A new approach on the upgrade of energetic system based on green energy. A complex comparative analysis of the EEDI and EEOI

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Abstract. In recent years, many environmental organizations was interested to optimize the energy consumption which has become, today, one of the main concerns to the whole world. From this point of view, the maritime industry, has strove to optimize the fuel consumption of ship through the development of engines and propulsion system, improve the hull design, or using alternative energies, this way making a reduction in the amount of CO₂ released to the atmosphere. The main idea of this paper is to realize a complex comparative analysis of Energy Efficiency Design Index and Energy Efficiency Operational Indicator which are calculated in two cases: first, in a classical approach for a crude oil super tanker ship and second, after the energy performance of this ship has been improved by introducing alternative energy sources on board.

1. Introduction
Nowadays, shipbuilding industry, is trying to improve the energy performance. In this paper we have a crude oil super tanker ship of 305000 dwt, and we are studying the possibility of introducing alternative energy sources and improving existing equipment on board. For VLCC ships, there are several possibilities of equipping them with LNG tanks are available. For smaller ship sizes, prefabricated vacuum-isolated cryogenic tanks can be found in a wide range of sizes with an allowable working pressure of up to 20 bars. Some of these tanks have been installed and are already in operation on ferries and supply vessels. We try to prove ship efficiency by introducing alternative technologies on board like shaft generators and motors, wind turbines, photovoltaic panels and dual fuel main engine. After that we calculate efficiency operational index and indicator for both states of ship and conclude the results (‘[1]’).

2. Considerations on energy efficiency operational index - EEOI and energy efficiency design index - EEDI
2.1. Energy Efficiency Design Index - EEDI
Energy Efficiency Design Index (EEDI) is a measure of ships energy efficiency (g/t\cdot nm) and is calculated by the following formula (‘[1]’):
C_F - is a non-dimensional conversion factor for fuel consumption, measured in g and CO_2 emission;
V_{ref} - is the ship speed, measured in nautical miles per hour (knot);
Capacity - is deadweight of the ship;
P - is the power of the main and auxiliary engines, measured in kW;
P_{ME(i)} - is 75 per cent of MCR for each main engine;

\[ P_{ME(i)} = 0.75 \times (MCR_{ME(i)} - P_{PTO(i)}) \]  

P_{PTO(i)} - is 75 per cent of nominal power of each shaft generator;
P_{PTI(i)} - is 75 per cent of the rated power consumption of each shaft motor divided by the weighted average efficiency of the generators;
P_{eff(i)} - is the output of the innovative mechanical energy efficient technology for propulsion at 75 per cent main engine power;
P_{AEeff(i)} - is the auxiliary power reduction due to innovative electrical energy efficient technology measured at \( P_{ME(i)} \);
P_{AE} - is the required auxiliary engine power to supply normal maximum sea load including necessary power for propulsion machinery / systems and accommodation ('[4]').

For the reference crude oil super tanker, main engine has a power up to 10000 kW, and \( P_{AE} \) is written:

\[ P_{AE(MCR ME>10000 kW)} = (0.025 \times \sum_{i=1}^{n ME} MCR_{ME(i)}) + 250 \]  

SFC - is the certified specific fuel consumption, measured in g/kWh, of the engines;
f_j - is a correction factor which for the crude oil super tank is written:

\[ f_j = \frac{0.516 \times 0.07^{0.57}}{\sum_{i=1}^{n ME} P_{ME(i)}} \]  

f_w - is a non-dimensional coefficient indicating the decrease of speed in representative sea conditions of wave height;
f_{eff(i)} - is the availability factor of each innovative energy efficient technology;
f_i - is the capacity factor for any technical / regulatory limitation on capacity, and should be assumed to be one (1.0) if no necessity of the factor is granted:

\[ f_i = \frac{0.00115 L_{PP}^{2.36}}{\text{capacity}} \]  

2.2. Energy Efficiency Operational Indicator - EEOI

The Energy Efficiency Operational Indicator is defined as the ratio of mass of CO_2 (M) emitted per unit of transport work.

