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RETROFIT SOLUTIONS TO ACHIEVE 55% GHG REDUCTION BY 2030

Characterization of the ship systems and Electric Load Analysis (ELA)

WP 6 – Electrification and energy management of on-board systems
Task 6.1 – Comprehensive investigation of potential power train
D6.1 – Characterization of the ship systems and Electric Load Analysis (ELA)
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Quality check review

Reviewer (s)	Main changes / Actions
Alessandro Iafrati (CNR)	Indications provided for: integration of the description of the case study (bulk carrier M/V Kastor), including powertrain, electrical power system (SLD) and the set of collected data; further description of innovative energy efficiency-related technologies such as photovoltaics, inverters for large motors, shaft generator systems; update of the list of references.
Cecilia Leotardi (CNR)	Technical and editorial review towards the final version

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Executive Summary

The ship's energy efficiency indicators named Energy Efficiency Design Index (EEDI) for new ships and Energy Efficiency Existing Index (EEXI) for existing ships, as well as Carbon Intensity Index (CII) related to carbon emissions for each specific ship, have been introduced by the International Maritime Organization (IMO) helping to characterize, or not, every ship as energy efficient.

Various technological solutions are proposed from time to time and applied to ships in order to make them energy efficient in compliance with the requirements of decarbonization regulations that they must meet both during their voyages and during their stay in ports.

Aim of the deliverable is to review the energy efficiency indexes of ships and to present technological solutions for their improvement focusing on the on-board electric energy systems.

The report consists in two main sections. Specifically, Section 2, presents in brief the basic energy indicators of ships, whereas Section 3 presents specific innovative solutions for the improvement of electric energy efficiency of the ship and, hence, the improvement of the total ship's energy efficiency index. Furthermore, case studies are included in Section 3 proving and supporting the increase of electrical efficiency of the ship by applying said solutions.

1 Introduction

The increasing demand for greener ships has become an ultimate aspiration in modern times.

From the first time that the IMO energy efficient indexes were introduced up to today a big effort was provided by all the shipping industry to reduce the greenhouse gases and produce ships which could be identified as eco-friendly. Voyage optimization, energy management new hull designs, all electric ship and application of alternative fuels are some of the solutions that have been proved to reduce the fuel consumption during operation of a ship. On the other hand, the task for greater energy efficiency improvements has triggered stricter legislation constraints leading the classification societies to issue new rules and regulations.

The development of maritime innovative applications combining increased robustness and flexibility in on board electrical systems aiming to reach the full electric vessel are being harmonized with the environmental request to restrain ships' harmful footprint. As the quest for the full-electric vessel seems to be more progressive than ever, innovative applications are emerging to make the reliable electric propulsion, the installation of battery energy storage systems, the use energy saving devices, etc., exceptionally promising.

2 Energy Efficiency Indicators

2.1 Energy Efficiency Design Index (EEDI)

The Energy Efficiency Design Index, EEDI, which is referred to new ships, is an index that calculates grams of CO_2 per transport work (gr CO_2 / ton-miles). It can be expressed as the ratio of '**Impact to environment**' divided by '**Benefit for society**'.

$$\text{EEDI} = \frac{\text{Impact to Environment}}{\text{Benefit for society}}$$

In other words

$$\text{EEDI} = \frac{\text{CO}_2\text{ Emissions}}{\text{Transport Work}}$$

2.1.1 Calculation of EEDI for new ships

EEDI is the most important tool that measures how energy efficient a ship is. It is related to the design, the equipment and the machinery of the ship and helps to reduce the greenhouse gases (GHG) produced by shipping.

The Marine Environment Protection Committee (MEPC) has developed an energy efficiency index for new ships (IMO, 2009) in order to stimulate innovation and technical development of all the individual elements that affect ship's energy efficiency from its design phase.

The attained energy efficiency design index for new ships is a measure of the CO_2 performance of the ships and is calculated using the formula given in

Figure 1, [1].

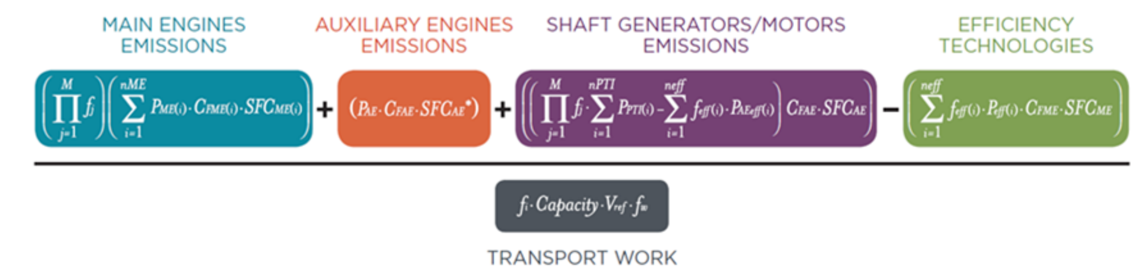


Figure 1: Calculation formula of EEDI [1]

Above formula is not applicable on ships with electric propulsion, steam turbine plants or any other hybrid propulsion system.

2.1.2 Explanation of terms

For the calculation of EEDI all the needed explanation of terms are included in the EPC.1/Circ.681 [1]. In brief the terms are presented in Table 1, which includes the source from where each term can be derived.

Table 1: Brief explanation of terms of EEDI

Parameter	Description	Source
C_F	Non-dimensional conversion factor between fuel consumption and CO_2 emission (see Table 2).	MEPC245(66) "2014 Guidelines on the calculation of the Attained EEDI for new ships" [2]
V_{ref}	Ship speed in nautical miles per hour	At design stage, speed – power curves obtained from model testing. At final stage, Sea trial report
Capacity	Function of deadweight (DWT). Explained in 2.3 and 2.4 of MEPC 245 (66) "2014 Guidelines on the calculation of the attained EEDI for new ships"	Stability booklet
P_{ME}	75% of the main engine Maximum Continuous Rating (MCR) in kW	NOx Technical file
P_{AE}	Auxiliary Engine power	MEPC245(66) "2014 Guidelines on the calculation of the Attained EEDI for new ships" [2]
P_{PTI}	75% of rated power consumption of shaft motor	
P_{eff}	Output of innovative mechanical energy efficient technology for propulsion at 75% main engine power.	
P_{AEeff}	Auxiliary power reduction due to innovative electrical energy efficient technology.	
SFC	Certified specific fuel oil consumption in gr/kWh	NO_x technical file
f_j	Correction factor to account for ship specific design elements.	MEPC245(66) "2014 Guidelines on the calculation of the Attained EEDI for new ships" [2]
f_w	Non dimensional coefficient indicating the decrease of speed in representative sea condition of wave height / frequency and wind speed	
fi	Capacity factor for any technical regulatory limitation on capacity.	
fc	Cubic capacity correction factor (for chemical tankers and gas carriers)	
fl	Factor for general cargo ships equipped with cranes and other cargo-related gear to compensate in a loss of deadweight of the ship	
feff	Availability factor of innovative energy efficiency technology	MEPC.1/Circ.815 [3]

Table 2: C_F values based on the type of fuel [1]

FUEL	TYPE	CARBON CONTENT	C_F (t-CO_2/t-Fuel)
Diesel / Gas Oil	ISO8217 grade DMX up to DMC	0.875	3.206
Light fuel oil (LFO)	ISO8217 grade RMA up to RMD	0.86	3.151040
Heavy Fuel Oil (HFO)	ISO8217 grade RME up to RMK	0.85	3.114400
Liquified Petroleum Gas (LPG)	Propane - Butane	0.819 – 0.827	3.000 – 3.030
Liquified Natural Gas (LNG)		0.75	2.750

2.1.3 EEDI limits

The EEDI index has an upper limit for every type and size of vessel. This limit is depending on the time period for which the study is carried out while it's reduced at regular time intervals (phases).

$$\text{Attained EEDI} \leq \text{Required EEDI} = \left(1 - \frac{X}{100}\right) \times \text{Reference}$$

where X is the reduction rate as given in Table 4.

The base line can be derived from below formula.

$$\text{Reference} = a \times b^{-c}$$

Where the a, b and c parameters are based on ship's type and given in Table 3.

Table 3: Parameter values based on ship's type [4]

Type of vessel	a	b	c
Bulk carrier	961.79	DWT of the ship	0.477
Gas carrier	1120.00	DWT of the ship	0.456
Tanker	1218.80	DWT of the ship	0.488
Container ship	174.22	DWT of the ship	0.201
General cargo ship	107.48	DWT of the ship	0.216
Refrigerated cargo carrier	227.01	DWT of the ship	0.244
Combination carrier	1219.00	DWT of the ship	0.488
Ro-ro cargo ship (vehicle carrier)	*	DWT of the ship	0.471
Ro-ro cargo ship	1405.15	DWT of the ship	0.498
Ro-ro passenger ship	752.16	DWT of the ship	0.381
LNG carrier	2253.7	DWT of the ship	0.474
Cruise passenger ship having non-conventional propulsion	170.84	Gross Tonnage (GT) of the ship	0.214

Description of asterisks in Table 3:

$$\begin{cases} \left(\frac{DWT}{GT}\right) - 0{,}7x780{,}36 & \text{if } \frac{DWT}{GT} \leq 0.3 \\ 1812.63 & \text{if } \frac{DWT}{GT} > 0.3 \end{cases}$$

There are four phases for the implementation of the EEDI in conjunction with the date of built of the vessel:

- Phase 0 (1 January 2013 – 31 December 2014),
- Phase 1 (1 January 2015 – 31 December 2019),
- Phase 2 (1 January 2020 - 1 December 2024),
- Phase 3 (1 January 2025 etc.).

For ships delivered between 2000 and 2010, for the first phase the reduction factor of CO_2 is 10% while at the third phase it's increased to 30%.

Table 4: Applicable ship types and reduction factors in % [5]

Ship Type	Size	Phase 0 1 Jan 2013 – 31 Dec 2014	Phase 1 1 Jan 2015 – 31 Dec 2019	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Jan 2025 and onwards
Bulk Carrier	20.000 DWT and above	0	10	20	30
	10.000 – 20.000DWT	n/a	0-10[1]	0-20[1]	0-30[1]
Gas Carrier	10.000 DWT and above	0	10	20	30
	2.000 – 10.000DWT	n/a	0-10[1]	0-20[1]	0-30[1]
General Cargo Ship	15.000 DWT and above	0	10	15	30
	3.000 – 15.000DWT	n/a	0-10[1]	0-15[1]	0-30[1]
Refrigerated Cargo Carrier	5.000 DWT and above	0	10	15	30
	3.000 – 5.000DWT	n/a	0-10[1]	0-15[1]	0-30[1]
Combination Carrier	20.000 DWT and above	0	10	20	30
	4.000 – 20.000DWT	n/a	0-10[1]	0-20[1]	0-30[1]
LNG Carrier ***	10.000 DWT and above	n/a	10[2]	20	30

Ro-ro cargo ship (vehicle carrier) ***	10.000 DWT and above	n/a	5[2]	15	30
Ro-ro cargo ship***	2.000 DWT and above	n/a	5[2]	20	30
	1.000 – 2.000DWT	n/a	0-5[3]	0-20[1]	0-30[1]
Ro-ro passenger ship***	4.000 GT and above	n/a	5[2]	20	30
	1.000 – 4.000GT	n/a	0-5[3]	0-20[1]	0-30[1]
Cruise passenger ship*** having non-conventional propulsion	85.000 GT and above	n/a	5[2]	20	30
	25.000 – 85.000GT	n/a	0-5[3]	0-20[1]	0-30[1]

n/a means that no «required EEDI» applies.

Description of superscripts in Table 4:

[1] Reduction factor to be linearly interpolated between the two values depending upon vessel size. The lower value of the reduction factor is to be applied to the smaller size.

[2] Phase 1 comments for those ships on 1st September 2015.

[3] Reduction rate applies to those ships delivered on or after 1st September 2019.

A ship delivered on or after 1 September 2019 means a ship:

1. for which the building contract is placed on or after 1 September 2015, or
2. in the absence of a building contract, the keel of which is laid, or which is at a similar stage of construction, on or after 1 March 2016, or
3. the delivery of which is on or after 1 September 2019.

In 2014, regulations were added for LNG, Cruise passenger and Ro-Ro ships, as those types of ships are responsible for the 85% of the CO_2 produced by the global fleet.

Designing using the EEDI represents a way to support the protection of the environment by setting limits on CO_2 emissions, while at the same time allows ship-owning companies to choose how to implement the regulations and adhere to the limits set. In other words, the companies have the freedom to choose the strategy for the investments they will make in new technologies and new designs, so that the CO_2 emitted by their ships will be within the permissible limits.

EEDI, however, according to research, overestimates the reduction of greenhouse gases, as ships usually operate at higher power than 75% of the MCR.

2.2 Energy efficiency existing ship index EEXI

EEXI is an index similar to EEDI, which is aimed to newly built ships, and concerns ships that already exist and are in operation. It is applicable to most ships with a gross tonnage greater than 400 tons and which travel around the world. EEXI was adopted by the IMO on July 17, 2011 and decided to enter into force from November 1, 2022.

The similarity between the two indexes is also shown by the fact that EEXI is calculated using the formula used to calculate EEDI. In addition, if a ship complies with the second and third phases of the EEDI index, this is sufficient to not require the calculation of the EEXI index as well.

2.3 Carbon intensity indicator CII

The CII [4] is a relatively new indicator related to the carbon emissions of a ship and the type of ship and which helps to characterize, or not, the ship as energy efficient.

A certain value of the index is determined, which is representative for each type of ship and, after calculating the index for each ship, it is concluded whether the ship is within the limit or whether it should comply. Thus, each ship will acquire the "identities" "A", "B", "C", "D" and "E", which Indicates "very good quality" to "moderate quality" and finally to "very poor quality (“major superior”, “minor superior”, “moderate”, “minor inferior”, “major inferior”).

Ships with the identities "A", "B" and "C" are considered within limits and energy efficient, while ships with identities "D" for three consecutive years, and "E" are considered non-compliant. Therefore, these non-energy efficient ships will have to submit a plan showing the interventions to make the vessel compliant.

The CII index is calculated according to the formula [4]:

$$\text{Attained CII} = \frac{\text{Aggregated M}}{\text{Aggregated W}}$$

where

- $\mathrm{M} = \mathrm{FC_j} \times \mathrm{CF_j}$ is the total mass of CO_2 consumed, j is the type of fuel, $\mathrm{FC_j}$ is the total mass of fuel j consumed, $\mathrm{CF_j}$ is the fuel mass to CO_2 mass conversion factor;
- $\mathrm{W} = \mathrm{C} \times \mathrm{D_t}$ is the transport work, C is the capacity of the ship (for Bulk carrier, Tanker, Container ships, Gas carrier, LNG, Ro-Ro cargo ships, refrigerated cargo carrier and Combination carrier, assumed to be the DWT, while for Cruise passenger ships, Ro-Ro cargo ships/ vehicle carriers and Ro-Ro passenger ships, is assumed to be the gross tonnage (GT) of the vessel, $\mathrm{D_t}$ is the total distance covered by the ship and measured in nautical miles.

In general, as mentioned above, the CII value of a ship should not exceed a certain value related to the type of ship.

