# SHIPS ENERGY EFFICIENCY AS EMISSIONS REDUCTION MEASURE

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**WP2** **Emissions and abatement strategies**

## Issue and revision

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## Executive summary

The importance of the work subject is determined by current trends in maritime transport, especially in the scope of energy efficiency and emissions of ships. Very ambitious emission reduction targets, as defined by IMO and EU, now set new directions for design and operation of vessels. Extremely significant achievement is related to energy efficiency of ships, as it stimulates the emission reduction of all exhaust components; $CO_2$, $NO_X$, $SO_X$, PM and HC. The improvement of ship's efficiency affects all propulsions i.e. main and auxiliary engines and boilers, which leads to a significant drop in ship total emission.

In the first sections of the report, a brief history and current status of the energy efficiency policy in shipping industry is presented, following by energy design and operational index methodology. Ship's performance records and data sets collection has been carried out on board of modern ultra large container carrier in order to present energy efficiency improvement.

Ship's performance records and data sets collection has been carried out on board of modern ultra large container carrier in order to present energy efficiency improvement. The main part of the report contains theoretical knowledge from the field of energy efficiency of merchant ships and marine waste heat recovery systems are presented in details. Furthermore, collected data from case ship is analyzed and processed in next sections. Data and calculations are demonstrated in a form of tables and graphically as diagrams.

The subsequent targets are formulated in a form of predications which requires set of information evaluation and verification, based on analysis of collected data, case ship's construction profile, drawings and instruction manuals and can be listed as follows: attained energy efficiency index and GHG reduction potential, possible impacts of WHRS on: vessel's design, safety, reliability and fuel savings. The predictions established, formulated and stipulated as a main effect of the work and are presented as principal findings and conclusions in last section. Theoretical and practical conclusions are drawn as well.

The report, can be used as an effective tool of learning about energy efficiency in shipping industry and modern marine waste heat recovery systems. Graphically presented data with conclusions and principal findings can be used by ship owners and operators and serve as one of the tools to determine and initially evaluate ship's energy efficiency, while predicting sailing and ship's load conditions influence. It can support the decision making process whether to retrofit older ships with at least some form of waste heat utilization. It can support ships' owner/operator deeper analysis of energy efficiency operational indicator, which could bring more fuel savings into the large fleet of vessels and help in selection of appropriate sailing profile for each and every vessel within its fleet.

# Contents

# Acronyms and abbreviations

| | |
|---|---|
| **A/E** | Auxiliary engine (as a part of diesel generating set) |
| **A/Es** | Auxiliary engines |
| **CEO** | Chief engineer officer |
| **DWT** | Deadweight tonnage |
| **EEDI** | Energy efficiency design index |
| **EEM** | Energy efficiency measure |
| **EEOI** | Energy efficiency operational indicator |
| **EGE** | Exhaust gas economizer |
| **FEU** | Forty-feet equivalent unit (single container size) |
| **GHG** | Greenhouse gas |
| **HP** | High pressure |
| **IMO** | International maritime organization |
| **ISO** | International organization for standardization |
| **KC** | Kalina cycle |
| **LP** | Low pressure |
| **MAS** | Master |
| **M/E** | Main engine |
| **MEPC** | Marine environment protection committee |
| **OFB** | Oil fired boiler |
| **ORC** | Organic Rankine cycle |
| **P/T** | Power turbine (as a part of turbo generating set) |
| **PTI** | Power take in (mode of shaft generator / motor) – Motor mode |
| **PTO** | Power take out (mode of shaft generator / motor) – Generator mode |
| **RC** | Rankin cycle |
| **RFO** | Residual fuel oil (e.g. HFO – heavy fuel oil) |
| **RPM** | Revolution per minute |
| **SCRC** | Super-critical Rankine cycle |
| **SEEMP** | Ship energy efficiency management plan |
| **SFOC** | Specific fuel oil consumption |

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|---|---|
| **S/G** | Shaft generator |
| **SRC** | Steam Rankine cycle |
| **S/T** | Steam turbine (as a part of turbo generating set) |
| **STG** | Steam & power turbine generator (turbo generating set) |
| **T/C** | Turbocharger |
| **TEU** | Twenty-feet equivalent unit (single container size) |
| **T/G** | Turbo generating set |
| **WHR** | Waste heat recovery |
| **WHRS** | Waste heat recovery system |

# 1 Background

Currently, the concept of “motorways” of the sea is under consideration in the European Union. Their creation on the Baltic, North and Mediterranean Seas can relieve and reduce land transportation on the territory of the EU member states. In sea transportation goods are shipped by different types of cargo vessels designed to carry a given kind of cargo such as; container and bulk carriers, general cargo vessels, tank and ro-ro ships and ferries. To complete a task given to a certain cargo ship, energy is indispensable. Most frequently, it is chemical energy contained in fuel oil delivered to the ship which must be converted into other kinds of energy, essential for a ship’s correct functioning such as: mechanical, electric, thermal and pressure energy.

The main propulsion, which delivers mechanical energy to move the ship, is the fundamental part of the ship’s power plant. Other systems e.g. electric in the engine room are auxiliary. Their main task is to deliver electric energy which essential for machineries and installations to operate the main propulsion as well as to deliver energy to all other installations and energy receivers. Ships’ power plant are complex systems located on moving objects and in connection with that, they are isolated and autonomous. The ship independence distinguishes the ship’s power plant room from stationary power plants, means that factors associated with the ship and its outward environment affect service conditions of machinery and installations.

The factors in question are the following: type and size of a vessel, its operating modes, used technologies, type of shipped cargo, crew qualifications, weather conditions, legal conventions and many others. With reference to that, machinery and installations are characterized by ship’s specific service conditions. For organizational and financial reasons there is no option of modelling ship’s realistic service conditions. Therefore, it becomes necessary to do survey on real objects – vessel power plant and in operating conditions.

Another source of information on engine power plant realistic performance are; documents from sea trials conducted by shipyard teams, manuals of engines and auxiliary systems producers as well as information in deck and engine log books, manoeuvring logs, control system printouts and in all kinds of service reports sent periodically to an owner’s technical staff. Generally, such data is not commonly accessible. The access is only given to the company staff and the data are confidential. Moreover, parts of documentation are destroyed, e.g. when a vessel is sold or when the archives are periodically removed. In this situation, conducting survey on realistic service performance of electric networks is challenging task to collect the comprehensive information on the object parameters. For that purpose, research projects are executed to build respectively broad ship data base and consequently create probabilistic models of phenomena and processes, taking place in ship's power plant.

Probabilistic models of phenomena and processes taking place in power plant would be needed at the vessel's draft design stage. Similarly, such results one could extract using deterministic models which so far have been employed in shipbuilding and are based on traditional approach. Such approach however, might lead to oversized machine selection and it also increases the investment and operating costs. Generally, the deterministic models are based on constrains and recommendations which were imposed by manufacturers or classification societies. Reproducing the so called 'similar vessels' technique in the design process, can convey the error transmission. It is meaningful because a vessel's draft design project, whose share in the direct costs amounts only to ~3%, in fact affects ~60% of the ship's costs.

As for ship operating, models of random phenomena and the ship power plant can be used for the purpose of ensuring the ship reliability and safety. Additionally, the machinery condition may be predicted and the engines and boiler exhaust emission may be modelled on the basis of the ship realistic data and observed phenomena. Moreover, appropriately created probabilistic models might be used by ship owners and their technical staff to solve the operating problems.

From among all the ship's power plant systems, one of the most important systems from the point of view of a ship safety and its functional structure is the main propulsion and the electric power plant in particular. The appropriately designed and operated electric network must perform all the tasks faced by transport and non-transport vessels. Because of the fact that ship's system is autonomous, power supply breakdown is dangerous not only for the ship itself but also for its crew and environment. Identifying real electric power demand level while operating transport ships becomes meaningful. The identification of the vessel power system, extreme values in particular, allows to specify their working conditions and it is indispensable while making the project assumptions.

Shipping is permanently engaged in efforts to optimize fuel consumption. And, while ships are universally recognized as the most fuel-efficient mode of bulk cargo transportation, the different studies, identified a significant potential for further improvements in energy efficiency, mainly through the use of already existing technologies such as more efficient engines and propulsion systems, alternative fuels e.g. LNG or, through technical- and design-based measures that can achieve noteworthy reductions in fuel consumption and resulting $CO_2$ emissions.

Although the easiest way to improve a vessel's fuel efficiency is, indeed, to reduce speed – hence the move to slow steaming by a significant number of ships – there is a practical minimum at which fuel efficiency will decrease as a vessel is slowed down further. There are other technical ways to improve fuel efficiency, such as waste heat generators, which do not impact on ship's speed. Indeed, improvements in road transport efficiency have been made through advances in technology. Also, there are economies of scale in ships' fuel efficiency. The larger the ship, the lower the fuel consumption per unit of cargo. However, such economies of scale are limited by trade considerations, physical port limitations e.g. draft or cargo logistics issues. Therefore, ships tend to be designed to be as large as practical for a given trade.

Fuel oil consumption represents a significant element of the cost of operating a ship today. Ship's energy efficiency performance can be optimised and operational energy efficiency measures employed either at sea or in port. Comparing the energy efficiency performance of one ship with that of a similar ship on the same trading route is more complicated as energy efficiency of different ships can be affected by many variables.

Relevance of this report is based on actual trends in marine industry, especially in the scope of energy efficiency and emissions of merchant ships. In the first sections, practical knowledge from the fields of energy efficiency of merchant ships is presented, which is necessary to achieve the main scope of work. All of background information is based on international legislation issued by IMO and ISO.

Furthermore, collected data from case ship is analyzed and processed in next sections. Data and calculations are demonstrated in a form of tables and graphically as diagrams. Theoretical and practical conclusions are drawn as well. The predications established, formulated and stipulated as an effect of the scope of work are evaluated and presented as principal findings and conclusions in last section.

This report, together with appendixes, can be used as an effective tool during courses about energy efficiency in shipping industry and modern marine waste heat recovery systems. Also, the data might be partially utilized in larger analytic works, which could incorporate data from many different kind of container carriers, built in different versions and equipped with various waste heat utilization systems.

Graphically presented data with conclusions and principal findings can be used by ship owners and operators and serve as one of the tools to determine and initially evaluate ship's energy efficiency while predicting sailing and ship's load conditions influence. It can support the decision-making process whether to retrofit older ships with at least some form of waste heat utilization. It can support ships' owner/operator deeper analysis of energy efficiency operational indicator, which could bring more fuel savings into the large fleet of vessels and help in selection of appropriate sailing profile for each and every vessel within its fleet.

# 2 A brief history and current status of the energy efficiency policy in shipping

Energy efficiency, connected to air pollution and reduction of greenhouse gas emissions, has been an issue within the IMO for a considerable time. The international Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI was adopted in 1997, at that time mainly focusing on air pollution, in particular $NO_X$ and $SO_X$ emissions were focused.

The next step was to attention on greenhouse gas emissions. In 2011, IMO adopted resolution MEPC.203(62) a suite of technical and operational measures which together provide an energy efficiency framework for ships. These mandatory measures entered into force on 1st January 2013, as Chapter 4 of MARPOL, Annex VI. Further amendments to those requirements mean that ship types responsible for approximately 85% of carbon dioxide ($CO_2$) emissions from international shipping are to be subject to strengthening requirements for energy efficiency and, together, they represent the first-ever, mandatory global regime for $CO_2$ emission reduction in maritime sector.

## 2.1 Marine energy management and technical measures, legislation and approach

Marine legislation dealing with energy efficiency, energy management and technical measures is rapidly evolving for the past several years. Currently we can observe numerous legal regulations, some of them are mandatory for all ship owners, operators and some of them are up until now voluntary.

By resolution MEPC.203(62), the Energy Efficiency Design Index (EEDI) was made mandatory for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships by regulation

22 stating that each ship shall keep on board a ship specific Ship Energy Efficiency Management Plan. This may form part of the ship's Safety Management System (SMS).

The SEEMP provides a possible approach for monitoring ship and fleet energy efficiency performance over time and some options to be considered when seeking to optimize the performance of the ship. At MEPC 62 also MEPC 1/Circ.684 guidelines for voluntary use of the Ship Energy Efficiency Operational Indicator (EEOI) was prepared for circulation.

During MEPPC 63 IMO also adopted the 2012 Guidelines for the development of a Ship Energy Efficiency Management Plan by resolution MEPC.213(63) in order to assist ship's masters, operators and owners to develop the SEEMP. In these guidelines, planning, implementation, monitoring, self-evaluation and improvement are introduced as a framework and structure of the SEEMP.

Among the mandatory regulations related to energy efficiency of the marine ships, which are already implemented and are being enforced, following regulations can be highlighted:

- MARPOL Annex VI, chapter 4 – regulations on energy efficiency for ships,
- resolution MEPC.203(62) – Amendments to MARPOL Annex VI on regulations for the prevention of air pollution from ships by inclusion of new regulations on energy efficiency for ships.

As a direct and practical way of implementation of above regulations into practice, following new methods have been stipulated [IMO, 2011]:

- attained EEDI – attained Energy efficiency design index (regulation 20 of MEPC.203(62)),
- required EEDI – required Energy efficiency design index (regulation 21 of MEPC.203(62)),
- SEEMP – Ship energy efficiency management plan (regulation 22 of MEPC.203(62)),
- Promotion of technical co-operation and transfer of technology relating to the improvement of energy efficiency of ships (regulation 23 of MEPC.203(62)),
- IEE – International energy efficiency certificate and supplement (appendix VIII of MEPC.203(62)).

In following sub-paragraphs, the main methods mentioned above, will be described and explained in general, applicable for all ships.

## Attained EEDI

The attained EEDI is being calculated for [IMO, 2011]:

- each new ship,
- each new ship which has undergone a major conversion,
- each new or existing ship which has undergone a major conversion, that is so extensive that the ship is regarded by the administration as a newly constructed ship.

The attained EEDI is specific for each and every ship (where mandatory) and is estimating performance of the ship from the point of view of energy efficiency. This must be accompanied by EEDI technical file, where all necessary data for calculation of EEDI must be entered and also process of calculation of EEDI must be shown.

The attained EEDI for a new ship is a measure of ship’s energy efficiency and it is being generally represented as a fraction where the numerator is represented by “impact to environment” and denominator is represented by “benefit to society” - transportation work. In regards to marine industry, the formula for calculation of EEDI can be simplified. Simplified formula for calculation of EEDI is shown:

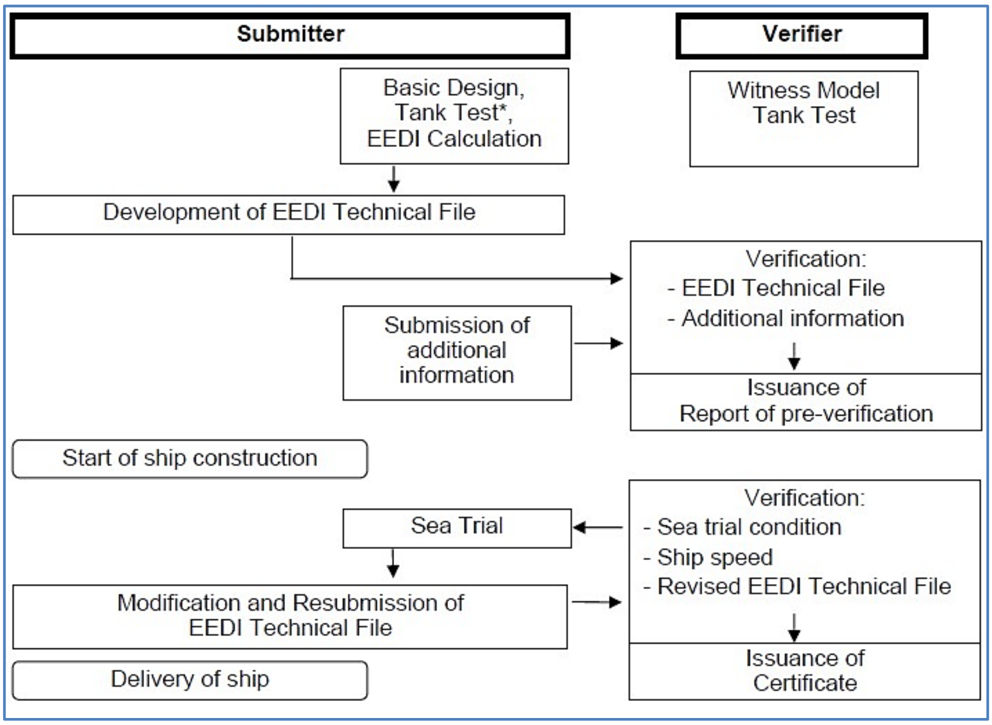
$$EEDI = \frac{total\ power \cdot total\ fuel\ consumption \cdot CO_2\ coversion\ factor}{capacity \cdot ship's\ speed} \qquad (2.1)$$

The full formula with thorough explanation of each and every step of calculation of EEDI and all required data can be found in Resolution MEPC.245(66).

Attained EEDI is being calculated during design and project stage of shipbuilding. Attained EEDI must be verified and approved by administration at final stage during sea trials. The basic flow of survey and certification process is presented in Figure 2.1.

The full description of methods and procedures of verification of attained EEDI is described in Resolution MEPC.214(63). The sea trial must be conducted in accordance with ISO standard 15016:2015. In this standard the whole process of conducting a sea trial and collection of data necessary for calculation and verification of attained EEDI is described in detail.

**Figure 2. 1:** EEDI – Basic flow of survey and certification process



Source: [IMO, 2011]

## Required EEDI

The EEDI is a benchmark on the energy efficiency set to reduce exhaust gas on new built vessels. It is a non-prescriptive measure that helps the industry decide which technologies should be installed on a specific ship design. When the emission of $CO_2$ is above this benchmark, the design of the vessel has to be changed. As long as the energy efficiency is below the target, the ship designers and builders are free to choose the most cost-efficient technologies to comply with the regulations. The benchmark will be progressively reduced in the future compared to a reference value, consequently decreasing the emission of greenhouse gases. The EEDI is not a technology but an attempt to force shipowners and shipyards to use state of the art technology.

The required EEDI is being mandatory for [IMO, 2011]:

- each new ship,
- each new ship which has undergone a major conversion,
- each new or existing ship which has undergone a major conversion, that is so extensive that the ship is regarded by the administration as a newly constructed ship.

The comparison between attained and required EEDI is shown in following equation (2.2).

The formulas for verifying and calculation of required EEDI are shown in equations:

$$Attained\ EEDI \leq Required\ EEDI \tag{2.2}$$

$$Required\ EEDI = \left(\frac{1-X}{100}\right) \cdot Reference\ line\ value \tag{2.3}$$

where:

X – reduction factor, specified in Table 1 of MEPC.203(62), for the required EEDI compared to the EEDI reference line.

The reference line values of required EEDI are being calculated in accordance with MEPC.203(62) from formula:

$$Reference\ line\ of\ required\ EEDI = a \cdot b^{-c} \tag{2.4}$$

where: a, b and c – parameters are given in Table 2.1

**Table 2. 1** Parameters of reference values for the different ship types

| Ship type | **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 carrier | 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 |

Source [IMO,2011]

The reference line values of required EEDI can be graphically presented in a form of line graph. The reference line for container ships with reduction factors as per Table 1 of MEPC.203(62) planned for following years is presented in Figure 2.2.

The reduction factors planning for next years:

- up to 31-Dec-14 – Phase 0 – no reduction factor relative to EEDI reference line,
- 01-Jan-15 to 31-Dec-19 – Phase 1 – 10% reduction factor relative to EEDI reference line,
- 01-Jan-20 to 31-Dec-24 – Phase 2 – 20% reduction factor relative to EEDI reference line,
- 01-Jan-25 onwards – Phase 3 – 30% reduction factor relative to EEDI reference line.