The Energy Efficiency Operational Indicator is calculated with this formula:

\[ EEOI = \frac{\text{Fuel consumption} \times \text{Carbon}}{\text{Cargo transported} \times \text{Distance}} \]  

The unit of EEOI depends on the measurement of cargo carried or work done, e.g., tones CO2 / (tones · nautical miles), tones CO2 / (TEU · nautical miles), tones CO2 / (person · nautical miles), etc
3. Calculation of energy efficiency indicators for two kind of power system configurations

3.1. Calculation of Energy Efficiency Design Index for crude oil super tanker in design version

To calculate the EEDI will adopt a number of parameters for the main engine, auxiliary engines, innovative technology and transport parameters according to the formulas below.

Parameters for main engine:

a. Conversion factor for heavy fuel oil:

\[ C_{FME} = 3.1144 \]  \hspace{1cm} (7)

b. Main engine power:

\[ P_{ME} = 0.75 \times (\text{MCR}_{MEi} - P_{PTOI}) = 0.75 \times (27020 - 0) = 20265 \text{ kW} \]  \hspace{1cm} (8)

c. Specific fuel consumption:

\[ SFC_{FME} = 163.6 \frac{\theta}{\text{kW} \cdot \text{h}} \]  \hspace{1cm} (9)

Parameters for auxiliary engines:

a. Necessary power for auxiliary engines:

\[ P_{AE(MCRME>10000 \text{ kWe})} = (0.025 \times \sum_{i=1}^{n_{ME}} \text{MCR}_{MEi}) + 250 = 0.025 \times 27020 + 250 = 925.5 \text{ kW} \]  \hspace{1cm} (10)

b. Conversion factor for marine diesel oil:

\[ C_{FAE} = 3.20 \]  \hspace{1cm} (11)

c. Specific fuel consumption:

\[ SFC_{FAE} = 190 \frac{\theta}{\text{kW} \cdot \text{h}} \]  \hspace{1cm} (12)

d. Corection factor:

\[ f_j = \frac{0.516 \cdot 1^{0.87}}{\sum_{i=1}^{n_{ME}} P_{IME}} = \frac{0.516 \cdot 324^{1.87}}{27020} = 0.945 \]  \hspace{1cm} (13)

e. Power for shaft generator (for design ship there is no shaft generators):

\[ P_{PTG} = 0 \text{ kW} \]  \hspace{1cm} (14)

f. Availability factor of each innovative energy efficient technology.

At design ship there is no efficiency technology.

\[ f_{eff} = 1 \]  \hspace{1cm} (15)

g. Auxiliary power reduction due to innovative electrical energy efficient technology.

At design ship there is no efficiency technology.

\[ P_{AE_{eff}} = 0 \text{ kW} \]  \hspace{1cm} (16)

Parameters for innovative technology:

At design ship there is no efficiency technology.
Parameters for ship transport work:

a. Capacity factor:

\[ f_i = \frac{0.00115^{1.36}}{capacity} = \frac{0.00115 \times 324^{3.36}}{305301} = 1.025 \]  \hspace{1cm} (17)

b. Factor for decrease of speed in representative sea conditions of wave height:

\[ f_w = 1 \]  \hspace{1cm} (18)

c. Ship speed:

\[ v_{ref} = 15.38 \]  \hspace{1cm} (19)

d. Ship deadweight:

\[ capacity = 305301 \text{ tdw} \]  \hspace{1cm} (20)

After these parameters, we can calculate Energy Efficiency Design Index for crude oil super tanker in design version:

\[ EEDI = \frac{f_i \times P_{ME} \times C_{FME} \times SFC_{FME} + P_{A} \times C_{FAR} \times SFC_{FAR}}{f_w \times v_{ref} \times capacity} \]  \hspace{1cm} (21)

\[ EEDI = \frac{0.945 \times 20265 \times 3.1144 \times 183.6 + 925.5 \times 3.20 \times 190}{1.025 \times 15.38 \times 305301} \]  \hspace{1cm} (22)

\[ EEDI = \frac{9757444.88 + 562704}{5225989.86} = 2.14 \text{ g/t \* knots} \]  \hspace{1cm} (23)

**Figure 1.** Value and interpretation of EEDI for ship initial design
After calculation is concluded that value of EEDI are within the tier 1 and tier 2 (see figure 1). So, for design ship we have a good result.

