A Suggested Energy Efficiency Index for Warships

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Synopsis

The International Maritime Organization (IMO) now has in place a set of metrics which allow the Transport Energy Efficiency (TEE) of the design and operation of a wide range of commercial ships to be assessed. These are the Energy Efficiency Design Index (EEDI) and the Carbon Intensity Indicator (CII).

The EEDI is the TEE at the nominal design point as prescribed by IMO at 75% loading of the ship's main engine with an electrical load which is a function of the ship's main engine rating. It is usually quantified in terms of mass of carbon dioxide (CO_2) equivalent emitted per "useful work done." The CO_2 emitted is based on the fuel consumption rate at the design point and its carbon factor. The useful work done is measured by the ship's deadweight capacity times the design speed.

These metrics are categorised by ship types using historical ships' TEE data from the large vessel population. The required IMO-regulated performance is to show a progressive year-on-year improvement compared to the average performance of the whole fleet of international ships.

Naval ships are leading diplomatic and functional representatives of their government and as such, the navies of the world are arguably morally bound to adopt best practice and present the best possible image of their country. However, each aval vessel is different: they have a wide range of sizes and a rage of service and top speeds, and so to create a single metric to allow a comparison and regulation is challenging.

Using information from the public domain, a means of setting a valid TEE target values for warships has been developed which makes use of their given hullform displacement and their declared cruise speed as stated for the associated range calculation.

A method for derivation of the warship TEE is proposed which uses fundamental principles to derive the (CO_2) emitted at the stated cruise speed. The approach includes the Ships Electrical Load (SEL) which is estimated using the IMO equation in this instance. This approach is independent of propulsion configuration and incentivises the design to reduce the SEL as well as to increase the overall propulsion energy efficiency.

To prescribe the required target TEE values, using values derived from existing vessels, 3D contour plots of the Naval Energy Efficiency Measure (NEEM) are presented for warships and for naval auxiliaries on diesel engines at their cruise speed. A spatial, contoured distribution plot of TEE versus the vessels' displacement and cruise speeds, allows targets to be set for vessels with intermediate displacements and speeds. The target TEE value is based on the declared cruise speed and the ship's displacement, the IMO Capacity term for the EEDI.

Key words: Transport energy efficiency, warships

1 Introduction

This study seeks to identify a means by which naval vessels can be assessed for their energy efficiency. The International Maritime Organization (IMO) has already developed a set of Energy Efficiency Metrics (EEM) which allow the efficiency of the design of ships and the operation of ships to be assessed. These metrics are categorised by ship types: e.g. bulkers, tankers and container ships and the required performance is identified through a progressive time-based improvement compared to the average performance of the whole fleet of international ships.

The objective was to identify a means of setting a valid Naval EEM (NEEM) target value for warships, having assessed a set of relevant conference papers that have sought to address this problem in the past.

The study is therefore to identify how can such a metric can be set for warships and other naval vessels, and more importantly, how this value can then be assessed against other ships that may be similar but which are of different displacements and may have different declared cruise speeds.

Author's Biography

John Buckingham is the Chief Mechanical Engineer at BMT. A Fellow of the IMechE, he has over 40 years' experience in marine engineering systems design. He has designed and analysed hybrid power and propulsion systems for naval and commercial vessels and is currently involved with the modelling and analysis of energy saving technologies. He has been the technical lead for a wide range of technology studies and concept development work, specifically on studies relating to hydraulic fluid power and heat management systems.

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The study reviewed the IMO energy efficiency metrics for ship design, Energy Efficiency Design Index (EEDI), and identified where it can be adopted for warship applications. Three leading technical papers were reviewed to identify their ideas that can be developed further.

A calculation for a NEEM is developed which uses first principles to derive the carbon dioxide (CO_2) emitted at a given cruise speed. The approach includes the Ship's Electrical Load (SEL) which has been estimated using the IMO equation in this instance, though the actual value would be included in the design dossier.

This approach is independent of propulsion configuration and incentivises the designer to reduce the SEL at normal cruise conditions, as well as to increase the overall propulsion efficiency.

2 Background

2.1 Commercial Ships

Over twenty years ago, the IMO and other agencies recognised that there is a pressing need for international commercial vessels of all types and sizes to show an appropriate regard to the need to reduce their greenhouse gas (GHG) emissions, by conserving energy and by using the fuel they consume in the most efficient manner.

The commercial maritime sector is advancing towards both improved energy efficiency and reduced emissions of GHG. This has been led by goals set at a multinational level through the IMO and the EU which embody targets to cut emissions by 50% by 2050 compared to a 2008 baseline, and at a national level through targets such as the UK Net Zero by 2050 presented in the Clean Maritime Plan (DfT, 2019).

2.2 Naval Ships

As naval ships are leading diplomatic and functional representatives of their governments', arguably the navies of the world are duty bound to adopt best practice and present the best possible image of their home country.

The UK Secretary of State for Defence, through the Defence Maritime Regulator (DMR), requires that adverse effects on the environment are minimised, and all safety risks are reduced to As Low As Reasonably Practicable (ALARP). There is currently a lack of guidance for naval ship designers and requirement writers in the areas of ship energy efficiency and GHG emissions reduction.