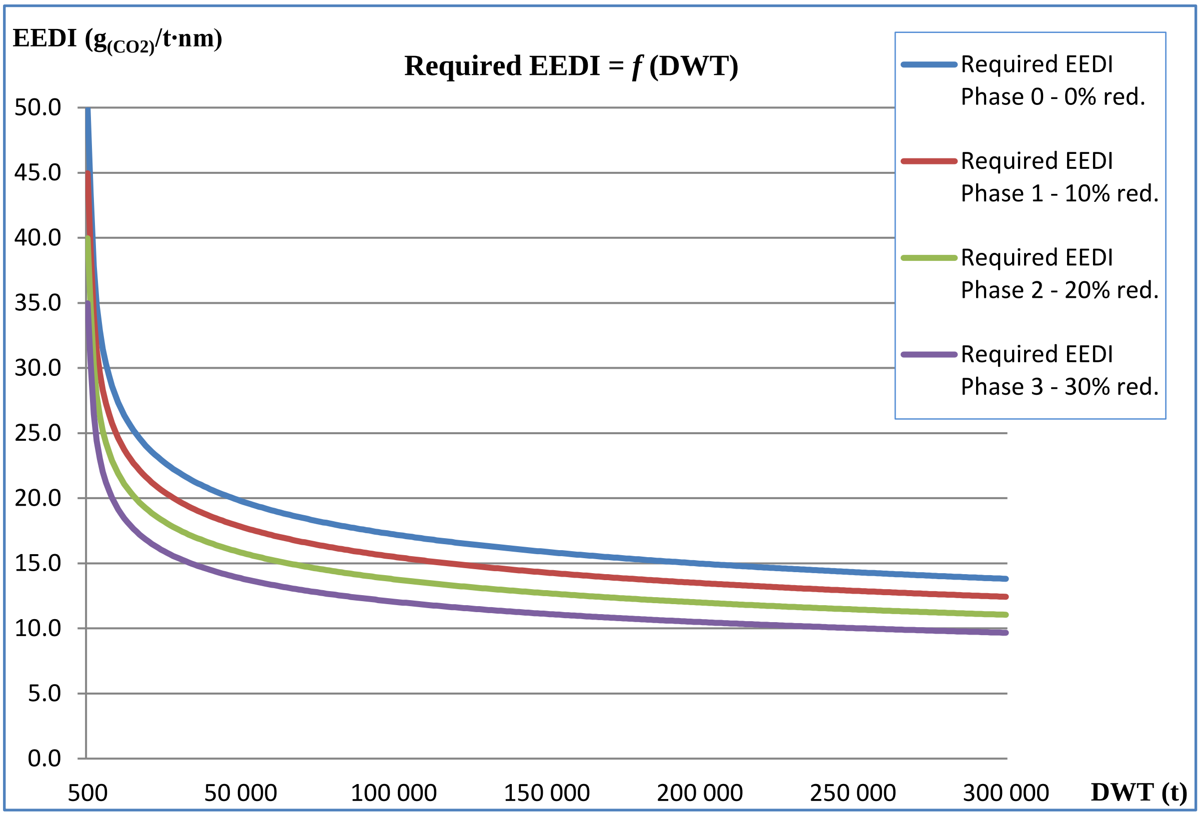


**Figure 2. 2:** EEDI – Reference line for container ships with reduction factors

## 2.2 Ship energy efficiency management plan - SEEMP

The SEEMP is mandatory for all vessels including non- transport vessels, such as working vessels. The conventional transport vessels, such as container vessels, tankers and bulk carriers, are easy to categorize as they are intended for a single purpose, with a single design point specifying a given cargo load and design speed. The European Union has issued an EU-wide legislative framework for Monitoring, Reporting and Verification (MRV) of $CO_2$ emissions from maritime transport (EU, 2015). This regulation, applies to larger vessels (over 5000 GT), calling at EU ports from 1st January 2018, and its aim is to collect data on $CO_2$ emissions and subsequently publish it. The European Commission estimates that the MRV system will lead to a 2% cut in $CO_2$ emissions (EC, 2015).

Each ship shall keep on board a ship specific Ship Energy Efficiency Management Plan. This may form part of the ship's Safety Management System (SMS). The SEEMP shall be developed by taking into account guidelines adopted by the Organization (ref. to IMO) [IMO, 2011].

The goal of SEEMP on board each ship is to give specific guidance to ship staff, in particular to MAS and CEO, to improve ship's energy efficiency and to reduce of ship's total fuel consumption (where applicable).

The SEEMP is a part of overall management system within the company. It is intended to assist ship-board staff and to contribute to ongoing energy performance and cost reductions. By using best-practice techniques, it is intended that these measures can be implemented as part of normal routine tasks by ship staffs without much additional administrative burden on their time. The SEEMP is in harmony with the requirements of MEPC.213(63) and encompasses the key processes required to continuously optimize energy consumption as shown in Figure 2.3.

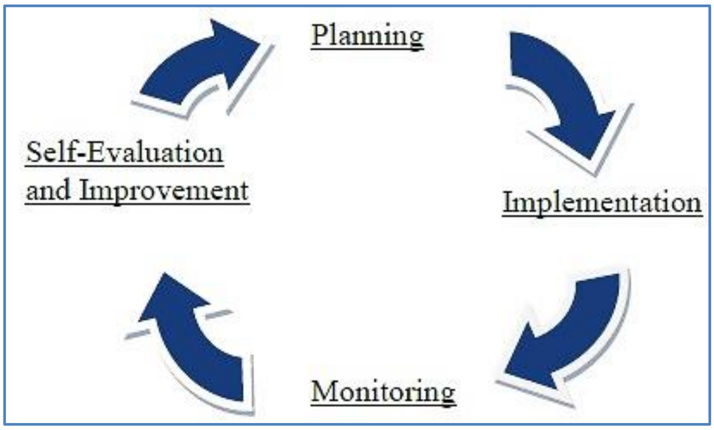


**Figure 2. 3:** SEEMP – optimization process of energy consumption

Source: [Zahradníček, 2017]

## Planning

Planning is the most crucial stage of the SEEMP, since it primarily determines both the current status of ship energy usage and the expected improvement of ship energy efficiency. As part of the planning, a number of Energy Efficiency Measures (EEM) are identified and described. Also roles and responsibilities for each EEM and procedures for implementation are identified. These are listed in Table 2.2. To achieve best-practice ship energy management, a number of key areas as outlined below need to be evaluated and monitored:

- Operational management
- Technical management
- Reporting and monitoring
- Goal setting, planning and reviews

Operational management is able to provide the most significant energy conservation by means of improved voyage planning and weather routing – arriving to next port just on time without advance or delays, optimization of trim and ballasting operations, optimization of port stays and energy used during port operations. This type of management is very complex and requires co-operation of all involved parties, such as ship staff, head office managers, charterers, port authorities, port operations, etc.

Technical management is able to provide moderate to significant energy conservation opportunities by means of avoiding hull fouling, implementation of improved coating systems, propeller and hull cleaning, upkeep of M/E in peak technical condition, optimization of M/E working mode from point of view of energy efficiency, upkeep of A/Es in peak technical condition, optimization of A/Es working mode from energy efficiency and running hours point of view, boilers and deep waste heat recovery systems energy efficiency, using of high quality fuels and efficient fuel treatment equipment. This type of management must be implemented and carried out by well-trained engineers on board with support from head office.

The evaluation during the planning phase is normally done as a desktop studies where suggested measures are evaluated and compared regarding expected performance. Since the operational measures often involve connecting to other systems for data collection and data transfer the compatibility with existing administrative as well as technical systems is also very important. Often these tools and measures can be tested without cost, therefore it is more common to do simple trials already during the planning phase. Different solutions are then ranked and the ones fulfilling the criteria are selected for implementation.

## Monitoring

The evaluation during normal operation, the monitoring phase, is done as part of the SEEMP. This is done to assess the long-time performance of the system as well as to assure that the equipment works as planned or expected. Typically, existing performance monitoring tools are used, either manual or automated ones

Effective implementation of SEEMP requires constant or periodical measuring, monitoring, documenting and reporting. Energy management as a tool for increasing ship’s energy efficiency must contain measurement of energy consumption and monitoring of performance indicators.

As measuring instruments following equipment can be used [Zahradníček, 2017]:

- Machinery power meters (kW or kWh) including propulsion shaft torque meter (where applicable), engine management systems,
- Fuel flowmeters – preferably mass flowmeters and machinery running hours counters,
- Analyses of noon reports versus periodical trials and tests and internally developed daily reporting scheme using excel sheet,
- Performance tests are performed every month at a certain load, compared with earlier results, machinery performance indicators – for internal combustion engines cylinder pressure analyzer should be used,
- Voyage analysis, real time monitoring system, speed performance monitoring system, optimizing autopilot system.

Monitoring of SEEMP implementation and its efficiency should be monitored by head office as well by means of evaluating various energy efficiency measures (EEM) and where applicable by monitoring of energy efficiency operational indicator (EEOI) for various voyage legs, average EEOI for entire voyage. EEOI from different sister ships should be compared and results evaluated.

### Self-evaluation and improvement

For best-practice in energy management, energy efficiency and performance goals need to be defined based on the energy efficiency measures being implemented. These goals are subsequently used for benchmarking purposes and evaluation of the efficiency of the measures employed. Wherever possible, goals are quantitative and time-based. Review and evaluation of achievements is carried out on a planned regular basis. Efficient tools of self-evaluation and improvement are target (goals) setting and subsequent evaluation (e.g. after one year) of EEM implemented.

For example, the target for a year is to be reduction of sulphur content in RFO by 0.5% within the company. After one year this target can be easily evaluated by means of reviewing bunker delivery notes, FO laboratory analysis results, etc. If the target has been achieved, then new target is set for next year. If the target hasn’t been achieved, new improvements and corrective actions are to be implemented.

## Implementation using EEM

Implementation of SEEMP into practice is carried out by means of EEM. The most significant EEM are presented in Table 2.2, taking into consideration their impact to ship's energy efficiency.

**Table 2. 2:** Energy efficiency measures, which can be implemented within SEEMP

| No. | Energy efficiency measure | Implementation actions | Responsible person(s) |
|---|---|---|---|
| **1.** | Speed / itinerary optimization | Operation department plans the schedule of the ships with important parameters such as port to port speed, in the different services which are informed to the ships, fleet and bunker dept.<br>Scope: reduction of time spent in anchorage or drifting and arrive at port close to the time for discharging/loading.<br>Records keeping: noon reports.<br>Monitoring: receiving monthly reports on most important parameters, such as fuel, lube consumptions, distance travelled last month and compare with other fleet vessels and fuel savings are calculated.<br>Completion date: continuous monitoring & improvement. | Network operations<br>MAS<br>Fleet monitoring center |
| **2.** | Weather routing and voyage planning | Selection of the most optimum route by considering wind, current, tide, sea condition of the intended passage prior and during voyage; taking help from weather charts and weather data.<br>Scope: implementation as far as practicable the weather routing services.<br>Records keeping: noon reports, weather routing reports, AWT reports (where applicable).<br>Monitoring: review above reports and check proper implementation on a regular basis during navigational audits.<br>Completion date: continuous monitoring & improvement | MAS<br>Marine department<br>Fleer monitoring center |
| **3.** | M/E fuel consumption monitoring and performance assessment | Scope: M/E fuel consumption monitoring on daily basis and carrying out M/E performance assessment on monthly basis. Specific fuel oil consumption (SFOC) and $P_{max}$ as parameters to be monitored.<br>Records keeping: monthly performance reports, M/E shop trial reports. | CEO<br>MAS<br>Fleet technical manager<br>Fleet monitoring center |

| | | | |
|---|---|---|---|
| | | Monitoring: daily monitoring of SFOC, review of the M/E performance report compared with shop test results to be monitored.<br>Completion date: continuous monitoring and improvement. | |
| **4.** | Waste heat recovery systems | Maximizing of WHRS usage, minimizing of auxiliary boilers usage.<br>Scope: taking under consideration ship's operational condition maximize utilization of WHRS.<br>Record keeping: engine log book, monthly and quarterly efficiency monitoring records.<br>Monitoring: ship's monitoring system, reviewing of daily / monthly / quarterly reports.<br>Completion date: continuous monitoring and improvement. | CEO<br>1st asst. engineer<br>Fleet technical manager<br>Fleet monitoring center |
| **5.** | Sludge generation monitoring | Minimization of sludge production from RFO on board<br>Scope: The ration of sludge generated from RFO per RFO consumed on board to be kept as low as possible, but not more than 2%. Subject to supplied RFO quality.<br>Record keeping: oil record book, monthly waste generation reports.<br>Monitoring: review of daily sludge generation records, comparing with actual daily RFO consumption.<br>Completion date: continuous monitoring and improvement. | CEO<br>Fleet technical manager<br>Fleet monitoring center |

Source: [Zahradníček, 2017]

## 2.3 EEDI and EEOI applicability for container carriers

According all available regulations, valid up to date, the main difference between EEDI and EEOI from the view point of legal legislation is that EEDI is mandatory for all ships covered within Regulation 20 and 21 of MEPC.203(62) and must be implemented in accordance with MEPC.203(62) – Amendments to MARPOL Annex VI on regulations for the prevention of air pollution from ships by inclusion of new regulations on energy efficiency, MEPC.214(63) – Guidelines on survey and certification of the energy efficiency design index, MEPC.245(66) – Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships whereas EEOI is voluntary and may be implemented as per MEPC.1/684 – Guidelines for voluntary use of ship energy efficiency operational indicator.

### EEDI – Applicability for container carriers

Since EEDI is mandatory for new ships it must be calculated, verified and recorded in “EEDI technical file” during ship’s design, construction and verification stages. It is giving very important information to shipbuilder and ship-owner as to the future fuel costs. Based on attained EEDI ship-owner or future charterer can predict fuel costs per unit of cargo per transported distance of one nautical mile.

As far as the applicability for container carriers goes, owner or future charterer can estimate, based on attained EEDI, by simple re-calculation of estimated cargo weight – container weight to twenty-feet equivalent unit (TEU) weight, estimate approximately the costs of one transported TEU. This is very helpful tool in relations between ship-owner or ship-operator and client or charterer in order to estimate future profits of transportation and profitability of such container carrier. Also, the decision, whether to build smaller, medium or large size ship can be influenced by attained EEDI, since larger ships as to the DWT, are having lesser value of attained EEDI than smaller ships as to the DWT. Simply, the large ships are usually having lower value of attained EEDI than smaller ships (also required EEDI is having this trend, Figure 2.2), which makes them more profitable than smaller ships from the view point of EEDI.

### EEOI– Applicability for container carriers

EEOI is voluntary only. It is not required by legislation. However, its implementation is giving ship-owner or ship-operator highly valuable information as to the ongoing ship’s energy efficiency. It is being calculated periodically, for voyage’s legs or for entire voyage. Also based on already collected data from previous voyages, average EEOI can be calculated. EEOI calculation formula is presented:

$$EEOI = \frac{\sum_j FC_j \cdot C_{Fj}}{m_{cargo} \cdot D} \tag{2.5}$$

where: *j* – type of fuel, $FC_j$ – total fuel consumption of fuel *j*, $CF_j$ – $CO_2$ conversion factor (mass of fuel to mass of $CO_2$), $m_{cargo}$ – cargo mass (in metric tons or TEU), *D* – transportation distance of cargo mass.

From the formula (2.5) it can be concluded that the units of EEOI are variable and determined by ship's type and ship-owner's or ship-operator's decision. For container carriers, units of EEOI acceptable in practical way can be stated in grams of produced $CO_2$ per nautical mile per TEU or in grams of produced $CO_2$ per nautical mile per metric ton of cargo.

If the usage of units per metric ton is selected, then comparison between design state (EEDI) and operational state (EEOI) can be achieved through ongoing monitoring (e.g. daily during noon reports) of needed parameter's values (e.g. total daily fuel consumption, distance, etc.). Also, comparison between other sister ships or different class ships can be done very easily. Company can monitor decrease in energy efficiency of its ships and take appropriate steps to increase that energy efficiency on each affected ship.

If the usage of units per TEU is selected, then comparison between similar type ships is possible. However, this unit is being mostly used for determination of ship's profitability and for determination of transportation prices and conveying this to company's clients. Also ongoing monitoring of EEOI in units per TEU is a very good tool to check ship's capacity to compete in business. Following, real-life calculations of EEOI per voyage's leg using formula (2.5) for modern ultra large container carrier (attained EEDI = 6.3091 $g_{CO2}$/ton·nm) are presented.

$m_{cargo} = 133847\ t,\ m_{cargo} = 12571\ TEU,\ D = 422\ nm,\ FC_j = 109.1\ t,$

$C_{Fj} = 3.1144$ (for ISO-F-RMK 700),

$$EEOI = \frac{FC_j \cdot C_{Fj}}{m_{cargo} \cdot D} = \frac{109.1 \cdot 10^6 \cdot 3.1144}{12571 \cdot 422} = 64.04\ \frac{g(CO_2)}{TEU\ \cdot\ nm}$$

$$EEOI = \frac{FC_j \cdot C_{Fj}}{m_{cargo} \cdot D} = \frac{109.1 \cdot 10^6 \cdot 3.1144}{133847 \cdot 422} = 6.02\ \frac{g(CO_2)}{t\ \cdot\ nm}$$

From above calculations it is clearly visible that EEOI compared to attained EEDI is lower. This can give valuable information to ship-owner or ship-operator related to ship's condition from energy efficiency's point of view. In conclusion, as for the container carriers, the most efficient is calculation of EEDI in both units, which is allowing company to monitor, compare and plan business strategies and keep an eye on competition as well.

## 2.4 Attained EEDI calculations of the case ship

There are many different ways in achieving EEDI calculations. All of them, however, must be in accordance with MEPC.245(66) – Guidelines in the method of calculation of the attained energy efficiency design index (EEDI) for new ships. Whether person responsible for attained EEDI calculations chooses one or another is not relevant if all calculations are done in accordance with legislation. For the purposes of this thesis the DNV-GL EEDI calculator has been selected [DNVGL, 2017].

First all necessary information about ship must be properly entered into the calculator (with actual values in brackets), such as:

- area of trade (international),
- propulsion system (diesel propulsion – conventional),
- DWT (149360 t),
- gross tonnage (153148 t),
- displacement at ballast condition (81262 $m^3$),
- displacement at summer load draft (194967 $m^3$),
- lightweight (45607 t),
- length between perpendiculars (352 m),
- breadth (51 m),
- summer load line draught (15.521 m),
- EEDI ship-type & sub-type (dry cargo/passenger & container, fully cellular),
- ice class (no),
- main engine, power take off / power take in, auxiliary engines, power reduction due to innovative technologies, correction factors, EEDI reference speed.

After entering all necessary data into calculator, results are presented in a form of graphical representation comparing required EEDI and attained EEDI.