Hence:

$$\text{Attained CII} \leq \text{Required annual operational CII}$$

The limit value of the CII index is calculated according to the formula:

$$\text{Required annual operational CII} = \left(1 - \frac{\mathrm{Z}}{100}\right) \times \mathrm{CII_{REF}}$$

where

- Z is a general reference to the reduction factors for the required annual operational CII of ship types from year 2023 to 2023 as specified in Table 1Table 5;

Table 5. Reduction factor (Z%) for the CII relative to the 2019 ref. line [4]

Year	Reduction factor relative to 2019
2023	5[1]
2024	7%
2025	9%
2026	11%
2027	-[2]
2028	-[2]
2029	-[2]
2030	-[2]

Description of superscripts on Table 5

[1]: Z factors of 1%, 2% and 3% are set for 2020 to 2022, similar to business as usual until entry into force of the measure.

[2]: Z factors for 2027 to 2030 to be further strengthened and developed taking into account the review of the short – term measure.

- $CII_{REF} = a \times Capacity - c$ is the reference value of year 2019, where a and c are parameters estimated through median regression fits, taking the attained CII and the capacity of individual ships collected through IMO DCS in year 2019.

The parameters a and c, for determining the 2019 ship type specific reference line, are summarized/indicated in Table 6:

Table 6. Parameters for determining a and c parameters for 2019 reference line CII_{REF} [6]

Type of ship		Capacity	a	C
Bulk carrier	279,000 DWT and above	279,000	4745	0.622
	Less than 279,000 DWT	DWT	4745	0.622
Gas carrier	65,000 and above	DWT	14405E7	2.071
	Less than 65,000 DWT	DWT	8104	0.639
Tanker		DWT	5247	0.610
Container ship		DWT	1984	0.489
General cargo ship	20,000 DWT and above	DWT	31948	0.792
	Less than 20,000 DWT	DWT	588	0.3885
Refrigerated cargo carrier		DWT	4600	0.557

Combination carrier		DWT	40853	0.812
LNG carrier	100,000 DWT and above	DWT	9.827	0.000
	65,000 DWT and above, but less than 100,000 DWT	DWT	14479E10	2.673
	Less than 65,000 DWT	65,000	14479E10	2.673
Ro-ro cargo ship (vehicle carrier)		GT	5739	0.631
Ro-ro cargo ship		DWT	10952	0.637
Ro-ro passenger ship		GT	7540	0.587
Cruise passenger ship		GT	930	0.383

Moreover, some “dd” vectors (vectors that indicates the direction and distance they deviate from the required value) have been calculated, depending on the type and size of the ship, which help to set the limits indicating the identities “A”, “B”, “C”, “D” and “E” to which the ship belongs. Specifically, d1 shows the boundary between categories “A” and “B”, d2 shows the boundary between categories “B” and “C”, d3 between categories “C” and “D” and d4 between categories "D" and "E" [7].

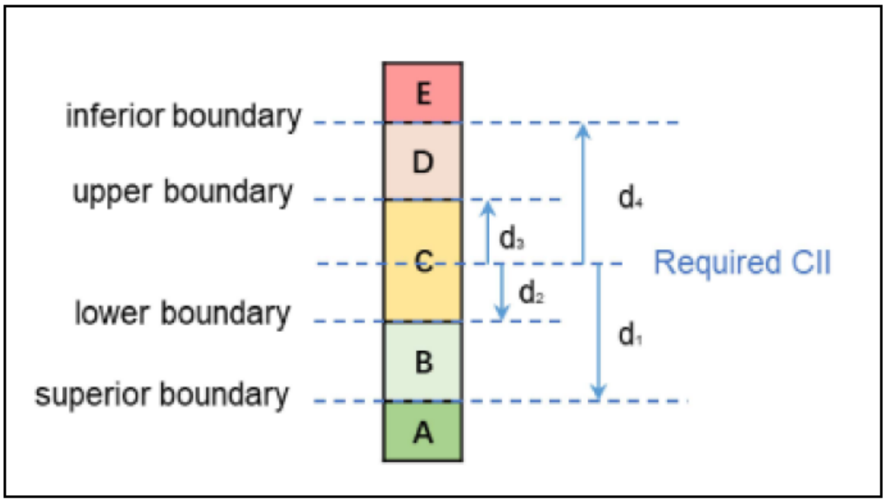


Figure 2: dd vectors and rating bands A to E [7]

Finally, the ratio

$$\frac{\text{Attained CII}}{\text{Required CII}}$$

is calculated and the result determines the category to which the ship under study will belong.

Regarding shipping, the reduction in carbon intensity, for a year y “y” with respect to a year y_{REF} taken as a reference, is obtained according to the formula [4]:

$$R_{SHIPPING}, y = 100\% \times \left(\frac{\text{Attained CII}_{SHIPPING}, y - \text{Attained CII}_{SHIPPING}, y_{REF}}{\text{Attained CII}_{SHIPPING}, y_{REF}}\right)$$

3 Innovative technologies for improving energy efficiency of ships

In order to improve the EEDI, the hull should be generally optimized as well as a reducing energy consumption with a corresponding mechanical efficiency increase for the ship's main engine, or in the electrical efficiency degree for ship's auxiliary engines (see Figure 3 and Figure 4).

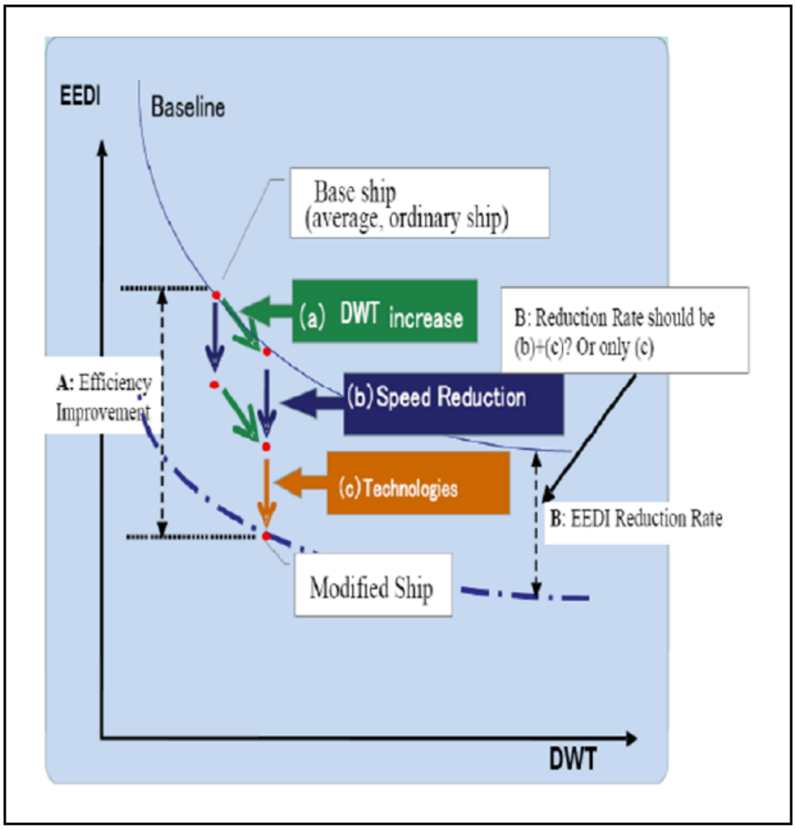


Figure 3: Reduction of energy index EEDI [5]

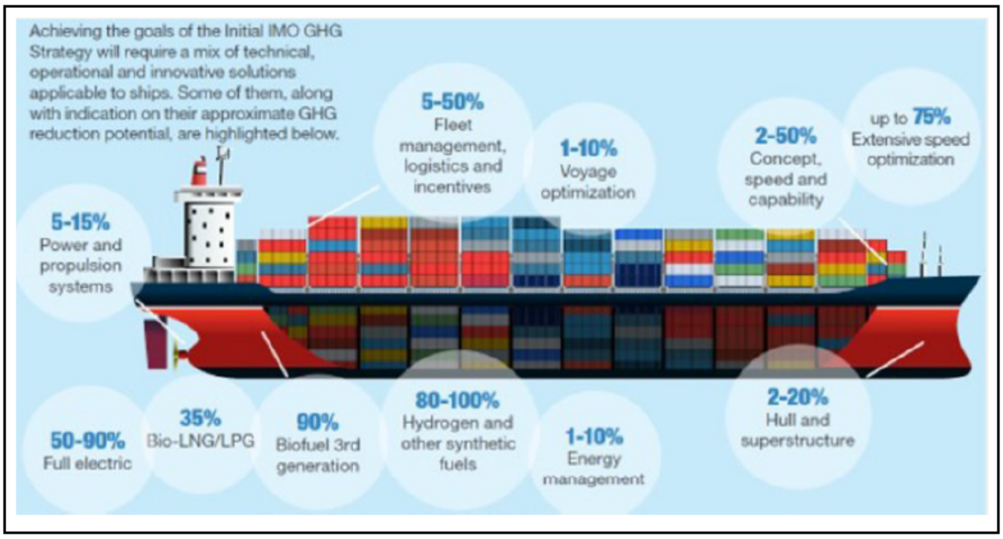


Figure 4: Technical, operational and innovative solutions for ships for reducing GHG [8]

Regarding the electrical efficiency degree, the areas where we can intervene to improve the EEDI index by energy consumption reduction along with the relevant electrical efficiency degree increase are summarized in the following section.

3.1 Measures for optimizing the electrical efficiency on board

The main areas where we can intervene to reduce energy consumption on-board with simultaneously increasing the electrical efficiency are listed below:

- Optimal selection of generator sets
- Electric load analysis for both active and reactive power
- Cold ironing
- Power converters for large motors
- Direct current integration
- Waste heat recovery – thermoelectric generators
- Shaft generator systems
- Optimum operation of electric energy system
- Photovoltaic solar panels
- Fuel cells
- Batteries

3.1.1 Optimal selection of generator sets

Quite often if not all the times, the load factors used in the theoretical electric load analysis for selecting generators are high which leads to overestimation. As a result, the generators are operating on about 50% of their nominal load leading to high fuel consumption and often unstable operation of the generator at load factors less than 50%. Further, the current practice is to select mainly three diesel generators for the majority of the vessels of same type and same nominal power. This has been proven to be problematic when the vessel is staying at port or at the anchorage without performing any operation. It has been evaluated that if the selection of the generator units starts from efficiently covering the power demands on port, then the resultant electric power plant is lighter and more compact [9].

M/V KASTOR - Case study

The bulk carrier M/V KASTOR (see Figure 5) has been proposed from the partner of the project, LASKARIDIS SHIPPING CO., LTD, as a case study for evaluating the optimal selection of generator sets as also on the integration of power converters on large electric motors.

Figure 5: M/V KASTOR[1]

The main particulars and the details of main and auxiliary engines of said vessel are presented in Table 7. The electric system of the vessel (see Figure 6) is a rather typical system for such type of ships consisting of three diesel generators of 450V which are able to run in parallel in pairs or threes in order to cover the energy demands of the vessel as those depicted and calculated at the electric power balance. Further one emergency diesel generator is fitted on board in order to cover the emergency loads of the vessel and a 24VDC sub system is also installed for covering loads of navigation equipment, supplementary lighting etc.

Table 7: Main features of M/V KASTOR

Main Particulars	
Length Over All (LOA)	229.00 m
Length Between Perpendiculars (LBP)	225.50 m
Breadth	32.3 m
Depth	20.05 m
D_{scant}	14.45 m
D_{design}	12.20 m
Deadweight (DWT)	81600 tonnes
Gross Register Tonnage (GRT)	43939
Year of built	2020
IMO No.	9843405
Flag	Liberia
Main Engine	
Type	MAN-B&W 6S60ME-C8.5
S.M.C.R	9930Kw x 90.4 r/min
NCR	7110 kW x 80.9 r/min
Auxiliary Engines	
Type	YANMAR 6EY22LW

[1] Source: Marine Traffic.com

Rated output of Diesel Engine	800kW
Rated revolution of Diesel Engine	720 min^{-1}
Type of A.C generators	TAIYO FE547C-10
Rated output of A.C gen	720kW
Rated revolution of A.C gen	720 min^{-1}
Voltage	450V
No of Gen sets	3

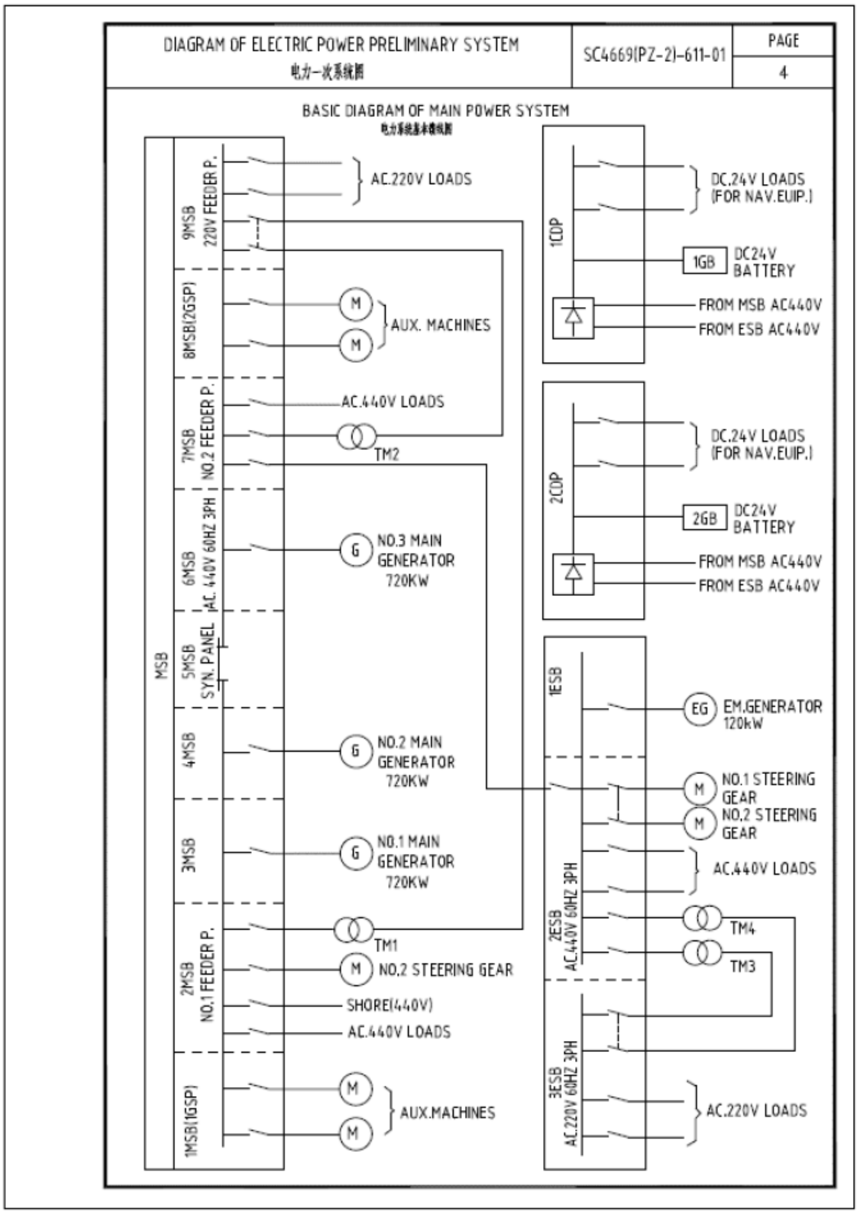


Figure 6: Basic Diagram of main power system of M/V KASTOR[2]

[2] Source: SDARI DWG No: SC4669 (PZ-2)-611-01.