Vessels on Government Service are excluded from the scope of IMO conventions including Marine Pollution (MARPOL) Annex VI (IMO, n.d.), meaning the energy efficiency improvement and emissions reductions metrics proposed by the IMO are not directly applicable to warships. There is however potential that some of the monitoring, verification, and reporting methodologies developed by the IMO to track energy efficiency in the commercial shipping sector could be adapted for warships.

This paper describes a proposed means by which a suitable NEEM may be determined.

2.3 Current IMO EEM

The IMO has a set of regulations under its MARPOL regulations for the prevention and control of pollution from ships, (IMO, Prevention of Air Pollution from Ships: https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx). The world's international commercial shipping fleet is subject to the laws and regulations imposed by the IMO. They are currently subject to three principal efficiency-based criteria:

1. Energy Efficiency Design Index (EEDI);
2. Energy Efficiency Operating Indicator (EEOI);
3. Carbon Intensity Indicator (CII).

This paper will focus on the EEDI only.

2.4 EEDI

The EEDI is a design-based simplistic measure of the energy efficiency of a ship design, stated in the emission rate of equivalent CO_2 emitted to atmosphere per tonne of cargo deadweight, per knot of speed. During the ship design phase, there might be assessments of the EEDI which would be compared to the specific IMO requirement for that vessel. If the EEDI value as designed exceeded the IMO requirement, extra measures are required to allow it to pass below that score.

The EEDI is also a measure of the damage inflicted to the world's environment in term of mass of CO_2 per unit work done (i.e., mass times distance).

The EEDI equation is shown here in simplified format:

EEDI = [Damage/impact to environment]/[Useful work done]

The fuel consumption at a main engine load of 75% is combined with the estimated fuel consumption for electrical power generation relating to a fraction of the main engine rating, not the actual SEL. The fuel rate is multiplied by the carbon factor to yield the emission of CO_2 per hour.

The IMO's EEDI regulation was originally defined in Resolution MEPC.203(62) within the document MEPC 62/24/Add.1 dated 15th July 2011, (IMO, regulations on energy efficiency for ships in MARPOL Annex VI., 2011).

The denominator is the product of the ship's service speed (expected to be when the main engine is at 75% load) and its cargo payload, i.e. its deadweight. The so-called "work done" term therefore does not factor in the weight of the ship transported, and for EEDI, it is also assumed that the ship is operating at 100% full capacity.

The "work done" term also assumes the ship to always be at its declared service speed for a given power, even though it is recognised that actual speeds will vary with the environmental factors stated above for a given shaft power.

At the design stage, the distances travelled and the ship speeds for the ranges of heavy weather, draught and fouling conditions are not known. Therefore, the EEDI uses the rated power of the main engine and its specific fuel consumption at a given design point, and load to determine the fuel consumption.

These short-comings are inevitable for the whole range of ship operating conditions which cannot be adequately captured in one number, but that number, using the same common assumptions, can be used for ship-to-ship comparisons as is now widely the case.

The EEDI for commercial ships are compared based on designated "ship types" i.e. bulker, tanker, containership, etc and their deadweight. Within a specific ship type category, the deadweight is used in an equation to determine the required EEDI performance. The equation has been determined from a set of IMO greenhouse gas (GHG) studies which have analysed the world's fleet to identify average EEDI values, which have been used as a baseline from which the target EEDI is progressively reduced so that there is less and less CO_2 emitted for every tonne-nm of useful work undertaken.

The EEDI is used at the ship design phase to encourage designers to provide future ship designs which are progressively better every four years. The targets encourage:

- progressive ship hullform designs which seek to match the ship's operating profile,
- the uptake of EST to reduce energy consumption and to recover lost energy;
- the uptake of alternative green fuels with have a lower overall Life Cycle Assessment (LCA) impact.

By having a common method for comparing designs, the efficiency of new-build commercial ships has progressively improved as better hullforms, propellers and main engines are developed together with the introduction of Energy Saving Technologies (EST) such as wind propulsion, hull air lubrication and Organic Rankine Cycles (ORC).

2.5 Application of EEDI to Naval Vessels

The application of the IMO's EEDI equations and methodology for warships and other naval auxiliaries is not straight forward. Naval vessels today often have all-electric and hybrid propulsion designs which are more complicated than the two-stoke main engines with fixed pitch propeller designs of most containerships, tankers, and bulkers.

Warships will often have booster engines for a top speed of between 25 to 35 knots. These may be additional main diesel engines or gas turbines. Simply considering the fuel demand when all these engines are operating at

75% is not a suitable representation of the likely power and propulsion (P&P) set up for the cruise speed at which the ship is operating for most of its service duties.

The Capacity term in the EEDI and CII equations is also a value that cannot be easily derived for a warship. The review of warship displacement data shows many with a common average displacement with a very low standard deviation of 1%. The data is based on draught readings by ships staff at the time of monthly trials and so the accuracy may not be as good as indicated. The data shows that the whole warship displacement does not vary significantly, and its variation has a negligible effect on NEEM calculations.