3.2. Parameters for calculation of Energy Efficiency Design Index for crude oil super tanker with energy efficient technologies.

For crude oil super tanker ship we adopt three type of energy efficient technologies on bord (‘[5]’):
- dual fuel main engine
- shaft generator
- wind turbines
- photovoltaic pannels (‘[2]’)

Against 1.1 paragraph we have some parameters for efficient energy:

a. Conversion factor for LNG (liquefied natural gas):
\[C_{FME} = 2.75\] (24)

b. Power for shaft motor:
\[P_{PTI} = 0.75 \times \frac{P_{SM}}{n_{SM}} = 812.5 \text{ kW}\] (25)
\[P_{SM} = 976 \text{ kW}\] (26)

c. Power for shaft generator:
\[P_{PTO} = 0.75 \times P_{SG} = 731.25 \text{ kW}\] (27)
\[P_{SG} = 976 \text{ kW}\] (28)

d. Availability factor of each innovative energy efficient technology (we have the same factor for wind turbines and photovoltaic panels) (‘[2]’).
\[f_{\text{eff}} = 1\] (29)

e. Auxiliary power reduction due to innovative electrical energy efficient technology.
This time, we have wind turbines energy and photovoltaic panels energy like electrical energy efficient technology (‘[3]’):
\[P_{AEff\text{turbine}} = 250 \text{ kW}\] (30)
\[P_{AEff\text{panels}} = 15 \text{ kW}\] (31)

3.3. Calculation of EEDI (option 1, we use shaft motor, wind turbines and photovoltaic pannels)

\[EEDI = \frac{f \times P_{ME} \times C_{FME} \times SFC_{FME} + (P_{AE} + f_{\text{eff}} \times P_{PTI}) \times C_{FAE} \times SFC_{FAE}}{f \times s_{\text{ref}} \times V \times \text{capacity}}\] (32)

\[EEDI = \frac{9345154.08 + [1693.31 - 265] \times 3.2 \times 190}{5225989.86} = 195 \text{ g/t * knots}\] (33)

\[EEDI = \frac{9345154.08 + 868414}{5225989.86} = 1.95 \text{ g/t * knots}\] (34)
At point 3.1. we had a value of 2.14 g/t * knots (see figure 2).
So, to conclude, was a drop with 0.19 g/t * knots.

![Energy Efficiency Design Index](image)

**Figure 2.** Value and interpretation of EEDI for ship with efficient energy and shaft motor.

### 3.4. Calculation of EEDI (option 2, we use shaft generator, wind turbines and photovoltaic pannels)

\[
EEDI = \frac{f_{\text{PM}} x C_{\text{FME}} x SFC_{\text{FME}} + (P_{\text{AE}} - f_{\text{eff}} x P_{\text{AREf}}) x C_{\text{FAB}} x SFC_{\text{FAB}}}{f_{\text{PM}} x v_{\text{ref}} x \text{capacity}}
\]  

(35)

\[
EEDI = \frac{9345154.08 + 112.06 \times 3.2 \times 190}{5225989.86}
\]

(36)

\[
EEDI = \frac{9413285.56}{5225989.86} = 1.80 \text{ g/t * knots}
\]

(37)

At point 3.1. we had a value of 2.14 g/t * knots (see figure 3), so like result was a drop with 0.34 g/t * knots.
**Figure 3.** Value and interpretation of EEDI for ship with efficient energy and shaft generator

3.5. Calculation of Energy Efficiency Operational Indicator for crude oil super tanker without efficiency energy technologies

To calculate EEOI we will adopt a ship voyage of 30 days. So, we have parameters below.

