise of settings to achieve the optimum within a particular engine.

Figure 2.11 shows a typical SFOC, or brake-specific fuel consumption (BSFC), versus NOx trade-off curve, in this instance a high-speed truck diesel engine. This curve is typical of all engines, and the lowest fuel consumptions have a tendency toward the highest NOx emissions. A step change in engine technology, such as common rail fuel injection, or the so-called second-generation common rail systems, with higher injection pressures will shift the curve toward the plot origin.

Fig. 2.11 Typical diesel engine BSFC vs NOx trade-off characteristic. (Source: IMechE)



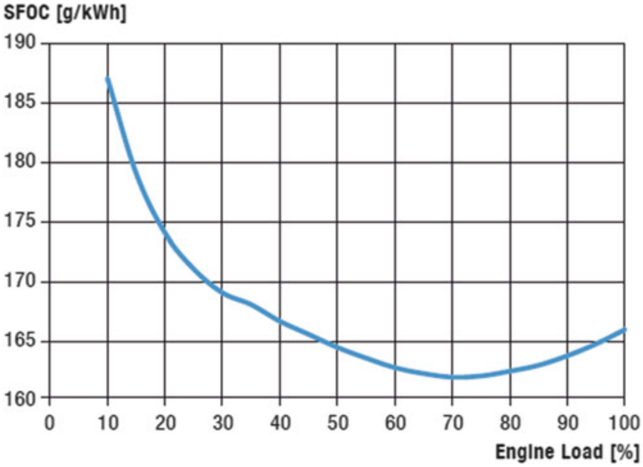


Fig. 2.12 Typical slow-speed SFOC vs engine load characteristic. (Courtesy MAN)

3.2.3 Fuel Consumption Characteristics

In addition to understanding the fuel consumption versus emissions trade-offs, to understand how to implement efficiency improvements effectively, it is also important to recognize the typical fuel consumption characteristics of internal combustion engines.

Figure 2.12 shows typical two-stroke slow-speed fuel consumption versus engine load curve, and optimum fuel consumption is in the 60–80% load range with significant increases in SFOC at lower engine loads. This plot is generated from the typical propeller curve based on the engine maximum continuous rating (MCR).

Seeing how the fuel consumption changes across the engine speed versus torque or BMEP map requires a much greater number of fuel consumption test points to be measured. These “ISO” SFOC maps are more readily available for medium- and high-speed engines and are therefore particularly useful for variable speed and variable load applications but are also important for direct-drive applications where the effects of heavy or light propellers, or propeller or hull fouling, can significantly shift the engine load away from the nominal propeller curve. This highlights the importance of accurate ship model and tank test results for the hull and propeller to enable accurate power demand estimation and therefore correct engine matching. The importance of understanding engine manufacturers’ recommended selection processes, in particular for direct-drive propulsion arrangements, and guidance on appropriate propeller and sea and power margins is critical to obtaining an efficient design that is also fit for purpose.

The use of high-voltage or DC power distribution systems, variable frequency drives (VFD), and inverters and the removal of the requirements for synchronous power generation speeds open the door for electric propulsion systems that incorporate a variety of fixed and renewable energy production and storage equipment.

However, the internal combustion engine is expected to remain at the heart of this mixed propulsion arrangement system for the time being and a key feature for targeting an overall fuel-efficient system.

3.2.4 Air Pollution Considerations

In 1997 IMO adopted a new protocol to amend the MARPOL Convention and adopt a new Annex VI "Regulations for the Prevention of Air Pollution from Ships." To balance all of the design variables and trade-offs for a particular slow-, medium-, or high-speed engine design to achieve improved performance and reduced fuel consumption, while meeting these air pollution limits, has emerged as one of the biggest challenges facing engine designers and the marine industry.

NOx formation is linked to peak combustion temperatures; therefore engine changes to optimize for fuel efficiency, for example, by increasing BMEP and maximum firing pressures (and hence combustion temperatures), can increase NOx. To shift the characteristic trade-off curves and reduce SFOC, at the same time reducing NOx, requires a step change in engine complexity or features, for example, mechanical to electronic fuel injection equipment (FIE), adoption of common rail system, or higher injection pressures.

The IMO NOx certification process incorporates steady-state testing undertaken at test-bed under reference conditions in accordance with the requirements detailed in the IMO NOx Technical Code, which was adopted by IMO at the same time as Annex VI and which is itself based on the ISO 8178 standard series for exhaust emission measurement of internal combustion engines. Each certified NOx emission value for a particular engine type is a cycle weighted value determined from the test-bed testing at discrete engine load points and the applicable weighting factor. These engine loads, or mode points, are weighted in accordance with the applicable duty cycle appropriate for that application.

The IMO NOx limits are based on engine rated speed, with the lowest limits applicable to medium- and high-speed engines, and these IMO Tier I, II, and III limits are shown in Fig. 2.13. The figure includes an example of typical NOx emissions from a Tier II slow-speed engine together with some example NOx emissions from low-pressure Otto combustion cycle dual fuel (DF) and gas engines running on gas and meeting the Tier III limit. The Tier I NOx limit was retrospectively applicable to engines fitted to ships with keels laid after 1 January 2000 once Annex VI entered into force on 19 May 2005. Once the Annex entered into force, steps were taken to progressively reduce the NOx limits, and the Tier II limit entered into force on 1 January 2011. The Tier III limit is only applicable in Emission Control Areas (ECA) and represents a NOx reduction of 80% from the Tier I limits. Currently the only NOx ECA in force is the North American ECA, which entered into force on 1 January 2016. The existing Baltic and North Sea SOx ECAs will also become NOx ECAs from 1 January 2021.

The IMO Tier III NOx emissions limits are now driving the use of new technologies and alternative fuels, such as DF engines and exhaust emission abatement

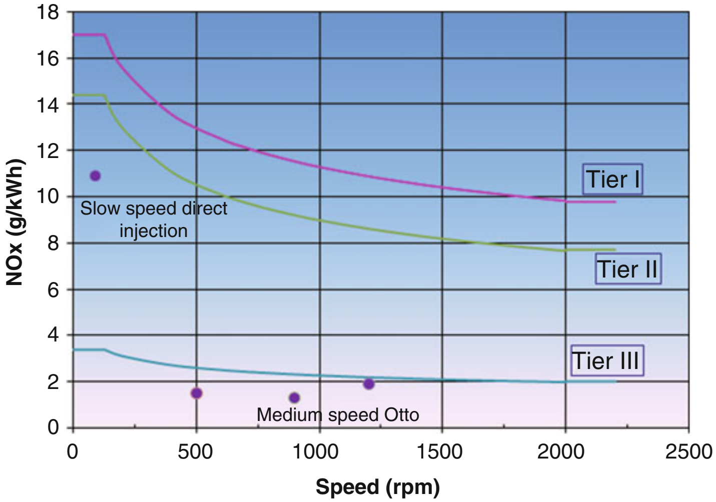


Fig. 2.13 IMO MARPOL annex VI regulation 13 engine speed-related NOx test limit

equipment. The most likely exhaust emission abatement systems to be used to meet the IMO Tier III limits are EGR and SCR. The challenge for the marine industry is the development of EGR and SCR systems suitable to the high sulfur and residual fuels currently prevalent in the marine sector.

3.3 Internal Combustion Engine Efficiency Improvements

From the ship efficiency perspective, improvements can be achieved via installation of new equipment and systems, via upgrades or modifications to existing machinery, by improved operating procedures, or a mixed combination of all three. Instrumentation and data collection equipment and analysis are essential additional requirements to verify the impact of any implemented efficiency reduction measures. This is a topic in its own right, but it is worth noting that the two most important parameters to validate any efficiency improvements, power output, and FOC are among the most difficult to measure accurately in a marine environment.