The actual load factor of the generators has been calculated during vessels operation and compared with the theoretical as given in the electric load analysis, to gain insights can into the efficiency and utilization of the generators in relation to their installed capacity. The general info of the data acquisition is presented in table 8 while the technical characteristics of the installed gens are shown in

Table 9.

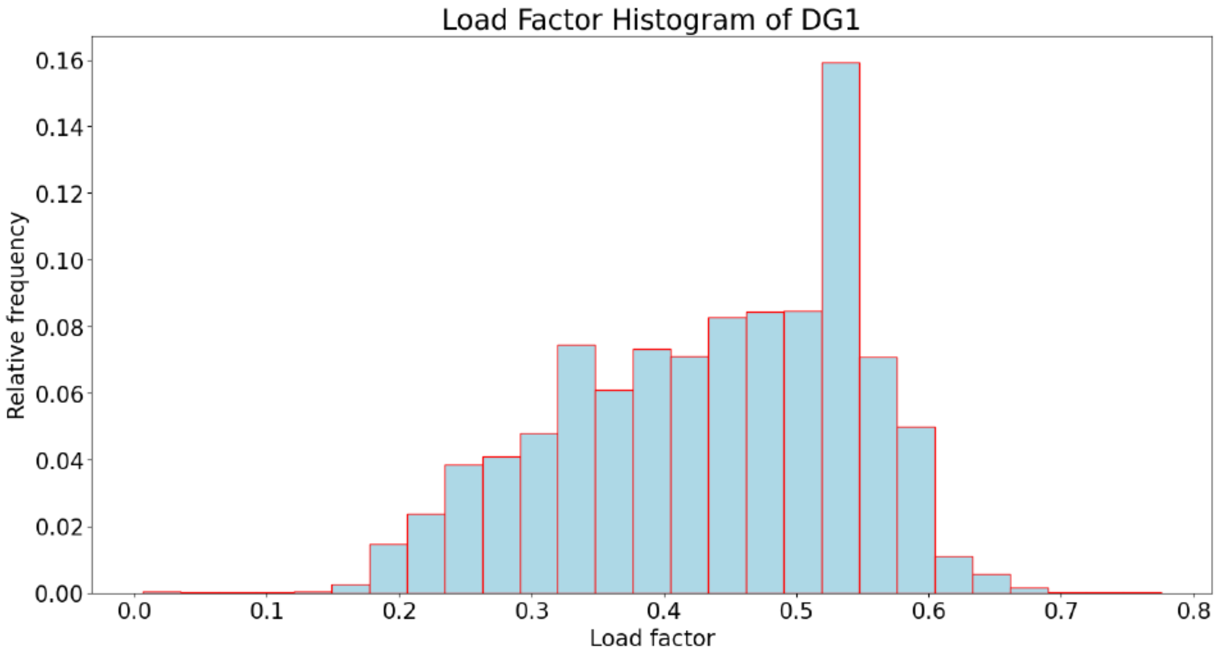
Table 8: Data acquisition info

	High-frequency data
Period	1-2-2021 to 10-2-2023
Sampling interval	1 minute
Number of points	1,064,161

Table 9: Technical characteristics of generators

	Diesel Generator Information
Manufacturer	YANMAR CO., LTD
Type	6EY22LW
Maximum continuous rating (MCR)	800 kW x 720 rpm
SFC at 50% of MCRAE	215 g/kWh
Fuel type HFO	HFO
Type of A.C generators	TAIYO FE547C-10
Rated output of A.C gen	720kW
Rated revolution of A.C gen	720 min^{-1}
Voltage	450V
No of Gen sets	3

After analysing the data (Table 8 and Figure 9), the relative frequency histograms for every generator running both alone and in parallel and the load demand curves of all three generators have been derived and presented in Figure 7 and Figure 8.


Load Factor Histogram of DG1
Relative frequency
Load factor
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
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0.0
0.1
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0.4
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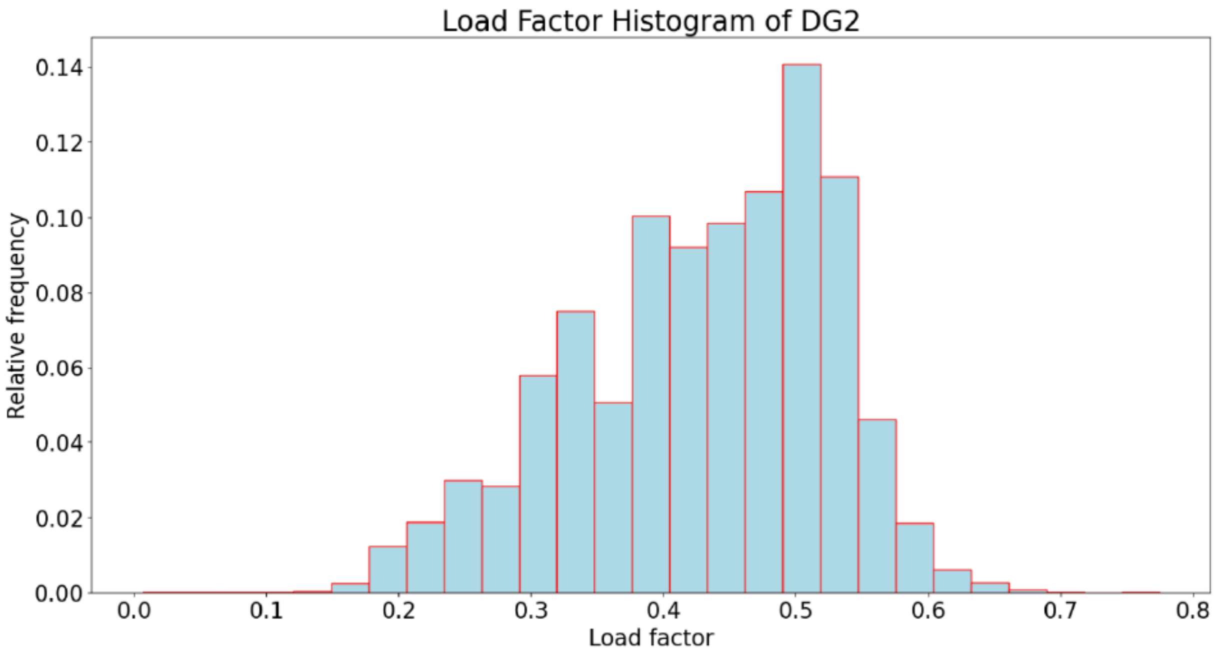
0.6
0.7
0.8

(a)


Load Factor Histogram of DG2
Relative frequency
Load factor
0.00
0.02
0.04
0.06
0.08
0.10
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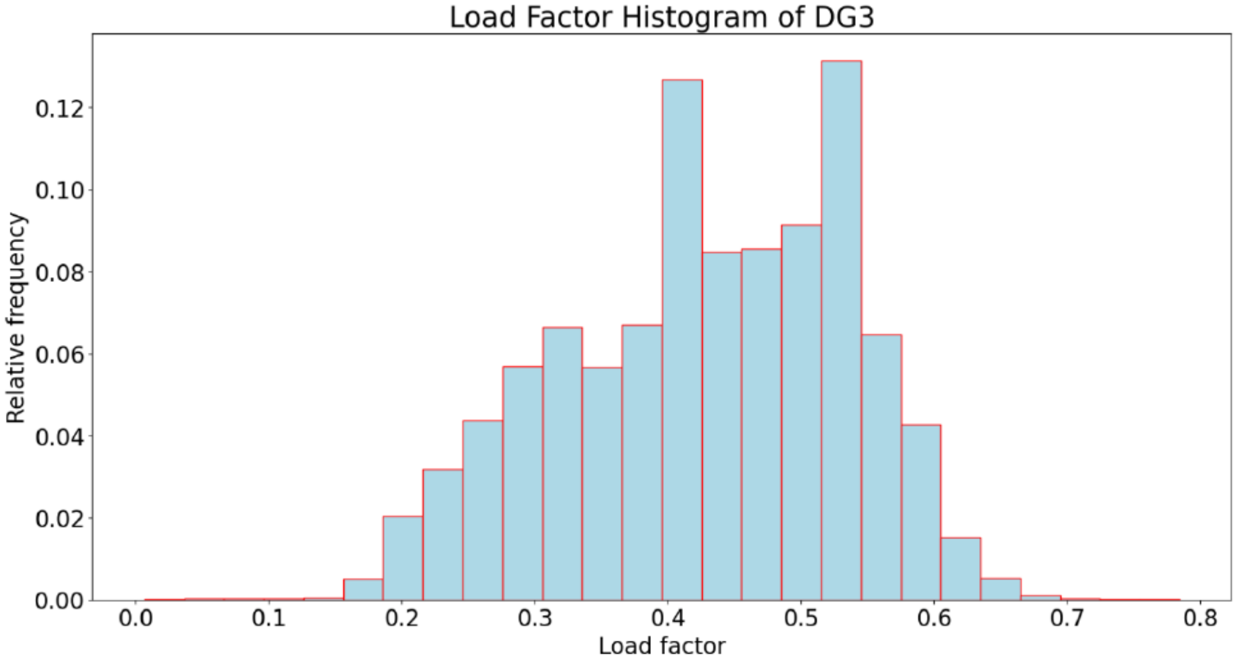
(b)


Load Factor Histogram of DG3
Relative frequency
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0.02
0.04
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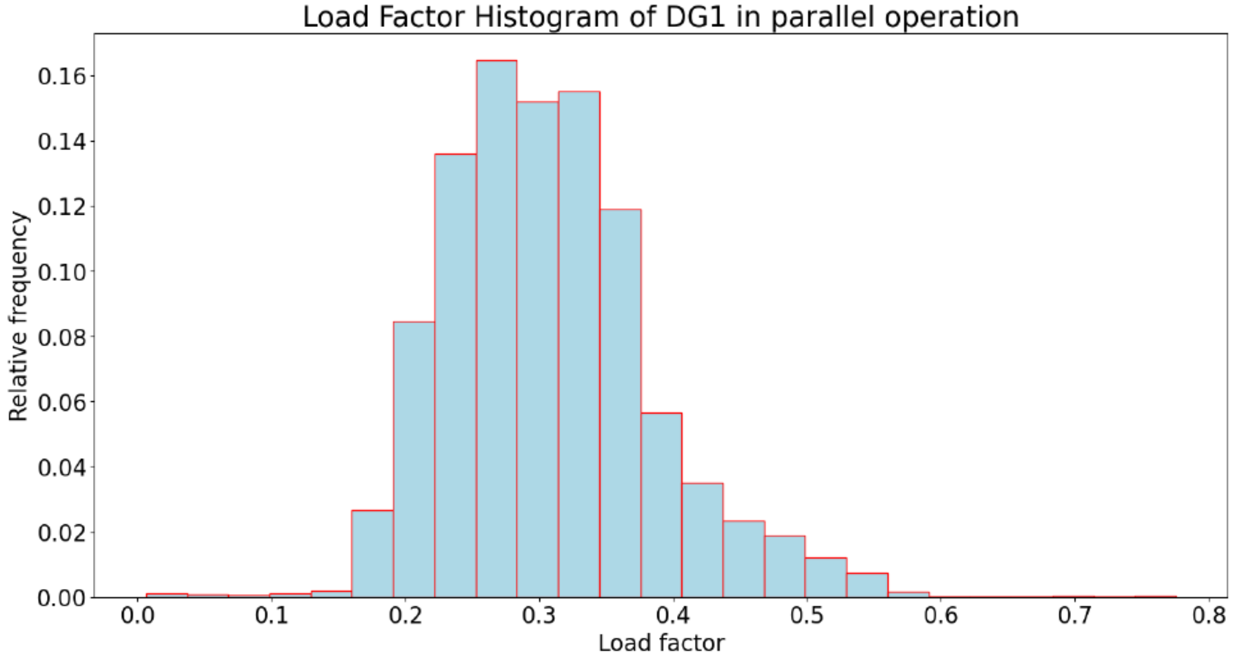
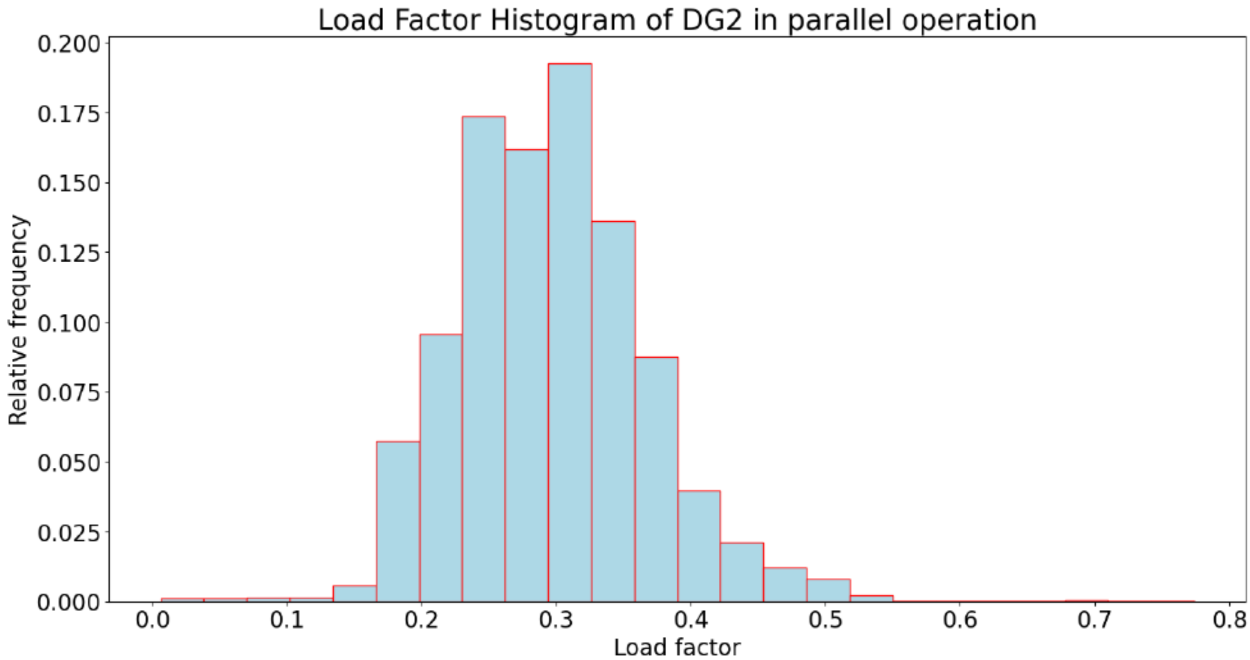
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Load factor