a. Fuel consumed (tones):

\[ \text{Fuel}_{\text{consumed ME}} = 977.20 \text{ tones HFO} \]  
\[ \text{Fuel}_{\text{consumed Boiler}} = 52.30 \text{ tones HFO} \]  
\[ \text{Fuel}_{\text{consumed DG}} = 143.2 \text{ tones MDO} \]

b. Carbon factor for each type of fuel:

\[ C_{\text{Carbon}} = 3.1144 \text{ for HFO} \]
\[ C_{\text{Carbon}} = 3.20 \text{ for MDO} \]

c. Crude oil transported:

\[ \text{Cargo}_{\text{transported}} = 250000 \text{ tonnes} \]

d. Distance during ship voyage (miles):

\[ \text{Distance} = 6506 \text{ miles} \]

\[ \text{EEOI} = \frac{977.2 \times 3.1144 + 52.3 \times 3.1144 + 143.2 \times 3.20}{250000 \times 6506} = 2.25 \times 10^{-6} \text{ tCO2/t x miles} \]
In conclusion we observe that EEOI value is 2.25 gCO2/t x mile. In figure no. 4 we had good result.

![Figure 4. Interpretation of EEOI for ship without efficient technologies](image)

**Figure 4.** Interpretation of EEOI for ship without efficient technologies

3.6. Calculation of Energy Efficiency Operational Indicator for crude oil super tanker without efficiency energy technologies, but with dual fuel main engine

To calculate EEOI we will adopt a ship voyage of 30 days. So, we have parameters below.

a. Fuel consumed (tones):

\[ \text{Fuel}_{\text{consumed ME}} = 977.20 \text{ tones LNG} \]  
\[ \text{Fuel}_{\text{consumed Boiler}} = 52.30 \text{ tones HFO} \]  
\[ \text{Fuel}_{\text{consumed DG}} = 143.2 \text{ tones MDO} \]

b. Carbon factor for each type of fuel:

\[ C_{\text{Carbon for LNG}} = 2.75 \]  
\[ C_{\text{Carbon for HFO}} = 3.1144 \]  
\[ C_{\text{Carbon for MDO}} = 3.20 \]

c. Crude oil transported:

\[ \text{Cargo}_{\text{transported}} = 250000 \text{ tones} \]

d. Distance during ship voyage (miles):

\[ \text{Distance} = 6506 \text{ miles} \]

\[ \text{EEOI} = \frac{977.2 \times 2.75 + 52.3 \times 3.1144 + 143.2 \times 3.20}{250000 \times 6506} \approx 2.03 \times 10^{-6} \text{ tCO2/t x miles} \]

In conclusion we observe that EEOI value is 2.03 gCO2/t x mile. In figure no. 5 we had good result.
3.7. Calculation of Energy Efficiency Operational Indicator for crude oil super tanker with efficient energy technologies

We calculate EEOI for a voyage of 30 days. To calculate the operational index we adopt the parameters below.

a. Fuel consumed (tones):

\[ \text{Fuel}_{\text{consumed,ME}} = 977.20 \text{ tones LNG} \]  \hspace{1cm} (55)
\[ \text{Fuel}_{\text{consumed,Boiler}} = 3.5 \text{ tones HFO} \]  \hspace{1cm} (56)
\[ \text{Fuel}_{\text{consumed,DS}} = 143.2 \text{ tones MDO} \]  \hspace{1cm} (57)

b. Carbon factor for each type of fuel:

\[ C_{\text{Carbon}} = 2.75 \text{ for LNG} \]  \hspace{1cm} (58)
\[ C_{\text{Carbon}} = 3.1144 \text{ for HFO} \]  \hspace{1cm} (59)
\[ C_{\text{Carbon}} = 3.20 \text{ for MDO} \]  \hspace{1cm} (60)

c. Crude oil cargo:

\[ \text{Cargo}_{\text{transported}} = 250000 \text{ tones} \]  \hspace{1cm} (61)

d. Distance during ship travel (miles):

\[ \text{Distance} = 6506 \text{ miles} \]  \hspace{1cm} (62)

\[ EEOI = \frac{977.2 \times 2.75 + 3.5 \times 3.1144 + 143.2 \times 3.20}{250000 \times 6506} = 1.95 \times 10^{-6} \text{ tCO2/t x mile} \]  \hspace{1cm} (63)
In conclusion we observe that EEOI value is 1.95 gCO2/t x mile. In figure no. 6 we had very good results. Between initial design and design with innovative energy was a drop of 0.30 gCO2/t x mile.