We can see from above that diesel engines generally have only one operating point in the speed versus power curve at the highest efficiency. To further understand how improvements to the main and auxiliary engine efficiency can support the ship system efficiency improvements, some of the background to engine characteristics, propulsion arrangements, and the techniques and equipment used to improve the fuel efficiency are further expanded below. Figure 2.14 shows the energy balance for a MAN 12S90ME-C9.2 two-stroke slow-speed engine design in standard configuration. As can be seen, extracting waste energy from the exhaust is the

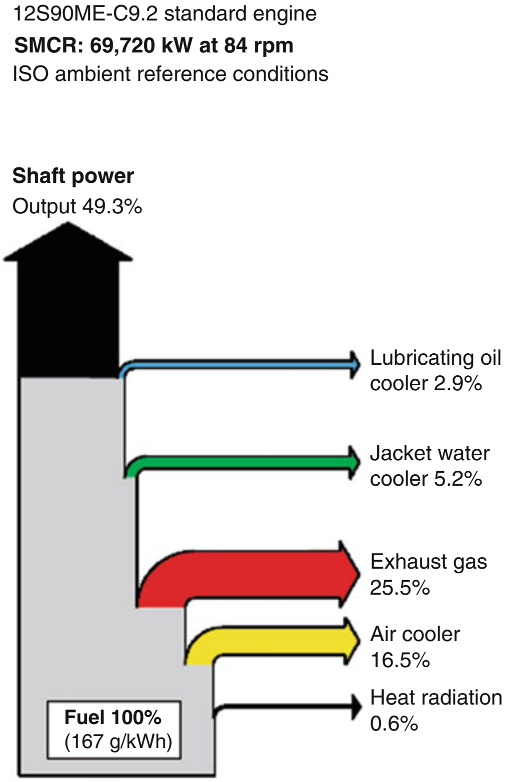


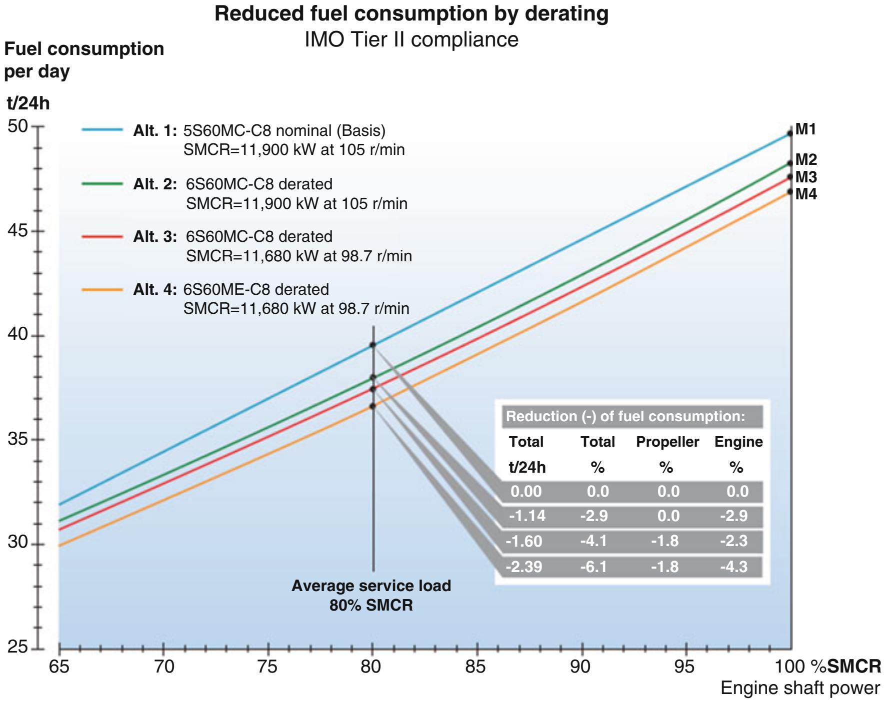
Fig. 2.14 Energy balance for MAN 12S90ME-C9.2. (Courtesy MAN)

obvious target for improving overall efficiency of the propulsion system, but there are also potential gains to be made from other areas, notably jacket and air cooler circuits.

3.3.1 Propulsion Engine Derating

One of the trends in recent years to reduce the main propulsion engine fuel consumption is by the selection of a derated engine. Engine selection is one of the critical factors to ensure acceptable vessel performance, but the overlap in possible engine types, bore sizes, and number of cylinders offered by manufacturers to deliver the required vessel design power provides the scope for a derated engine selection. Slow-speed two-stroke engine designs are typically offered with a wide range of potential engine ratings in the rating layout, with the normal MCR offered at the highest engine speed and power density.

Generally, selecting an engine type with a larger stroke/bore ratio, higher BMEP, and lower design speed provides improved fuel efficiency and gives improved propulsion system efficiency through the use of a larger-diameter, more efficient



Reduction (-) of fuel consumption:

Total t/24h	Total %	Propeller %	Engine %
0.00	0.0	0.0	0.0
-1.14	-2.9	0.0	-2.9
-1.60	-4.1	-1.8	-2.3
-2.39	-6.1	-1.8	-4.3

Fig. 2.15 Sample effects of derating and larger propeller on fuel consumption. (Courtesy MAN)

propeller. This is a trend supported by the latest slow-speed two-stroke ultra-long-stroke engine designs from both MDT (“G” series) and WGD (“X” type). Selecting a contract rating, sometimes referred to as NCR (nominal contract rating), CMCR (contract maximum continuous rating), or SMCR (service maximum continuous rating), that is in the lower range of the layout map provides the opportunity to run the engine at a lower engine speed and BMEP, hence a lower SFOC. An example of how this engine type and rating selection can be applied to MDT engine designs is shown in Fig. 2.15. In this example savings of 2.9–6.1% are possible with a combination of alternative engine selections and propeller optimization at lower speeds for the same power demand. The main advantages of each example are achieved by adding an extra cylinder, selecting a lower operating speed and selecting the electronically controlled version of the engine. Since operating and maintenance costs can be increased by the number of cylinders, as with all modifications, any savings by selection of a derated engine need to be weighed against the total cost of ownership through a life cycle analysis for the specific ship design and operating profile.

3.3.2 Slow Steaming

While “slow steaming” and “super slow steaming” are not design changes to improve efficiency and hence would fall under operation practices and route optimization (for which more in Chap. 10 of the book), it is worth briefly putting into context how these savings are achieved with respect to engine fuel consumption characteristics and engine modifications. The fundamental of this is the generic ship propulsion power demand of the nominal propeller curve, which can be represented typically by a cube law relationship to speed. As we have seen from previous subsections, all engine design systems, parameters, and settings are a compromise to balance the engine within the engine thermodynamic and mechanical limits while remaining compliant within statutory air emissions requirements. The engine is optimized toward the vessel design point.

For the direct-drive slow-speed main engine arrangements, reducing engine speed will obviously reduce vessel speed, but the potential fuel savings are very significant if the operator can commercially accept this and the engine is not put into a barred speed position. The cubic propeller law relationship means that only 12.5% power is needed to deliver 50% engine speed. This would put the engine into a part of the fuel consumption map that has approximately 10% worse SFOC. Although engine efficiency will vary a little across the speed range, total FOC is approximately proportional to power. Therefore, the total fuel consumption can be reduced by approximately 80% by slow steaming and reducing ship operation speed, for example, from 25 to 15 knots.

In times of high fuel prices and overcapacity, this is the low-hanging fruit and quick fix, but it may have other longer-term impacts on the engine. Since the engine is not running at the design point, there will be increased smoke and increased fouling, which would need to be managed with operational practices such as increasing engine speed for a short period of time and/or managing this with additional maintenance. In many respects the costs of these actions may be more than compensated from the savings in reduced overall maintenance costs from running the engine at much lower BMEPs, where the engine is less stressed. If slow steaming becomes a permanent mode of operation, then the efficiency can be further optimized by making engine changes, such as turbocharger cut out, to bring the engine back toward optimum operating performance at the new operating point. More permanent ship changes such as changing propellers and modifying ship bows can also be applied to optimize for the new operating speed. Figure 2.16 shows a turbocharger cut out upgrade kit from MAN where gate valves are installed to reduce the number of turbochargers in operation during slow steaming and the potential SFOC benefits, depending on the number of installed turbochargers that are cut out during slow steaming, for each engine type.

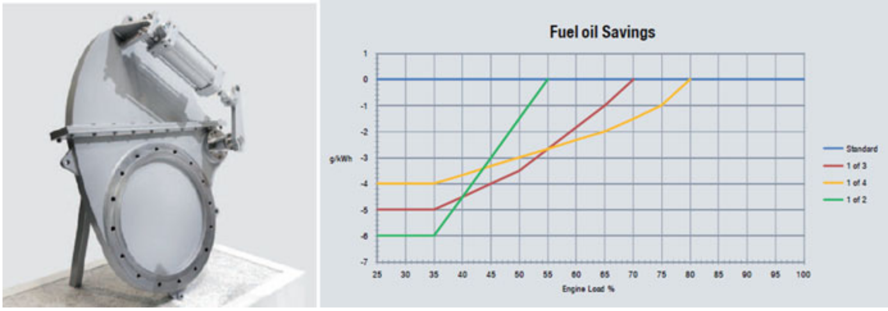


Fig. 2.16 Turbocharger cut out upgrade kit and SFOC reductions. (Courtesy MAN)

3.3.3 Electronic Engine Control and Common Rail

The adoption of electronically controlled engines represents the most important step change in engine technology that opens the door for flexibility on control of many engine related parameters, ancillary systems and the ability to achieve significant fuel consumption reductions. In a similar way to the introduction of electronic fuel injection controls to the automotive and off-road diesel engines in the 1980s, the advent of reliable microprocessors and computer controls has enabled the same transition for marine engines since around 2000. Primarily aimed at providing electronic control of fuel injection timing and fuel quantity, it is now possible, and indeed a necessity, to also control many other engine components and systems. For two-stroke slow-speed engines, the control of exhaust valve timing and lift is an additional key feature, but electronic control of turbocharger waste gates, variable geometry turbochargers, sequential turbocharging, turbocharger cut out, air management bypass valves, variable valve timing, and emission control features are just some examples of electronically controllable engine features that can be adjusted to provide the optimum fuel efficiency, transient response, and exhaust emissions settings. The balancing of these settings for any given point in the engine speed versus power map is a complex compromise to achieve the optimum fuel efficiency within the mechanical, thermal, and air fuel ratio limits and exhaust emissions limits for any particular engine type. This “calibration” of the engine electronic control unit (ECU), or “map” settings, is now perhaps the most important aspect of modern electronically controlled engines and is one that can have significant statutory air emissions implications.