One method of identifying a standard duty speed is to take the given speed often declared for the total amount of carry-on fuel. This is often stated as the range requirement to sail a distance in nautical miles at a given naval service speed in knots. For the purposes of the naval EEDI, only the fuel consumed by those engines normally operating at this naval service speed would be considered. This would be for a common set of environmental operating conditions suggested as:

4. Sea state 1 (i.e. calm with very little wind);
5. A clean hull;
6. Standard displacement, i.e. start of life at standard draught;
7. Trim near as can be to original design intent.

The required resistance, and thus fuel demand, for this condition is straight forward to calculate as there is no requirement for added resistance in waves to be assessed. This can be something which is very difficult to determine with confidence at higher sea states even with first principles or empirical methods.

2.6 EEDI Target Values

If it can be established/agreed that the use of standard displacement for Capacity and the declared range speed to be the servcie speed then the determination of warship EEDI is straight forward, but to what target value is the design to be fashioned?

A warship is not directly comparable to any of the standard IMO ship type classes. A RoRo vessel was considered the closest in terms of operating speed and the use of four-stroke engines. The EEDI for a RoRo passenger vessel with the Type 23 displacement used as the deadweight has an EEDI target score of 30.66 g.CO_2/tonne.nm. This is from the IMO EEDI equation for RoRo vessels:

$$EEDI = 752.16 \times {D_{wt}}^{-0.381}$$ Equation 1.

However, the RoRo’s deadweight is a small part of its displacement, and the Type 23 has low average speed of around 10 knots compared to a RoRo’s 18 knots, so a comparison with a RoRo is thus invalid.

The EEDI values are much lower than CII as the CII value includes the fuel consumed by DG sets when the ship is alongside or at anchor.

Typical EEDI values are likely to be much lower than the calculated EEDI for the given cruise speed because the average speed of warship vessels is now closer to 10 knots, below the declared service speed of many. The study of speed-time operating profile for a number of warships shows most of the speeds to be below the servcie speed declared at build.

2.7 EEXI

The Energy Efficiency EXisting Ship Index (EEXI) has been applied as a one-off assessment to those commercial ships that were not designed to meet the original EEDI regulations, (IMO, GUIDELINES ON THE METHOD OF CALCULATION OF THE ATTAINED ENERGY EFFICIENCY EXISTING SHIP INDEX (EEXI), 10-Jun-2022). It uses the same equation as the EEDI but allows some adaptation where the ship has been operating at a load point away from the 75% main engine loading condition.

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For warships, the IMO EEXI method therefore has the same drawbacks as the commercial ship EEDI.

3. Review of past papers

3.1 Introduction

The limited set of papers and articles on the issue of how to define the energy efficiency of a warship so that it can be compared to other warships and other vessels to identify best practice are shown in Table 1.

Table 1. Warship Energy Efficiency Metrics Papers

Title	**Authors, Year**
Controlling greenhouse gas emissions from ships and the implications for Military Ships,	A R Greig, UCL, 2009
Low Carbon Shipping: Consideration of the applicability of IMO Greenhouse gas regulations to warships,	Dr R.W Bucknell, Lt Cdr T.H.H Wyand & Dr A Greig, UCL, 2012
CO_2 reduction design strategies for naval ships	Lt Cdr B Michalchuck & Prof R Bucknell, UCL, 2014

These papers have been reviewed to identify the ideas they propose and to allow those ideas to be reviewed in the content of this study.

3.2 Greig, 2009

In his paper, "Controlling greenhouse gas emissions from ships and the implications for Military Ships," Dr Alistair Greig of UCL gives a summary of the development of the EEDI and points out that it could be difficult to navies to adapt to meet market-based measures (MBM) because of the work they operate.

Greig recognises that EEOI has a role to play so that a given ship can be operated progressively more efficiently. Clearly, if this were developed further, the MoD's fuel and lubricants consumption (FlubCon) data reporting system could offer feedback on the ship given a suitable algorithm, and/or sufficient additional information.

Greig also identifies that an incentive-based measure may be useful but for the UK, it is known that the FlubCon system, in part, is a means by which Commanding Officers (CO) are incentivised to reduce fuel usage. The ships' COs are given average monthly fuel consumption targets to which they must justify any significant deviation in a text box in their monthly FlubCon submission. Hence, they are obliged to behave within limits but arguably, they are not incentivised to push below them.

3.3 Capacity Term

Greig states that the total ship displacement could be used instead of the IMO deadweight value for the Capacity term as the payload/cargo value is not applicable to warships. The use of the ship's standard displacement can be justified by observing that when bulkers and tankers trade, they unload their cargo to take on new cargo. A warship takes its "cargo," or capability, with it at all times and arguably, the whole ship is one integrated capacity, thus supporting the argument for the whole ship standard displacement to represent the "Capacity" term.