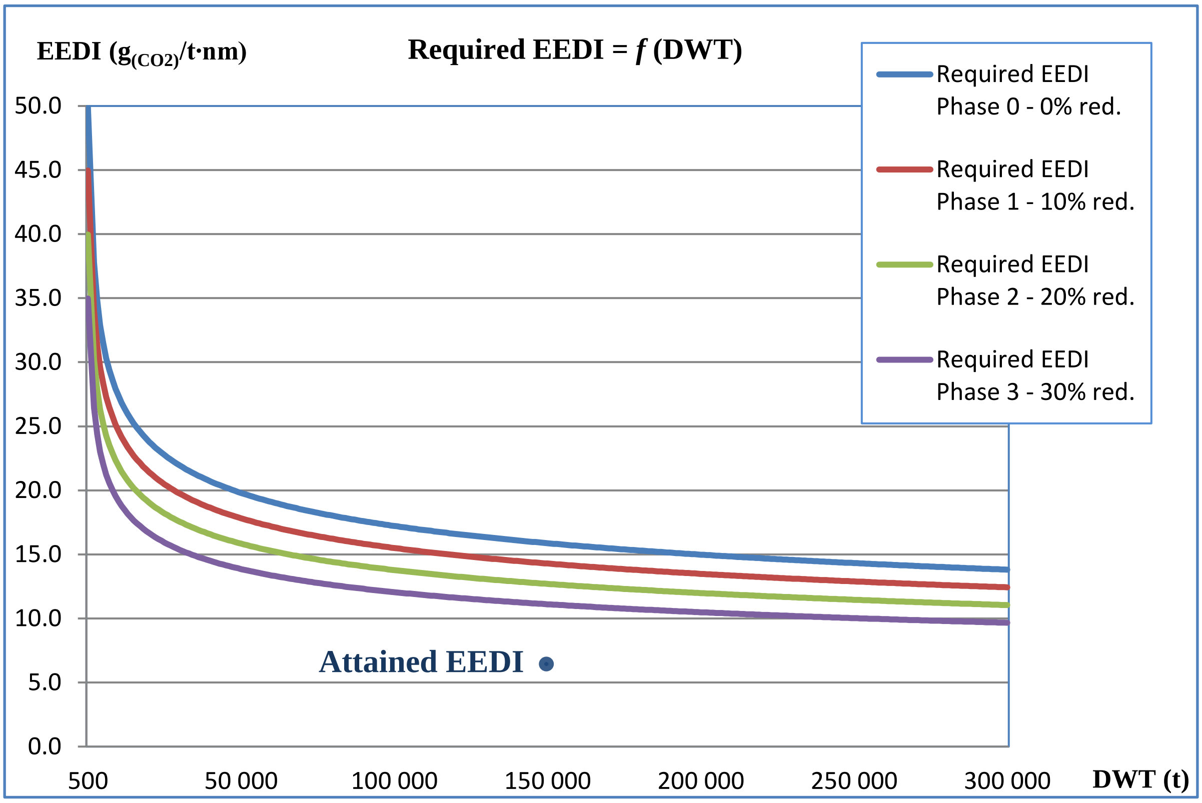


**Figure 2. 4:** Attained EEDI of case ship compared to required EEDI of ship’s type

Relevant information regarding attained and required EEDI and its calculations are described in paragraph 2, section 2.1.

### EEDI Technical file of the case ship

As per legal requirements, after attained EEDI calculations are completed, EEDI technical file must be created, verified and approved by administration [IMO – EEDI, 2012]. Case ship’s sample EEDI technical file was created using DNV-GL calculator.

# 3 Marine waste heat recovery systems overview

The analysis of possibilities for waste heat recovery begun at early 70's after as a result of first world major crude oil crisis, in 1973. Since then the waste heat recovery from ship's machinery is growing as to the great significance for ship owners, operators and ship builders. It has been determined by calculations and measurement that the largest part of wasted energy of marine propulsion engines is discharged to the environment in a form of exhaust gas flux and cooling, presented in Figure 3.1. It can be observed that over a 50% of total chemical energy, supplied to the engine in a form of fuel oil flow is dispersed to the environment and largest part in a form of flue gas stream, giving over 25% total provided energy.

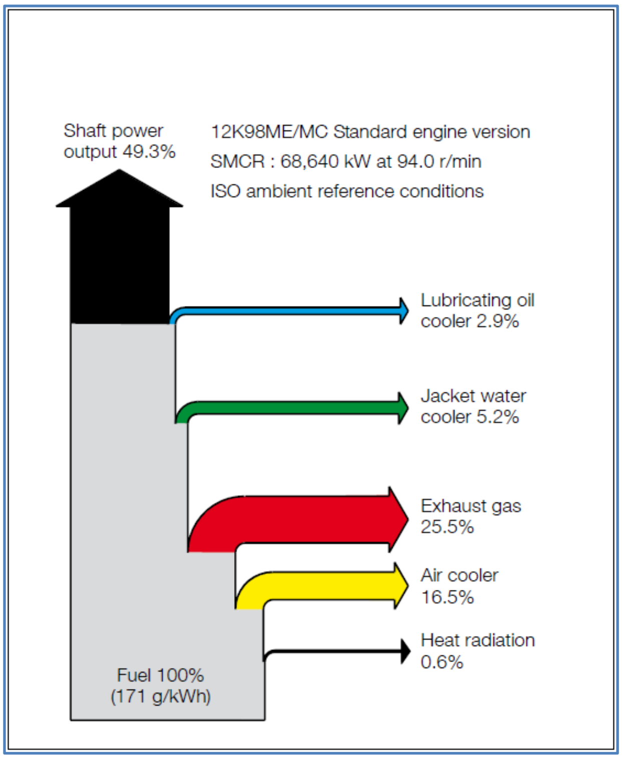


**Figure 3. 1:** Heat balance diagram of a typical main propulsion diesel engine

Source: [MAN Diesel & Turbo, 2014]

The effectiveness of waste heat is determined by the available enthalpy. Heat energy utility is usually categorized by process temperature as:

- low <232°C,
- medium 232°C ÷ 649°C,
- high >650°C.

The marine machinery presents potential of low and medium temperature waste heat recovery e.g. diesel engine exhausts at outlet 200°C ÷ 500°C, diesel engine scavenge air at T/C compressor outlet (100°C ÷ 170°C). The mentioned examples of temperature ranges varying for 2-stroke and 4-stroke engines, where in the latter the temperatures are usually higher.

In respect to the operation of the ship's machinery, quantity and advantage, the engine's exhaust gas has been selected for further consideration, as a high potential source of waste energy. The availability of exhaust gas energy depends mainly on the lowest temperature, to which it can be cooled down in heat exchanger. Mostly, merchant vessels are equipped with conventional means of propulsion, 2-stroke slow-speed diesel engine directly coupled with propeller by means of shaft arrangement and adapted for HFO use. Thus, fuel oil composition and specifically sulphur contents needs to be considered as main risk of low temperature corrosion caused by sulphuric acid condensation in flue gas stream, and WHRS utilizing exhaust gas as a primary source of energy, should be designed to ensure that exhaust gas is not cooled down, below the acid dew point. Currently, MAN Diesel & Turbo recommends to avoid temperatures below 165°C on the outlet of exhaust gas from heat exchanger to prevent acid corrosion (low temperature corrosion) and soot buildup in exhaust gas heat exchangers [Singh and Petersen, 2016].

A WHRS on merchant ship can be designated to operate on single or multiple energy sources. Usually, single energy source is flue gas only, which is easy to build solution, while multiple energy sources are flue gas and M/E scavenging air e.g. scavenging air is used to pre-heat boiler feed water. However, this is more advanced solution which gives deeper waste heat utilization. In both arrangements, single and multiply energy source, waste heat is utilized in WHRS with maximum possible efficiency.

## 3.1 Main WHRS technologies

Based on the available wasted energy, as mentioned before, marine WHRS should have subsequent features:

- high efficiency of waste heat recovery,
- adaptable to the vessel's operational profile,
- easy to integrate and co-operate with other power systems on board,
- reliable in operation,

- safe in operation and handling,
- easy to maintain high technical efficiency.

The marine diesel engine available waste heat varies, mainly due to the nature of and ambient conditions as well, e.g. air and sea water temperature, which is changing with the vessel’s location and seasonal variations. A WHRS operating within such dynamic boundaries should be able to adjust and adapt the external changes in order to deliver peak performance. Nevertheless, every additional system installed on board increase complexity to the overall energy system. Additionally, modern WHRS needs to be integrated with the existing electric power systems therefore facilitating a smooth power sharing.

In following parts of this section, the most suitable WHRS options for marine use are presented, taking also into consideration historical development of such systems. Despite the fact that the list is not exhaustive and doesn’t mention a number of investigated and tested technologies, it includes the most important ones with high utilization potential applicable onboard merchant vessels. Those systems are contributing towards improvement of vessel’s overall energy efficiency, reduction of emissions and improving financial gains of the vessel. As mentioned before, following described options can be utilized as a single source or can be combined and are based on ship owner’s demands and shipyard’s capabilities.

### WHRS based on Rankine cycle

Rankine cycle (RC) is a thermodynamic cycle which converts heat energy into mechanical work. A circulating working fluid is continuously evaporated and condensed during the operation. A simple power plant operating on RC essentially comprises of four main components namely, vapor-generator (boiler and super heater), expansion device (turbine), condenser and feed-pump. The layout of the system components is given in Figure 3.2.

According to its definition, the RC does not restrict the use of any particular working fluid or a temperature range, but different variations have been given specific names in the field of research and industrial applications. Below the most common variants of a RC plant are listed:

- Steam Rankine Cycle (SRC) – also known as “Conventional RC” – water based system using water / steam as the working fluid.
- Organic Rankine Cycle (ORC) – modified form of SCR where the working fluids are organic fluids like hydrocarbon gases or refrigerants like hydrofluorochlorocarbons, etc. instead of water / steam.

- Super-critical Rankine Cycle (SCRC) – the working fluid is fed to boiler at a pressure higher than its critical pressure and then it is directly heated from its liquid state to the supercritical state, by-passing two-phase region.

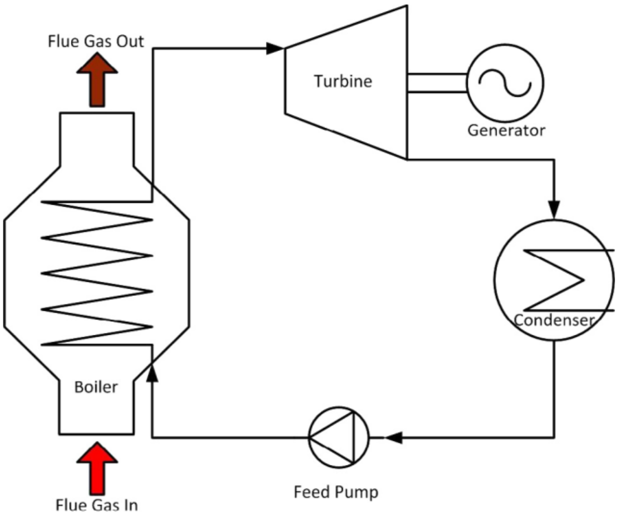


**Figure 3. 2:** The simple form of Rankine cycle plant

Source: [Singh and Petersen, 2016]

Presently, SRC – Steam / Conventional Rankine cycle variant is commonly used on board of conventional merchant vessel taking into account investment costs, maintenance, operational training and qualification of the ship's crew. Usually, SRC is combined with exhaust gas turbine system that further surges waste heat recovery efficiency.

### WHRS based on Kalina cycle

Kalina cycle (KC) is thermodynamic cycle based on ammonia – water mixture and it was proposed in 1983 by Alexander Kalina. It is a modified RC and has improved operating efficiency for several applications. The most promising utilization and significant efficiency achievements are realized in low temperatures heat sources, which makes it, from this point of view, very suitable for marine use. In terms of layout, KC plant is quite similar to a RC plant with a few additional components. A simple KC plant has a recuperator, separator, couple of mixers and flow control valves in addition to the standard components of a RC plant as shown in Figure 3.3.

KC uses ammonia and water mixture as the working fluid to operate in variable compositions with variable boiling and condensation temperature ranging between the bubble and dew points. For a given pressure and ammonia mass fraction, the liquid starts boiling at the bubble-point and continues until the dew-point where all of the fluid turns into vapor.

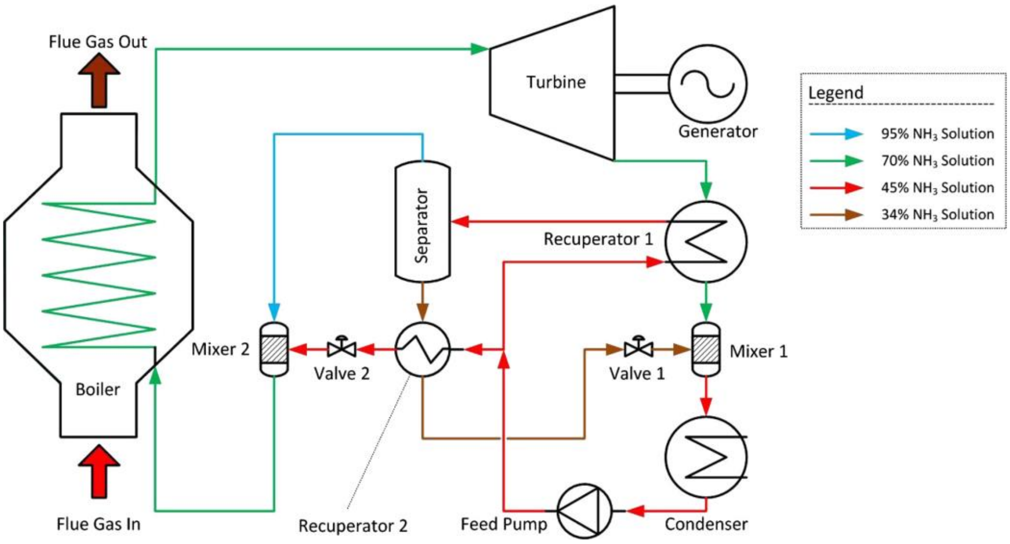


**Figure 3. 3:** Diagram of a simple Kalina cycle plant

Source: [Singh and Petersen, 2016]

The variable temperature boiling/condensation process has yet another advantage – that yields a better thermal match with the sensible heat source and the coolant during the phase change process. This contributes to improvement of thermodynamic efficiency of the boiler and brings down the minimum temperature of the condensate outlet. By changing the ammonia mass fraction, the bubble and dew point of the fluid can also be varied to suit the source and the sink temperature in the boiler and the condenser, respectively.

With its merits KC could be used in marine WHRS and being suitable for low temperature waste heat source applications and with higher cycle efficiencies than RC and ORC. KC based WHRS provides financial savings as to the costs of fuel and environmental effects like reduced emissions. However, the KC based WHRS using ammonia solution could discourage ship owners to utilize this method due to high investment and running costs comparing to other systems e.g. SRC.

### WHRS based on exhaust gas turbine

Continuous improvements in T/C efficiency over the time resulted in surplus diesel engine exhaust energy, more than required for supercharging process within the whole engine load range. The trends in the T/C efficiency improvements over the past few decades have been shown in Fig. 3.4. The excess exhaust energy can be harvested by expanding the flue gas either in the turbine side of a T/C itself or in a separately installed dedicated power turbine. For an optimally designed high efficiency T/C, modern diesel engine does not need all amount of the exhaust gas to flow through T/C turbine, even under the nominal engine load, to provide sufficient scavenging. Thus, the excess amount from the exhaust gas receiver is lead to the power turbine (PT) where it expands to the stack pressure and giving output.

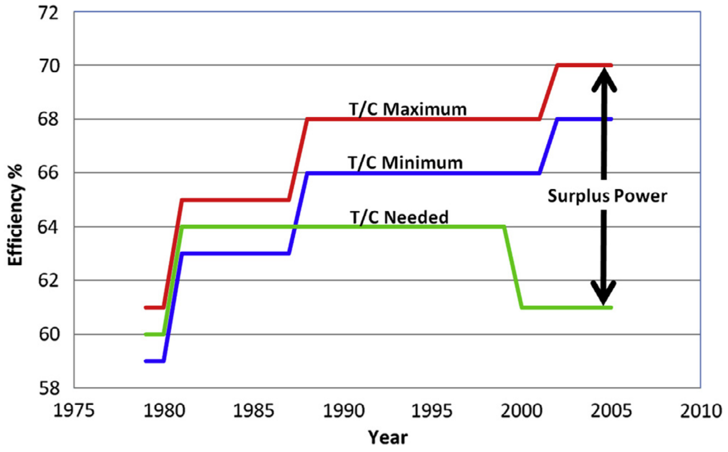


**Figure 3. 4:** T/C efficiency improvement trends with highlighted surplus efficiency for new generation T/Cs

Source: [Singh and Petersen, 2016]

Currently, available high-efficiency marine T/C matched for ambient air intake, delivers about 10–12% of the exhaust gas flow, that can be branched off at upper engine load range to drive a power turbine [4]. Still there have been attempts of another design which would allow utilization of excess energy produced by high efficiency T/Cs:

- Hybrid turbocharger – high speed motor / generator set is mounted on T/C's shaft and example is given in Figure 3.5.

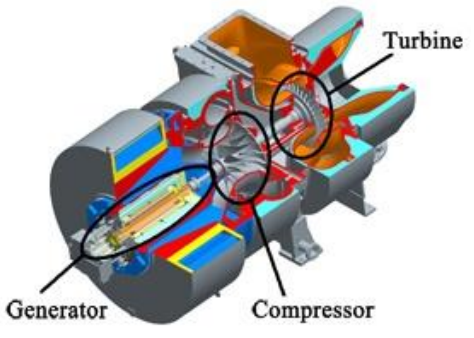


**Figure 3. 5:** Diagram of model hybrid T/C

Source: [Zahradníček, 2017]

- Mechanical turbo-compound system – excess energy from T/C is led through mechanical gearbox to engine's shaft increasing total output, but system is not stable in transient engine operation and requires bulky mechanism, shown on Figure 3.6.

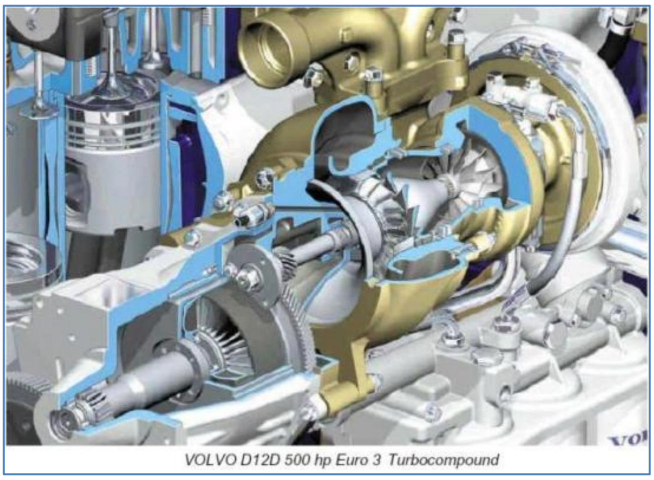


**Figure 3. 6:** Diagram of model mechanical turbo-compound system

Source: [http://www.heat2power.net/, 2017]

- Hydraulic turbo-compound system – excess energy from T/C is being transferred to hydraulic power pack- pump and motor, which is coupled to engine's shaft increasing total power, example on Figure 3.7.

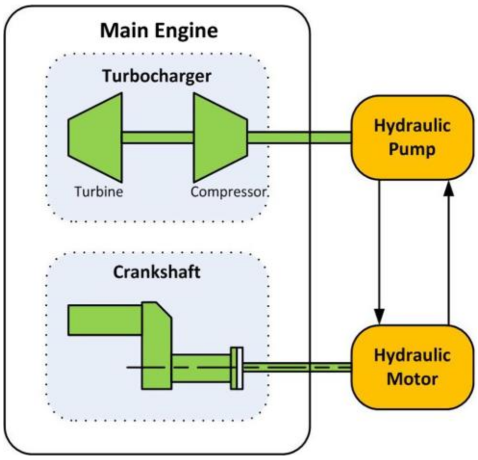


**Figure 3. 7:** Schematic layout of hydraulic turbo-compound system

Source: [Singh and Petersen, 2016]

- Electric turbo-compound system – excess energy from T/C is led to generator, which is directly connected to T/Cs shaft, producing alternating current at high frequency, next transformed to direct current and then back to alternating current using energy-electronic components such as rectifier and inverter and finally fed electric consumers connected through switchboard, example on Figure 3.8

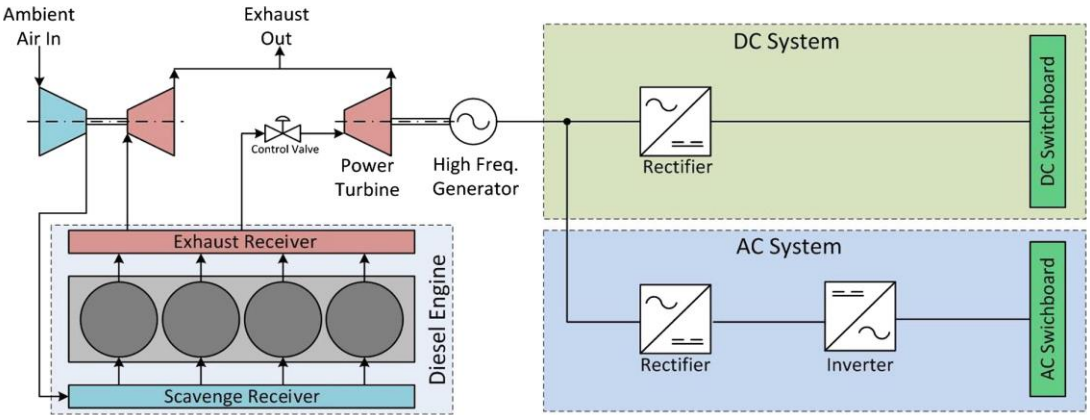


**Figure 3. 8:** Schematic layout of electric turbo-compound system

Source: [Singh and Petersen, 2016]

## 3.2 Outline of the modern WHRS of the ultra large container carrier

As a case example ultra, large container carrier has been selected. Ship was built by Korean shipyard and delivered in November 2014. On request from owner, multiple solutions for utilization of waste heat (unused energy transmitted to environment) have been selected. The complete ship's waste heat recovery system is composed of multiple SRC based WHR subsystems, power turbine and shaft generator / motor.