From the fuel efficiency perspective, the switch from pure mechanical drive and control of fuel injection systems to electronic control can achieve fuel efficiency improvements of approximately 5%. This optimization is maximized when the electronic control is combined with application of the so-called “common rail” principles. While the maximum fuel injection pressures and phasing thereof are historically limited by the mechanical camshaft drive in conventional internal combustion engines with mechanical fuel injection, in common rail engines, the available fuel pressure curve is delinked from the engine speed. This gives the opportunity for much higher fuel injection pressures, particularly at lower engine loads, then achievable with camshaft-driven conventional mechanical drives. This enables fuel efficiency improvements and smoke-free operation.

Electronically controlled engines provide an opportunity to have accurate control of the fuel injection timing and quantity; common rail engines give the opportunity for much higher injection pressures at lower loads, and for the two-stroke designs, the exhaust control provides an opportunity to adjust compression pressures and cylinder scavenging. Medium-speed designs are also adding electronic capability for air management with turbocharger waste gates, air bypass valves, and inlet valve camshaft phasing or variable valve timing (VVT) units. The range of electronic "calibration" settings is almost limitless, but from the above trade-off characteristics, we can understand that any given "calibration map" is targeting a robust all-round performance but may be optimized for a particular application. Electronic engine control therefore represents the key engine technology shift to enable improvements in fuel efficiency and perhaps more importantly enable control of many other engine and system design features to achieve the optimum performance and efficiency while meeting the exhaust emissions regulations.

Figure 2.17 shows an example of the various electronic fuel tuning maps offered that are targeting the lowest possible SFOC in certain parts of the load curve: "delta tuning," "low-load tuning," "part load optimized." SFOC savings of 2–7% are possible compared to standard tuning and are well suited to support low-load ship operation, such as slow steaming or high-load applications.

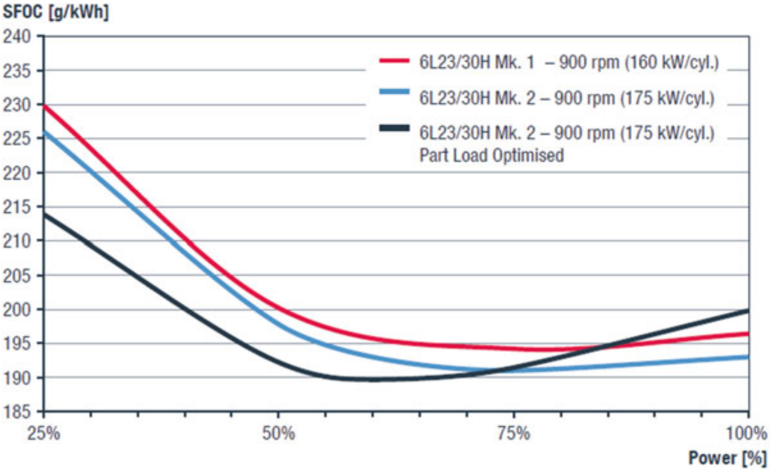


Fig. 2.17 "Part Load Optimized" electronic engine control. (Courtesy MAN)

3.3.4 Engine Instrumentation, Monitoring, and Control

Assessment of the total ship operational efficiency and machinery condition is always likely to include some element of manual data collection; however, the increase of electronic control systems enables the automation of much of this data collection. An electronically controlled engine, propulsion system, cargo control system, or other such system must be built around the capability to effect a change of settings or parameters, such as pump speed, valve position, etc. These changes are typically effected through actuators and speed control and are built around continual monitoring of basic parameters such as temperature, pressure, and position with more complex instrumentation measuring flow, vibration, or utilizing strain gauge instrumentation techniques. Complex machinery, such as engines, monitors such functions at a very high frequency that is linked to engine speed on a combustion cycle basis.

The installation of comprehensive instrumentation and the collection of such data therefore become essential to ensuring ship machinery systems, equipment, and components continue to operate in the most efficient way in service. Much of this instrumentation will be installed as part of the base machinery instrumentation, some can be added for additional capability and some would need to be added to provide a more total picture of ship operational efficiency.

To evaluate the energy efficiency of a ship's propulsion system, it is necessary to accurately measure and track fuel consumption and power. The installation of accurate power or torque measuring instrumentation and fuel consumption equipment are examples of additional ship instrumentation that may be fitted. Alternatively, these may be fairly accurately predicted from the data collected from the engine instrumentation and known as "calibration" map data. The addition of supplementary condition monitoring equipment for engines, such as bearing wear monitoring, cylinder drain oil analysis, and water in oil sensing, is a further example of additional instrumentation that can be added to improve condition monitoring and efficient operation. Full details on specific machinery or ship instrumentation are beyond the scope of this publication.

The collection of data or the use of this for optimization, condition-based monitoring, and predictive analytics is not a new technology but is an important emerging trend in the marine industry. Concerns such as cyber security, intellectual property on data, and how any service provision to help shipowners operate in the most efficient and sustainable way can be delivered in a practical way are current industry themes.

3.3.5 Energy Efficiency Optimization

When considering the total ship efficiency, it is important to consider parasitic loads as part of the operation of the main engine. The number of pumps, compressors, and other items of equipment installed is determined by classification society, IMO, and flag state regulations, based on the need for redundancy in case of failure of a running unit and to provide operational flexibility. Unit size/capacity and the number of units installed are selected to meet the most severe design conditions. These coolant, oil, and fuel pumps are typically driven by electric motors, the power for which is provided by the auxiliary generators running at four-stroke SFOC values. With these pumps driven at constant speed, the delivery rates are typically set for maximum load, and hence there is a lot of waste energy from throttling or spilling the pump output. For example, often three sea water cooling pumps are provided, each rated for 50% of the maximum sea water demand when the sea water is at the maximum design temperature. In service, the sea water temperature is often significantly below the maximum design temperature, some cooling loads may not be in operation, heat exchangers may not be fouled to the extent assumed in the design specifications, and the main engine is operating at less than its maximum continuous rating. The result is that the system's cooling requirements may be served by only one pump, thus providing the potential of saving the energy required for running a second pump. The use of variable speed motors and VFD drives can also recover some of these losses and operate the systems in a more efficient manner.

With the main engine parasitic and supplementary system loads increasing with engine complexity and after treatment demands, for example, hydraulic servo systems, DF fuel supply systems, EGR blowers, SCR heating, reductant dosing and soot blowing, etc., these parasitic loads can be significant and need to be considered within the total ship optimization plans.

3.3.6 Exhaust Emission Abatement Equipment

Exhaust emission abatement equipment is covered briefly here to highlight the impact on the base engine considerations. As discussed above, the primary international air emissions control regulations are those detailed in MARPOL Annex VI Regulation 13 for NOx and 14 for SOx. Most shipowners are expected to comply with Regulation 14 using sulfur compliant fuels and a number using exhaust gas cleaning technologies. For NOx compliance, engines are expected to install either SCR or EGR systems or to apply Otto-cycle process gas as fuel operation, to comply with the Tier III limits.

All of these Tier III technologies involve significant additional equipment and a change in the operational mode and settings of the engine. There are also associated supplementary support systems that impact the machinery space arrangements and the dosing of additional consumables, together with additional pump, compressor, and heating loads. At present there are still a small number of Tier III installations in operation, so real-world experience is limited; obtaining the optimum efficiency will require careful management of engine and Tier III technologies to ensure both environmental compliance and efficient operation.