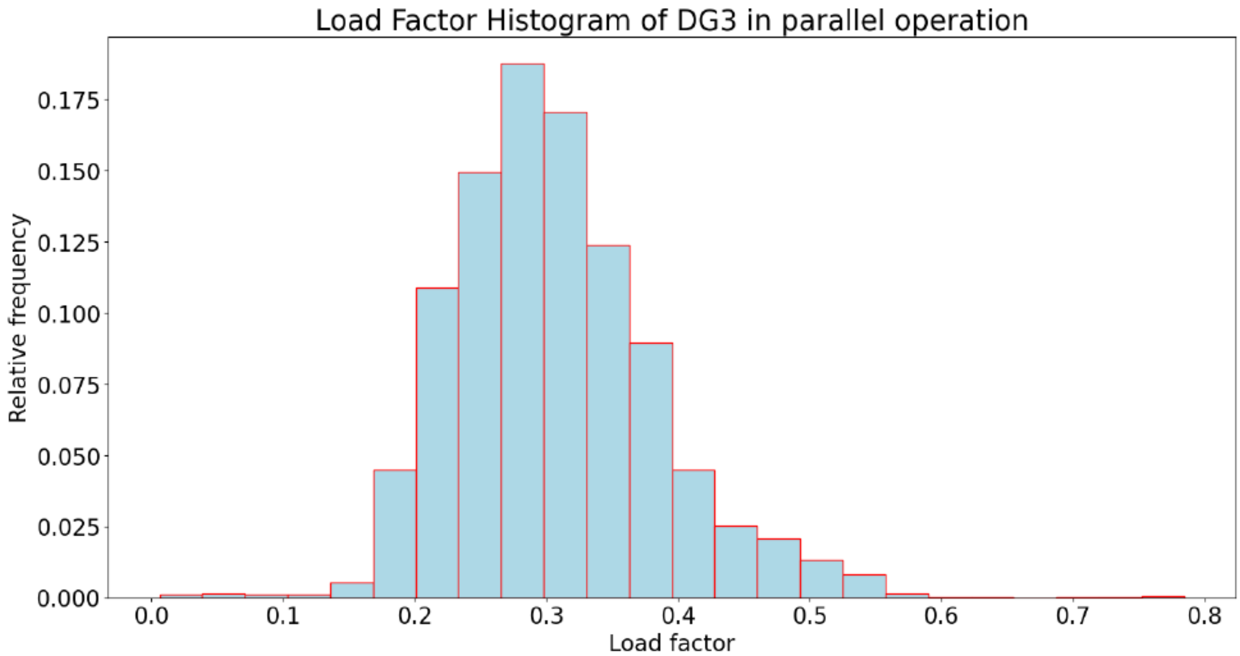
(c)


Load Factor Histogram of DG1 in parallel operation
Relative frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Load factor

(d)



(e)



(f)

Figure 7: a) Relative frequency histogram of DG1 load factor; b) Relative frequency histogram of DG2 load factor; c) Relative frequency histogram of DG3 load factor; d) Relative frequency histogram of DG1 load factor in parallel operation; e) Relative frequency histogram of DG2 load factor in parallel operation; f) Relative frequency histogram of DG3 load factor in parallel operation.

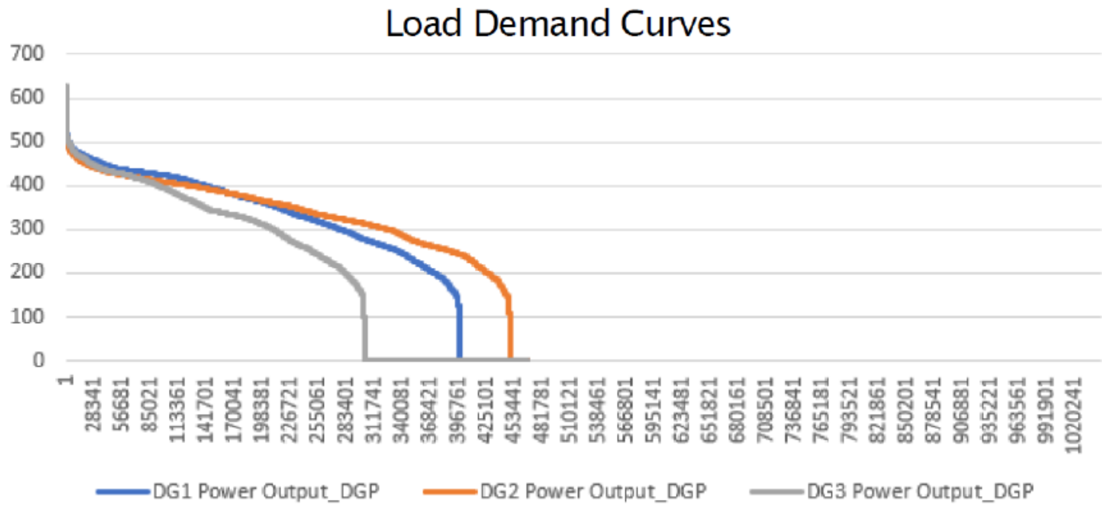


Figure 8: Load Demand Curves of the three generators

The time percentages of DG parallel operation modes with criterion of operation the Diesel Generator Power Output, DGPi >5[kW], i=1,2,3 has been calculated and the results are shown in Table 10. It appears that for operation in open seas (STW > 6[kn]), a standalone operation of DGs is observed while the parallel operation of the DGs by combinations of two is increased for the range 2[kn]<STW<6[kn] which corresponds mainly to maneuverings. Moreover in

Table 11 the loading time of each generator as a percentage of the total time has been calculated. The examined load factors are grouped and increased at 12,5% steps.

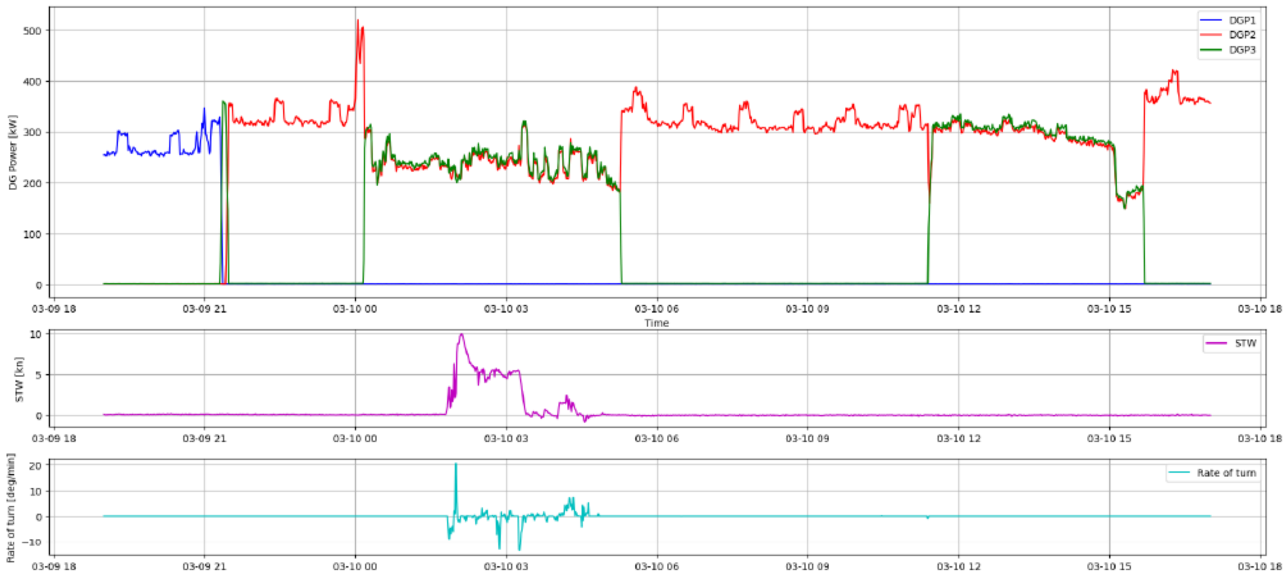


Figure 9: Time histories of DG Power, STW, and Rate of Turn during Parallel Operation Intervals with shared time axis.

Table 10: Parallel operation of diesel generators

	All reporting period	STW > 6[kn]	2[kn] < STW < 6[kn]	STW < 2[kn]
DG1+DG2+DG3	0.03%	0.04%	0.03%	0.01%
DG1+DG2	5.06%	4.55%	8.47%	4.50%
DG1+DG3	4.71%	4.87%	10.56%	3.75%
DG2+DG3	3.02%	3.35%	4.51%	2.27%
DG1	27.66%	29.52%	20.8%	29.61%
DG2	34.85%	34.94%	9.95%	37.39%

DG3	21.53%	18.47%	44.67%	21.18%
None	3.15%	4.27%	1.02%	1.29%

Table 11: Loading time of each generator

Load factor			**Loading time (% of the total time)**			
fs				**DG1**	**DG2**	**DG3**
	>	75 %	>600[kW]	0.0078	0.0048	0.0100
62.5 %	-	75 %	500-600[kW]	0.8036	0.4485	0.7604
50 %	-	62.5 %	400-500[kW]	29.8903	27.0607	19.6338
37.5 %	-	50 %	300-400[kW]	29.8990	43.6614	25.3248
25 %	-	37.5 %	200-300[kW]	20.6115	21.7712	15.9138
12.5 %	-	25 %	100-200[kW]	5.3234	4.7958	4.0600
	<	12.5 %	<100[kW]	13.4643	2.2576	34.2972

For the actual specific fuel oil consumption and due to the large variability of the specific fuel oil consumption, SFOC values per load, the load range has been split in a number of sub-ranges. For each sub-range the SFOC values were calculated (see Table 12). Finally, the mean and standard deviation SFOC curves has been derived. The results of mean and standard deviation curves are presented in Figure 10 and in Figure 11 the reference curve from the operational data of all generators is presented.

Table 12: SFOC values per load range

	DG1			**DG2**			**DG3**		
	mean	std	# points	mean	std	# points	mean	std	# points
0.20<load<0.35	230.4	45.6	9649	237.1	31.3	16725	242.7	37.4	11566
0.35<load<0.40	243.9	39.8	21355	221.9	26.9	16725	229.4	35.1	14176
0.40<load<0.45	236.4	38.4	15962	220.9	27.1	45312	224.2	29.2	25573
0.45<load<0.50	214.2	42.0	40089	214.4	48.8	63136	269.3	85.5	28751
0.50<load<0.55	205.3	55.1	48015	222.6	59.8	61372	270.9	84.7	40513
0.55<load<0.60	204.3	48.1	15583	215.9	64.7	14802	277.8	88.6	16643
0.60<load<0.65	207.4	35.4	3631	180.5	78.6	3405	257.9	84.9	3447
0.65<load<0.80	203.1	30.2	468	189.1	65.2	636	213.1	43.6	536

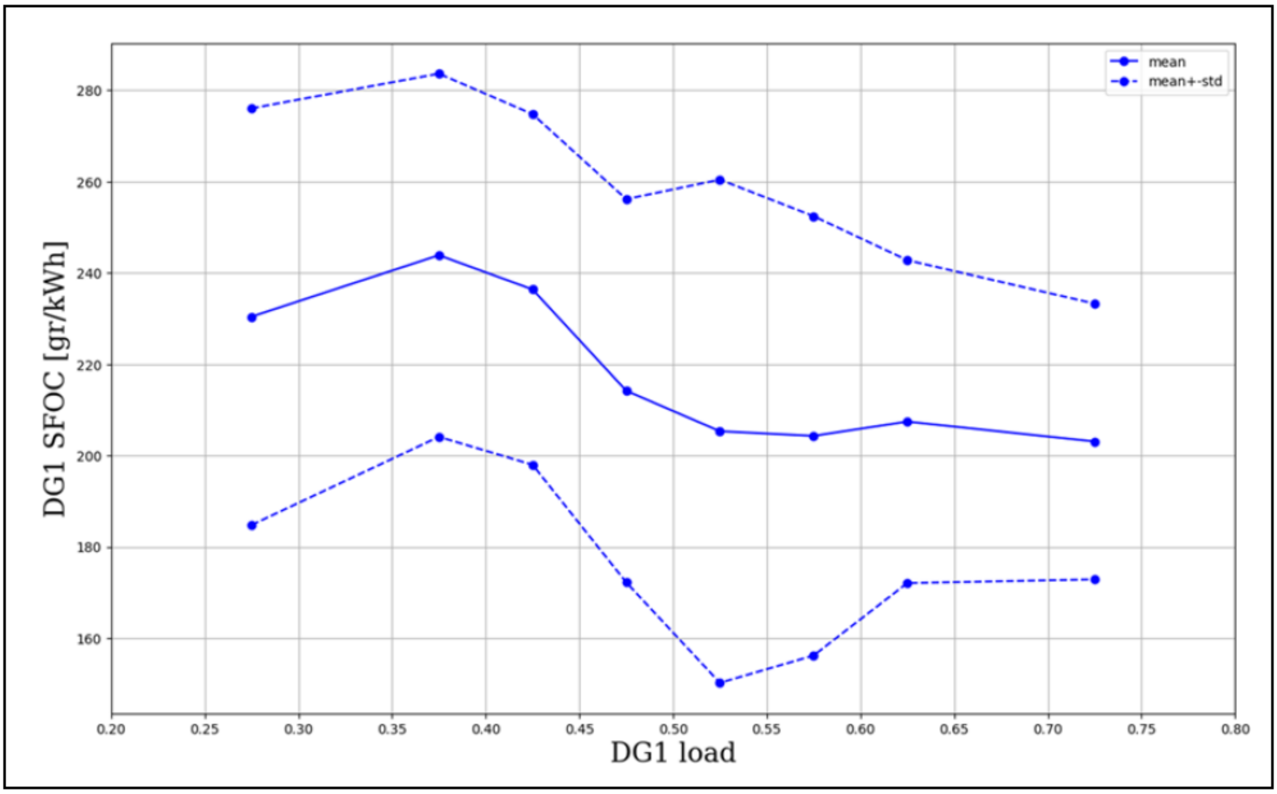


Figure 10: Mean and standard deviation SFOC curves for DG1.

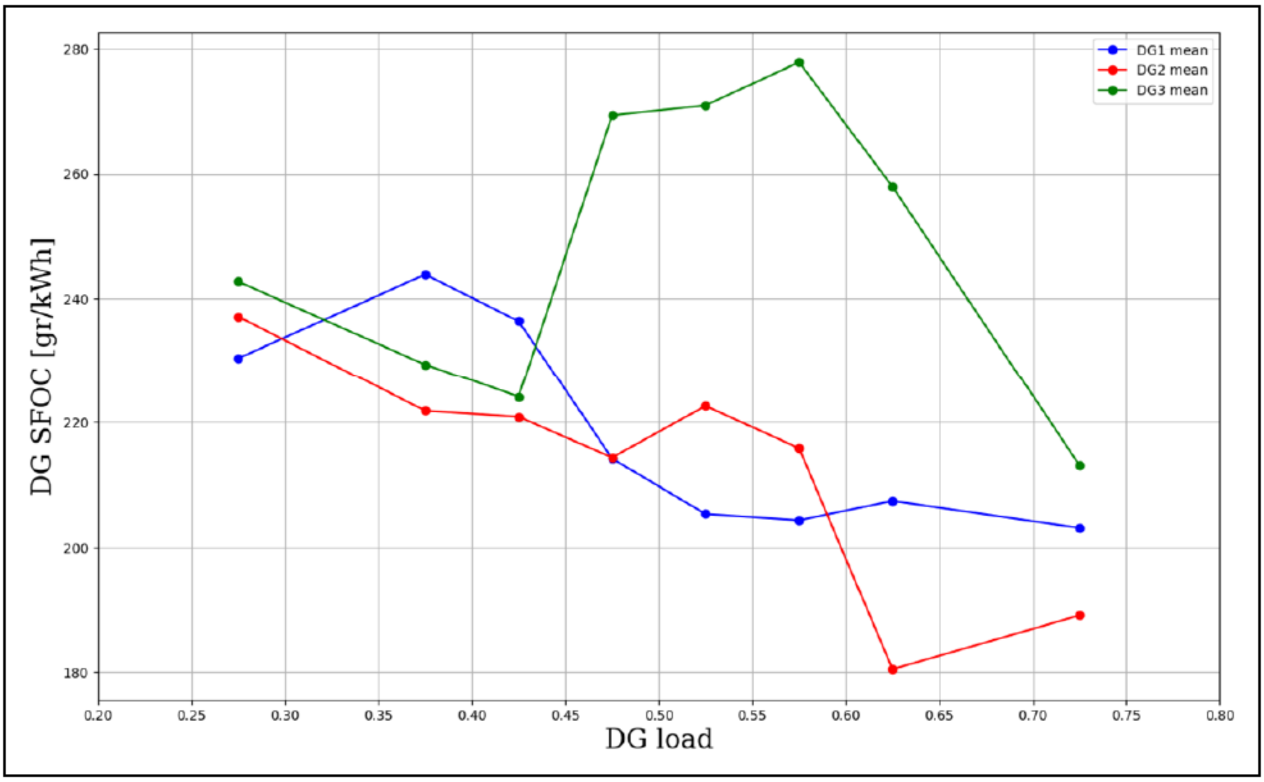


Figure 11: Mean and standard deviation SFOC curves for DG1.