3.4 EEDI Comparisons

For warships, there is no easy set of ship-based EEM for the world's fleet by which to compare the EEDI for a given vessel. Whatever is developed as a NEEM will need to be easy to define whilst still being valid so that there is a general buy-in from other NATO and associated navies. If such navies can agree to pool and share their basic ship P&P system data, there would be a growing basis for performance benchmarking so that informed decisions about setting NEEM limits, and how to design to meet them could be developed further.

3.5 Electrical Demand

Greig states that the electrical power term for warships need not include ship systems such as Replenishment At Sea (RAS), weapons, and sensors. This is compared to liners and ferries where the payload consumption of the passengers is not included as they are part of the payload. However, as outlined above, on ferries the cargo gets off whilst on a warship the crew and overall capability remain, so it is suggested that the SEL is used. This could

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still use the equation stated in the IMO regulations as a first estimate, whilst those who wish to submit the value of the NEEM to a central assessment centre would have the scope to submit a technical dossier which explained why their SEL was lower than the IMO equation.

As the electrical demand of a warship will be a complex interaction of different loads, all of which are essential for the ship to function at all times, it is to be assumed that the SEL when cruising is used, unless a dossier is submitted. As the EEDI is all about economy, i.e. the time-averaged demand, this is considered a valid basis as active use of the weapons and sensors in their high-power states for any period of time will not occur when cruising.

3.6 Electrical Propulsion

Greig notes that the EEDI prevailing in 2009 did not adequately address the need to capture the use of electric propulsion in hybrid and full electrical forms. The Power Take-In (PTI) arrangement is now in the IMO equation set and this allows for this to be treated as in the Type 23 where the electric propulsion motors (EPM) are used for almost all the time.

Given the issues raised by Greig, it is considered that the loading of the electrical propulsion machinery set be determined from the declared cruising speed. If one deconstructs the EEDI approach, they have assumed that main engines operate at 75% load because the engine’s best specific fuel consumption (Sfc) is at this point. This was set before the Global Financial Crisis in 2008, after which slow steaming was introduced to save money and was accommodated by much lower trade volumes. Engine suppliers were then able to tweak the engine’s set-up to achieve an Sfc sweet spot at lower loadings.

If the ship is declared to operate at a given speed when in cruise mode, and this is on electric or mechanical propulsion, the propulsion fuel demand at this condition and the CO_2 emissions that go with it could be used.

3.7 Summary

Greig's paper covers a large number of issues associated with the issue of a warship EEM but does not readily present a proposed way forward. He makes a case for the ship’s displacement being the Capacity value in the EEDI equation.

3.8 Bucknall, 2012

Prof Richard Bucknall’s paper “Low Carbon Shipping: Consideration of the applicability of IMO Greenhouse gas regulations to warships", follows on from Dr Greig’s 2009 paper by supporting the use of ship displacement for the Capacity term instead of payload/deadweight, by showing that the so-called deadweight of a warship never leaves it as it would then be lightship and not in service. He makes the case for the use of the deep departure displacement condition, which may also be considered as the standard displacement.

The variable load due to weapons in terms of weight and power demand is a small change to the ships weight and SEL, respectively and so can be ignored. Bucknall outlines why the gross tonnage should not be used for Capacity as the warship’s superstructure is generally quite small, but more importantly it is not a term used to define warships.

Bucknall proposes a warship EEDI, (wEEDI) using cruise speed conditions for power and fuel consumption purposes. He does not address specifically the SEL demand requirements, or how these can be assumed.

He assumes that only those propulsion engines to be used at cruise speed are assessed and the Sfc comes from their loading at that condition.

Bucknall discusses how ship designers might be tempted to design ships bigger to achieve lower wEEDI. The point is made that the whole set of complex design challenges and the cost of a vessel tend to make the vessel the “right-size” to achieve the right blend of the requirement set of operating performances.

As larger ships are more efficient and have a lower EEDI, the trend to larger warships may enhance the efficiency measure but of course they will still burn more fuel because they still need more energy to achieve the same speed as a small vessel. Warships are not bulkers, so a larger more efficient warship may still carry the same mission systems whereas a larger bulker carries more cargo.

To address the issue with the need to compare a calculated wEEDI against a peer-set of values, Bucknall analysed a set of 12 western warships of various ages to show how their wEEDI varies with displacement.

He observed that warship EEDI values:

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- Have fallen with time;
- Fall with lower cruise speeds;
- Fall with dedicated cruise engines;
- Increase with decreasing displacement, a trend common to commercial ships.

In Figure 1, Bucknall presents a plot of wEEDI vs displacement for the 12 data points and added a regression curve using the logarithmic trend as used by the IMO to determine maximum allowable EEDI values.

Although there is a fair degree of scatter due to the spread of warship ages, the trend of the regression line has the same shape as commercial ships.