For EGR systems there are the additional electrical loads associated with operation of the EGR blowers, operation of scrubbing water systems, the additional NaOH consumable for neutralizing acid formations in the wash water systems, and additional compressed air consumption for sealing of the EGR blower together with

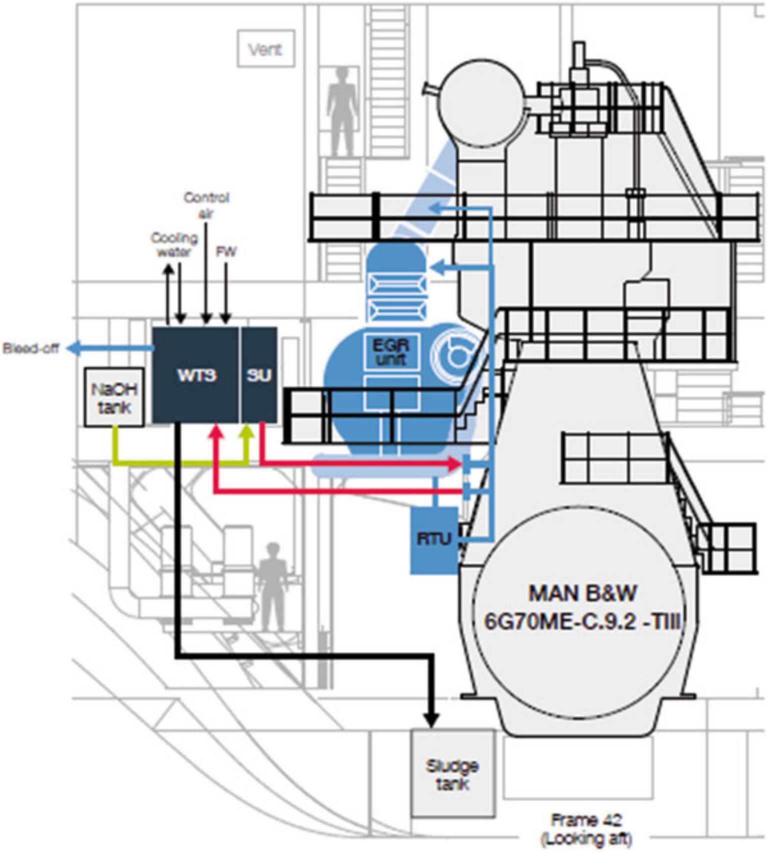


Fig. 2.18 Example of an EGR installation. (Courtesy MAN)

the increase in SFOC associated with EGR combustion. For Tier III operation at 100% engine load, the increase in SFOC can be 5 g/kWh (from the Tier II only engine); across the load range, it varies between 2 and 5 g/kWh. There is also an increase in cooling water flow required for the charge air cooling system to accommodate the higher heat load from the recirculated exhaust gases. Depending on the concentration of NaOH solution used in the water treatment system (WTS), there may be additional loads for the heating of the NaOH tank. There is the collection and disposal of the residues collected by the WTS to be considered. Figure 2.18 shows a schematic of an EGR installation, and Table 2.1 gives an example of the additional fuel consumption (compared to Tier II only engine), loads, and consumables for a slow-speed MDT 6G60ME-C9 engine with an MCR of 16,080 kW at 97 rpm operating in Tier III EGR mode.

For SCR systems the additional considerations depend on whether a before turbine, high-pressure (HP) SCR is installed or an after turbine, low-pressure (LP)

Table 2.1 Example MAN 6G60ME-C9 Tier III EGR data

Load, %	Additional fuel, kg/day	Power EGR blower, kW	Power WTS, kW	NaOH, liter/day
100	1929.6	88.4	64.3	108.1
75	1157.8	67.5	54.7	96.5
50	578.9	69.1	46.6	69.5
25	0	45.0	37.0	46.3

system is installed. In both cases there are the costs associated with the dosing of the reductant (typically UREA) together with air supplies for reductant injection and soot blowing of the SCR reactor. For HP systems there is the additional heat load that will be necessary to heat the SCR reactor, probably through electrical trace heating, and for LP systems, this will be seen through the additional cost of supplying fuel to the exhaust gas burner fitted upstream of the SCR reactor to raise exhaust gas temperatures. These reactor heating loads will increase dramatically with extended low-load operation. SCR operation will increase SFOC compared to a low-load tuned engine across the load range but may actually have lower SFOC (compared to a high load tuned engine) at the 50% and 25% load points; an increase of 2 g/kWh at 100% load is typical. The auxiliary blowers will need to be upgraded from the standard arrangement since they will need to be capable of being operated across the whole engine load range and require approximately 2.2 times the capacity of standard blowers. It is also important to note that even though there are control systems and operation strategies in place for reductant dosing and to minimize ammonia slip, it is likely that ammonium bisulfates would form in the exhaust gas boiler or economizer if operated at the same time as the SCR. Therefore it is strongly recommended to install a bypass of the boiler for when the SCR is in operation. SCR catalysts have a finite life which will depend on many factors; the catalysts may be considered consumables. Figure 2.19 shows a schematic of an HP SCR installation, and Table 2.2 gives an example of the additional (and reduced) fuel consumption (compared to Tier II only engine), loads, and consumables for a slow-speed MAN 6G60ME-C9 engine with an MCR of 16,080 kW at 97 rpm operating in Tier III mode with a HP SCR.

The above illustrates that there are considerable additional equipment, electrical loads, and costs associated with the operation of Tier III technologies to be considered. Tier III operation may also have indirect impacts on operation of other waste heat recovery systems and hence impact the total ship efficiency. The actual costs will be very dependent on the specific operational profile, time in ECAs, and engine load profile when operating in the ECA. The advent of Tier III technologies is challenging the status quo of traditional ship and machinery space designs, and highlighting that a ship-specific assessment for total cost of ownership is the only way to determine the most fuel efficient and sustainable way to operate ships of the future.

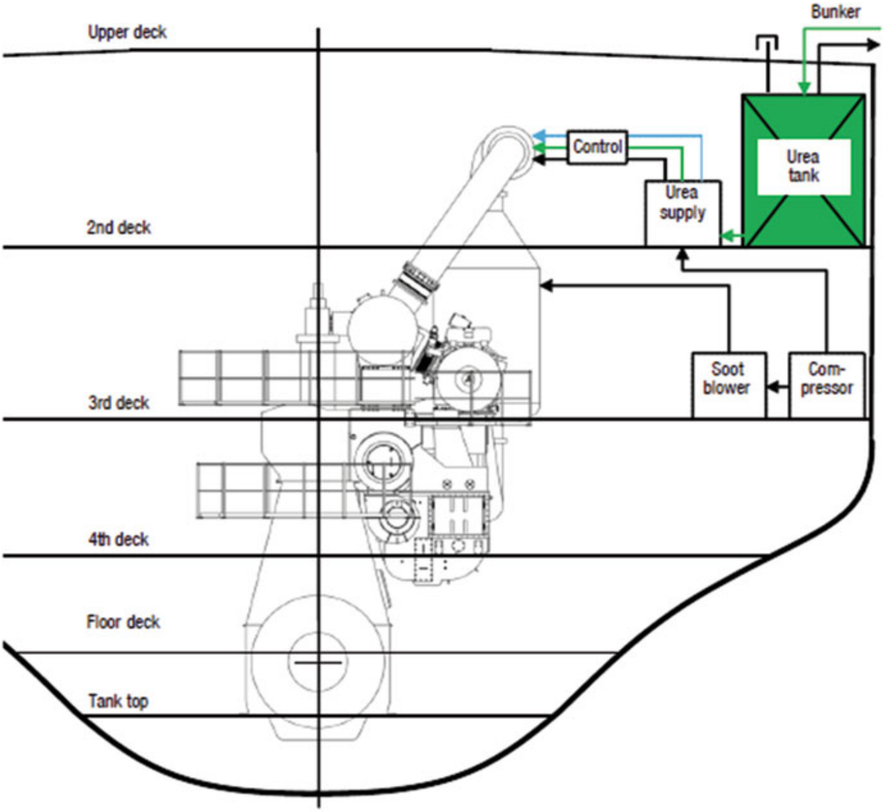


Fig. 2.19 Example of an HP SCR installation. (Courtesy MAN)

Table 2.2 Example MAN 6G60ME-C9 Tier III HP SCR data

Load, %	Additional fuel, kg/day	Power, kW	UREA, liter/day
100	771.84	80.4	6560.6
75	144.72	80.4	4920.5
50	−675.36	80.4	3280.3
25	−964.8	80.4	1640.2

3.4 *Waste Heat Recovery*

While modern diesel engines are very efficient, they still generate a large amount of waste heat when running at full load which can be utilized to improve the overall propulsion system efficiency. Figure 2.20 shows an example of the MAN 12S90ME-C9.2 (previously shown in Fig. 2.14) increasing the plant efficiency from 50% to 55% by the use of waste heat recovery (WHR) techniques.