Results of the case study

1) Regarding the actual fuel oil consumption and, as can be derived from Figure 7, the DG3 seems to be the less energy efficient where its SFOC is about 270 [g/kWH] at 50% load while the manufacturer's manual state the SFOC at 50% loading with the 2-stage turbocharging system is 215 [g/kWH]. On the other hand, No1 D/G is quite less than 215 [g/kWH] and No.2 D/G is slightly higher, about 218 [g/kWH].
2) The actual load factors of diesel generators are measured to be less than 65% in all cases and this is coming in contradiction with the theoretical electric load analysis where the loading of the generators is 76.2% at normal sea going, 82.6% at port and 66% at loading and unloading (see Figure 12).

ELECTRIC POWER BALANCE																		SC4669(PZ-2)-601-01JS						PAGE 9
		load		Normal sea service				At port (In/Out)				At Loading/unloading				Harbour Service				Emergency Service				Remark
No.	Consumer	P	Set	Load	Use	C.L.	I.L.	Load	Use	C.L.	I.L.	Load	Use	C.L.	I.L.	Load	Use	C.L.	I.L.	Load	Use	C.L.	I.L.	
		kW		Factor	Set	kW	kW	Factor	Set	kW	kW	Factor	Set	kW	kW	Factor	Set	kW	kW	Factor	Set	kW	kW	
	CONTINUOUS LOAD					472.3				1034.5				276.1				240.2				72.6		
	INTERMITTENT LOAD						122.3				201.2				336.3				291.9					
	INTERMITTENT LOAD DIVERSITY FACTOR						0.4				0.4				0.4				0.4					
	INTERMITTENT LOAD REQUIRED POWER						48.9				80.5				134.5				116.8					
	TOTAL REQUIRED POWER (kW)					521.2				881.2				410.6				357.0				72.6		
*	BALLAST WATER EXCHANG AND EGCS					1097.2				1189.4				948.6										
RUNNING GENERATORS CONDITION																								
1	RUNNING GENERATORS (kW x SET)			720x1				720x2				720 x 1				720x1				120X1				
	STANDBY GENERATORS (kW x SET)			720X2				720x1				720x2				720x2				0				
	LOAD FACTOR (%)			72.40%				61.19%				57.03%				49.58%				60.53%				
2	RUNNING GENERATORS (kW x SET)			720x2				720x2				720x2												
	STANDBY GENERATORS (kW x SET)			720x1				720x1				720x1												
	LOAD FACTOR (%)			76.20%				82.60%				66%												
	NOTES :																							
1	*C.L. : CONTINUOUS LOAD*																							
	I.L. : INTERMITTENT LOAD																							
2	**BALLAST EXCHANGE AT SEA , CARGO HOLDING & ARRIVAL OR DEPARTURE*																							
3	*CONDITION 1:WITHOUT BALLAST , SCRUBBER SYSTEM at VGP OPERATION (SULPHUR REDUCTION 3.5% to 0.1%)*																							
	CONDITION 2:WITH BALLAST,SCRUBBER SYSTEM at VGP OPERATION (SULPHUR REDUCTION 3.5% to 0.1%)																							

Figure 12: Electric Power Balance (summary table) of M/V KASTOR[3]

3.1.2 Electric load analysis (ELA) for both active and reactive power

The ship electrical energy system is an autonomous system comprising a limited number of generators and a large number of loads, the majority of which consist of asynchronous motors [10]. From the electrical energy balance point of view, the generators must be rated at the ship design stage to meet all energy demands, namely in terms of active power (in W) and reactive power (in VAr). However, as the electric load analysis performed often only covers the demands in terms of active power it is likely to encounter problems meeting the reactive power demands. This is why it has been proposed, the electric load analysis should take into account the reactive power too at the design stage [11], [12]. In a ship's electrical energy system, the induction AC motors require reactive power, whereas the synchronous AC generators produce reactive power, acting as capacitors. In this manner equilibrium is satisfied. Alleviating measures concerning meeting reactive power demands, often called 'reactive power compensation', must be taken If this balance is not satisfied. The main reasons to apply reactive power compensation devices are as follows.

[3] Source: SDARI DWG No: SC4669 (PZ-2)-601-01JS].

- Reduction of demands in total electrical energy and hence in the corresponding fuel consumption
- Reduction of I^2R losses and therefore heating in the power distribution system
- Increase of the voltage at the load, increasing production and/or efficiency of operation

3.1.3 Cold Ironing

Auxiliary engines operate while a ship's berthing to produce electricity which covers various hoteling needs, e.g., lighting and ventilation, and cargo handling systems. Taking under consideration the significant amount of fuel that is required during berth it is widely recognized that the produced emissions are substantial and constitute a major issue with serious consequences to human health and to the wellness of the environment in densely populated areas. The optimal solution to the above-mentioned problem is the use of Cold Ironing which is also known as "Alternative Maritime Power" or "On Shore Power Supply" or alternatively "Shore-side Electricity".

Cold Ironing enables vessels to shut down their auxiliary engines while at berth and plug into an onshore power source through a main incoming station which is connected to the local power grid (see Figure 13). Electrical power is transferred with the use of several underground and aerial cables to the vessel without any disruption to its on-board services. In this way emissions that are produced within the local surroundings by the vessels' auxiliary engines are eliminated whereas noise pollution and vibrations from auxiliary engines are significantly reduced. It is worth stating that the use of shore power does not minimize the overall emissions produced by a vessel during berthing time since steam that is produced through the on-board boilers is essential for operation of critical equipment.

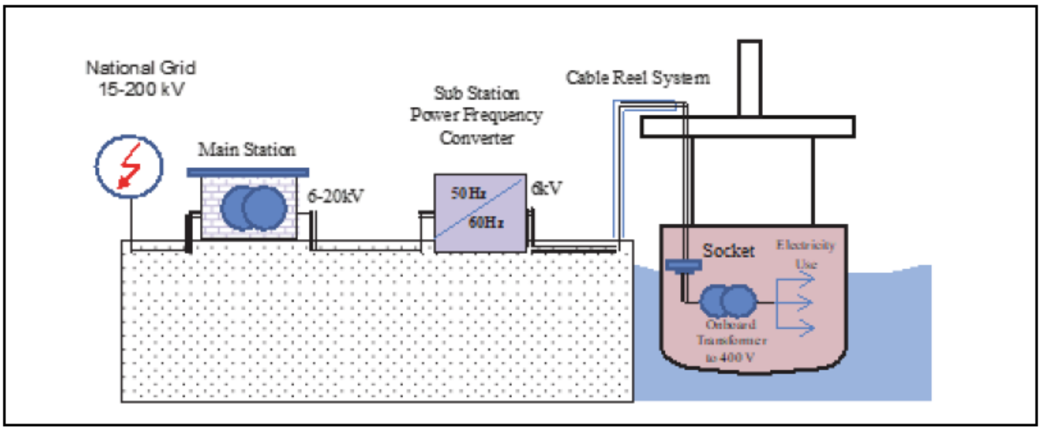


Figure 13: Electric supply system configuration according to EU regulation

It is argued that this transition of electricity source does not contribute to the mitigation of air pollution but rather shifts the emissions created to the onshore power generation facilities. However, taking under consideration the significant growth of renewable energy sources over the last decades from which electricity is produced as well as the higher efficiency of the power plants, the overall emissions reduction which is achieved is considered major. Furthermore, it shall also be noted that these stationary power plants are usually located remotely from densely populated areas whereas shipping emissions often occur within a city region thus having a direct negative impact to human health as well as the environment. From this standpoint, a study published in 2016, which updated and extended the study of shore power conducted for the Port of Long Beach (PoLB) in 2004, proposed some optimal solutions to the problem of maximizing the total benefit of shore connection in U.S. ports. A relevant result of this study was that the sum of the private savings to ship owners/operators (fuel savings) and the environmental benefit would be completely offset by vessel and berth retrofit costs if two-thirds of the 1.910 considered cargo vessels and 250 out of the considered 300 berths are retrofitted [13][13]. Additionally, another advantage of Cold Ironing is the benefit of lower operating costs for the ship owners due to the reduced time that the auxiliary engines are turned on and functioning allowing also in this way a more holistic maintenance schedule to be followed.

3.1.4 Power converters for large electric motors

Introduction

On- board vessels there are a number of so-called large electric motors which absorb high active and reactive powers and moreover are characterized by high inrush currents during their starting up, if directly supplied by the on-board power grid.

Onboard ship energy efficiency can be, for example, significantly improved acting on large pumps and fans, driven by electric motors, not running continuously and at full capacity. Target ships for such a kind of retrofitting solution are basically all types of vessels, including bulk carrier, container ships, cruise ships, LNG carriers, drilling rigs, offshore support vessels, icebreakers and special purpose vessels.

As for the pumps, for example, a diesel-powered cargo ship needs almost 36-50 pumps of various type accounting for 20-30% of the total mechanical equipment of the ship.

In general, the following set of pumps are present in a vessel [14]:

- **Pumps for marine plants**
    - Fuel oil pumps
    - Lubricating oil pumps
    - Seawater pumps
    - Freshwater pumps
    - Hydraulic pumps for steering
    - Cooling water pumps of refrigerating units
- **General purpose pumps**
    - Bilge water pumps
    - Ballast water pumps
    - Fire pumps
    - Daily freshwater pumps
    - Hot water circulation pumps
- **Special pumps for special ships**

Among all the above, the seawater pump system (see Figure 14) reveals among the most power demanding.

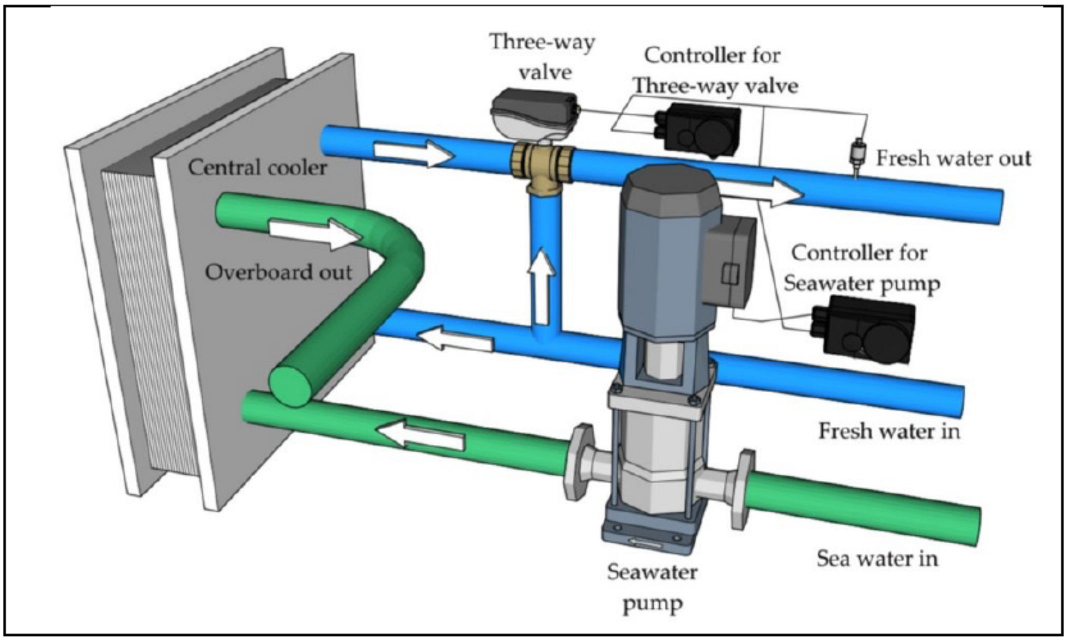


Figure 14: Seawater pump system

The engine room ventilation is lung of the ship. A proper engine room ventilation system serves two purposes:

1) providing sufficient oxygen for fuel combustion,
2) cooling the room by dissipating the heat radiated from propulsion and auxiliary engines.

This process can involve large amounts of air, with huge engine room fans and ducting systems dividing the air across the room. For this reason, the improvement of the efficiency of the related motors is crucial. Besides the engine room fans, cargo ships present specific ventilation requirements [15], [16] for:

- minimizing the formation of sweat by dew point control,
- removing hazardous gases which may be emitted by the cargo,
- preventing excessive heating of the cargo,
- removing taint (see Figure 15).

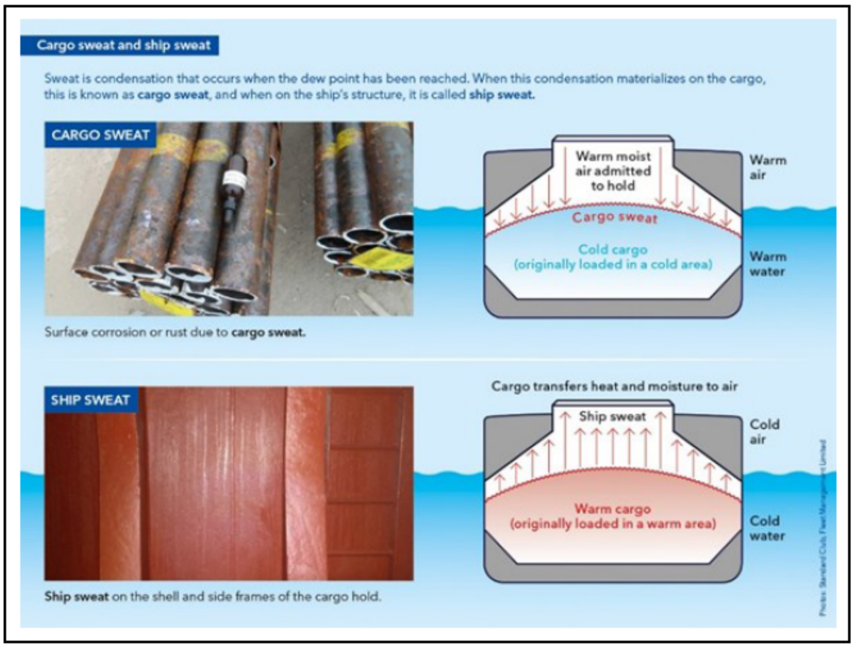


Figure 15: Specific ventilation requirements of cargo ships

It has been evaluated that the two the applications presenting the fastest return-on investment, in some cases even less than a year, are the sea water pumps and the engine room fans. For the above reasons, sea water fans and engine room fans, besides the high-power fans for specific ventilation requirements of cargo ships, have been selected as system to be retrofitted for improving efficiency in the framework of the project.