Shaft generator / motor is able, at higher loads of M/E, utilize excess of electrical power produced by WHRS (steam and power turbines), which is not required for momentary need for electrical supply of the vessel, and support M/E shaft by changing its operating mode to shaft motor (PTI). This operating mode can be compared to modified and amended Electric turbo-compound system.

From the point view point of ship's design and construction, the complete ship's WHRS can be divided into two subsystems – auxiliary WHR subsystem (linked to A/Es and to electrical power generation) and main WHR subsystem (linked to M/E and to ship's propulsion). Both subsystems' operational profile is described below.

Goal of auxiliary WHR subsystem is to fulfill, or at least to support, ship's steam heating needs by co-operating with ship's auxiliary steam generation plant. This subsystem is mainly operated when using auxiliary engines (as a part of diesel generating set) as producers of electrical power. From view point of ship's operational profile, it is mostly in ports, during maneuverings, and during short passages between ports. It can be summarized that auxiliary WHR subsystem is in use whenever main WHR subsystem is not in operation.

On the other hand, the goal of main WHR subsystem is to fulfill, or at least support (based on operational profile), ship's electrical power and steam heating needs by co-operating with ship's main steam generation plant and with steam / power turbine (as a part of turbo generating set). From view point of ship's operational profile, it is mostly during long passages between ports (for electrical and steam generation needs), however steam production part of main WHR subsystem can be engaged even during short passages between ports (mainly depends on M/E load and on decision made by CEO).

In subsections, both ship's WHR subsystems are described and design operating parameters are given. The design calculations are presented as well to allow comparison between design waste heat utilization achievements and operational achievements of both WHR subsystems. Simplified layout of case ship's WHRS with division to auxiliary and main WHR subsystems is presented on Fig 3.9.

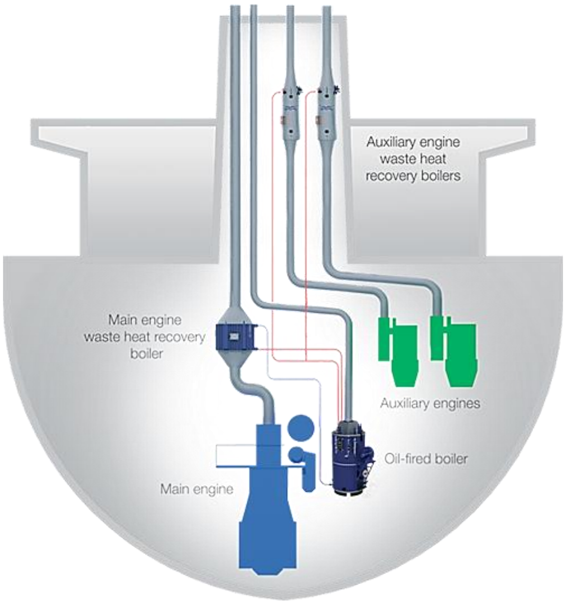


**Figure 3. 9:** Simplified layout of case ship's auxiliary WHRS

Source: [http://www.alfalaval.com/, 2017]

### Auxiliary WHR subsystem description

As described in above sub-paragraph, the main goal of auxiliary WHR subsystem is to fulfill, or at least to support, ship's steam heating needs by co-operating with ship's auxiliary steam generation plant. This subsystem is directly linked with two A/Es (from total number of four A/Es) and thus composes of two A/Es as a source of waste heat in a form of unused exhaust gas energy, each equipped with its own auxiliary exhaust gas economizer (auxiliary EGE).

Steam / water mixture is being circulated through auxiliary oil-fired boiler drum, serving as a separation receptacle (to separate steam from the mixture), by means of forced circulation using circulation pumps (centrifugal pumps). Simplified system layout is shown on Figure 3.10.

**Figure 3. 10:** Simplified layout of case ship's auxiliary WHR subsystem

Source: [Alfa Laval, 2017]

From the separating receptacle, in this case auxiliary oil-fired boiler drum, steam is channeled towards heating steam receivers, e.g. RFO tanks heaters, purifier's pre-heaters, domestic water heaters, main and auxiliary FO heaters, etc. Photo of ship's A/E with installed auxiliary WHR subsystem is presented on Figure 3.11. Basic data related to the waste heat source in auxiliary WHR subsystem, Auxiliary engines, is listed [5]:

| | |
|---|---|
| maker: | Hyundai HIMSEN, |
| engine type: | 9H35DF x 4 sets, 2 sets in auxiliary WHRS, |
| design: | internal combustion, four cycle engine, |
| engine power: | 4320 kW @ 720 RPM, |
| generator output: | 4140 kW @ 60 Hz (6600 VAC), |
| SFOC @ MCR: | 196.31 g/kWh (ISO corrected), |
| combustion air consumption: | 28510 kg/h (+/- 5%) @ MCR, |
| exhaust gas flow: | 29358 kg/h (+/- 5%) @ MCR, |
| FO consumption: | 862 kg/h @ MCR. |

**Figure 3. 11:** Case ship's A/E with installed auxiliary EGE

In order to be able to determine what is the design quantity of an unused heat in a form of exhaust gas energy produced by A/E, the basic operational and design parameters of the engine, allowing to calculate heat dissipation and acquire basic and simplified energy balance of the engine, are given in Table 3.1.

**Table 3. 1:** A/E design data, simplified heat dissipation calculations and engine energy balance calculations

| **Auxiliary Engine** | **100% MCR** | **Energy balance** |
|---|---|---|
| FO consumption | 848.06 kg/h | |
| FO LCV | 42700.00 kg/kJ | |
| FO SFOC | 196.31 g/kWh | |
| Energy A/E IN | 10058.92 kJ/s | 100.00 % |
| Combustion air consumption | 28510.00 kg/h | |
| Exhaust gas flow | 29358.06 kg/h | |
| Exhaust temp out | 293.00 °C | |
| Temp surroundings | 24.80 °C | |
| **Heat Dissipation** | | |
| Cylinder jacket | 678.00 kJ/s | 6.73 % |
| Lubricating oil | 731.00 kJ/s | 7.27 % |

| | | |
|---|---|---|
| HT Charge air | 1011.00 kJ/s | 10.05 % |
| LT Charge air | 337.00 kJ/s | 3.35 % |
| **Exhaust gas** | **2351.21 kJ/s** | **23.37 %** |
| Radiation | 115.68 kJ/s | 1.15 % |
| SUM (waste heat) | 5223.89 kJ/s | 51.93 % |
| Effective energy (el. power) | 4835.03 kJ/s | |
| **Engine energy efficiency** | 48.07 % | |

As calculated and presented in Table 3.1 it can be observed that little over 23% of engine's input energy (chemical energy in a form of fuel) is being transmitted to the environment without utilization in a form of heat carried by exhaust gas. Graphical representation of calculated heat dissipation in A/Es of case ship together with engine's energy balance is shown in Figure 3.12. From the graph, the portion of wasted heat (unused energy transmitted to environment) carried by exhaust gas, is clearly visible.

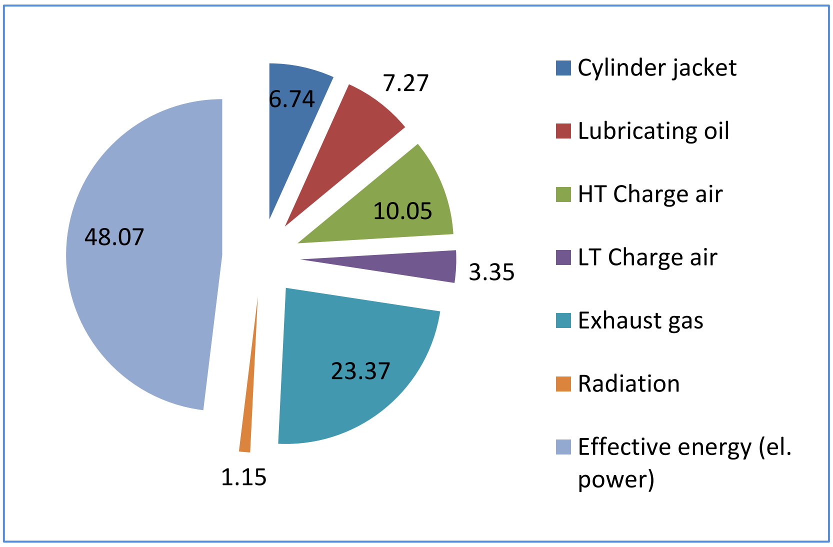


**Figure 3. 12:** Graphical representation of A/Es energy balance

By installation of Auxiliary EGEs into the exhaust gas piping of two A/Es, to utilize above calculated unused energy carried by exhaust gas, we can significantly improve engine's overall energy balance. Installed auxiliary EGE on boar case ship is shown on Figure 3.13.

Basic data related to the waste heat recovery equipment in auxiliary WHR subsystem, Auxiliary exhaust gas economizers (EGE), are listed [5]:

- maker: Alfa Laval,
- EGE type: Aalborg XS-TC7A x 2 sets,
- design: exhaust gas economizer, forced circulation,
- steam output: 1100 kg/h (per unit) ,
- working pressure: 7.0 bar (g),
- working temp.: 170 °C (saturated steam & water mixture),
- feed water temp.: 80 °C,
- maximum temperature inlet: 340.0 °C (exhaust gas),
- designed temperature inlet: 281.3 °C (exhaust gas),
- maximum temperature out: 231.1 °C (exhaust gas),
- designed temperature out: 191.2 °C (exhaust gas).

**Figure 3. 13:** Auxiliary EGE installed on board case ship

Based on A/E energy dissipation calculations, energy balance calculations and designed parameters of A/E and Auxiliary EGE, determination of how much waste heat (unused energy carried by exhaust gas from A/E) is utilized can be done. The calculations are shown in Table 3.2.

**Table 3. 2:** Simplified A/E energy balance with Auxiliary EGE waste heat utilization calculations

| **Auxiliary EGE** | **@ 100% A/E MCR** | **Energy balance** |
|---|---|---|
| Energy A/E IN | 10058.92 kJ/s | 100.00 % |
| Exhaust gas energy from A/E | 2351.21 kJ/s | 23.37 % |
| Temp. EGE IN exhaust | 281.28 °C | |
| Temp. EGE OUT exhaust | 191.19 °C | |
| Exhaust gas flow | 29358.06 kg/h | |
| **Energy utilized (compared to total A/E energy IN)** | **789.81 kJ/s** | **7.85 %** |
| | 2843306.21 kJ/h | |
| **Energy utilized (compared to A/E exhaust gas energy)** | **789.81 kJ/s** | **33.59 %** |
| | 2843306.21 kJ/h | |
| **Steam production** | | |
| Temp. water IN | 80.00 °C | |
| Temp. water/steam mix out | 170.00 °C | |
| Specific heat | 2.03 kJ/kg.K | |
| Latent heat of evaporation | 2046.53 kJ/kg | |
| Needed energy to evaporate | 2228.93 kJ/kg | |
| Maximum steam output | 1275.64 kg/h | |

As calculated results and presented in Table 3.2, it can be observed that almost 33.6% of waste heat carried by exhaust gas can be utilized to produce steam for heating purposes of the ship. Comparing with the total energy input consumed by A/E in a form of chemical energy of fuel, it is showing that 7.85% utilization is achieved. This utilized waste heat (unused energy) carried by exhaust gas is significantly improving the overall engine’s energy efficiency as shown in Table 3.3.

Graphical representation of calculated heat dissipation in A/Es of case ship together with engine’s energy balance with installed exhaust gas utilization facilities – auxiliary WHR subsystem, is shown in Figure 3.12. From the graph is visible that the portion of wasted heat (unused energy transmitted to environment) carried by exhaust gas, is clearly reduced compared to Figure 3.14 by portion which has been utilized and used to generate steam for heating purposes.

**Table 3. 3:** A/E overall energy balance calculations with exhaust gas utilization

| **Heat Dissipation** | **Engine's energy balance** | |
|---|---|---|
| Cylinder jacket | 678.00 kJ/s | 6.74 % |
| Lubricating oil | 731.00 kJ/s | 7.27 % |
| HT Charge air | 1011.00 kJ/s | 10.05 % |
| LT Charge air | 337.00 kJ/s | 3.35 % |
| **Exhaust gas with utilization** | **1561.40 kJ/s** | **15.52 %** |
| Radiation | 115.68 kJ/s | 1.15 % |
| SUM (waste energy) | 4434.08 kJ/s | 44.08 % |
| Effective energy (el. power) | 4835.03 kJ/s | 48.07 % |
| **Effective energy (heating steam)** | **789.81 kJ/s** | **7.85 %** |
| SUM (effective energy) | 5824.84 kJ/s | 55.92 % |
| **Engine overall energy efficiency** | **55.92 %** | |

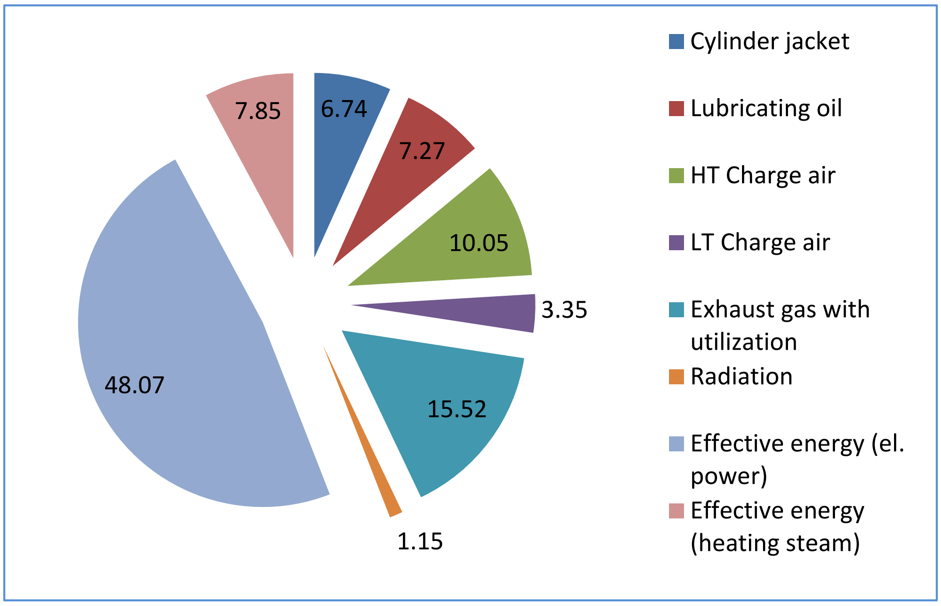


**Figure 3. 14:** Graphical representation of A/Es energy balance with installed WHRS

In order to establish financial advantage of installing Auxiliary WHR subsystem compared to not installing one, it is necessary for ship owner to “translate” above data to quantifiable denominator such as a potential fuel savings by Auxiliary oil-fired boiler with Auxiliary WHR subsystem. Those calculation results are presented in Table 3.4.

**Table 3. 4:** Potential FO savings with installed Auxiliary WHR subsystem compared to Auxiliary OFB

| **Auxiliary oil-fired boiler** | **100% capacity** | |
|---|---|---|
| FO consumption | 479.00 | kg/h |
| FO LCV | 42200.00 | kg/kJ |
| Energy IN | 5614.94 | kJ/s |
| Exhaust gas flow | 9270.00 | kg/h |
| Exhaust temp out | 330.00 | °C |
| Temp surroundings | 25.00 | °C |
| Exhaust gas energy loss | 844.28 | kJ/s |
| Electric motor loss (flue fan) | 17.50 | kJ/s |
| Temp water IN | 80.00 | |
| Temp water/steam mix out | 170.00 | |
| Specific heat | 2.03 | kJ/kg.K |
| Latent heat of evaporation | 2046.53 | kJ/kg |
| Needed energy to evaporate | 2228.93 | kJ/kg |
| Maximum steam output (OFB) | 7676.95 | kg/h |
| FO consumption / steam production (oil fired boiler, maximum) | 0.0624 | $kg_{FO}/kg_{STEAM}$ |
| **Comparison - Auxiliary EGE savings of FO compared to Auxiliary oil-fired boiler** | | |
| Maximum steam output (EGE) | 1275.64 | kg/h |
| OFB FO consumption | 0.0624 | $kg_{FO}/kg_{STEAM}$ |
| **FO potential savings** | **79.60** | **kg/h** |
| **Compared to aux boiler** | **16.62** | **%** |

From the Tab. 3.4 is clearly visible that with installed Auxiliary WHR subsystem at least for one A/E (on board case ship installed 2 sets for two A/Es) potential fuel savings while using Auxiliary WHR subsystem can be up to 16.6% of total fuel oil consumption by Auxiliary OFB to fulfill the ship's steam heating needs.

In translation, for owner, establishing that auxiliary OFB with auxiliary WHR subsystem will be used with one A/E for duration 240h per months (10 days) and the ship's heating needs are of designed capacity of auxiliary OFB – 7000 kg/h – FO consumed by auxiliary OFB will be around 105 mt of FO per month without auxiliary WHR subsystem. With auxiliary WHR subsystem it means potential savings of 17.4 mt of FO per month. If owner will calculate it per year, the potential FO saving can be up to 210 mt of FO per year. At average price (from May 2017) of 280 US$ per mt of FO the potential savings can go up to 58000 US$ per year.

To summarize, it is up to each and every ship owner to decide whether to implement such an option for waste heat recovery or not. However, with respect to new trends in shipping industry, where the fuel savings and thus lowering of emissions is becoming priority, this solution seems adequate, not only from view point of investment costs, but very low maintenance costs and lifespan as well.

### Main WHR subsystem description

As described in above sub-paragraph, the goal of main WHR subsystem is to fulfill, or at least support (based on operational profile), ship's electrical power and steam heating needs by co-operating with ship's main steam generation plant and with steam / power turbine (as a part of turbo generating set). This subsystem is directly linked with ship's main engine and thus composes of M/E as a first source of waste heat in a form of unused exhaust gas energy and main exhaust gas economizer (main EGE). There are three sources of heat in this subsystem, not like in auxiliary WHR, where was only one source:

- M/E exhaust gas energy,
- M/E scavenging air energy,
- M/E jacket cooling water energy.

Main EGE comprises of two sections – high pressure (HP) and low pressure (LP) section. HP section is equipped with two steam coils, one is to produce high pressure saturated steam and the other one is to superheat high pressure saturated steam and channel that superheated HP steam into WHRS steam turbo-generating set. LP section comprises of only one steam coil, which is to produce saturated low-pressure steam. This LP saturated steam is then channeled to WHRS steam turbo-generating set (to support HP superheated steam) and to steam heating receivers, such as purifiers' heaters, RFO storage tanks heating coils, etc.