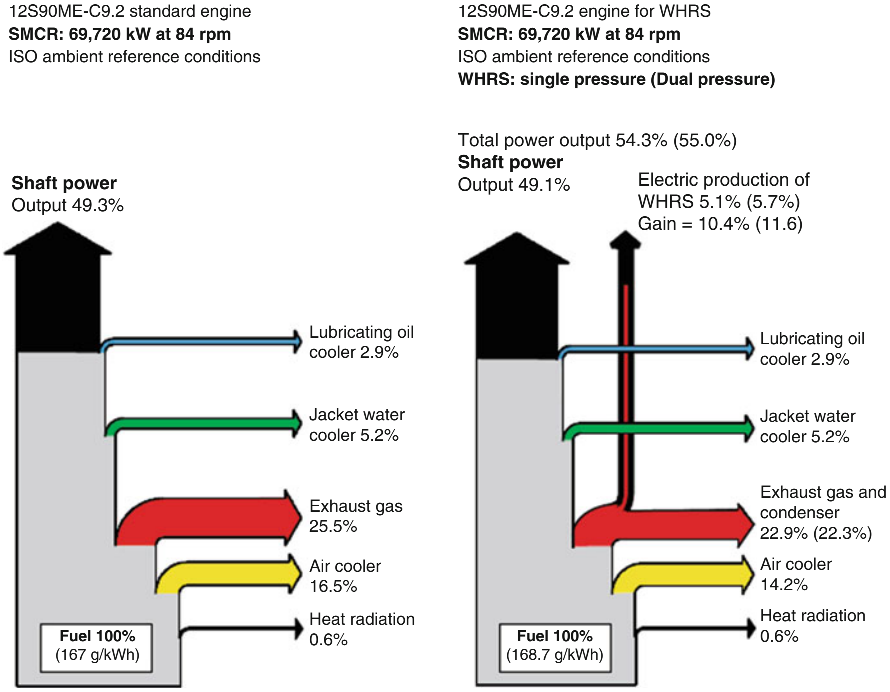


Fig. 2.20 Example of increase in overall propulsion engine efficiency by WHR. (Courtesy MAN)

As can be seen, about 5% of the fuel energy goes to the engine jacket cooling water system, and about 25% is contained in the exhaust gas. For many years it has been common to use the heat from the main engine jacket cooling system to generate fresh water and the heat in the exhaust gas to generate steam for heating. As the size of the ship and its engine increase, the amount of exhaust heat available increases much more rapidly than the demand for steam for heating. This is because the primary uses for the steam are heating oil tanks and accommodation spaces. For most commercial ships, the total size of the accommodations is about the same, and the amount of steam for oil heating grows only slightly with the engine size. This results in a surplus of heat available on ships with large engines after the more traditional services have been fulfilled. The 15% waste energy in the air cooling circuit is another potential source of WHR. In all cases, the actual quantities of WHR available and the efficiencies of the WHR systems need to be carefully considered with respect to the available waste heat at any particular engine load point. For example, the slow steaming operation mentioned above may impact the available waste heat to the extent that it is just not efficient to extract by the WHR plant. However, the right systems and operation modes can significantly improve overall engine efficiency. A few of the common WHR systems are discussed below.

The simplest form of exhaust WHR is by the use of a steam generating exhaust gas boiler or economizer. The developed steam can be utilized for ship systems and reduce the energy demand on the ships auxiliary boiler. Typical exhaust gas boilers are available in ranges from 0.1 to 21 MW with 0.2–17 t/h steam capacity and specifically designed to minimize soot build up.

More sophisticated systems utilize an off-engine skid unit that comprises either a standalone exhaust gas-driven turbine driving an electrical generator, a standalone steam turbine driving an electric generator, or a unit containing an exhaust gas turbine and a steam turbine connected to a common generator. With up to 10% of the main engine MCR available from such a WHR unit, it is possible to reduce the amount of electrical power generated by the auxiliary generators.

Recovering additional waste heat from other parts of the engine support systems, such as the jacket cooling system, is possible, but the low-grade heat available is difficult to capture in conventional waste heat recovery systems, freshwater generators being a typical application. Several pilot studies have looked at using a process unit that uses the Rankine cycle to provide supplementary electrical power. While approximately 5% of MCR power is potentially available from the jacket heating system, in practical terms, 1% would be an achievable amount.

A promising application for waste heat recovery is available by extracting some of the 15% of MCR power that is lost to the charge air cooling system. The pressure ratios and high boost pressures utilized in modern turbocharged engines mean that it is not unusual to need to cool charge air from temperatures over 150 °C at full load, which represents a potential higher grade heat source. However, the quality of the available waste heat is very dependent on engine load. The greatest benefits would perhaps come where the recovered energy could be used in association with existing steam turbine waste heat recovery units, in a feedwater preheater arrangement. The use of two or multistage air cooler units would be necessary and would add to engine complexity and cost but can contribute to obtaining the maximum achievable WHR from the installed systems.

3.5 Auxiliary Equipment

Adopting a complete ship system approach to energy efficiency means any assessment needs to consider the potential improvements to be gained from the auxiliary equipment; this section looks at some of that auxiliary equipment.

3.5.1 Shaft Generator

The addition of a shaft generator powered by a two-stroke slow-speed main engine gives the potential to generate electric power at low SFOC but under certain conditions. There are several different types of shaft generators in common use on ships. The simplest type is a shaft generator connected to the main engine by a gearbox with a fixed gear ratio. To obtain constant frequency electric power, the main engine must operate at constant RPM, which requires the use of a CPP. Such a shaft generator cannot operate in parallel with the ship's auxiliary generators since the main engine speed variation will vary more than the diesel generators speed, particularly when the ship is pitching in waves. The transient response of the two different engine types is also very different which makes load sharing at constant frequency difficult. The losses from such gear-driven shaft generators reduce efficiency to approximately 92%, and operating the CPP anywhere other than full load will put the propeller into a less efficient point of operation. This type of shaft generator will therefore only offer overall fuel-saving benefits where the engine and CPP are operated near full load for long periods.

Alternative shaft generators are available that have either variable ratio gears or frequency control. Both of these types can work with a fixed pitch propeller over a range of RPM (usually 75–100% RPM), alleviating some of the issues with the constant gear ratio shaft generator. However, these shaft generators are more expensive and less efficient. Typical efficiency for a variable speed gear drive is 88–91% and for the variable frequency shaft generator 81–88%. If the incorporation of a shaft generator can enable a reduction in the number of auxiliary generators, then it is a viable option for improving overall efficiency and maintenance costs. The greatest benefits however perhaps would come where the unit is a combined generator/motor and used in a hybrid PTO/PTI configuration – see below.

3.5.2 Number/Size of Ships Auxiliary Generators and Power Management Systems

The number and size of installed auxiliary generators is chosen to provide sufficient power for the electrical loads for various modes of operation of the vessel, with sufficient standby power to meet SOLAS requirements and replace the largest generator in operation should a failure occur. For some ships the use of a shaft generator can be sized to provide all hotel loads during ship voyages and hence avoid operation of the higher SFOC generator sets. However, in most cases, the generator sets will be in operation, and as we have seen from previous sections, optimum efficiency only occurs in a small part of the engine speed/load map. So the target loading of the generators should be to keep the engines within this maximum efficiency operating point. The use of Power Management Systems (PMS) to automatically determine how many of the installed generators should be in operation simultaneously and how each of those is loaded therefore becomes an essential tool in obtaining maximum ship efficiency.

3.5.3 Heating, Ventilation, and Air Conditioning (HVAC)

While heating, ventilation, and air conditioning (HVAC) systems are typically not large consumers of power on commercial cargo ships, a holistic approach to the total ship systems should assess the systems for potential improvements in design and/or operation. For example, modern heating and air conditioning systems incorporate preheating and recirculation features that reduce the required energy input. Upgrading to this type of system can offer significant reductions in operational energy demands. Similarly, ventilation fans may frequently be sized for the maximum air change requirements and controlled with crude speed controls. The use of variable speed motors and the use of automated control systems can significantly reduce the energy demands and should be considered along with any changes to operation that can be implemented to encourage low energy usage.

3.5.4 Variable Speed Motors: Pumps and Fans

In a similar manner to the reductions achievable with the engine parasitic loads detailed above, the use of variable speed motors and VFDs can improve the operating efficiency of pumps and fans that operate at variable loads in other ship systems. With a variable speed pump, the required flow rate can be achieved at a reduced head by slowing the pump down. Although the variable speed system consumes slightly more power at full load, pumps are rarely operated at maximum demand. Therefore, there are significant savings to be gained over the range of flow rates that the pump would typically operate. Similar benefits can be obtained from variable speed control of all other auxiliary equipment onboard.

3.6 Hybrid Systems and Equipment

One of the promising areas for future ship propulsion system developments, and the potential for significant ship efficiency improvements combined with lower emissions, comes from the adoption of the so-called hybrid technologies. One of the key enablers for this is a switch to electric propulsion systems. However, the additional complexity and inherent system losses do pose challenges, while the overall potential gains can be significant. The connected equipment and system nodes, such as the use of DC systems, increased control electronics, system integration, data logging, online optimization, data collection, etc., all feed into a future for ships and ship propulsion systems, where connectivity and ship power grids allow the integration of unconventional energy production and storage systems with conventional power generation and propulsion systems. Hybrid propulsion and hybrid ships: an evolutionary rather than revolutionary approach, but a key enabler to more efficient and sustainable shipping in the future.