The standard ways to modify the duty point of a pump are:

- Bypassing,
- Throttling,
- On - Off control,
- Variable Frequency Drive (VFD) pumps.

Figure 16 shows on the Q-H (flow-head) plane the differences among the above cited solutions.

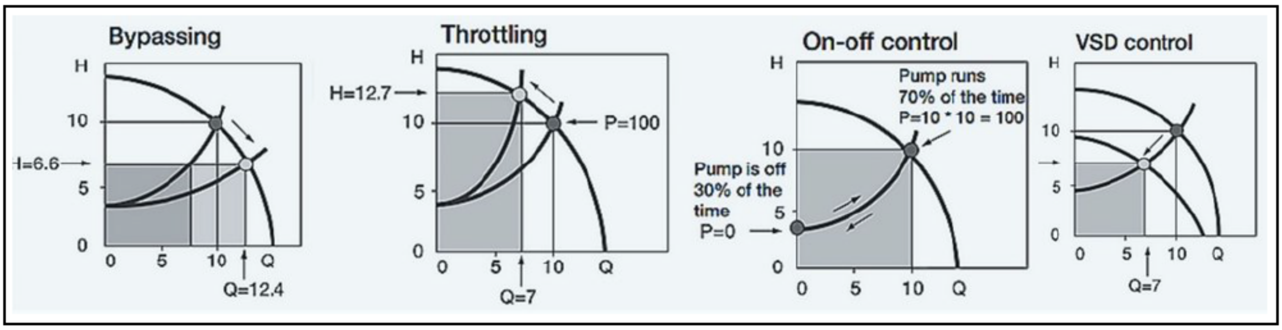


Figure 16: Differences among the above cited solutions in the Q-H plane

Among the above solutions, the VFD pumps reveals the most interesting solution in the project perspective. They change the pump speed in accordance with the affinity laws. If the pump impeller speed is reduced, the pump curve moves downwards. If the speed is increased, it moves upwards.

They permit the pumping capacity to be exactly matched to the process requirements. VFD motor drives operate pumps and fans more efficiently in partial loads: during slower sailing speeds (seawater pumps) or with reduced ventilation requirements (engine room fans).

The electric power consumption of a pump is related to the pump volumetric flow according to affinity laws. The reduction of pump speed will affect the system pressure, Head, to the power of two and the electric power consumption to the power of three. For example, a reduction in the pump speed of 10% will save 27% of the consumed power.

The advantages of VFD Pumps are (Figure 17):

- ✓ change the duty point of the pump in the most efficient way,
- ✓ reduce the power consumption.
- ✓ more flexible pump control,
- ✓ Reduction of the risk of cavitations.

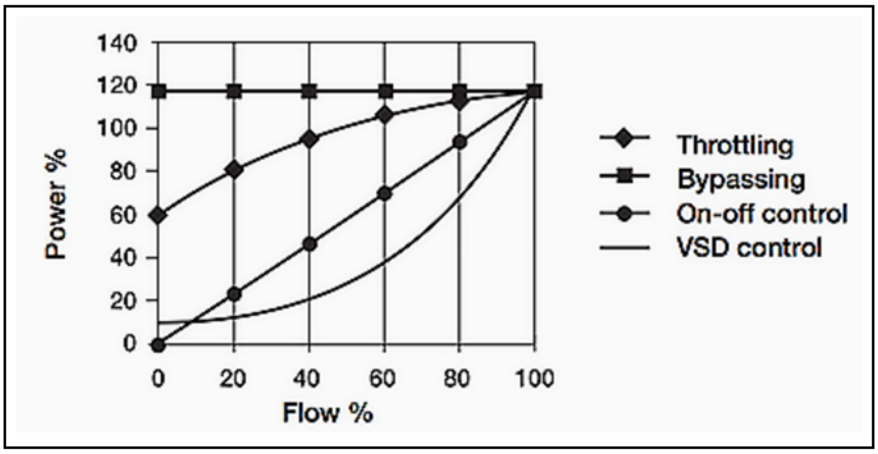


Figure 17: Flow vs power curves with different solutions

In pump and fan applications on board vessels, using VFDs can cut the energy consumption by 60% [17].

Another typical large motor present in ships is the bow thruster motor of power demand, in the order of 0.5 up to 2.5 MW, which increases considerably the electric power demands that the electric power generation set has to meet. Moreover, things are getting worse during starting-up of such huge electric power system, when -like any other motor- the thruster motor absorbs a transient “inrush current” of high values (varying, in general, between 4-7 times the rated current) [18]. Consecutively, during the inrush phenomenon (i.e., for approximately up to 15-20 s after its time zero) the thruster motor power demands in terms of active and reactive power are high, too. During this interval, the “transient power factor” is fairly low, as the reactive power required is significantly higher than in steady-state. This high energy demand at a low power factor cannot be easily covered by the vessel’s generator sets leading to their possible overloading or even tripping. Furthermore, as a result of the transient inrush current, large voltage drops take place in the entire network, introducing “symmetrical” voltage dips to all three-phases [19].

Direct on-line connection

In the direct on line DOL connection which is the simplest connection of an electric motor to the system the transient inrush current is mainly due to the low impedance of the motor during its starting-up and the slip rotor resistance, in particular. Due to the highly inductive character of this impedance, a DC offset is also introduced. Eventually, as speed grows-up close to its nominal value, slip decreases, slip rotor resistance, and hence total motor impedance increases to its steady-state value. Moreover, as the current is of high value, a voltage dip occurs in the entire electric system, of magnitude even up to 20% (see Figure 18).

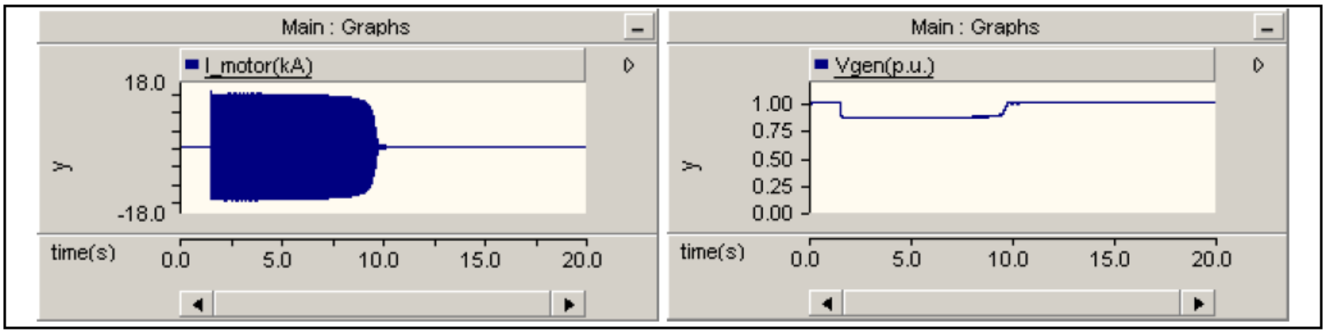
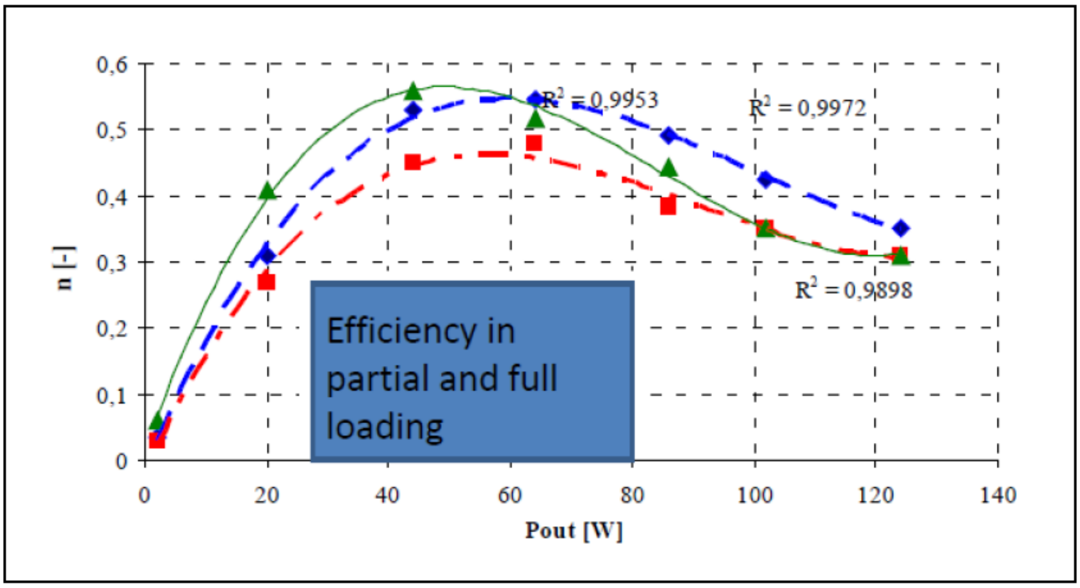


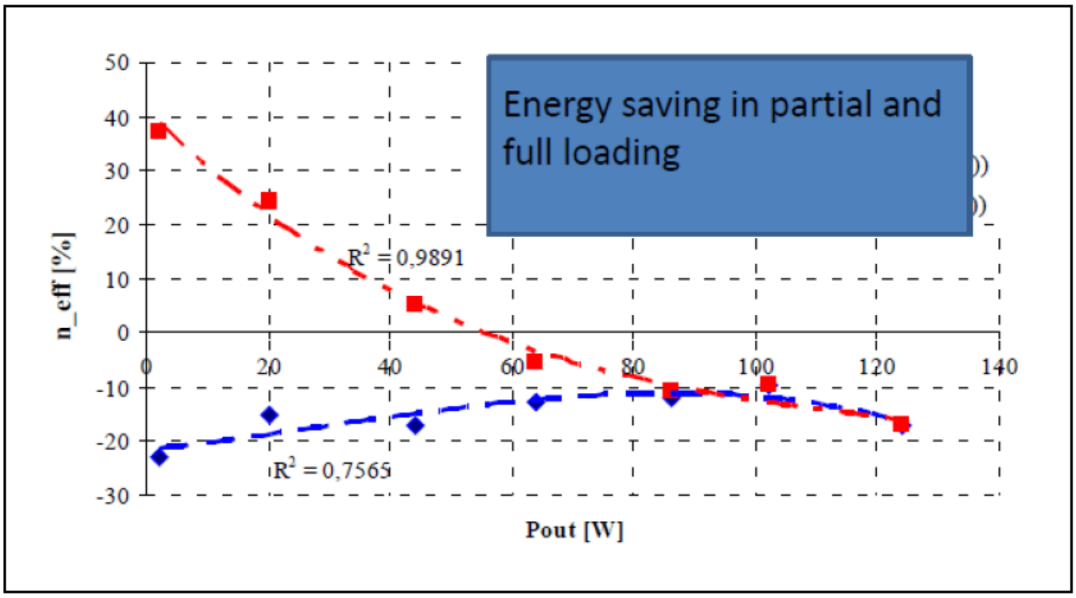
Figure 18: Transient inrush current and Voltage dip during starting-up of a 1.0 MW motor [19]

Starting-up of motors via power converters

The solution for above emerged problems is the starting – up of the motor via power converter. In this way the motor absorbs less power and current while it takes longer to reach the final speed with or without load. In partial loading conditions (up to 60%) the supply via a power converter leads to significant energy savings by up to 35% (see Figure 19). This is because the losses which are depended on voltage and independent on load, are significantly dropped.



(a)



(b)

Figure 19: a) Efficiency in partial and full loading via applying power converter; b) Energy saving in partial and full load via applying power converter

By using power converters, the active power is reduced by almost 22% while the reactive power by almost 43% respectively (see Figure 20). The active power reduction influences the power consumption of this motor while the reactive power reduction decreases the respective reactive currents and losses, resulting in a more efficient operation of the ship electric grid.

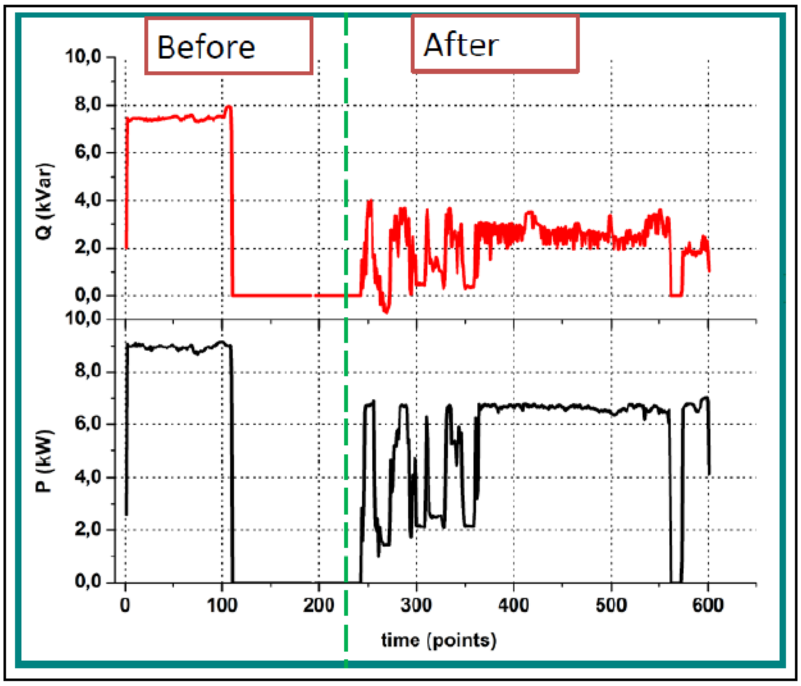


Figure 20: Reduction of reactive and active power with the use of power converters

M/V KASTOR – Case study

On the under-study vessel, M/V KASTOR of LASKARIDIS SHIPPING CO., LTD, a proposal was made for fitting variable frequency drives on large motors. Results are presented in Table 13.

Table 13: Retrofit of large motors with VFDs

Equipment subject to VFD	Rated power (kW)	Load factor	Approximate Cost [€]
Main cooling SW pump	30	0.85 → 0.55	16500
LT cooling F.W. pump	45	0.85 → 0.55	24750
Main L.O. Pump	90	0.76 → 0.50	49500
Bilge & G.S pump	75		41250
Ballast pump	165	0.85 → 0.55	90750
M/E auxiliary blower	55		30250
Main air compressor	43		23650
A/C compressor	42.6	0.72 → 0.47	23430
Main pump unit for windlass	120		66000
Main pump for mooring winch	120		66000
Ballast water treatment	110	0.85 → 0.55	60500

On Table 13, the rated power of the VFD for the calculations have been assumed equal to ~1.1 times of the rated power of motor while the cost is about 500 Euros/kW. Hence the savings from the no load losses are ~10-20%.

3.1.5 Direct current integration

In recent developments, the on-board DC grid applications are being integrated due to their benefits in comparison with AC grids, regarding dynamic positioning, improved efficiency, optimization of operation and fast ramping connected with the integrated energy storage systems. While the need of synchronization of generation units in AC systems, reactive power flow, harmonic currents and three-phase imbalances demand detailed management, switchgears and transformers are to be removed in a DC grid, providing increased space and weight savings, as well as fuel reservation, flexibility and system's stability [20].