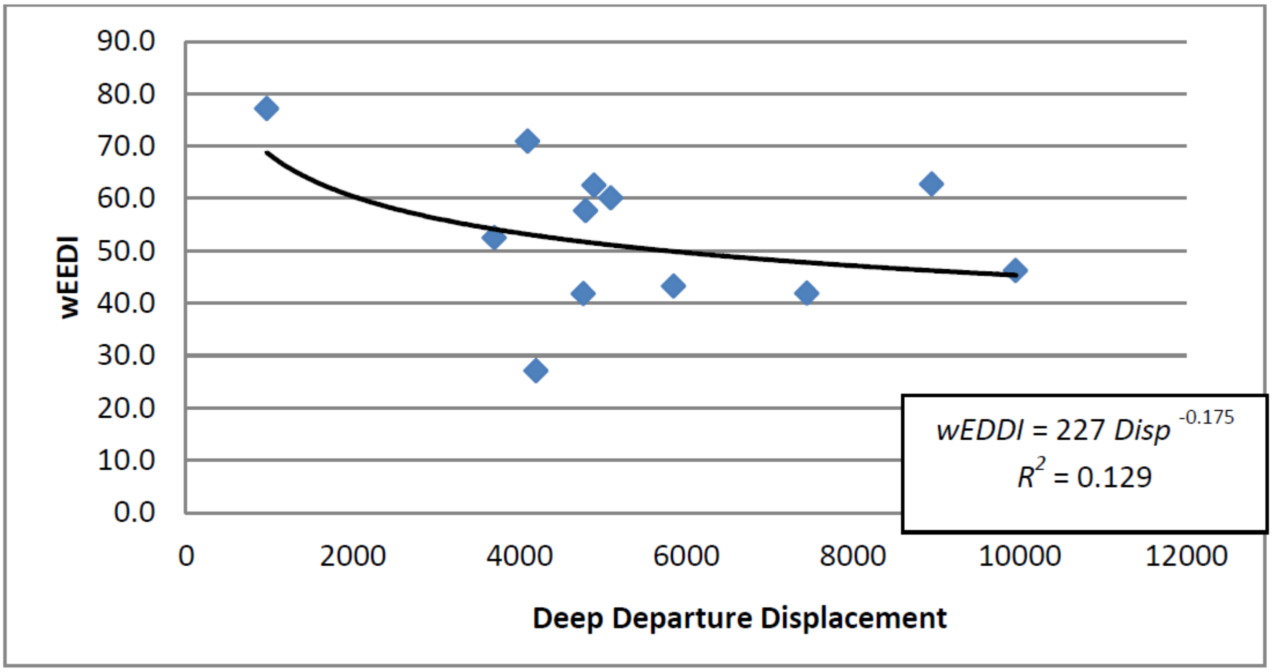

Figure 1. wEEDI versus Deep Departure Displacement

In addition to the observations by Bucknall, the scatter is probably due to a number of factors, chiefly:

- The varying cruise speeds for each vessel ranging from 12 to 20 knots;
- The range of engines used at the cruise speed (diesel or Gas Turbine (GT) engines);
- The different propulsion configurations (electric or mechanical).

The key factor is the variation in cruise speed as the power demand at 20 knots is over four times that at 12 knots. The use of the EEDI trend line as shown in Figure 1 is therefore inadequate for warships if the use of their stated cruise speed is to be adopted in the assessment .

Bucknall’s work shows that there is a basis for adapting the IMO EEDI to develop a naval-based measure of efficiency. However, the obvious observation from his work is that those vessels with similar displacement but slower cruise speeds have a better, lower EEDI. When setting ship’s requirements, the speed is chosen to meet necessary duties associated with accompanying convoys and the company of other ships as well as requirements associated with the time to achieve specific transit distances for operational purposes. It is therefore considered that a means of comparing warships using both speed and displacement as measures is required.

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Bucknall clearly shows that there is a basis for developing a wEEDI or more generically a NEEM, to allow warship energy efficiency performance to be assessed.

The paper does not address SEL or how the cruise speed selection can be accommodated to allow ships of the same displacement but different cruise speeds to be compared to each other for example.

The paper suggests that the wEEDI could accommodate a set of different speeds and it is known that this has been adopted for a recent ship contract competition.

The paper does not observe that the removal of the fixed 75% power load and its alignment with the cruise speed, now makes it much easier to accommodate electric propulsion. By orienting the whole equation around the selected cruise speed, its propulsion load and the standard SEL at cruise speed, the equations are not driven by the individual term for the specific actual architecture of the P&P system, but by the actual total fuel consumed and the associated (CO_2) emissions.

3.9 Michalchuk, 2014

Michalchuk re-iterates the concept of a Warship EEDI as presented in Bucknall's paper. He states that the long lifetimes of warships means that a Fleet EEDI may be better so that the change of the total fleet energy efficiency can be plotted as new ships enter and old ones leave the fleet. He plots the fleet EEDI for 14 navies and shows that the line of EEDI versus average displacement comes out close to the size and shape of the warship EEDI.

However, the fleet EEDI idea has limited usage as it does not allow the ship owner to specify a target EEDI for a new ship design. Michalchuk states that to become more efficient, the ships will get bigger but then this has a natural restraint that such ships would be overly costly. Arguably this situation leads to good place where ship designers will seek an efficient but affordable ship design.

From the work of Michalchuk, Bucknall, and colleagues, it would appear that one way forward for the EEDI criterion to be met is to be driven by not only displacement but also by the cruise speed.