As a means of supporting waste heat utilization from exhaust gas, second source of waste heat is selected in this system – M/E scavenging air – to work in parallel to give best possible degree of waste heat utilization. Feed water for main EGE, for both LP and HP sections, is initially passed through heating coil installed in M/E scavenging air cooler. This heating coil is installed directly after compressor of engine's turbocharger, thus providing maximum possible quantity of waste heat energy to be utilized. Such pre-heated feed water is then channeled into EGE. The third source of waste heat in this system is M/E jacket cooling water. Condensate from vacuum condenser is channeled through heater, where source of heat is M/E jacket cooling water and led to hot-well. As described above, there are two sections in main EGE. Each section has its own separating receptacle (to separate steam from the mixture) – LP EGE drum and HP EGE drum and its own forced circulation system. Main EGE system layout is presented on Figure 3.15.

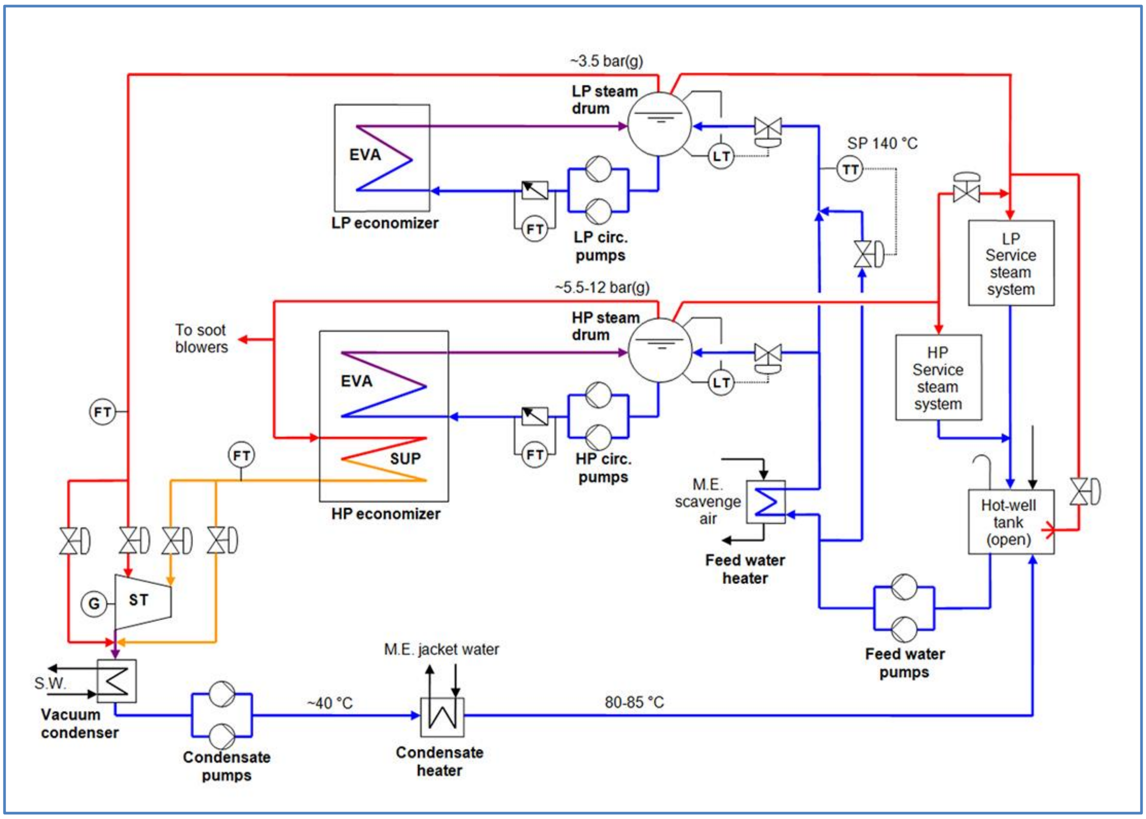


**Figure 3. 15:** Simplified layout of case ship's main WHRS

Source: [http://www.alfalaval.com/, 2017]

View of ship's M/E with installed main WHR subsystem is presented in Figure3.16. Basic data related to the waste heat source in main WHR subsystem, main engine, are listed:

| | |
|---|---|
| maker: | Hyundai – MAN B&W, |
| engine type: | 9S90ME-C10.2-TII, |

| | |
|---|---|
| • design: | internal combustion, two cycle engine, |
| • engine power: | 37620 kW @ 72 RPM, |
| • mean effective pressure: | 16.8 bar, |
| • maximum combust. pressure: | 185 bar, |
| • SFOC @ MCR: | 168.79 g/kWh (ISO corrected), |
| • cylinder bore: | 900 mm, |
| • cylinder stroke: | 3260 mm, |
| • combustion air consumption: | 238211 kg/h @ MCR, |
| • exhaust gas flow: | 244657 kg/h @ MCR. |

**Figure 3. 16:** Main engine of case the ship

The case ship's main WHR subsystem is fully capable of producing steam in such quantity, that when in operation, it is substituting auxiliary WHR subsystem and auxiliary oil-fired boiler as a source of heating steam. In table, Table 3.5, same as for auxiliary WHR subsystem are presented M/E design data, simplified heat dissipation calculation results and engine's energy balance.

**Table 3. 5:** M/E design data, simplified heat dissipation calculations and engine energy balance calculations

| **Main engine** | **100% MCR** | | **Energy balance** |
|---|---|---|---|
| FO consumption | 6349.88 | kg/h | |
| FO LCV | 42700.00 | kg/kJ | |
| FO SFOC | 168.79 | g/kWh | |

| | | |
|---|---|---|
| Energy A/E IN | 75316.63 kJ/s | 100.00 % |
| Combustion air consumption | 238211.00 kg/h | |
| Exhaust gas flow | 244657.00 kg/h | |
| Exhaust temp out | 275.50 °C | |
| Temp surroundings | 31.90 °C | |
| **Heat Dissipation** | | |
| Scavenging air | 9321.00 kJ/s | 12.38 % |
| Lubricating oil | 3513.00 kJ/s | 4.66 % |
| HT cooling water | 5592.00 kJ/s | 7.42 % |
| Exhaust gas | 17796.76 kJ/s | 23.63 % |
| Radiation | 753.17 kJ/s | 1.00 % |
| SUM (waste heat) | 36975.92 kJ/s | 49.09 % |
| Effective energy (propulsion) | 38340.71 kJ/s | |
| **Engine energy efficiency** | 50.91 % | |

Source: [Hyundai Himsen, 2017]

As stated in Table 3.5, there are three waste heat sources being utilized in main WHR subsystem. From the M/E heat dissipation calculations follows that almost 23.6% of unused energy (relative to M/E inlet energy, chemical energy in a form of fuel) is contained within exhaust gas leaving M/E. Next, second most prominent source, is M/E scavenging air cooler, where almost 12.4% of unused energy is contained. And the third source is M/E HT cooling water, where almost 7.5% of unused energy is contained. Graphical representation of M/E energy balance is presented in Figure 3.17.

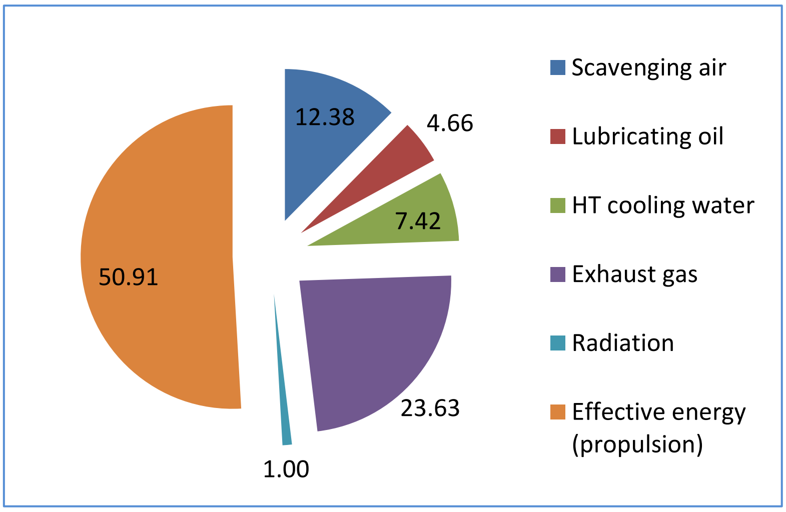


**Figure 3. 17:** Graphical representation of M/E energy balance

All of these three sources are being used simultaneously, when main WHR subsystem is in use. Exceptions are made only for brake downs and unforeseen situations. Basic data related to the waste heat recovery equipment in main WHR subsystem, main exhaust gas economizer (EGE), are listed:

- maker: Alfa Laval,
- EGE type: Aalborg XW-TG with Aalborg Q-5 drums,
- design: exhaust gas economizer, forced circulation,
- number of stages: 2 – LP and HP
- steam output LP system: 1000 kg/h saturated steam for heating,
  1250 kg/h saturated steam to turbine,
- steam output HP system: 800 kg/h saturated steam for heating,
  5730 kg/h superheated steam to turbine,
- working pressure LP: 3.6 bar (g),
- working pressure HP: 7.4 bar (g),
- working temperature LP: 149 °C (saturated steam & water mixture),
- working temperature HP: 172 °C (saturated steam & water mixture),
- working temperature HP: 246 °C (superheated steam),
- feed water temperature LP: 140 °C,
- feed water temperature HP: 145 °C,
- design temperature inlet HP: 257.2 °C (exhaust gas),
- design temperature inlet LP: 186.0 °C (exhaust gas),
- design temperature out LP: 162.0 °C (exhaust gas).

The system element which consumes saturated LP steam, superheated HP steam and M/E exhaust gas is turbo generator. It comprises of steam turbine, power turbine (exhaust gas turbine) and generator. All elements are connected by means of shafts, reduction gears, couplings and clutch (between steam and power turbine). In Figure 3.18 presented simplified diagram of case ship's turbo generator and in Figure 3.19 presented schematic concept of turbo generator set control as well.

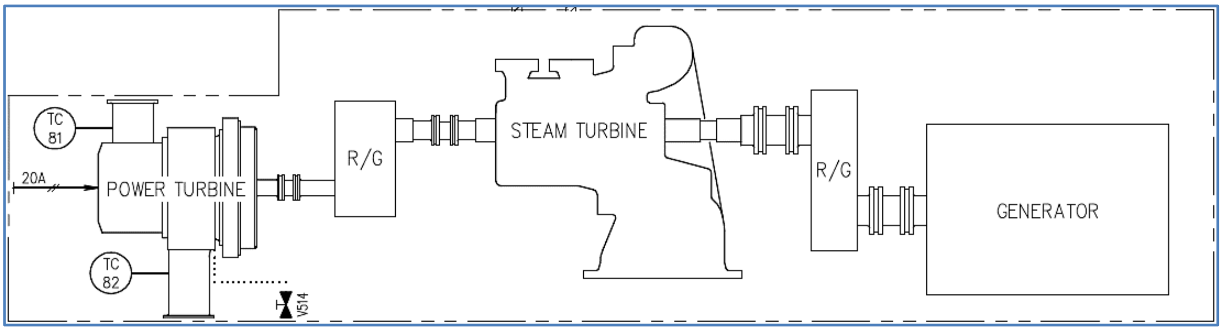


**Figure 3. 18:** Case ship's simplified diagram of turbo generator set

Source: [Mitsubishi Heavy Industries, 2017]

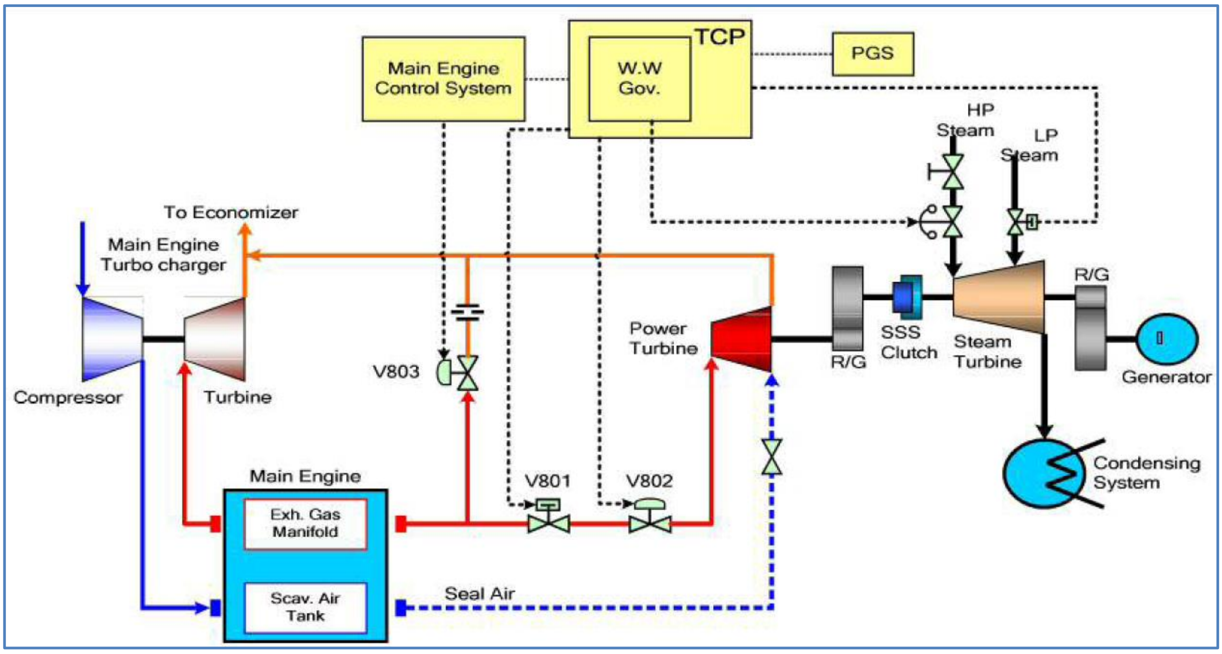


**Figure 3. 19:** Case ship's schematic concept of turbo generator set control

Source: [Mitsubishi Heavy Industries, 2017]

Basic data related to the waste heat recovery equipment in main WHR subsystem, turbo generator (T/G), are listed:

| | |
|---|---|
| maker: | Mitsubishi heavy industries (MHI), |
| generator rated output: | 2650 kW @ 60 Hz (6600 VAC), |
| steam turbine type: | horizontal multi-stages impulse condensing, |
| steam turbine model: | ATD52CLM2, |
| power turbine type: | axial flow, |
| power turbine model: | MPT33A, |
| no. 1 reduction gear type: | horizontal, single helical, |
| no. 1 reduction gear speed: | 8685 RPM / 1800 RPM, |

- no. 2 reduction gear type: horizontal, double helical,
- no. 2 reduction gear speed: 24258 RPM / 8685 RPM.

Output of whole main WHR subsystem is dependent from load of M/E. System is designed in such way, that when in operation, heating steam needs are always fully tended to and excess of steam and exhaust gas is being channeled to turbo generator set. Power output of T/G is dependent from M/E load and atmospheric conditions – tropical or winter. In Figures 3.20, 3.21 and 3.22 the influence of atmospheric conditions on T/G set output as function of M/E load is presented. Three characteristics are presented – at ISO conditions, tropical conditions and winter conditions.

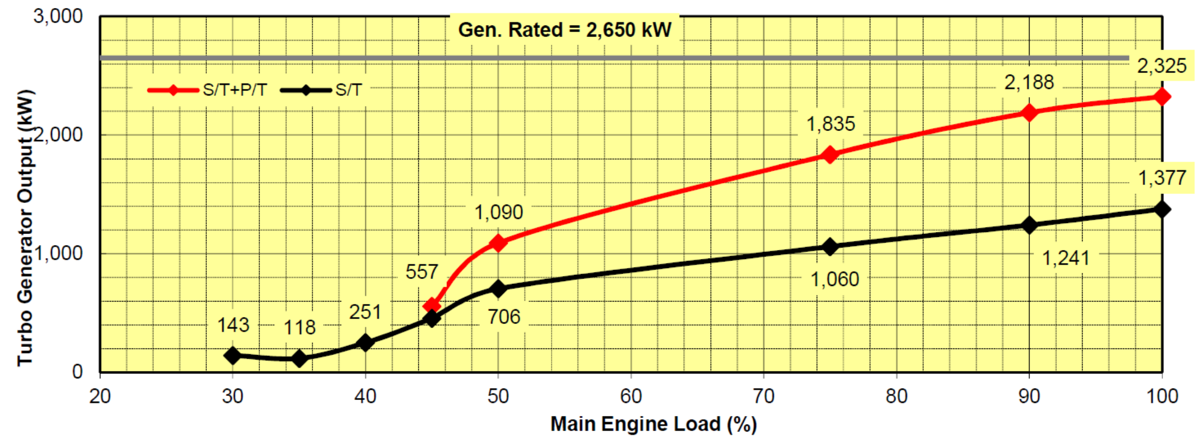


**Figure 3. 20:** T/G set output as function of M/E load – ISO conditions

Source: [Mitsubishi Heavy Industries, 2017]

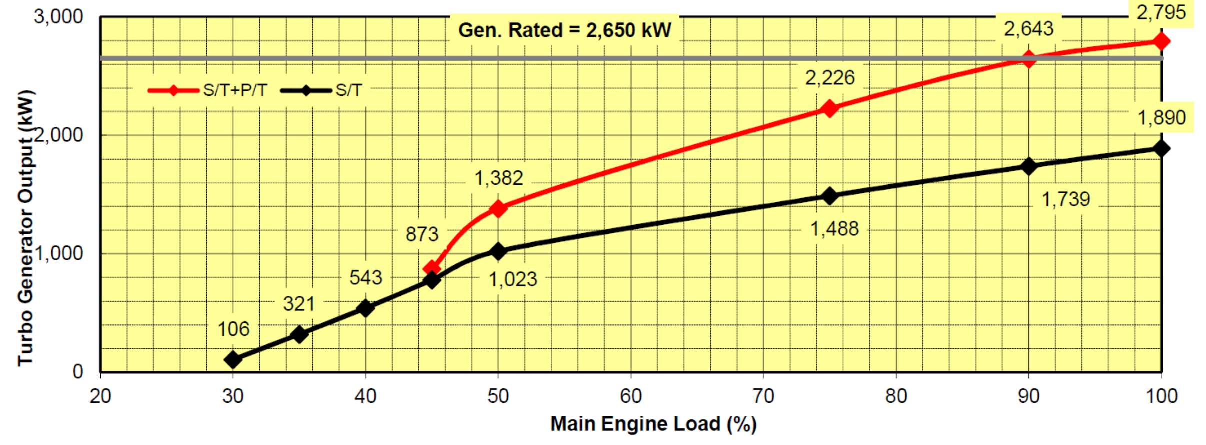


**Figure 3. 21:** T/G set output as function of M/E load – tropical conditions [19]

Source: [Mitsubishi Heavy Industries, 2017]

As presented earlier, waste heat utilization and subsequent electrical power production using turbo generating set is ambient conditions and M/E load dependent. Power output of such main WHR subsystem depends on many various parameters, such as ship's operational profile, length of voyages, weather conditions, ship's loaded condition, ship' speed, etc.

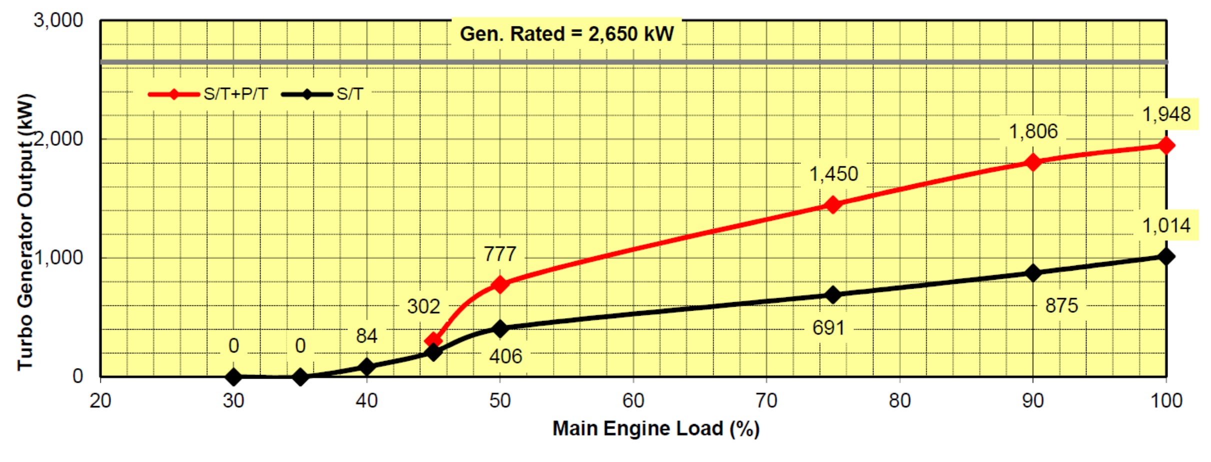


**Figure 3. 22:** T/G set output as function of M/E load – winter conditions [19]

Source: [Mitsubishi Heavy Industries, 2017]

To be able to utilize waste heat even further and more efficient, shaft motor / generator is installed. Depending on M/E load and ship's electrical power consumption demands, the operational profile of such motor / generator can be automatically switched from one to another.