The on-board DC grid provides a high-efficient power distribution and allows a wide range of sea-faring vessels to minimize their fuel consumption, as well as incorporate DC energy sources including Battery Energy Storage Systems. The implementation of a DC grid may reduce the electrical equipment footprint of up to 30% and the fuel consumption and emissions by 20% [21].

Classification regulations emphasize that the promising installed on-board DC distribution systems are expected to sufficiently provide electrical power and redundancy with respect to relative essential and habitual requirements. They should be designed to ensure safety and availability during emergency conditions and to provide adequate protection to prevent not only injury to passengers or crew, but also, damage to relative electrical equipment and its connections.

3.1.6 Waste heat recovery – Thermoelectric generators

Introduction

The largest percentage of waste heat in internal combustion engines comes from the exhaust gases, charge air and cooling water of the main engine (see Figure 21). A typical internal combustion engine converts about 30% of the fuel energy into mechanical energy while the rest escapes to the environment.

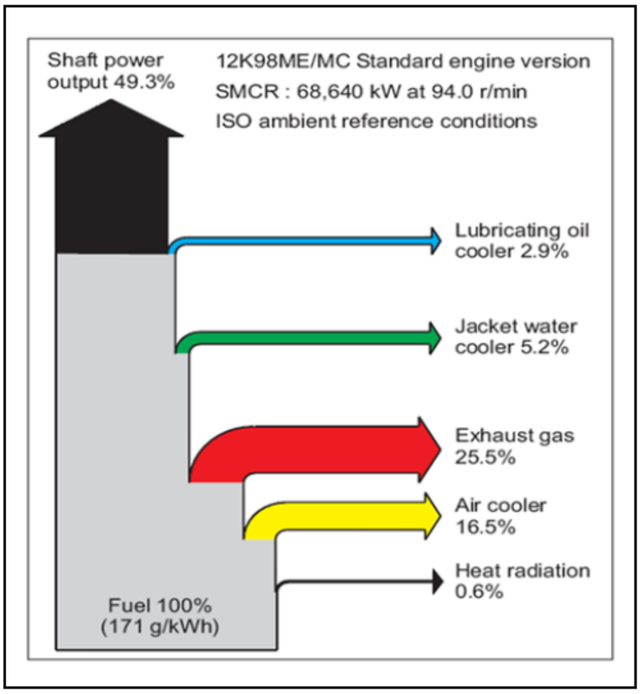


Figure 21: Identification of heat loss sources in a 2-X internal combustion engine [22]

The heat of the exhaust gases is used to produce steam in exhaust gas boilers. The produced steam is used in auxiliary steam turbine machines and in other auxiliary uses of steam on board e.g., fuel oil preheaters.

Heat from the charge air is transferred through the air cooler to the boiler feed water in order to raise the water temperature and reduce the heat required for the steam to reach saturation at a specific pressure.

The heat removed from the cooling water of the main engine is mainly used in the production of potable water at the evaporators, in the pre-heating of the water as well as in the heating of domestic water.

The Organic Rankine Cycle (ORC) technology has the ability to convert small or medium-range thermal energy into electrical or mechanical energy and is considered worldwide as the most promising waste heat energy exploitation technology.

Integrating a well-designed ORC system into an internal combustion engine can significantly increase its efficiency, reduce pollutants to the environment and pay back the investment needed for its construction within 2-5 years.

Thermoelectric generators are using the Seebeck effect to convert any temperature difference into potential difference and thus electricity. They have been used for decades in applications where large temperature differences are observed, mainly in space, and their most important feature making them attractive to an investor is their reliability with their infinite lifetime.

Organic Rankine Cycle (ORC)

Engine manufacturers in order to increase the efficiency of their engines, reduce emitted pollutants and improve the thermal mechanical efficiency are using technologies such as the use of air compressors (turbo), valve opening-closing synchronization, more efficient ways of fuel injection as well as technologies for reducing friction in the engine.

In recent years, the research and development of the internal combustion engines has hardly increased the efficiency of the engines up to 40% and this only in very large applications.

Consequently, 60-70% of the fuel's energy is not exploited and is either used by the engine's cooling system or lost to the environment.

For solving this problem, there are different approaches. On one hand there are studies on engines that run on alternative fuels, such as ethanol blends (see Figure 22), or hybrid engines to recover some of the lost kinetic energy.

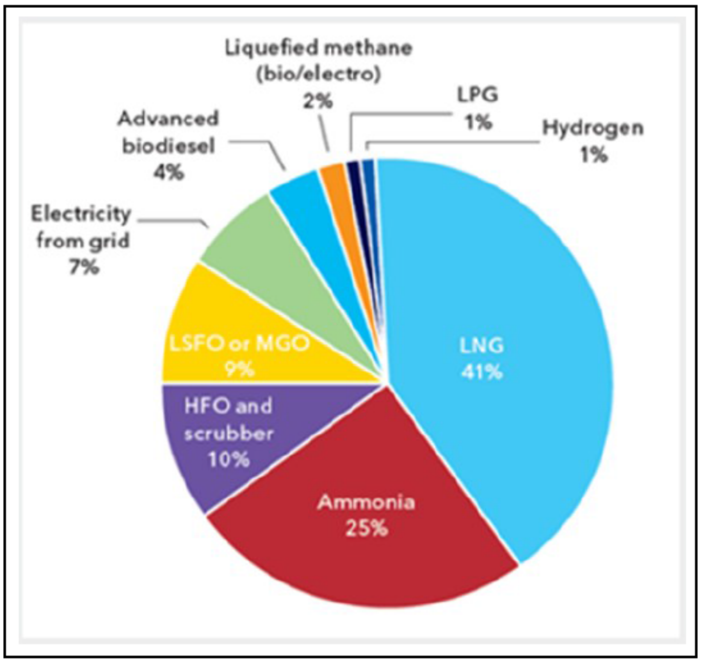


Figure 22: Forecast of use of alternative fuels in shipping industry on 2050 [23]

On the other hand, more recent research is focused on the development of the recovery of lost / rejected thermal energy. The most promising of these seems to be the ORC technology.

The ORC technology enables the exploitation of thermal energy available in the internal combustion engine and its conversion into electrical and/or mechanical energy.

More general thermal sources that can be utilized in an ORC system are biomass burning, geothermal energy as well as any thermal energy lost from any system e.g., internal combustion engine.

The purpose of adopting an ORC system is to increase the efficiency of the system and to reduce emissions to the environment. The basic operating principle of an ORC system is an electric generator driven by a turbine, which is driven by steam and thus converts thermal energy into mechanical energy and then into electrical energy.

Conventionally, water is the working medium for producing steam. But in an ORC system, the medium that evaporates and is used for energy production, is an organic fluid, which is characterized by a higher molecular mass than water. The lower molecular mass results in the slower rotation of the turbine, operation at lower pressures and mainly avoiding corrosion of the metal parts of the turbine blades.

A well-designed ORC system should be able to support a payback period of 2-5 years through reduced fuel consumption, depending on the size of the application.

However, F. Vélez [24] in his article mentions that the market of ORC systems, with a production potential of 0.2-2 [MWe] at a cost of approximately 1-4 x 103 [€/kWe], is still at a non-commercial stage due to the long payback periods of small-scale ORC systems.

Thermoelectric generators (TEG)

The thermoelectric phenomenon itself [25] is the direct transformation of temperature gradient to electrical voltage and vice-versa. A Thermoelectric device (see Figure 23) produces a voltage when its sides have different temperatures and respectively when voltage is applied a temperature gradient is developed (known as the Peltier phenomenon). If examined on the atomic scale an applied temperature gradient impels the electrically charged subatomic particles (electrons or holes) bearing electrical charge, to the hot or cold side, much likely as a typical gas expanding by temperature.

This happens because the electron energy levels shift differently in the different metals, creating a voltage between the junctions which in turn creates an electrical current through the wires, and -by own means- a magnetic field around the wires. The electricity generators based on the Seebeck effect do not depend on the nature of consumable heat and, therefore, they can be used in different areas. It is important to note that the initial device built by Seebeck can be used not only for conversion of the heat into electricity but also for the inverse process. When current is supplied to this device, it produces the difference in temperatures between its two sides (the Peltier effect, as mentioned above was discovered in 1834). In this case, the device is called Thermo-Electric Cooler (TEC).

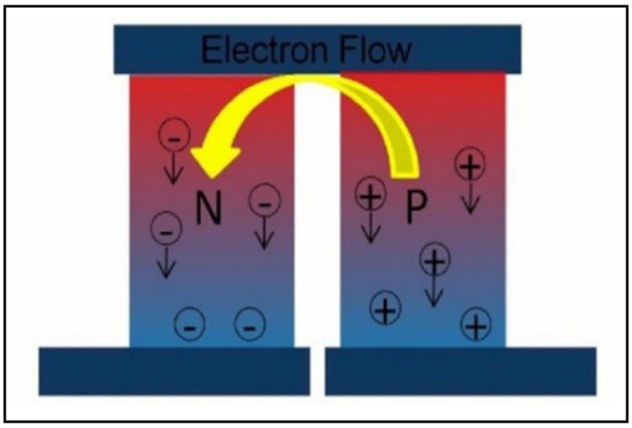


Figure 23. Thermoelectric device

The Seebeck effect (see Figure 24) appears when two different thermoelectric materials forming electrical conductors and attached at their ends, have their junctions in different temperatures. In such a case potential difference is built at the junctions, depending on the temperature gradient between the junctions.

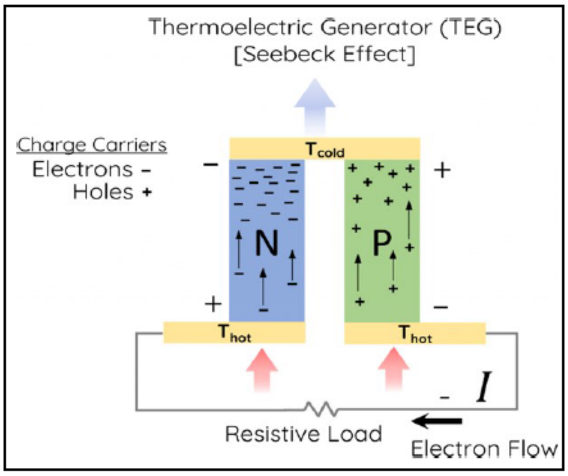


Figure 24: Thermoelectric generator – Seebeck effect

Several companies, mainly in the microprocessor or Semiconductor manufacturing business have started building commercially oriented TEG modules since the early '90s. The fact that the reverse Seebeck phenomenon (Thermoelectric cooling or "Peltier") uses almost the same modules for practical cooling implementations gave a significant boost to the relevant research by revealing a significant market interest. The research for semiconductors aiming to improve the overall power factor of commercial TEG modules, gave room for more practical uses.

Now, TEGs producing a significant 16 to 19 [W] of power for 200-250°C temperature gradient at a 40x40x3 [mm] are commercially available at affordable prices which are dropping rapidly. As wasted heat is practically everywhere, the increasing use of TEGs for its harvesting appears to be the most possible guess.

A case study

A typical voyage of a bulk carrier sailing from China to the USA have been considered in terms of fuel-saving by the recovery of waste heat carried by the exhaust gases produced by the vessel's main engine and the use of them in a system of TEG arrays attached to the ship's hull under the waterline. In this case study [25] assumed that the ship is sailing full of cargo at the MCR of its engine.

The calculations through modelling process [25] shown that the total energy capability per m^2 of TEG arrays for a six-month period (109 days sailing and the rest days the vessel is remaining at port or anchorage where the main engine is out of order) will be 13590 [kWh] while this energy amount correspond to fuel saving per m^2 of TEG arrays equal to 2582 [kg] (the calculation is based on a fuel consumption of an auxiliary gen set 190 [g/kWh]) (see Figure 25).

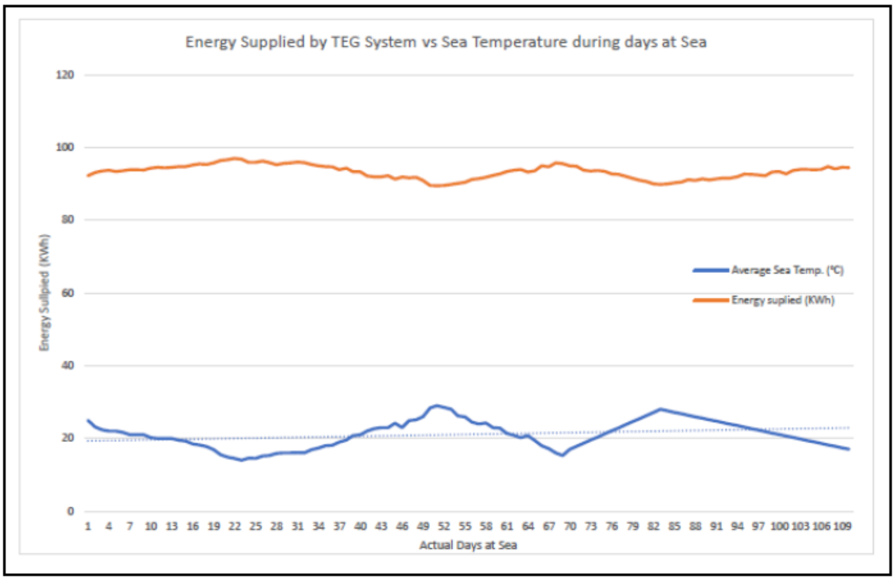


Figure 25: Energy supplied by TEG to the system during 109 days at sea itinerary [25]

3.1.7 Shaft generator systems

Among the most promising alternatives in terms of reduced emissions and consumption is the shaft generator systems. Shaft generator systems often met as Power Take Off (PTO) [17][17], [26] systems (see

Figure 26) are coupled to the main propulsion engine and generate electricity supplied either directly to the main ship grid or to specific loads on-board.

The main characteristics of PTO are the following:

- Part of the propulsion engines mechanical rotating power is transferred into the electrical network via gearbox and generator.
- For frequency variations and voltage matching, complete drive chain is required for utilizing the energy.
- It diminishes the need to burn extra fuel to power these systems through separate diesel gensets.
- The result in fuel savings is significant, especially when coupled with improved operational flexibility.
- The system can also drastically decrease the operating hours of auxiliary generators - and their need for maintenance - for additional operational cost savings.
- It helps main engines run at a more efficient operating point with lower fuel consumption.

The main advantages of these systems consist in more efficient electric power generation due to the higher efficiency of the main engines compared to the auxiliary ones, as well as the associated reduced maintenance costs. Furthermore, via this operation, PTO's can improve the efficiency of the main propulsion engine, as they can shift its operating point closer to its MCR. Moreover, in reverse operation (Power Take In – PTI's) they can offer additional degrees of freedom in propulsion acting either as boosting propulsion devices or as an emergency propulsion system.
In PTI configuration, propulsion electrical motor work as a part of propulsion system. The electrical propulsion has several options for utilization:

- Electrical mode: Used typically lower in power range, for example to sail out from harbour or emission-free.
- Hybrid mode: Used typically either to improve propulsion engine performance by taking the power off or to boost maximum speed / thrust out of the propulsion train. If operation profile contains short term need for full power, like pushers, harbour tugs often do, or in case small propulsion engine size brings benefit to vessel design, this mode is very interesting option.
- PTH (Power-take-home), it also can increase propulsion system redundancy by electrical driving, in case of absence of Main Engine.