However how does one set the target EEDI for a given speed and displacement? The required target EEDI could take the more developed form of the equation below.

$$EEI_{reqd} = A \times V_{cruise}{}^{b\ X\ Disp^{c}} \qquad \text{Equation 2.}$$

Where A, b and c are coefficients derived from a regression analysis of a set of modern warships. In this way the highly influential factor of ship speed would be accommodated so that the wide range of calculated EEDI values in the figures of Bucknall and Michalchuk are brought closer once cruise speed is factored in.

But curve fitting to one overall equation by complex regression means that there will be significant deviations on some part of the speed-capacity plot.

4 Discussion

4.1 Commercial Vessels

The current measures utilised by the IMO are designed for international shipping which has a large baseline population with a coherent set of estimated efficiencies which have been developed from the four IMO sponsored GHG studies. This set of ship operating efficiency data allows the developed IMO metrics to be compared to the data average, thus showing whether a specific ship is above or below the average value for comparable ships of the same ship type and displacement.

The IMO's EEDI and CII approach both assume that ships of the same deadweight and type will have comparable installed propulsion power and therefore a comparable speed. IMO also assumes, for the most-part, that ships will operate at a full deadweight capacity, when often the ships are in ballast for return trip (e.g. an ore carrier), or part loaded due to commercial reasons.

In the IMO EEDI calculation, the rated power of the electrical power generation demand is based on an equation which uses the rated propulsion power. This is recognised as a generalisation but as the electrical load is usually a small proportion of the propulsion load this is considered so far to be an acceptable approach for simple cargo vessels (i.e. not cruise liners).

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4.2 Naval Vessels

As with commercial vessels, the CO_2 emitted per unit of useful work done is a good basis for assessing the vessel's energy efficiency. For naval vessels, especially warships, there is no deadweight which is carried and then disembarked at the destination port. Arguably the whole vessel is the valuable cargo which stays "onboard" and the weight which is considered as the Capacity when assessing the useful work done.

The study has found that the naval vessel's declared operating speed in its range statement is a good basis for assessing the NEEM as the operational range speed is required for long periods and is also the speed at which the vessel has been designed for its best efficiency at the start of life.

5. NEEM Target Setting

Although Equation 2 indicated that the required EEDI could be prescribed by an equation including a cruise speed term, the ability to have a more flexible 3D NEEM contour plot approach based on the EEDI values of specific existing warships and their service speeds was explored.

The machinery set-up for the declared cruise speed is usually that for an efficient operating condition and so gives the best EEM for the vessel at the speed it is designed to operate at, therefore, this all looks like a sound basis for assessing the NEEM.

However, once a value of NEEM is determined there is no standard set of values against which it can be compared. Unlike commercial ships with standard and therefore comparable speeds, warships can have cruise speeds which are typically between 12 and 20 knots as shown in Figure 2. This large speed range has a correspondingly larger range of power and NEEM.

To allow the NEEM values to be compared, it was considered that a 3D contour plot based on a set of modern, in-service warships could be used to set the baseline targets. To add extra data points, a vessel with an 18 knot cruise speed is also considered at slower speeds to identify the NEEM scores at those points.

Figure 2 shows an example 3D contour plot with target NEEM contours in g.CO_2/tonne.nm on the z-axis, ship cruise speed on the y-axis and the ship's displacement (i.e. Capacity) in tonnes on the x-axis. This plot is for diesel powered ships only, i.e. for ships that are operating on diesel engines at the cruise speed. This includes warships such as Type 26 up to a specific speed even though they use GT boost engines above this speed. The plot is based on calculated NEEM at a range of speeds for Type 23, Type 31, Type 45, and the Type 26 as well as models of other vessels.

The models to define the performance have been developed using publically available data which was then fed into the BMT marine P&P modelling capability to determine the fuel consumption at the declared service speed, and at other speeds to help populate the plot.

The current example version shown is based on relatively few data points and so the contours are not as regular as they would be with more data points. However, it may also indicate step points in ship hullform design for the top design speed will vary between ships and this will affect their slenderness (block coefficient).