The internal combustion engine will remain at the heart of these hybrid ships for many years due to its high power density but to a different level of integration and complexity than has been traditional. The propulsion norm may no longer be large, slow-speed main engines directly coupled to propellers but may shift toward medium- and high-speed power units supplementing the power in energy storage systems for use in electric propulsion units and for hotel loads. The use of electric propulsion pods and azimuthing thrusters will become more prevalent and are particularly suited to applications requiring accurate station keeping. Eventually the internal combustion (IC) engine may be completely replaced by fuel cells, but the difficulties with hydrogen as a fuel, the poor transient response characteristics of fuel cells, and the challenges for development of the hydrogen economy may mean that fuel reforming remains a part of the fuel cell deployment strategy for many years and fuel cells will only form part of the total power system. The types of fuel supplied to the marine industry in the years ahead will have a large influence on how the details of the hybrid systems will evolve, including the continued use of IC engines.

Though some have seen a shift to gas as the next big step in ship propulsion, i.e., from sail to coal and from coal to oil and from oil to gas, the shift is likely to be to electric propulsion using a variety of "fuel" sources. Sooner, rather than later, all energy and transport infrastructure will need to shift from fossil fuels for climate change reasons. If bio fuels, or perhaps more accurately, carbon free or carbon neutral fuels, can be developed and supplied in sufficient quantities and at competitive prices, then the ships of the future will still look much like they are now. It is just there will be increased use of hybrid power generation and storage systems, and ships will be thought of as total "electric" systems rather than just by a handle linked to propulsion method or fuel. To achieve this will require a multilateral approach to how primary energy is produced. It makes sense to generate hydrogen from a "clean" source, such as land-based solar or wind and deliver this as a clean fuel for use in the transport sector, either directly as hydrogen or in a hydrogen carrier fuel.

The early marine hybrid adopters will be the local and short sea shipping sectors where limited range and frequent refueling will not hinder performance and operation. The most suited applications are those with large transient power requirements and where continuous operation at high load is not a dominant part of the ship operation profile; but transient operation is a factor for all ships, and all ships can benefit from some form of energy storage system to smooth out the transient demands and improve overall efficiency. This energy storage approach enables equipment such as fuel cells or DF engines that have reduced transient capability to be efficiently deployed. It is no longer important for the engine to meet traditional transient response requirements or be type tested across a wide speed/load map that is not appropriate for its use but merely that the engine is capable of delivering power reliably and efficiently at a constant speed within a small-speed/load window. It is therefore the ship power generation and storage system, and how that system is managed, that must meet the transient performance that a particular ship type needs.

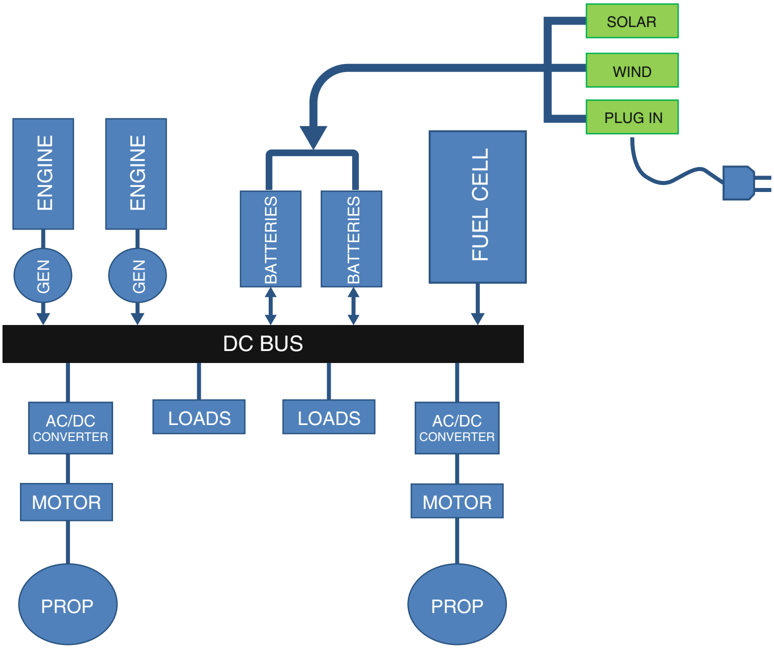


Fig. 2.21 Hybrid power system example

While wind and solar may find some small niche supplementary power generation capability for certain ships, the dominant energy storage technology being deployed will be batteries. The ratio of batteries to engines and fuel tanks will be what changes between a given ship type based on peak power demand and vessel range requirements. The use of batteries enables “cold ironing,” or perhaps a more appropriate name would be “plug in hybrid,” when at berth so that power generation requirements for the ship at berth can be delivered from clean shoreside sources and the power used to fully charge the batteries for use in the next sea deployment. The combination of energy storage and electric drive also enables ships to be operated with no exhaust emissions in sensitive air quality areas such as ports, rivers, and estuaries or even completely within ECAs.

Figure 2.21 shows how a hybrid ship with a variety of energy storage and production equipment is integrated by connection to a DC grid.

3.6.1 Batteries

Battery technology has advanced quite rapidly over the past few decades with significant steps being made away from the traditional lead/acid battery chemistry through nickel cadmium (NiCd) and nickel-metal hydride (NiMH) chemistries to lithium ion. These advances have obviously been seen in the development

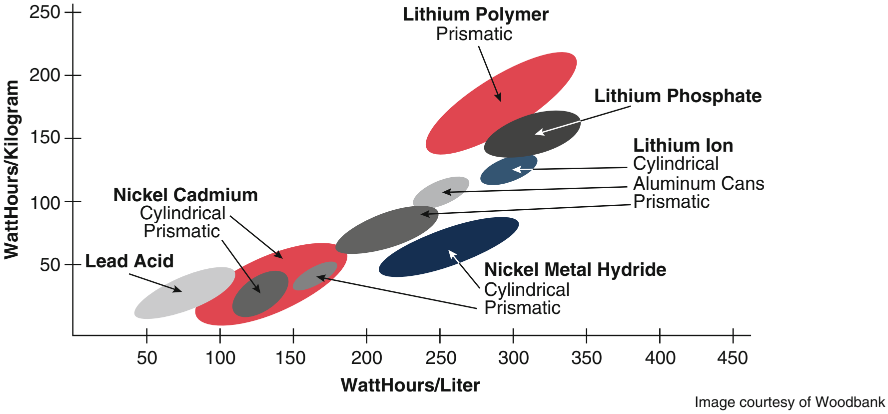


Fig. 2.22 Battery development (ABS 2017)

of batteries for mobile phones and laptops, but the energy density and weight advantages of the lithium-ion batteries have now enabled significant performance increases in the range of electric and hybrid vehicles. While still facing challenges on energy density and cost, lithium-ion batteries represent the most practical energy storage unit for marine applications. Figure 2.22 shows the development in energy density of the various battery chemistries.

One of the critical factors for lithium-ion batteries is thermal management. Battery cooling requirements and the prevention of thermal runaway are perhaps the most significant practical and safety issues to be considered when integrating batteries into a hybrid ship. The battery is no longer a simple cell, or group of cells within a casing, but is typically a power unit with its own battery management system (BMS) measuring cell temperatures and controlling charge and discharge rates. The cells, BMS, and sensors may be referred to as a module and the battery pack comprised of a number of modules. The battery packs may themselves be grouped in an array or system to complete the battery power storage and supply unit. Safety aspects and battery system application issues are addressed in, for example (ABS 2017).

The main application for battery systems will be for balancing loads and peak-shaving where they can act as the transient buffer in the system both to supply and absorb energy when there is excess production. This can allow generator sets to be operated at a near constant load at the most efficient load point. This capability also has the potential to improve operational efficiency by reducing maintenance on engines due to optimal loading and reduced engine running hours. Battery power also enables a vessel to operate in electric mode in port or during transit to give a zero emission operation mode or can be used to supplement propeller power when high speed is required.

Dependent on the type of ship, significant savings are also possible if the battery system is large enough to be considered a standby power source and may mean fewer generators need to be installed or in operation. The ability to be used to prevent ship blackout and act as an emergency power source provide additional redundancy and safety benefits.

Supercapacitors and flywheels are also potential alternative energy storage devices that have found application in other industries and are therefore being considered for the marine industry. However, both are unlikely to find significant marine application soon, particularly as the sole energy storage equipment on board.

3.6.2 Alternative Energy Sources

As indicated above, wind and solar power may provide some niche supplementary power on certain ship types. However the energy density is very low, and the area and volume requirements on board the ship make these technologies difficult to implement in a practical manner. For example, utilizing all available surface area for photovoltaic (PV) installations on a bulk or oil carrier may enable generation of 2–10% of main engine power but places sensitive equipment in cargo areas. The costs for PV cells have dropped dramatically in recent years, so this may provide a viable payback in certain circumstances; however the most promising alternative energy source in the long term is the fuel cell.