E.g. M/E is running at high load (90% MCR), electrical power demand is low (1300 kW) and main WHR subsystem is operational and in service, atmospheric conditions ISO. From Figure 3.20 we can read that at this M/E load, turbo generating set will provide approximately 2200 kW of electrical power. Ship's demand is only 1300 kW. By using shaft generator / motor in auto mode, we can channel the extra electrical power to boost M/E by using shaft motor (PTI mode).

Another example is that M/E is running at medium load (50% MCR), electrical power demand is high (2500 kW) and main WHR subsystem is operational and in service, atmospheric conditions ISO. From Figure 3.20 we can read that at this M/E load, turbo generating set will provide approximately 1100 kW of electrical power. Ship's demand is however 2500 kW. By using shaft generator / motor in auto mode, we can produce the needed electrical power by using shaft generator (PTO mode). By doing so, we do not have to run additional A/Es unnecessarily, thus saving fuel, environment, running hours of A/Es, spare parts, etc. To summarize, it is up to each and every ship owner to decide whether to implement such an option for waste heat recovery or not. However, with respect to new trends in shipping industry, where the fuel savings and thus lowering of emissions is becoming priority, this solution seems adequate, not only from view point of investment costs, but low maintenance costs and high lifespan as well.

# 4 Energy operational index methodology to measure energy efficiency of container carrier

## 4.1 Analysis of the data based on the ship's recorded logs

All presented data have been collected from case ship's recorded logs. All data are divided into segments, based on voyage and leg. Data collection has been done from October 2015 until March 2017, encompasses one and half year of ship's sailing period. Comparison is done for each same leg from different voyages. Tables include data such as:

- total distance sailed (nautical miles),
- total RFO consumed per leg (metric tons) corrected to ISO,
- total DO consumed per leg (metric tons) corrected to ISO,
- total cargo transported per leg (metric tons),
- total cargo transported per leg (TEU),
- EEOI per leg ($g_{(CO2)}$/t·nm),
- EEOI per leg ($g_{(CO2)}$/TEU·nm).

Calculation of EEOI is done in accordance with MEPC.1/Circ.684 as per formula (2.5) presented in chapter 2, section 2.3. The formula (2.5) has been modified for case ship and is shown as formula:

$$EEOI = \frac{FC_{RFO} \cdot C_{FRFO} + FC_{DO} \cdot C_{FDO}}{m_{cargo} \cdot D} \tag{4.1}$$

where: $FC_{DO}$ – total fuel consumption of diesel oil (ISO corrected), $FC_{RFO}$ – total fuel consumption of residual fuel oil (ISO corrected), $C_{FDO}$ – $CO_2$ conversion factor for diesel oil ($C_{FDO}$ = 3.206 $t_{(CO2)}$/t(fuel) [12]), $C_{FRFO}$ – $CO_2$ conversion factor for RFO ($C_{FRFO}$ = 3.114 $t_{(CO2)}$/t(fuel) [12]), $m_{cargo}$ – cargo mass, $D$ – transportation distance of cargo mass.

Each leg is characterized by sailing in specific region and specific climatic conditions. Values characteristic region of sailing are presented:

- average sea water salinity (psu),
- average sea water density (kg/m$^3$),
- average sea water surface temperature (°C),
- average sea water alkalinity (pH).

In Table 4.1 there are presented data, collected during sailing in first leg. This leg has following characteristic seawater parameters: salinity 32 psu, density 1006 kg/m³, temperature 26°C, alkalinity pH 8.0. Obtained EEOI from calculations are graphically presented as function of transported cargo mass in Figure 4.1.

**Table 4. 1:** Case ship collected data and EEOI calculations, Leg 1

| voyage number | D | $FC_{RFO}$ | $FC_{DO}$ | $m_{CARGO}$ | $m_{CARGO}$ | EEOI | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [nm] | [mt] | [mt] | [mt] | [TEU] | [g/t·nm] | [g/TEU·nm] |
| 1545 | 728 | 144.55 | 0.00 | 50244 | 5406 | 12.306 | 114.375 |
| 1605 | 688 | 166.08 | 0.00 | 60240 | 7267 | 12.478 | 103.440 |
| 1618 | 745 | 134.69 | 0.00 | 64750 | 7255 | 8.694 | 77.597 |
| 1630 | 718 | 228.60 | 0.00 | 62857 | 6700 | 15.773 | 147.979 |
| 1642 | 694 | 167.90 | 0.00 | 69592 | 8258 | 10.826 | 91.230 |
| 1701 | 707 | 176.16 | 0.00 | 62138 | 7428 | 12.487 | 104.457 |

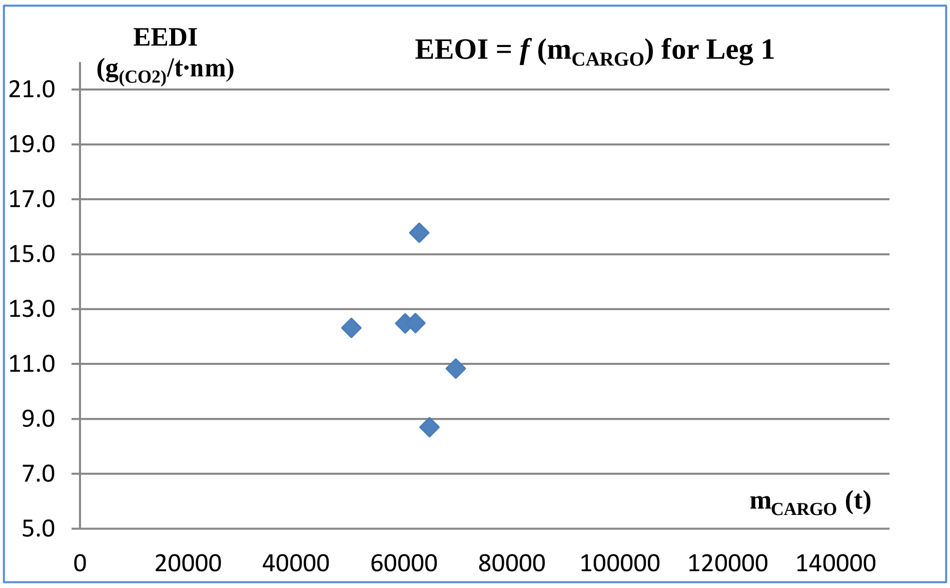


**Figure 4. 1:** Case ship EEOI as function of cargo mass for Leg 1

In Table 4.2 there are presented data collected during sailing in second leg. This leg has following characteristic seawater parameters: salinity 31 psu, density 1005 kg/m³, temperature 27°C, alkalinity pH 8.0. Obtained EEOI from calculations are graphically presented as function of transported cargo mass in Figure 4.2.

**Table 4. 2:** Case ship collected data and EEOI calculations, Leg 2

| voyage number | D | $FC_{RFO}$ | $FC_{DO}$ | $m_{CARGO}$ | $m_{CARGO}$ | EEOI | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [nm] | [mt] | [mt] | [mt] | [TEU] | [g/t·nm] | [g/TEU·nm] |
| 1545 | 919 | 199.93 | 0.00 | 83293 | 9943 | 8.133 | 68.134 |
| 1605 | 878 | 236.40 | 0.00 | 85891 | 11007 | 9.762 | 76.173 |
| 1618 | 922 | 229.13 | 0.00 | 87236 | 10116 | 8.871 | 76.502 |
| 1630 | 954 | 342.53 | 0.00 | 88669 | 10582 | 12.609 | 105.658 |
| 1642 | 939 | 255.58 | 0.00 | 64665 | 11284 | 13.107 | 75.114 |
| 1701 | 920 | 186.37 | 0.00 | 85610 | 10423 | 7.369 | 60.522 |

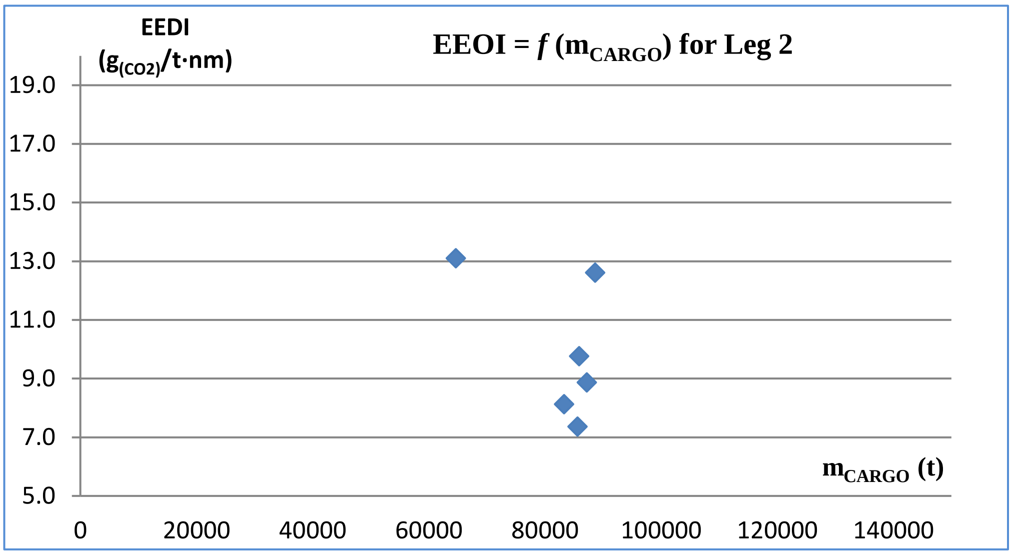


**Figure 4. 2:** Case ship EEOI as function of cargo mass for Leg 2

In Table 4.3 there are presented data collected during sailing in third leg. This leg has following characteristic seawater parameters: salinity 32 psu, density 1007 kg/m$^3$, temperature 29°C, alkalinity pH 8.1. Obtained EEOI from calculations are graphically presented as function of transported cargo mass in Figure 4.3.

**Table 4. 3:** Case ship collected data and EEOI calculations, Leg 3

| voyage number | D | $FC_{RFO}$ | $FC_{DO}$ | $m_{CARGO}$ | $m_{CARGO}$ | EEOI | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [nm] | [mt] | [mt] | [mt] | [TEU] | [g/t·nm] | [g/TEU·nm] |
| 1545 | 780 | 152.90 | 0.00 | 82047 | 8837 | 7.440 | 69.078 |
| 1605 | 792 | 199.56 | 0.00 | 102487 | 12591 | 7.656 | 62.316 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1618 | 813 | 171.14 | 0.00 | 93626 | 10937 | 7.001 | 59.936 |
| 1630 | 818 | 254.70 | 0.00 | 101994 | 12002 | 9.506 | 80.787 |
| 1642 | 819 | 246.54 | 0.00 | 109620 | 13010 | 8.551 | 72.051 |
| 1701 | 813 | 214.75 | 0.00 | 101407 | 12365 | 8.111 | 66.521 |

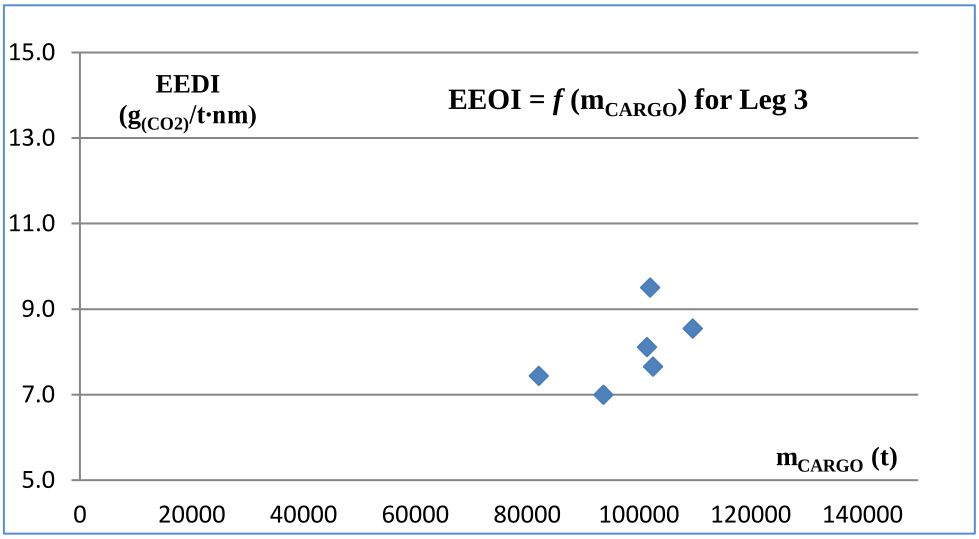


**Figure 4. 3:** Case ship EEOI as function of cargo mass for Leg 3

In Table 4.4 there are presented data collected during sailing in fourth leg. This leg has following characteristic seawater parameters: salinity 35 psu, density 1012 kg/m$^3$, temperature 30°C, alkalinity pH 8.2. Obtained EEOI from calculations are graphically presented as function of transported cargo mass in Figure 4.4.

**Table 4. 4:** Case ship collected data and EEOI calculations, Leg 4

| voyage number | D | $FC_{RFO}$ | $FC_{DO}$ | $m_{CARGO}$ | $m_{CARGO}$ | EEOI | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [nm] | [mt] | [mt] | [mt] | [TEU] | [g/t·nm] | [g/TEU·nm] |
| 1545 | 4758 | 1420.92 | 0.00 | 111991 | 12521 | 8.304 | 74.272 |
| 1605 | 4823 | 1203.04 | 0.00 | 112673 | 13517 | 6.894 | 57.465 |
| 1618 | 4798 | 1287.82 | 0.00 | 119027 | 13087 | 7.022 | 63.867 |
| 1630 | 4919 | 1606.21 | 0.00 | 115292 | 13417 | 8.819 | 75.786 |
| 1642 | 4820 | 1540.31 | 0.00 | 116081 | 13756 | 8.573 | 72.342 |
| 1701 | 4783 | 1370.84 | 0.00 | 117058 | 13702 | 7.624 | 65.136 |

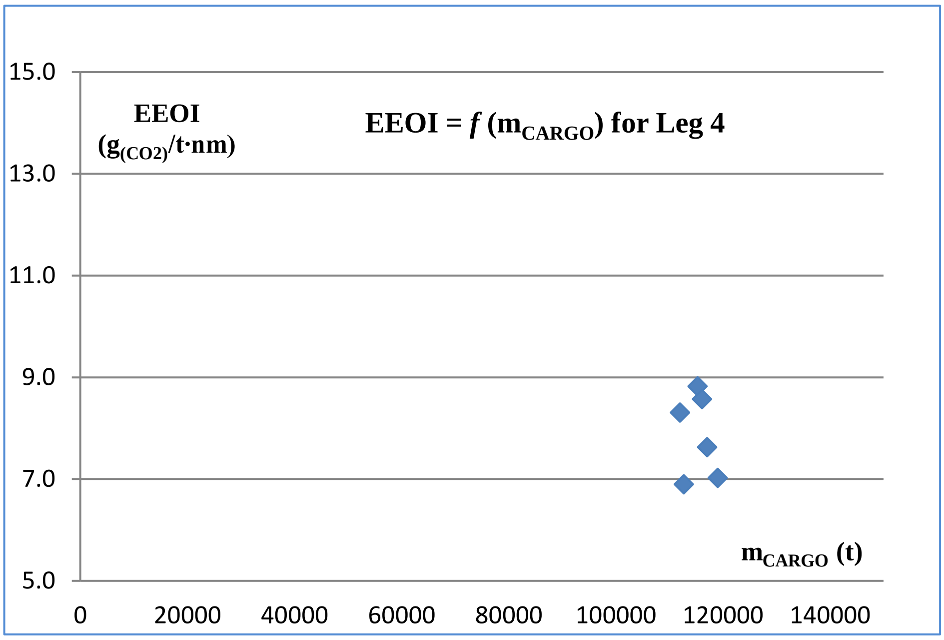


**Figure 4. 4:** Case ship EEOI as function of cargo mass for Leg 4

In Table 4.5 there are presented data collected during sailing in fifth leg. This leg has following characteristic seawater parameters: salinity 37 psu, density 1021 kg/m$^3$, temperature 22°C, alkalinity pH 8.2. Obtained EEOI from calculations are graphically presented as function of transported cargo mass in Figure 4.5.

**Table 4. 5:** Case ship collected data and EEOI calculations, Leg 5

| voyage number | D | $FC_{RFO}$ | $FC_{DO}$ | $m_{CARGO}$ | $m_{CARGO}$ | EEOI | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [nm] | [mt] | [mt] | [mt] | [TEU] | [g/t·nm] | [g/TEU·nm] |
| 1545 | 3168 | 815.12 | 113.23 | 111991 | 12521 | 8.178 | 73.142 |
| 1605 | 3238 | 919.33 | 69.77 | 112673 | 13517 | 8.460 | 70.519 |
| 1618 | 3145 | 902.75 | 95.75 | 119027 | 13087 | 8.330 | 75.759 |
| 1630 | 3135 | 872.60 | 84.82 | 115292 | 13417 | 8.270 | 71.066 |
| 1642 | 3151 | 981.20 | 80.22 | 116081 | 13756 | 9.057 | 76.424 |
| 1701 | 3194 | 860.83 | 50.82 | 117058 | 13702 | 7.605 | 64.974 |

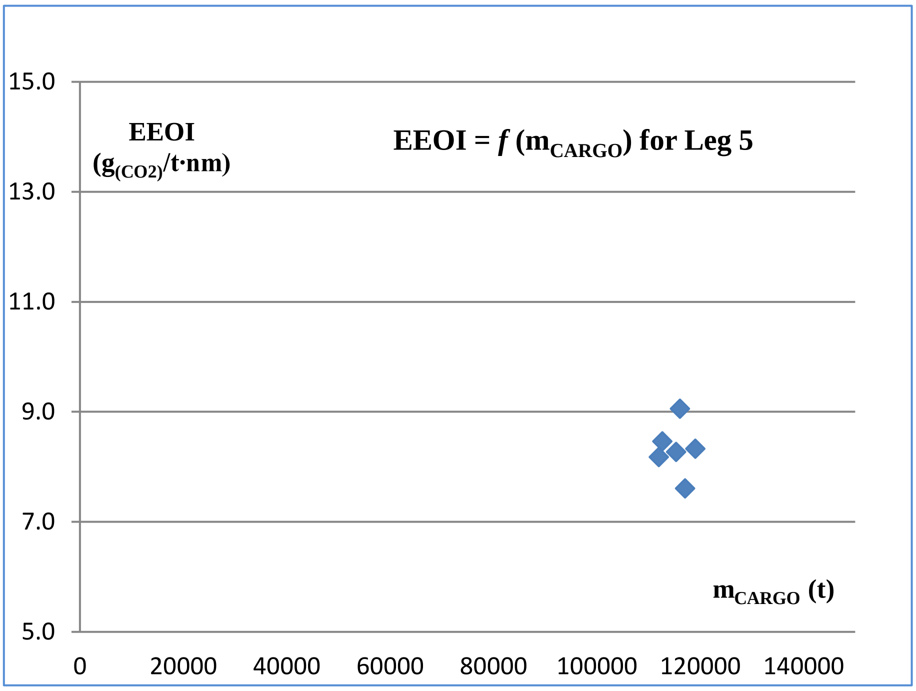


**Figure 4. 5:** Case ship EEOI as function of cargo mass for Leg 5

In Table 4.6 there are presented data collected during sailing in sixth leg. This leg has following characteristic seawater parameters: salinity 37 psu, density 1021 kg/m$^3$, temperature 22°C, alkalinity pH 8.2. Obtained EEOI from calculations are graphically presented as function of transported cargo mass in Figure 4.6.