It has been proven in a case study of an LNG carrier [27], where a PTO system installed that the vessel become more fuel and environmentally efficient. Moreover, it has been computed that 7.6 tons of Lubricating Oil are saved due to the PTO operation while the load factor of the ME was improved, as it operates more smoothly and more efficiently (see Figure 27). Finally, the use of PTO allocated the loading of the Auxiliar Engines (Generators) much better, reducing in this way the Maintenance Costs.

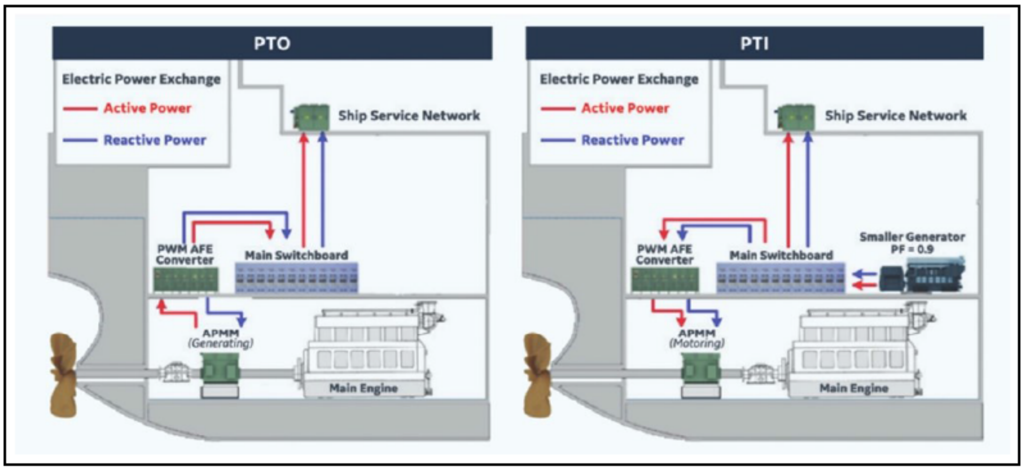


Figure 26: Typical PTO / PTI system

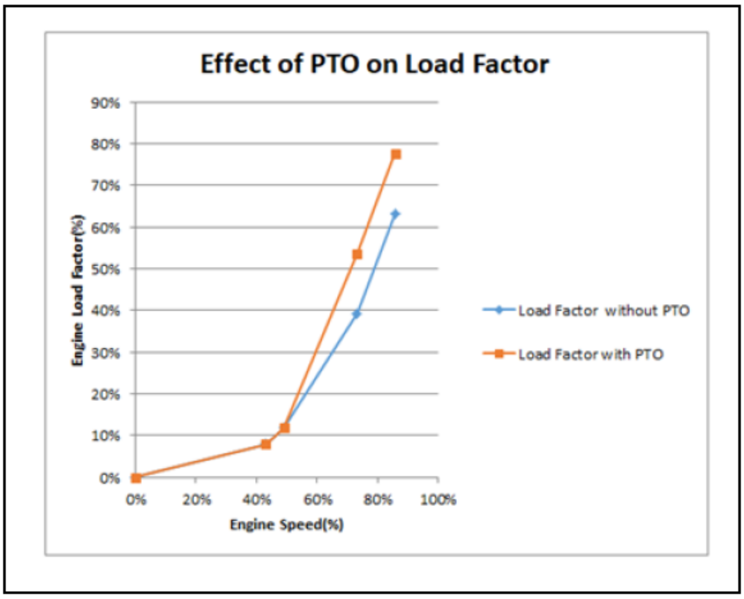


Figure 27: Load Factor with or without PTO

It should be emphasized that the main engine of the ship under study IMO: 9843405, KASTOR, the MAN B&W 98-50 MC is constructed so to foresee the PTO/PTI solution with several configurations (see Figure 28):

- PTO/RCF (Power Take Off/Constant Frequency): Generator giving constant frequency, based on mechanical / hydraulically speed control.
- PTO/CFE (Power Take Off/Constant Frequency Electrical): Generator giving constant frequency, based on electrical frequency control.
- PTO/GCR (Power Take Off/Gear Constant Ratio): Generator coupled to a constant ratio step-up gear, used only for engines running at constant speed.

In perspective, it should be noted that batteries to be integrated with the frequency converter to ensure Electrical / hybrid mode with energy storage (ES), advance ES functions, enhance operation mode and safety (see Figure 29).

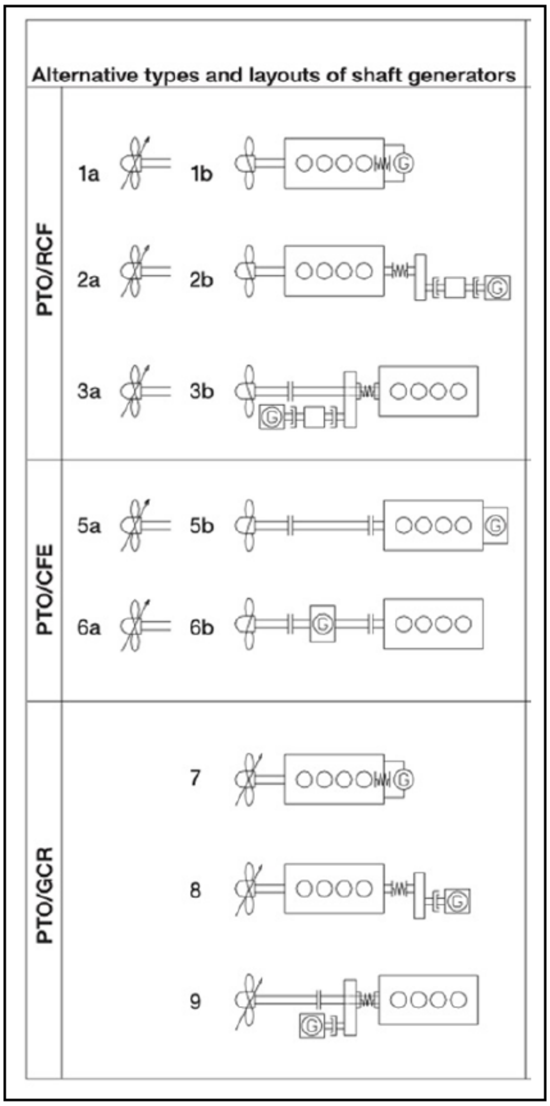


Figure 28: Alternative solutions of PTO/PTI for the ship under study IMO: 9843405, KASTOR

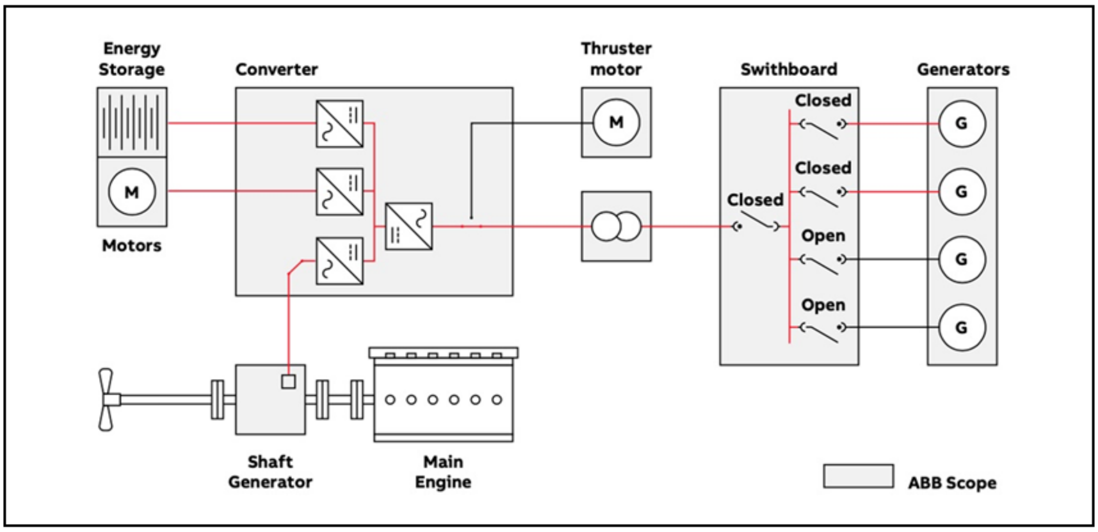


Figure 29: Integration of batteries in the PTO

3.1.8 Optimum operation of electric energy system

The major targets of the optimum operation of the electric energy system are the minimization of the operation cost and the limitation of the gas emissions. Optimization process of the energy system is subject to technical constraints which are briefly described here below [28]:

- Power balance constraint: It assures balance between generation and consumption as well as frequency stability.
- High loading constraint: Generator should not be loaded above a certain power level for more than a specific time interval as thermal and mechanical losses are increased and blackout prevention capability is limited.
- Low load constraint (technical minimum): The engine should not be loaded below a certain value specified by the engine manufacturer in order to reduce the maintenance costs and possible damage.
- GHG emissions constraint: Energy efficiency operational indicator (EEOI) should be monitored on-line and limited below a certain upper limit.
- Ramp rate constraint: High rate of change of generator loading must be avoided in order to eliminate mechanical stress and damages.
- Blackout prevention constraint: It defines the maximum allowable continuous loading of the generators where the system is blackout-proof.
- Generator Start/stop constraint: Frequent start/stop of the generator results in increased maintenance cost and fuel consumption. It is a secondary priority constraint and it can be applied by imposing a time window between successive start/stop of the generator.

3.1.9 Photovoltaic solar panels

The use of photovoltaic (PV) panels to power marine vessels could provide more efficient and sustainable operation by relieving the working load on the generators and prolonging their maintenance times. The low electrical output per unit surface, anyway, makes photovoltaic solar panels 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 at a cost of $1.68 million. The energy generated by the 40[kW] solar array on this ship is used to power lighting and other applications in the crew's living quarters.

The obvious drawback of PV solar power is the high capital cost [29] of these plants that have not yet benefited from large scale economies. It is to be hoped that as other land-based applications increase demand for this type of technology, the wider application in the shipping industry will be made viable. Meanwhile, promising results come from a recent report by Wood Mackenzie Solar System and Technology Service. The report showed that the U.S. turnkey EPC PV prices, broken down by market segment, are trending downward with an expected reduction in 2026 of about 70% for residential PV and 85% for utility PV compared to 2007 prices.

Current interest in the implementation of PV generation in the marine environment is evidenced by the development of several scientific and industrial projects aiming at demonstrating innovative solutions for an effective and faster decarbonization of shipping.

The EU-funded ENGIMMONIA project is promoting the global introduction of alternative fuels like ammonia and transfer clean energy technologies successfully demonstrated in terrestrial applications, like renewables, to the maritime sector; in particular, the installation of PV composite surfaces easily installable on vessel structural parts is under consideration for three different kinds of vessels (i.e., an oil tanker, a ferry and a container ship) [30].

A joint venture composed of ship design company Aurelia, shipping company NEPA and wind propulsion specialists Aloft Systems is developing a project to retrofit a 203,000 DWT Newcastlemax bulk carrier having Category D so to make it compliant with EEXI and CII and rise it to category C [31]. This project involves the on-board installation of a PV/battery (see Figure 30) generation system to reduce the hours in service for the auxiliary engines, while taking advantage of the free area on deck as shown in Figure (a). The full deck area, including hatch covers, will be fully equipped with solar panels for a peak power of 1MWh. The CO_2 emission reduction is estimated to be around 6%, which is equivalent to about 3.300 tonnes of CO_2 reduction per year. Such a PV plant installation on board is also expected to provide a MGO fuel reduction of 97.5% with an overall fuel cost reduction equal to 12.5%, corresponding to about 1.288.000 USD per year.

Figure 30: Rendering of the retrofitted bulk carrier with PV system installed [31]

Use of PV generation combined with hybrid power systems on cargo ships is also a hot topic, as demonstrated by the interest of both industry and academia. By this standpoint, it is worth citing the maritime industry's first installation and commissioning of a hybrid power system combined with a PV solar energy system on board a bulk carrier vessel recently realized by the group Wärtsilä [32] and the research work presented in [33] where a case study using Flettner rotors in combination with PV panels on bulk carriers is analysed to determine the power contribution of renewables to the propulsion and to assess their impact on attained EEDI through calculation using IMO's guidelines.

Finally, PV integration is also receiving consideration in the sector od Ro-Ro type marine vessels, where recently a developed design/layout approach demonstrated a 7.38% reduction of the fuel requirement for the considered case study vessel [33].

3.1.10 Fuell cells

Provided that fuel storage and bunkering problems are resolved, they can serve as complementary power sources i.e., during reaching the port and berthing. They cannot react to fast at load changes unless they will be combined with supercapacitors or batteries.

3.1.11 Batteries

The use of electricity is not only limited to electricity in ports for land equipment, but has application in the operation of ships and also in the propulsion systems of ships, electric ships as they are called. Batteries can be used as main power sources in short-sea shipping vessels, or as complementary power sources for short time intervals.

The shipping industry, in recent years, has been investigating the use of electric propulsion in large ships and mainly in container ships, either as hybrids with a combination of motor and battery or only with batteries. The benefits of this technological solution are the significant reduction of greenhouse gas emissions if some important steps are taken such as cost reduction in battery manufacturing technology, new battery manufacturing materials of greater capacity, smaller volume and also in the development of charging points on sea routes.

A new study [34], written by three energy researchers at the Lawrence Berkeley National Laboratory points out that, battery electric propulsion has not been explored as a potential low-emissions alternative in the shipping sector, despite its significant emissions reduction potential, the recent of battery costs, improvements in battery energy density, increased availability of low-cost and renewable electricity, and its substantial performance advantage over e-fuels.

An important point from the study is that less space is needed to place batteries than to place alternative fuel tanks inside the ship and at the same time if the proper energy supply infrastructure is created, the proper charging stations then the ships would be able to stop and recharge, at en-route stations, while battery costs, lost TEU capacity and additional energy requirements from battery weight would be significantly reduced.

Electric propulsion and electric charging of ships may be among the zero-emission alternatives that are gaining ground, but it is quite a complex, demanding and capital-intensive process that requires coordinated actions. The advantages offered by electric propulsion are the following:

- Precise control of the speed of rotation of the propeller and the ship, as well as its position
- High manoeuvrability
- Quick response during manoeuvres
- Low noise and vibration levels
- Fuel economy, since it is possible to load the engines close to the optimum point
- Low operating and maintenance costs
- Increased reliability with multiple systems connected in parallel, and therefore increased safety
- Reduction of emitted pollutants, since fuel consumption is lower.

4 Closing remarks

For recapping all above Table 14 with all the proposed measures for improving the electric efficiency of the vessels in conjunction with the retrofit feasibility and the maturity of the proposed technology is presented below.

Table 14: Feasibility and maturity of the proposed technologies

Measure	Design stage	Retrofit feasible	Mature technology	Technology needs further development
Optimal selection of generator sets	Appropriate if not mandatory	Difficult, if not impossible	✓	
Active and reactive load analysis	Appropriate if not mandatory	Difficult, if not impossible	✓	
Shaft Generator systems	Yes	Possible	✓	
Cold ironing	Yes	Yes	✓	
Power Converters for large motors	Yes	Yes	✓	
Photovoltaic solar panels	Yes	Possible	✓	
Optimum operation of electric energy system	Yes	Difficult, BUT not impossible	✓	
Direct Current integration	Yes	Difficult if not impossible	✓	
Waste heat recovery - TEG	Yes	Possible	✓	
Fuel Cells	Yes	Difficult, BUT not impossible		✓
Batteries	Yes	Possible		✓

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