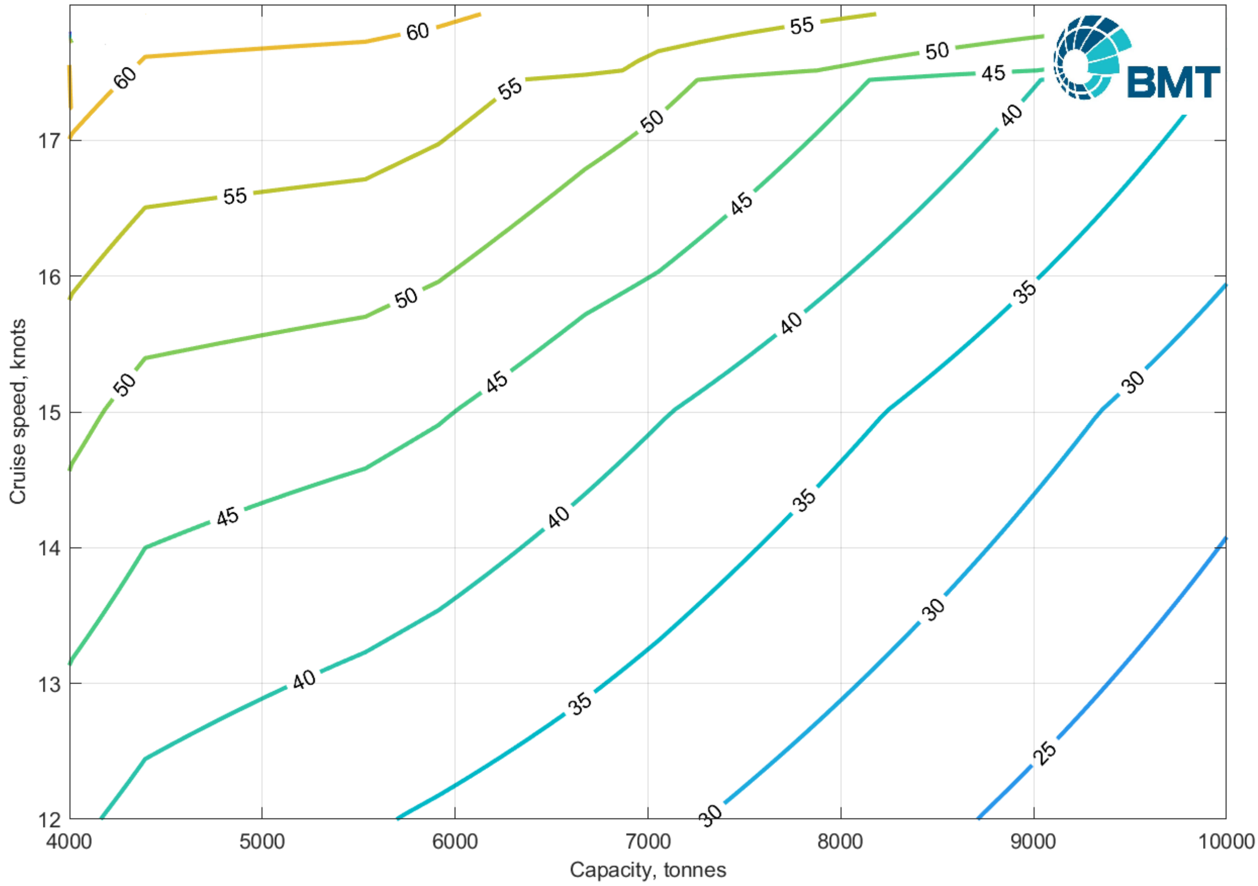

Figure 2. 3D contour plot of NEEM on warship speed v displacement

Figure 2 therefore, may serve as the basis of a reference plot from which the current NEEM for a given speed and displacement for a new build might be expected to occur. The Ship Authority may then choose to set a target NEEM for the design competition which is less than the derived current stand from the plot.

As an example, a 6,000 tonne ship with a 15 knot cruise speed is indicated to have a current NEEM of 45g.CO_2/tonne.nm. The Authority may choose to set a design target which is below this value so as to encourage a positive approach to designing the ship for efficiency at this speed. The offered EEDI performance with its supporting technical dossier will then provide a basis for scoring the offered designs for this criterion.

The reference plot may also allow the benefits of changes to ships, such as the addition of an EST, to be compared.

There is a clear change of EEDI between warships that are designed for a high top speed on GT engines, and naval auxiliaries which operate at much lower top speeds and who use diesel for all P&P duties. Consequently, Figure 3 shows the contour plot of NEEM values on ship cruise speed (y-axis) versus ship displacement (x-axis) for non-warships, i.e. naval auxiliaries.