**Table 4. 6:** Case ship collected data and EEOI calculations, Leg 6

| voyage number | D | $FC_{RFO}$ | $FC_{DO}$ | $m_{CARGO}$ | $m_{CARGO}$ | EEOI | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [nm] | [mt] | [mt] | [mt] | [TEU] | [g/t·nm] | [g/TEU·nm] |
| 1545 | 3136 | 666.21 | 139.31 | 117831 | 10746 | 6.823 | 74.815 |
| 1605 | 3127 | 598.24 | 46.22 | 108010 | 11088 | 5.954 | 58.004 |
| 1618 | 11718 | 3037.59 | 41.48 | 102983 | 12965 | 7.949 | 63.137 |
| 1630 | 3198 | 691.94 | 40.63 | 90827 | 11059 | 7.867 | 64.607 |
| 1642 | 3134 | 542.63 | 53.84 | 129062 | 12704 | 4.604 | 46.776 |
| 1701 | 3204 | 723.62 | 87.08 | 133847 | 12571 | 5.905 | 62.877 |

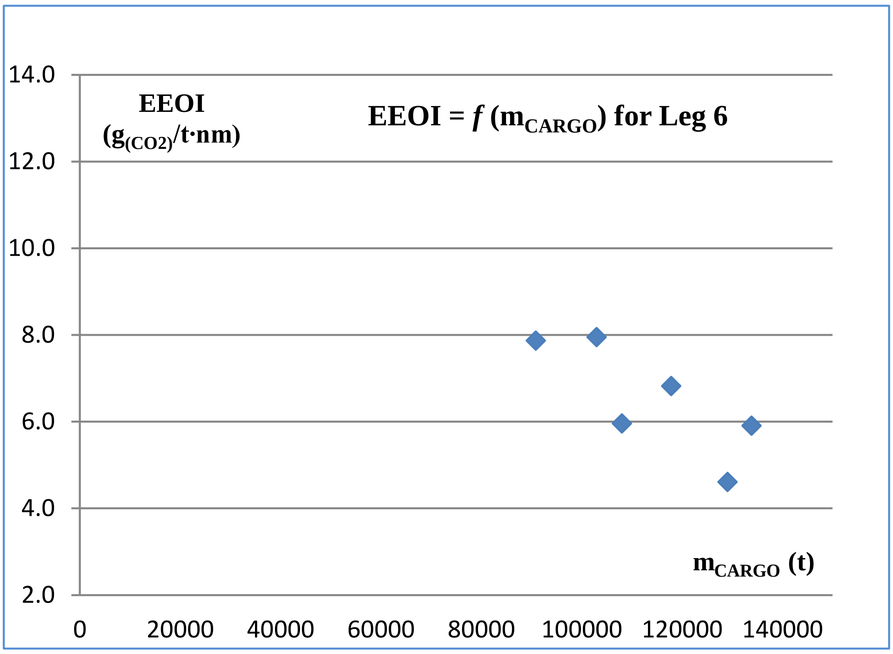


**Figure 4. 6:** Case ship EEOI as function of cargo mass for Leg 6

In Table 3.7 there are presented data collected during sailing in seventh leg. This leg has following characteristic values: salinity 35 psu, density 1011 kg/m$^3$, temperature 30°C, alkalinity pH 8.1. Obtained EEOI from calculations are graphically presented as function of transported cargo mass in Figure 4.7.

**Table 4. 7:** Case ship collected data and EEOI calculations, Leg 7

| voyage number | D | $FC_{RFO}$ | $FC_{DO}$ | $m_{CARGO}$ | $m_{CARGO}$ | EEOI | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [nm] | [mt] | [mt] | [mt] | [TEU] | [g/t·nm] | [g/TEU·nm] |
| 1545 | 4573 | 859.61 | 0.00 | 73033 | 9285 | 8.015 | 63.043 |
| 1605 | 4329 | 712.62 | 0.00 | 72897 | 11555 | 7.032 | 44.363 |
| 1630 | 4298 | 656.96 | 0.00 | 85651 | 13137 | 5.557 | 36.232 |
| 1642 | 4417 | 860.21 | 0.00 | 104716 | 12997 | 5.791 | 46.661 |
| 1701 | 4409 | 780.15 | 0.00 | 112895 | 13176 | 4.881 | 41.819 |

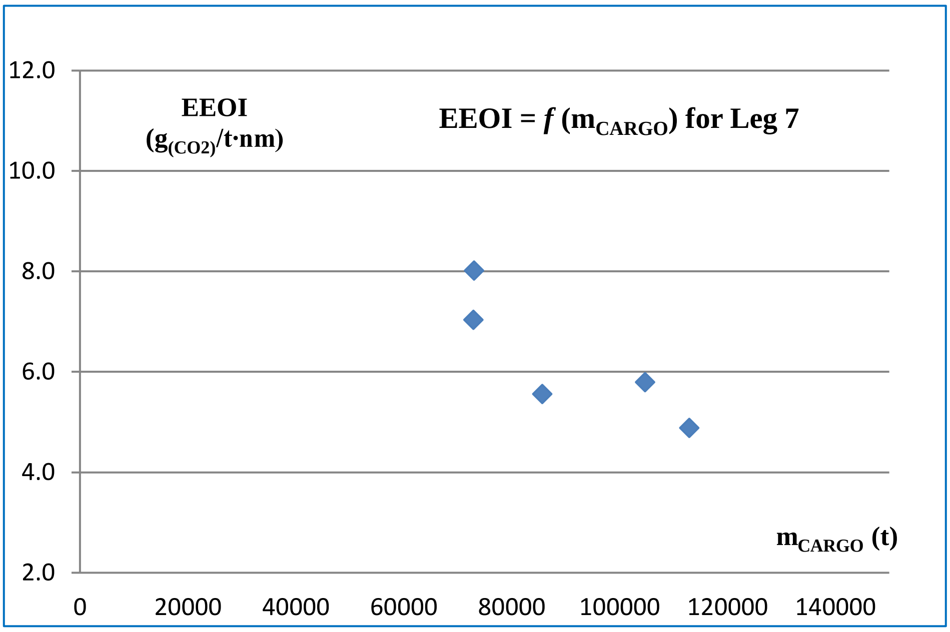


**Figure 4. 7:** Case ship EEOI as function of cargo mass for Leg 7

In Table 4.8 there are presented data collected during sailing in eighth leg. This leg has following characteristic values: salinity 31 psu, density 1007 kg/m$^3$, temperature 28°C, alkalinity pH 8.0. Obtained EEOI from calculations are graphically presented as function of transported cargo mass in Figure 4.8.

**Table 4. 8:** Case ship collected data and EEOI calculations, Leg 8

| voyage number | D | $FC_{RFO}$ | $FC_{DO}$ | $m_{CARGO}$ | $m_{CARGO}$ | EEOI | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [nm] | [mt] | [mt] | [mt] | [TEU] | [g/t·nm] | [g/TEU·nm] |
| 1545 | 1709 | 266.95 | 0.00 | 54212 | 8692 | 8.973 | 55.962 |
| 1605 | 1659 | 261.15 | 0.00 | 78769 | 12573 | 6.223 | 38.988 |
| 1618 | 1623 | 497.33 | 0.00 | 79380 | 11024 | 12.021 | 86.558 |
| 1630 | 1613 | 373.39 | 0.00 | 71910 | 11950 | 10.025 | 60.323 |
| 1642 | 1703 | 454.87 | 0.00 | 96568 | 12312 | 8.613 | 67.556 |
| 1701 | 1658 | 287.54 | 0.00 | 90514 | 11902 | 5.966 | 45.374 |

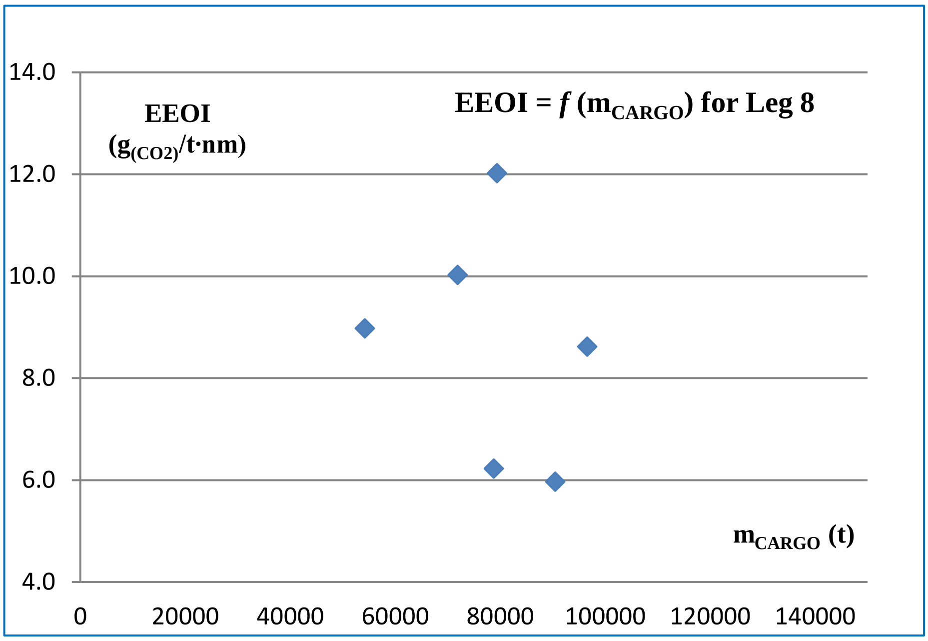


**Figure 4. 8:** Case ship EEOI as function of cargo mass for Leg 8

In Table 4.9 there are presented data collected during sailing in ninth leg. This leg has following characteristic values: salinity 32 psu, density 1006 kg/m$^3$, temperature 26°C, alkalinity pH 8.0. Obtained EEOI from calculations are graphically presented as function of transported cargo mass in Figure 4.9.

**Table 4. 9:** Case ship collected data and EEOI calculations, Leg 9

| voyage number | D | $FC_{RFO}$ | $FC_{DO}$ | $m_{CARGO}$ | $m_{CARGO}$ | EEOI | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [nm] | [mt] | [mt] | [mt] | [TEU] | [g/t·nm] | [g/TEU·nm] |
| 1545 | 924 | 153.39 | 0.00 | 19016 | 5010 | 27.184 | 103.181 |
| 1605 | 850 | 115.51 | 0.00 | 26569 | 8652 | 15.928 | 48.911 |
| 1618 | 796 | 134.51 | 0.00 | 31569 | 7477 | 16.668 | 70.375 |
| 1630 | 820 | 183.76 | 0.00 | 51733 | 8458 | 13.489 | 82.506 |
| 1642 | 837 | 145.35 | 0.00 | 38764 | 7131 | 13.950 | 75.833 |
| 1701 | 731 | 99.76 | 0.00 | 39256 | 8312 | 10.826 | 51.129 |

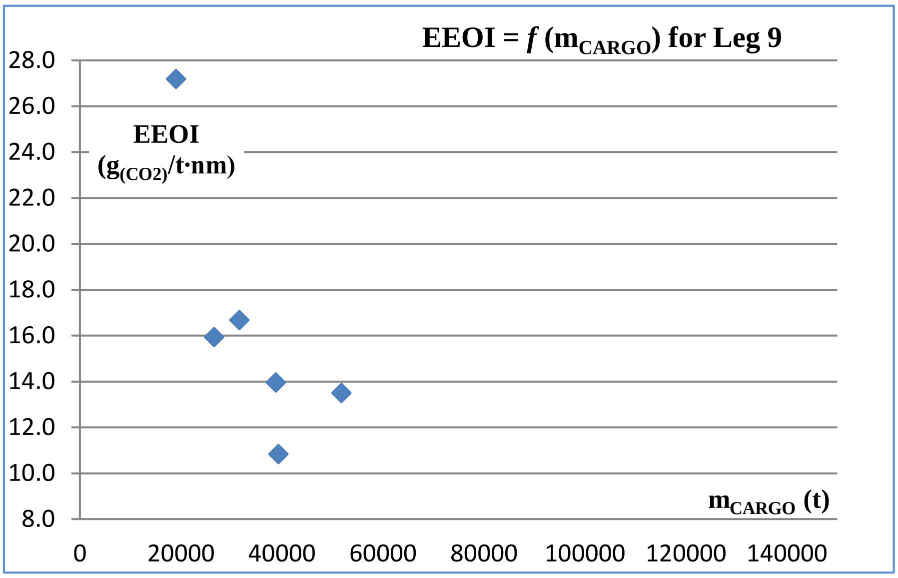


**Figure 4. 9:** Case ship EEOI as function of cargo mass for Leg 9

The following Figure 4.10 presents EEOI for all legs and voyages with exponential regression, compared with required EEDI for the case ship.

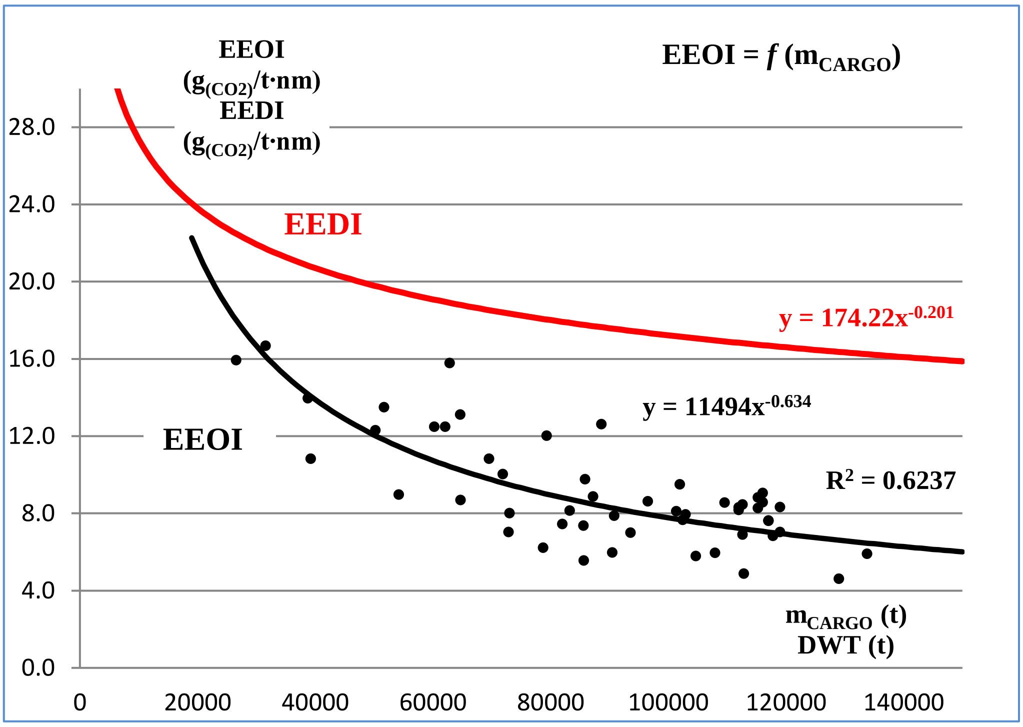


**Figure 4. 10:** Calculated EEOI for all legs against required EEDI limit for the case ship

## 4.2 Evaluation of ship speed dependent energy efficiency performance and attained EEOI

Evaluation on ship speed dependent energy efficiency is done analogically as presented in section 4.1. In Table 4.10 are presented extracted data of case ship relevant to ship speed dependent energy efficiency.

**Table 4. 10:** Case ship collected data and EEOI calculations, speed dependent

| Leg | Voyage number | Speed (LOG) | EEOI | Leg | Voyage number | Speed (LOG) | EEOI |
|---|---|---|---|---|---|---|---|
| [-] | [-] | [knots] | [g/t·nm] | [-] | [-] | [knots] | [g/t·nm] |
| 1 | 1545 | 15.01 | 8.133 | 6 | 1545 | 14.22 | 6.823 |
| | 1605 | 20.24 | 9.762 | | 1605 | 13.63 | 5.954 |
| | 1618 | 15.52 | 8.871 | | 1618 | 18.16 | 7.949 |
| | 1630 | 17.18 | 12.609 | | 1630 | 17.31 | 7.867 |
| | 1642 | 18.07 | 13.107 | | 1642 | 13.22 | 4.604 |
| | 1701 | 18.46 | 7.369 | | 1701 | 17.32 | 5.905 |
| 2 | 1545 | 18.76 | 7.440 | 7 | 1545 | 13.95 | 8.015 |
| | 1605 | 21.16 | 7.656 | | 1605 | 12.03 | 7.032 |
| | 1618 | 18.82 | 7.001 | | 1618 | - | - |
| | 1630 | 19.55 | 9.506 | | 1630 | 11.74 | 5.557 |
| | 1642 | 17.89 | 8.551 | | 1642 | 13.22 | 5.791 |
| | 1701 | 14.42 | 8.111 | | 1701 | 13.59 | 4.881 |
| 3 | 1545 | 15.76 | 8.304 | 8 | 1545 | 14.61 | 8.973 |
| | 1605 | 18.42 | 6.894 | | 1605 | 12.20 | 6.223 |
| | 1618 | 15.63 | 7.022 | | 1618 | 20,21 | 12,021 |
| | 1630 | 19,02 | 8,819 | | 1630 | 16,96 | 10,025 |
| | 1642 | 19,18 | 8,573 | | 1642 | 15,36 | 8,613 |
| | 1701 | 18,65 | 7,624 | | 1701 | 12,37 | 5,966 |
| 4 | 1545 | 19,91 | 8,178 | 9 | 1545 | 8,36 | 27.184 |
| | 1605 | 19.22 | 8.460 | | 1605 | 10.90 | 15.928 |
| | 1618 | 18.24 | 8.330 | | 1618 | 13.72 | 16.668 |
| | 1630 | 18.60 | 8.270 | | 1630 | 12.62 | 13.489 |
| | 1642 | 19.81 | 9.057 | | 1642 | 12.92 | 13.950 |
| | 1701 | 19.52 | 7.605 | | 1701 | 11.39 | 10.826 |
| 5 | 1545 | 19.50 | 6.823 | | | | |
| | 1605 | 18.94 | 5.954 | | | | |

| | | | |
|---|---|---|---|
| | 1618 | 19.41 | 7.949 |
| | 1630 | 19.17 | 7.867 |
| | 1642 | 19.45 | 4.604 |
| | 1701 | 17.22 | 5.905 |

In following Figure 4.11 there is graphically presented EEOI for all legs and voyages with exponential regression based theoretical curve for all plausible ship's speeds. However, with coefficient of determination $R^2=0.0099$, the exponential regression based curve is considered strictly informative and theoretical.