The fuel cell concept can be traced to the 1830s but did not find commercial application until deployment in the space program. A fuel cell is an electrochemical cell that produces electricity by a chemical process reaction from hydrogen rich fuel and air supplies. Ideally the only emission from a fuel cell is water. As indicated above, a pure hydrogen fuel supply provides the simplest fuel cell arrangement, and this has found limited application in the automotive car and bus sectors. Fuel cell power densities and cost are approaching levels where they can be considered a viable alternative to the internal combustion engine.

There are however still significant challenges with the use of hydrogen as a fuel, and commercial marine application is likely to come where the fuel cell is close coupled with a reformer to produce hydrogen rich fuel from a fuel source such as natural gas or methanol. There are still challenges with the packaging of this type of fuel cell power system, as well as the inherent poor transient performance, fuel sensitivity of the fuel cell stack, and issues with excess fuel or fuel slip in the exhaust stream. When looking at the full hybrid system approach, fuel cells could be incorporated in the power generation system as an alternative auxiliary power source and potentially replace one, more or all of the diesel generator sets. When combined with a battery storage energy unit, the fuel cell represents a viable part of the hybrid power mix. The marine regulations for fuel cells are still under development but will form part of the IMO International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code).

There are many different types of fuel cell available that are largely characterized by the type of electrolyte: proton-exchange membrane (PEM), alkaline, phosphoric acid, molten carbonate, and solid oxide fuel cells. The high-temperature PEM fuel cell is emerging as one of the most suitable for marine applications.

4 Ballast Water Management

Shipping moves over 80% of the world's commodities and transfers approximately 3–5 billion tons of ballast water internationally every year. Ballast water is essential to the safe and efficient operation of shipping, but it also poses a serious ecological, economic, and health threat through the transfer of invasive aquatic species inadvertently carried in it.

The transfer of invasive marine species into new environments via ballast water has been identified as one of the major threats to the world's oceans. In response, the International Maritime Organization (IMO) adopted the Ballast Water Management Convention (BWM Convention) in 2004, which later entered into force 8 September 2017.

The BWM Convention includes two-tiered steps to comply with its requirements, which apply to all vessels irrespective of age, size, type, or trade, unless trading in domestic waters, naval ships, or for ships that do not discharge ballast water.

While the IMO aims at regulating ballast water in a similar manner worldwide, individual countries have the right to enforce their own domestic regulations. The most important of those countries that have local ballast water requirements that are different than those of the IMO is the United States. Australia is another example, but the majority of the Australian regulations are similar to those of the IMO.

4.1 Requirements Under the BWM Convention

Regulation B-3 of the BWM Convention stipulates the dates at which ships flying the flag of a Party or discharging ballast water in the waters of a Party must comply with the D-1 standard or the D-2 standard.

The D-1 standard applies as of 8 September 2017 and requires ships to perform mid-ocean exchange of their ballast water. The exchange must ensure that at least 95% of the water is exchanged and can only be done following one of the three methods:

Flow-through: which means the water is pumped into a full tank and out on deck through adequate openings, long enough to ensure exchange of three times the volume of each ballast tank

Sequential: which means the water is emptied and refilled

Dilution: which is similar to flow-through, only the ship ensures that the ballast tank level is kept constant until three times the volume exchanged. Dilution applies to ships with ballast tanks partially filled.

In addition to the above, ballast water exchange is to take place as follows:

Whenever possible, at least 200 nm from the nearest land and at least 200 m in depth.
In cases where the above is not possible, at least 50 nm from the nearest land and at least 200 m in depth.
When the above is not possible, designated areas or ballast water exchange must be used. In all cases, ships are never required to deviate from their original routes to meet the requirements for exchange stipulated above.

The D-2 standard applies to new ships keel-laid after 8 September 2017 and to existing ships mainly at their first IOPP Renewal Survey after 8 September 2019. The D-2 standard is a biological performance standard that requires all ballast water discharge to not exceed:

Ten organisms/m^3 for organisms with size larger than 50 μm
Ten organisms/mL for organisms with size between 10 and 50 μm
Toxicogenic *Vibrio cholerae* (O1 and O139) with less than 1 colony forming unit (cfu) per 100 ml or less than 1 cfu per 1 g (wet weight) zooplankton samples
Escherichia coli less than 250 cfu per 100 ml
Intestinal *Enterococci* less than 100 cfu per 100 ml

To meet the requirements above, ships have several options, including non-discharge of ballast water, discharge to reception facility, or treatment onboard. Treatment onboard is required to be done by a type-approved ballast water management system (BWMS), following the Code for Type Approval of BWMS.

4.2 Requirements in the United States

For ships trading in the United States (US), different sets of requirements are applicable when discharging ballast water in the United States.

4.2.1 Federal Regulations Under the US Coast Guard

The Federal Regulations falling under the USCG require exchange or treatment (by a USCG Type Approved BWMS, not only IMO Type Approved). The compliance dates for treatment are the first scheduled dry-dock after 1 January 2016 or 1 January 2014 (depending on the ballast capacity of the ships), with extensions to those dates issued by the USCG in case the ship cannot find suitable USCG Type Approved BWMS.

4.2.2 Federal Regulations Under the US Environmental Protection Agency

The US EPA regulates ballast water through the Vessel General Permit (VGP), following in general the same standards as the USCG Regulations, but requiring annual testing of the Ballast Water and reporting back to the EPA.

4.2.3 State Regulations

Individual states in the US are allowed to have their own additional requirements to the discharge of ballast water under the VGP. The State of California is the most active state, requiring additional measures on top of the USCG and the EPA.

4.3 Ballast Water Management Systems

Ballast Water Management Systems (BWMS) are the most common way for ships to comply with the D-2 standard and the US Regulations. In order to do so, BWMS must be type approved by an Administration and the USCG, following the BWMS Code requirements of the IMO and the §162.060 requirements of the USCG.

Type Approval consists of three parts, (a) Readiness Evaluation where the system's ability to meet the requirements, its documentation, and test plans are evaluated. (b) Once satisfied that the BWMS is ready to be tested, a series of land-based tests (five tests for each salinity: fresh-, brackish-, and marine water) is conducted with challenge water to verify the efficacy of the BWMS. A series of three shipboard tests (IMO) or five (USCG) is also required onboard a commercial vessel. The electric and electronic components of the BWMS are tested for environmental compatibility. (c) When the test reports show that water treated by the BWMS managed to pass the D-2 standard, a type approval application is submitted to the IMO Administration and the USCG for issuance of the type approval certificate.

4.4 Technologies Used in BWMS

Treatment technologies can be divided into three bulk areas: mechanical, chemical, and physical. In those main categories, it is possible to identify 12 main processes divided in turn into some 23 specific types that are used by the industry today. Table 2.3 is a summary of technologies used by BWMS.

We will briefly introduce the technologies that are mainly used by ships, which are filtration, UV, and electrolysis.

Table 2.3 Overview of technologies used in BWTS

Main technology	Technology	Sub-technology
Physical	Ultraviolet (UV)	Low pressure
		Medium pressure
	Ultrasound (US)	
	Cavitation	
	Deoxygenation	Inert gas stripping
		Nitrogen injection
	Heat treatment	
Mechanical	Filtration	Screen filters
		Disk filters
		Hydrocyclones
		Magnetic separation and coagulation
	Pressure drop	
Chemical	Electrolysis	Electrolysis
		Electrocatalysis
		Electrochlorination
	Ozonation	
	Chemical injection	Sodium hypochlorite
		Chlorine dioxide
		Other
	High energy plasma	
	Advanced oxidization	Titanium dioxide
		AOP: Ozone + UV
		AOP: Other

4.4.1 Filtration

The aim of filtration is the separation of larger organisms and solids from ballast water. Most BWMS using mechanical processes use screen filters. Filters are always used as a pre-step to another technology, for example, UV or electrolysis.

Screen filters range from 10 to 50 μm screens weaved in many ways and according to different standards. Even references to screen sizes are not standardized so knowing exactly what is meant with a 50 μm screen can be a challenge and can differ from one vendor to the other. All screen filters in the market are of a self-backwashing design, creating a challenge related to the ballast water pumping capacity of ships as filters typically use the same ballast water to backwash, reducing significantly the flow rate during the backwashing period. Up to 30% of flow rate loss can be expected during the backwashing period, which is significant in the cases where filters backwash continuously depending on the conditions of the water being filtered. The installation of a backwash pump will increase the volume of water being backwashed and so increase the loss in ballasting capacity.

Screen filters are currently used together with most other processes in ballast water treatment with the main aim to remove larger organisms (pore sizes of 25–50 μm are mainly used) and reduce the number of solids in ballast water.

Screen filters will generally not reduce the amount of sediments in the ballast tanks as most sediment in the seas where ships take on ballast water are fine silt and clay with nominal pore sizes between 2 and 10 μm. However, caking is a known phenomenon where small-sized TSS can clog a filter pore.