![Figure 6. Interpretation of EEOI for ship with efficient technologies](image)

4. Comparative analysis of energy efficient technologies results

4.1. Comparative analysis of Energy Efficiency Design Index.

In conclusion, comparative results for the values of EEDI are:

- for option no.1 with shaft motor, wind turbines and photovoltaic pannels, we had a value of 1.95 g/t * knots, against 2.14 g/t * knots with ship without energy efficient technologies. So, was a drop with 0.19 g/t * knots,
- for option no.2 with shaft generator, wind turbines and photovoltaic pannels, we had a value of 1.80 g/t * knots, against 2.14 g/t * knots with ship without energy efficient technologies. So, was a drop with 0.34 g/t * knots.

![Figure 7. Interpretation of EEDI](image)
4.2. Comparative analysis of Energy Efficiency Operational Indicator
Calculating EEOI just with dual fuel, we observe that value is 2.03 gCO2/t x mile against the ship without efficient energy technologies with value of 2.25 gCO2/t x mile. So was a drop of 0.22 gCO2/t x mile.

For ship with dual fuel main engine and innovative technologies we had a drop of 0.30 gCO2/t x mile against the ship in design phase.

![Figure 8. Interpretation of EEOI for ship with efficient technologies](image)

5. Conclusions
Using LNG as ship fuel will reduce sulfur oxide (SO\_x) emissions by 90% to 95%. This reduction level will also be mandated within the so-called Emission Control Areas (ECAs) by 2015. A similar reduction is expected to be enforced for worldwide shipping by 2020. Global natural limited resources dominate our times, and the maritime industry faces the same challenges as the rest of the world in terms of energy consumption. Ship owners and port authorities want to reduce fuel consumption and improve efficiency. This will please both, the investors and legislators, because, ultimately, lower energy consumption means lower costs. With this paper we tried to prove that alternative technologies mean lower pollution and lower energy consumption means lower costs. By calculating energy efficiency indicators for two kind power configuration of a crude oil super tanker ship, we try to show which is the difference between a ship with and without innovative technologies on-board. Without innovative technologies, we calculate EEOI and EEDI only for main engine, auxiliary diesel engine and boiler. Also, we adopt efficient technologies on-board like dual fuel main engine, shaft motor and generator, wind turbines and photovoltaic panels ([6]). In modern state, power configuration of ship was the dual fuel main engine, auxiliary diesel engine and boiler. Also, we adopt efficient technologies on-board like dual fuel main engine, shaft motor and generator, wind turbines and photovoltaic panels.

After calculation of energy efficiency indicators, for energy efficiency design index we had results:
- in design state we calculate a value of 2.14 g/t * knots, that is as a good value referring at INO tiers.
- when we use innovative technologies with shaft motor configuration we had a value of 1.95 g/t * knots, with a difference of 0.19 g/t * knots,
-when we use innovative technologies with shaft generator configuration we had a value of 1.80 g/t * knots, with a difference of 0.29 g/t * knots against ship without innovative technologies.

To conclude results for energy efficiency design index, using innovative technologies like dual fuel main engine, photovoltaic panels, wind turbines, shaft motor and generator we had very good results referring at IMO tiers expects for 2020 - 2025 year (‘[7]’).

After calculation of energy efficiency indicators, for energy efficiency operational indicator we had results:

- in design state we calculate a value of 2.25 gCO$_2$/t x mile, that is a a good value that characterizes last ships in service,
- when ship use just a dual fuel LNG main engine and without another innovative technologies, we calculate a value of 2.03 gCO2/t x mile, that is a a very good value and is above the results for last ships in service,
- when ship use a dual fuel LNG main engine and innovative energy, we calculate a value of 1.95 gCO$_2$/t x mile, that is a a very good value that characterizes the ships of 2020 – 2025 year (‘[8]’).

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