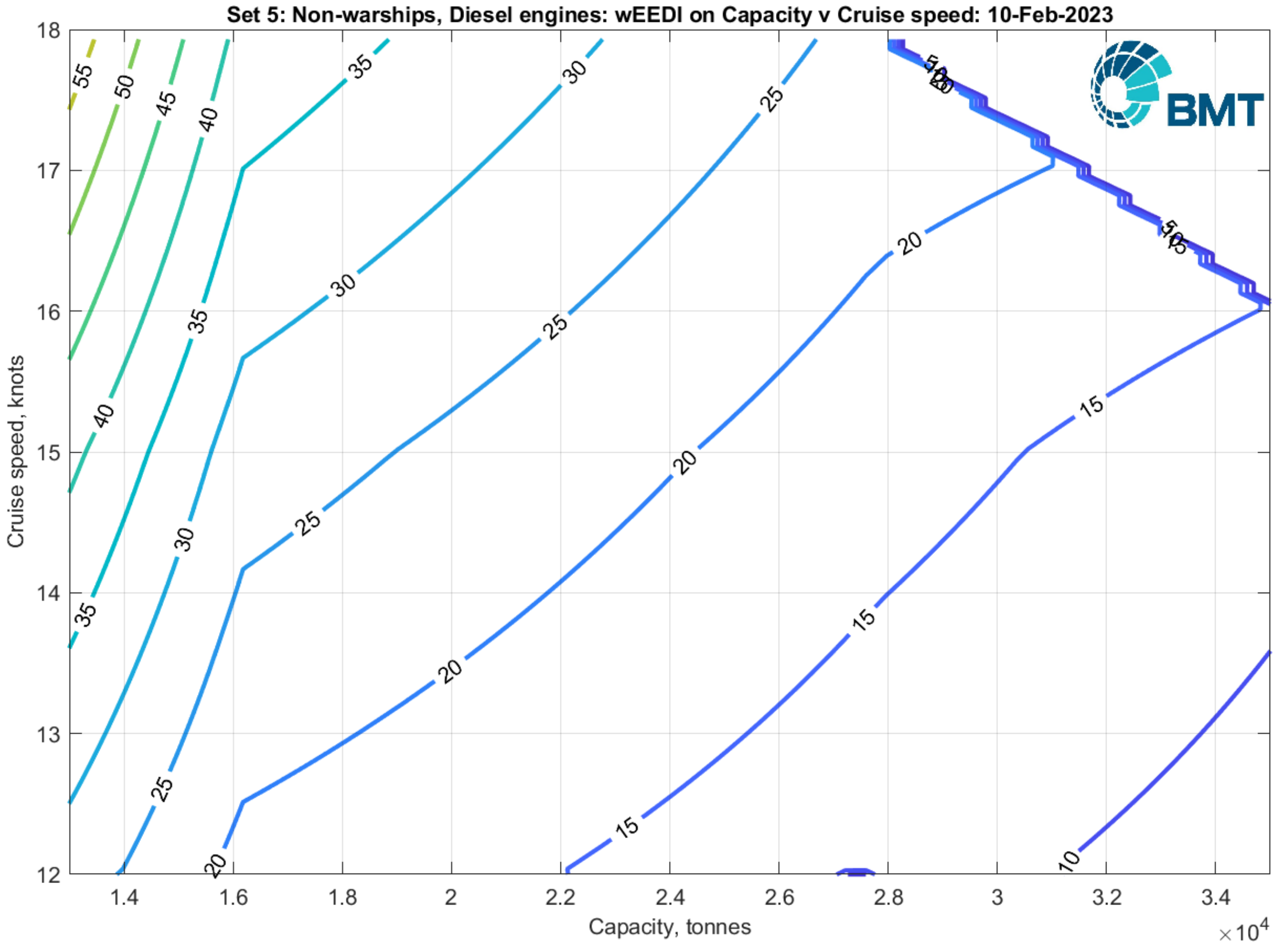

Figure 3. 3D contour plot of NEEM on naval auxiliary speed v displacement

As naval auxiliaries are closer to commercial bulkers and tankers, future work may consider how similar the plot compares with the IMO EEDI equation settings.

6 Conclusions

The study has reviewed the IMO energy efficiency metrics and has identified where they can be adopted for warship applications. Three leading technical papers on the subject have also been reviewed to identify their ideas that can be developed further.

The NEEM plot has been based on the basic P&P information for a set of existing modern warship designs. The EEDI value is based on the vessel's cruise speed and its capacity term is based on its displacement. There would be separate contour plots for vessels which rely on GT engines at the nominated cruise speed.

A calculation for the ship's NEEM score is developed which uses first principles to derive the CO_2 emitted at a given cruise speed. The approach includes the ship's SEL which in this study has been estimated using the IMO equation. This approach is independent of propulsion configuration and incentivises the design to reduce the SEL as well as to increase the overall propulsion efficiency.

To prescribe the required NEEM target values, using values derived from existing vessels, target NEEM contour plots are presented for warships on diesel engines and for naval auxiliaries. The NEEM score is based on the vessel's cruise speed and its capacity term is set to its displacement.

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References

DfT. (2019). Retrieved from Clean Maritime Plan: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815664/clean-maritime-plan.pdf

Fuels, I. (2019). *Buying fuel on calorific value as means to achieve savings.*

IMO. (n.d.). Retrieved from Marpol Annex VI: https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx

IMO. (10-Jun-2022). GUIDELINES ON OPERATIONAL CARBON INTENSITY INDICATORS AND THE CALCULATION METHODS (CII GUIDELINES, G1). *MEPC 78/17/Add.1, RESOLUTION MEPC.352(78).*

IMO. (10-Jun-2022). GUIDELINES ON THE METHOD OF CALCULATION OF THE ATTAINED ENERGY EFFICIENCY EXISTING SHIP INDEX (EEXI). *MEPC 78/17/Add.1, RESOLUTION MEPC.350(78).*

IMO. (2011). regulations on energy efficiency for ships in MARPOL Annex VI.

IMO. (n.d.). Prevention of Air Pollution from Ships: https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx.

ISO. (n.d.). *ISO 8217, Quality specifications for marine bunker fuels.*

MoD. (2013). *Def STan 91-004, Fuel, Naval, Distillate NATO Code: F-76 Joint Service Designation DIESO F-76, Issue 9* .

OLMER, N. (2017). GREENHOUSE GAS EMISSIONS FROM GLOBAL SHIPPING, 2013–2015.

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