4.4.2 UV Technologies

All BWTS using UV use amalgam lamps surrounded by quartz sleeves to produce UV light. Generally, at doses used for disinfection of water, UV light changes the molecular structure of DNA in organisms and thereby prevents them from reproducing. New interpretations of the regulations by the USCG have led the industry to increase the dose significantly in order to kill the organisms directly, not only damaging their DNA.

The majority of UV-based BWMS use medium-pressure amalgam lamps. UV efficiency depends on five main parameters:

The type of lamp used (low pressure or medium pressure)
The length of the lamp being used (the arc length)
The physical design of the UV's water exposure chamber
The water flow rate through the UV's exposure chamber
The condition of the water being treated

With items 1–3 being fixed by the design of the BWMS without the possibility to change, and the flow rate (item 4) being tested at its continuous maximum (Treatment Rated Capacity or TRC), the only variable affecting the efficiency of UV lamps is the condition of the water being treated, which will also affect the amount of energy needed to clean the ballast water.

Of all water quality parameters, ultraviolet transmittance (UV-T) is the most important. This is because the UV-T of the water will determine how well the UV light will penetrate the water in order that the pathogens in the water may be exposed to sufficient UV light to be inactivated. Although parameters such as POC, DOC, and turbidity all influence the extent to which UV light penetrates the water, they are all effectively accounted for by the UV-T reading. Total suspended solids (TSS) is also important. TSS is important because of the phenomenon known as "shielding" whereby the pathogens can be "shielded" from the UV light by the particles suspended within the water.

4.4.3 Electrolysis

Electrolysis is the process of oxidizing seawater through an electrolytic process using all or part of the seawater as the source of the ions. Electrolysis is by far the most used in situ process in ballast water treatment.

Both temperature and salinity are critical parameters affecting the efficiency of electrolysis.

In general terms, and common to all electrolysis processes used by BWMS, the lower the temperature, the higher energy you need to produce hypochlorite and disinfect the water. The increase in energy need by the BWMS follows an increasing exponential curve. Normal lower temperatures for operation of electrolysis processes in BWMS range between 10 and 17 °C, although some manufactures claim that their electrodes would still be efficient at 1 °C. Low salinity makes it difficult for those processes to generate disinfectants.

The last common issue to all electrolysis processes is the generation of hydrogen and chlorine gases that are explosive and toxic. High temperatures and high salinity of water are ideal for the generation of large volumes of hydrogen. Mixture of hydrogen and chlorine has a wider range of flammability than mixtures of hydrogen in air and so must be avoided. Management of dangerous gases is an important parameter to consider when installing BWMS using electrolysis on ships.

In ballast water management, electrolysis has been applied in two ways:

1. Side stream where a small percentage of water is taken from the main stream of ballast water and stimulated by a certain voltage difference to create the hypochlorite and other chemicals needed to disinfect the main stream, once injected back into it.
2. Full stream where the complete flow of water is stimulated by the voltage difference.

The side-stream solution is by far the most common when applying electrolysis as a process in the BWMS in the market. Some advantages of side-stream injection of in situ generated hypochlorite are the ability to overcome the temperature challenge by applying heating jackets to the side-stream pipe and to overcome the salinity challenge by using a storage tank with adequate water (salinity and temperature) to drive the treatment process through at least one ballasting sequence.

4.5 Compliance Challenges and Alternatives

As the BWM Convention's aim is to reduce the risk of spread of non-indigenous species through ships' ballast water, many questions started popping up regarding the usefulness of the D-1 and D-2 discharge in certain trades and areas:

- Short sea shipping including especially ferries like in the North Sea; Baltic Sea; the area around Singapore, Indonesia, and Malaysia; the area between China, Korea, and Japan; the intra-Great Lakes trade; etc.
- The effect of biofouling on spread of invasive species

We will shortly discuss the problematic aspects of the BWM Convention, although those issues deserve their own book digging deep into the technical and economic aspects of this regulation.

4.5.1 Short Sea Shipping

While the most known aspects of the BWM Convention are its requirements to exchange ballast water or treat ballast water, other less widely applied or discussed alternatives include the use of freshwater as ballast water, exemptions from the requirements and exceptions to the requirements.

Freshwater as Ballast Water

It is a common misconception that using freshwater generators onboard ships should be good enough for that ship to meet the D-2 standard when it uses that water as ballast water. The IMO through the course of many years had long and detailed discussions about this issue where it was concluded that while fresh or potable water generated onboard might meet the D-2 standard, those generators must go through a type approval process like any other BWMS to prove their ability to consistently meet the D-2 standard under the challenging conditions the type approval process presents.

The BWM Convention does not allow use of fresh, municipal water taken from shore as being ballast water meeting the D-1 or D-2 standard, so this is not an option for ships under the BWM Convention. However, the USCG opens up for such a possibility by allowing ships to take US municipal water and discharge it in the sea in the United States.

While at first sight, the IMO regulations seem unreasonable as water suitable for drinking should be good enough to discharge in the sea, a closer look at the different standards applied around the world on drinking water, the experience of algae growing in still fresh, drinkable water onboard vessels (like Offshore Supply Vessels when those fail to deliver the water to the platforms due to weather), as well as the problematic of access to freshwater in certain parts of the world may shed a new light on this aspect of the BWM Convention.

Exemptions and the Application of Same Risk Area

Regulation A-4 of the BWM Convention opens up for allowing ships to be exempted from the requirements in Regulations D-1 and D-2, when trading between specific ports where a risk assessment applied in accordance with Guidelines G7, have concluded that there is no risk of spread of invasive species between those ports.

This regulation was further expanded to introduce the concept of Same Risk Area, where such risk assessments, always done in accordance with Guidelines G7, apply to a region or area with multiple ports. This concept is especially useful in heavily trafficked seas like the Southeast Asian passages around Singapore/Malaysia and Indonesia, the Great Lakes, the North Sea, and other local areas and ports.

Furthermore, such exemptions are very much applicable to ferries and passenger ships going on shuttle traffic between two and three ports or on very short voyages (e.g., ferries going between Norway, Denmark, and Sweden with less than 6–12 h sailing route).

The challenge with applying those exemption guidelines, according to several sources in the shipping industry, is that the exemption work is done by the ship owner but is then applicable to all other ships in the same route, so that the cost of such exemption is carried by one owner, for the benefit of all. This has shown to be challenging for shipping companies to apply. This fact, in addition to the complex sampling and analysis procedure for establishing the noninvasive nature of organisms between two ports, has led so far to very little, if any, such analysis taking place.

Exceptions from the Requirements of the BWM Convention

Regulation A-3 of the BWM Convention allows ships, in certain circumstances, to discharge unmanaged ballast water. Those circumstances are:

- The uptake or discharge of Ballast Water and Sediments necessary for the purpose of ensuring the safety of a ship in emergency situations or saving life at sea
- The accidental discharge or ingress of Ballast Water and Sediments resulting from damage to a ship or its equipment
- Ballast operations for the purpose of avoiding or minimizing pollution incidents from the ship
- The uptake and subsequent discharge on the high seas of the same Ballast Water and Sediments
- The discharge of Ballast Water and Sediments from a ship at the same location where the whole of that Ballast Water and those Sediments originated and provided that no mixing with unmanaged Ballast Water and Sediments from other areas has occurred

Exceptions are operational situations that, on a case by case basis, ships do not need to manage their ballast water. However, those ships must still be able to discharge ballast water compliant with the D-1 or D-2 standard, as applicable, including having onboard a BWM Plan, an International BWM Certificate and a Record Book.

4.5.2 Biofouling

Biofouling is also considered one of the main vectors for bioinvasions and is described as the undesirable accumulation of microorganisms, plants, algae, and animals on submerged structures (especially ships' hulls). Studies have shown that biofouling can be a significant vector for the transfer of invasive aquatic species. Biofouling on ships entering the waters of States may result in the establishment of invasive aquatic species which may pose threats to human, animal, and plant life, economic and cultural activities, and the aquatic environment.[2]

The IMO adopted in 2011 the Biofouling Guidelines, which are voluntary guidance for ship owners on how to avoid this important vector of spread of invasive species. In 2012, the IMO expanded those guidelines to include recreational craft with length less than 24 m through *Guidance for minimizing the transfer of invasive aquatic species as biofouling for recreational craft*.

Biofouling is also recognized by a large number of coastal states as a threat to their environment, which forced them to regulate how often ships clean their hulls, propellers, and other submerged parts. In the United States, biofouling is regulated through the EPA's VGP, and the USCG requires Biofouling Management Plans for ships.

Means to control biofouling include mainly routine cleaning of the hull of the ship, anchor chains, and niche areas like thruster tunnels, rudders, propellers, and sea chests, to name a few. The VGP includes a detailed list of actions required to do proper biofouling management.

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[2] From the IMO website www.imo.org.

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