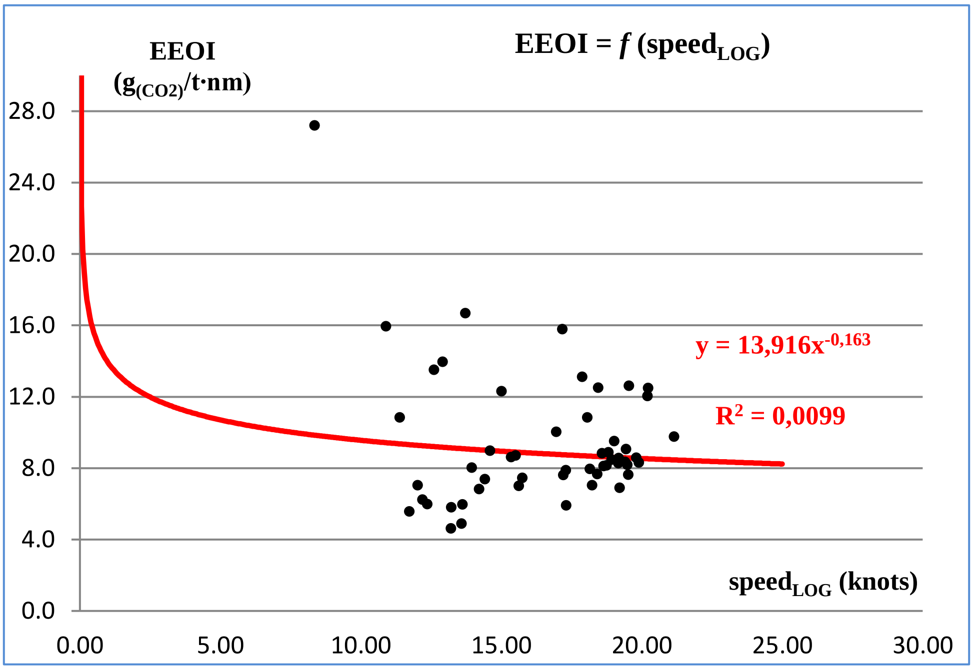


**Figure 4. 11:** Calculated EEOI reliant on ship's log speed

In order to be able to practically use the collected data for analysis of ship speed dependent energy efficiency the data from Table 3.10 has been divided into three groups. These groups are conditioned by mass of cargo on board (in drawings presented as percentage of DWT). First group concerns all legs and voyages where the ship has been loaded (comparing to DWT) more than 75% of DWT. Second group analogically for (50 ÷ 75)% DWT and third group for less than 50% of DWT.

The data are presented in Table 4.11 and different groups (base on ship's loaded condition as % of DWT) are marked with different colors for better transparency.

**Table 4. 11:** Case ship collected data and EEOI calculations, speed dependent, cargo mass dependent (ship loaded in % of DWT)

| Leg | Voyage number | Ship loaded | Speed (LOG) | EEOI | Leg | Voyage number | Ship loaded | Speed (LOG) | EEOI |
|---|---|---|---|---|---|---|---|---|---|
| [-] | [-] | [%DWT] | [knots] | [g/t·nm] | [-] | [-] | [%DWT] | [knots] | [g/t·nm] |
| 1 | 1545 | 43.68 | 15.01 | 12.306 | 6 | 1545 | 88.93 | 14.22 | 6.823 |
| | 1605 | 50.37 | 20.24 | 12.478 | | 1605 | 82.36 | 13.63 | 5.954 |
| | 1618 | 53.39 | 15.52 | 8.694 | | 1618 | 78.99 | 18.16 | 7.949 |
| | 1630 | 52.13 | 17.18 | 15.773 | | 1630 | 70.85 | 17.31 | 7.867 |
| | 1642 | 56.64 | 18.07 | 10.826 | | 1642 | 96.45 | 13.22 | 4.604 |
| | 1701 | 51.65 | 18.46 | 12.487 | | 1701 | 99.66 | 17.32 | 5.905 |
| 2 | 1545 | 65.81 | 18.76 | 8.133 | 7 | 1545 | 58.94 | 13.95 | 8.015 |
| | 1605 | 67.55 | 21.16 | 9.762 | | 1605 | 58.85 | 12.03 | 7.032 |
| | 1618 | 68.45 | 18.82 | 8.871 | | 1618 | | | |
| | 1630 | 69.41 | 19.55 | 12.609 | | 1630 | 67.39 | 11.74 | 5.557 |
| | 1642 | 53.34 | 17.89 | 13.107 | | 1642 | 80.15 | 13.22 | 5.791 |
| | 1701 | 67.36 | 14.42 | 7.369 | | 1701 | 85.63 | 13.59 | 4.881 |
| 3 | 1545 | 64.98 | 15.76 | 7.440 | 8 | 1545 | 46,34 | 14,61 | 8,973 |
| | 1605 | 78,66 | 18,42 | 7,656 | | 1605 | 62,78 | 12,20 | 6,223 |
| | 1618 | 72,73 | 15,63 | 7,001 | | 1618 | 63,19 | 20,21 | 12,021 |
| | 1630 | 78,33 | 19,02 | 9,506 | | 1630 | 58,19 | 16,96 | 10,025 |
| | 1642 | 83,44 | 19,18 | 8,551 | | 1642 | 74,70 | 15.36 | 8.613 |
| | 1701 | 77.94 | 18.65 | 8.111 | | 1701 | 70.64 | 12.37 | 5.966 |
| 4 | 1545 | 85.02 | 19.91 | 8.304 | 9 | 1545 | 22.77 | 8.36 | 27.184 |
| | 1605 | 85.48 | 19.22 | 6.894 | | 1605 | 27.83 | 10.90 | 15.928 |
| | 1618 | 89.73 | 18.24 | 7.022 | | 1618 | 31.18 | 13.72 | 16.668 |
| | 1630 | 87.23 | 18.60 | 8.819 | | 1630 | 44.68 | 12.62 | 13.489 |
| | 1642 | 87.76 | 19.81 | 8.573 | | 1642 | 36.00 | 12.92 | 13.950 |
| | 1701 | 88.42 | 19.52 | 7.624 | | 1701 | 36.33 | 11.39 | 10.826 |
| 5 | 1545 | 85.02 | 19.50 | 8.178 | | | | | |
| | 1605 | 85.48 | 18.94 | 8.460 | | | | | |
| | 1618 | 89.73 | 19.41 | 8.330 | | | | | |
| | 1630 | 87.23 | 19.17 | 8.270 | | | | | |
| | 1642 | 87.76 | 19.45 | 9.057 | | | | | |
| | 1701 | 88.42 | 17.22 | 7.605 | | | | | |

Based on the new division into the three groups based on ship's loaded condition, three graphical representations of EEOI for all legs and voyages with linear regression based theoretical curve for all plausible ship's speeds are presented in Figures 4.12, 4.13 and 4.14.

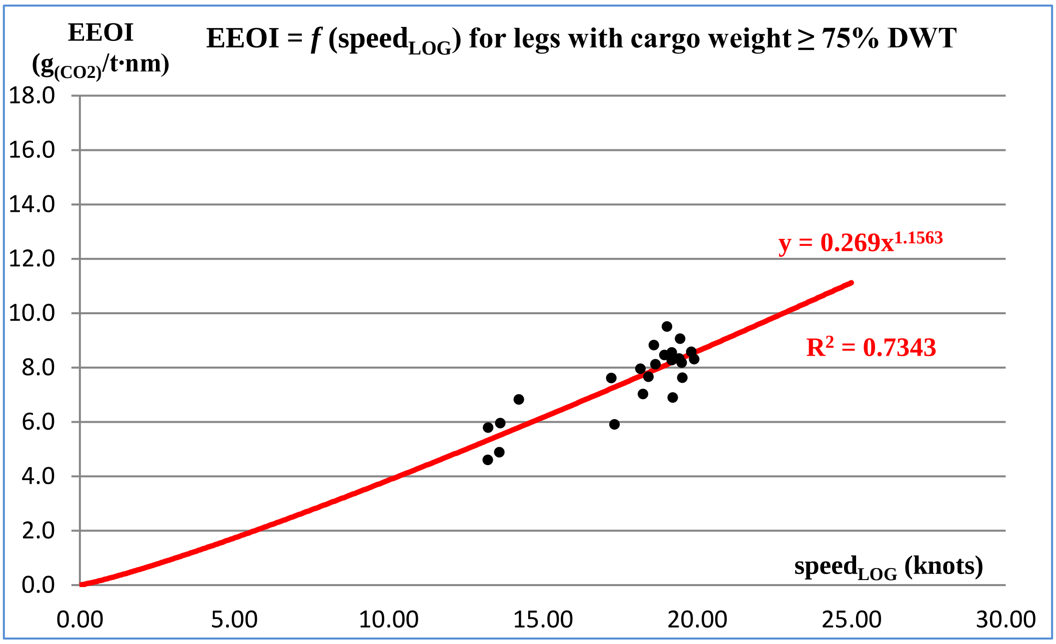


**Figure 4. 12:** Calculated EEOI for legs with high cargo load and plausible ship's speeds

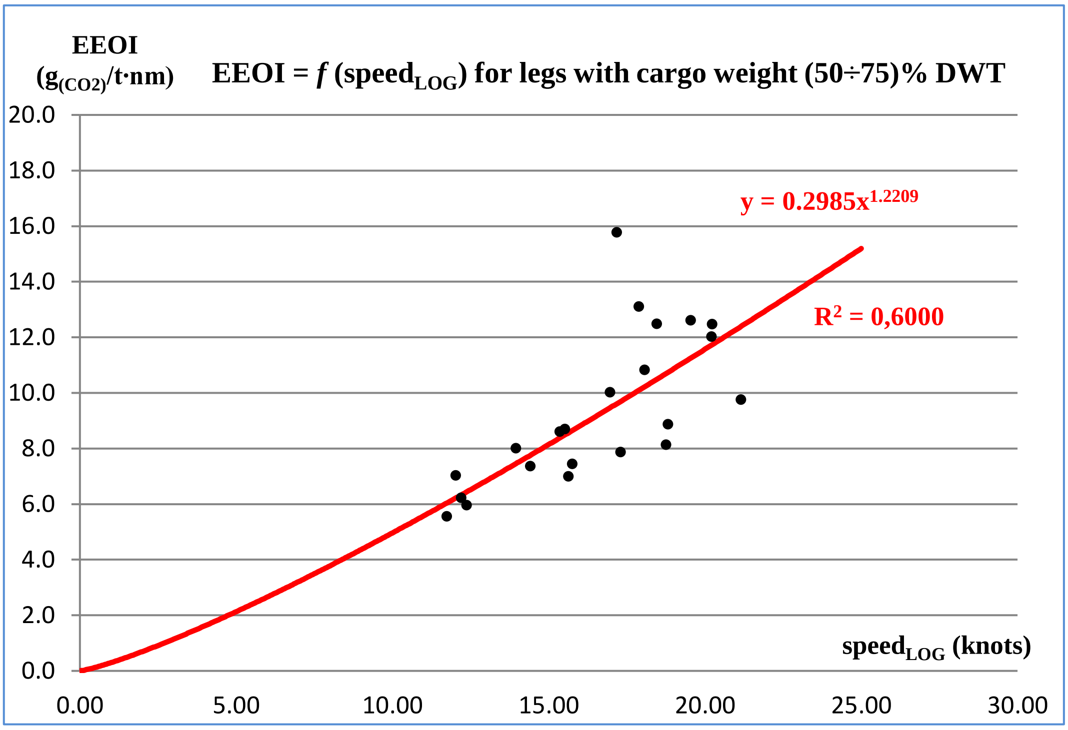


**Figure 4. 13:** Calculated EEOI for legs with moderate cargo load and plausible ship's speeds

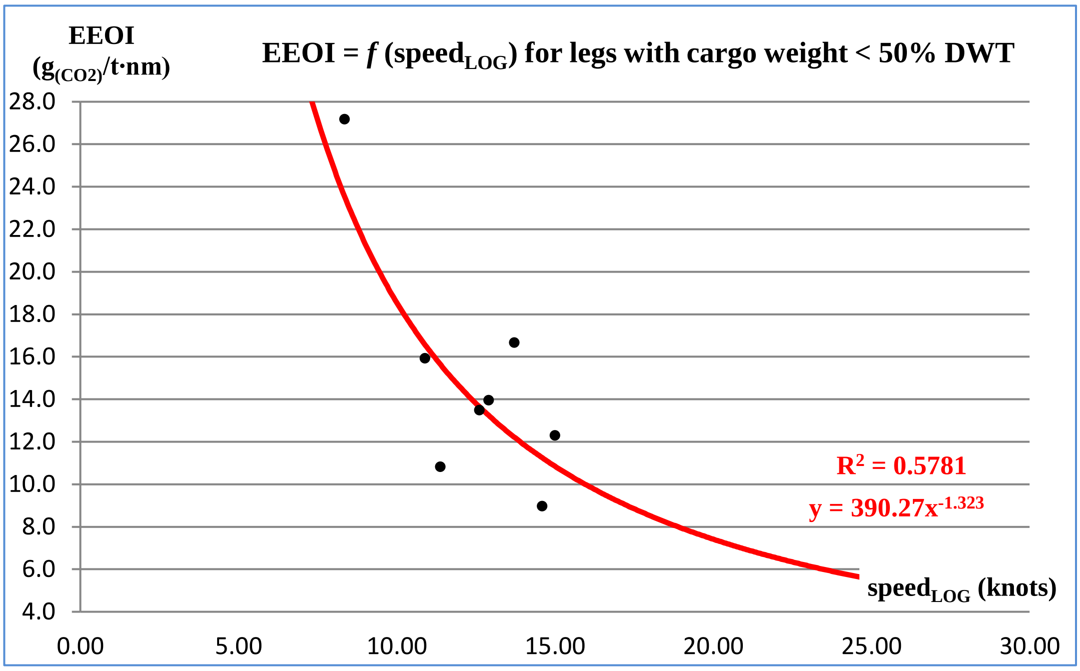


**Figure 4. 14:** Calculated EEOI for legs with low cargo load and plausible ship's speeds

Based on collected and graphically presented data, principal conclusions can be made. Ship owner or operator can adjust and predict, based on ship's loaded condition, ship's speed. For loaded condition more than 50% DWT, with increasing speed, energy efficiency is decreasing (EEOI increasing). For loaded condition less than 50% DWT, with increasing speed, energy efficiency is increasing (EEOI decreasing).

This gives owner or operator information that, if the ship is to sail any leg loaded less than 50% DWT, in order to obtain lower EEOI for that leg, increased speed is required. This in translation to economical costs means lower transportation costs per TEU (or ton of cargo) per nautical mile.

Analogically if the ship is to sail loaded more than 50% DWT, in order to obtain lower EEOI for that leg, speed decrease is required. And again, lower the EEOI lower the costs per TEU (or ton of cargo) per nautical mile.

From presented data (Figure4.12) conclusion can be made that for lowest EEOI ship is to be loaded more than 75% DWT and sailing with speed around 13.5 knots.

## 4.3 Case examples of different WHRS operational modes

Basically, the operational modes can be divided into two groups – auxiliary WHR subsystem in operation and main WHR subsystem in operation. As described in section 3.3 auxiliary WHRS is mainly used during short passages and in ports and it is used for production of heating steam only. On the other hand, main WHRS is being used during passages when M/E is producing power more than 30% MCR. When the power of M/E is more than 50% MCR, beside steam generation, electrical power generation through T/G is being done as well. The following WHRS operational modes can be implemented on board case ship:

- auxiliary WHR subsystem – heating steam generation only,
- main WHR subsystem (M/E power between (30 ÷ 50)% MCR) – heating steam generation only,
- main WHR subsystem (M/E power >50% MCR) – heating steam generation and electrical power generation using T/G

In following Table 4.12 case ship collected data selection is presented. Calculations of fuel savings obtained by usage of T/G to produce electrical power in kg/h and as percentage compared towards ships total fuel consumption per hour per relevant legs are presented in Table 4.12 as well. All fuel savings of T/G electrical power generation are calculated relative to A/Es electrical power generation fuel consumption. A/Es ISO SFOC @ 50% MCR is 214.615 g/kWh [5].

**Table 4. 1** Case ship collected data and WHRS modes, increase of energy efficiency calculations

| Leg | Voy. no. | M/E load | Ship's speed LOG | Spec. T/G savings | T/G savings | Leg | Voy. no. | M/E load | Ship's speed LOG | Spec. T/G savings | T/G savings |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [-] | [-] | [%MCR] | [knots] | [kg/h] | [%] | [-] | [-] | [%MCR] | [knots] | [kg/h] | [%] |
| 1 | 1545 | 38.69 | 15.01 | 0.00 | 0.00 | 6 | 1545 | 53.87 | 14.22 | 0.00 | 0.00 |
| | 1605 | 78.86 | 20.24 | 281.90 | 5.77 | | 1605 | 43.11 | 13.63 | 0.00 | 0.00 |
| | 1618 | 43.25 | 15.52 | 74.37 | 2.65 | | 1618 | 74.00 | 18.16 | 323.62 | 6.78 |
| | 1630 | 71.83 | 17.18 | 0.00 | 0.00 | | 1630 | 61.69 | 17.31 | 80.19 | 2.02 |
| | 1642 | 65.35 | 18.07 | 0.00 | 0.00 | | 1642 | 36.03 | 13.22 | 0.00 | 0.00 |
| | 1701 | 65.28 | 18.46 | 0.00 | 0.00 | | 1701 | 66.00 | 17.32 | 104.96 | 2.40 |
| 2 | 1545 | 63.73 | 18.76 | 200.73 | 4.92 | 7 | 1545 | 39.20 | 13.95 | 160.86 | 6.13 |
| | 1605 | 89.58 | 21.16 | 410.16 | 7.20 | | 1605 | 27.02 | 12.03 | 207.50 | 10.48 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1618 | 74.79 | 18.82 | 320.06 | 6.84 | | 1618 | | | | |
| | 1630 | 92.18 | 19.55 | 0.00 | 0.00 | | 1630 | 20.35 | 11.74 | 0.00 | 0.00 |
| | 1642 | 76.01 | 17.89 | 145.75 | 2.99 | | 1642 | 33.71 | 13.22 | 0.00 | 0.00 |
| | 1701 | 37.76 | 14.42 | 0.00 | 0.00 | | 1701 | 35.32 | 13.59 | 64.28 | 2.67 |
| 3 | 1545 | 45.22 | 15.76 | 0.00 | 0.00 | 8 | 1545 | 34.49 | 14.61 | 64.73 | 2.84 |
| | 1605 | 72.75 | 18.42 | 426.72 | 9.19 | | 1605 | 25.38 | 12.20 | 0.00 | 0.00 |
| | 1618 | 47.36 | 15.63 | 267.55 | 8.13 | | 1618 | 92.99 | 20.21 | 460.97 | 7.44 |
| | 1630 | 85.02 | 19.02 | 143.46 | 2.42 | | 1630 | 60.14 | 16.96 | 77.47 | 1.97 |
| | 1642 | 83.20 | 19.18 | 206.94 | 3.58 | | 1642 | 55.65 | 15.36 | 0.00 | 0.00 |
| | 1701 | 71.15 | 18.65 | 0.00 | 0.00 | | 1701 | 27.25 | 12.37 | 168.70 | 7.86 |
| 4 | 1545 | 87.72 | 19.91 | 404.65 | 6.81 | 9 | 1545 | 14.58 | 8.36 | 0.00 | 0.00 |
| | 1605 | 77.15 | 19.22 | 323.61 | 6.75 | | 1605 | 17.59 | 10.90 | 0.00 | 0.00 |
| | 1618 | 76.51 | 18.24 | 350.28 | 7.15 | | 1618 | 27.15 | 13.72 | 0.00 | 0.00 |
| | 1630 | 91.50 | 18.60 | 211.46 | 3.48 | | 1630 | 40.57 | 12.62 | 0.00 | 0.00 |
| | 1642 | 91.34 | 19.81 | 265.82 | 4.20 | | 1642 | 27.33 | 12.92 | 0.00 | 0.00 |
| | 1701 | 86.49 | 19.52 | 233.60 | 4.18 | | 1701 | 19.44 | 11.39 | 0.00 | 0.00 |
| 5 | 1545 | 89.06 | 19.50 | 407.31 | 7.13 | | | | | | |
| | 1605 | 85.11 | 18.94 | 381.28 | 6.59 | | | | | | |
| | 1618 | 91.24 | 19.41 | 401.03 | 6.51 | | | | | | |
| | 1630 | 88.23 | 19.17 | 181.17 | 3.09 | | | | | | |
| | 1642 | 91.66 | 19.45 | 229.55 | 3.50 | | | | | | |
| | 1701 | 73.43 | 17.22 | 230.60 | 4.69 | | | | | | |

Based on the collected data, calculations are graphically presented as Figure 4.15. Drawing has two independent curves, one for S/T and P/T running simultaneously (black dots) and second one for S/T running alone (red dots).

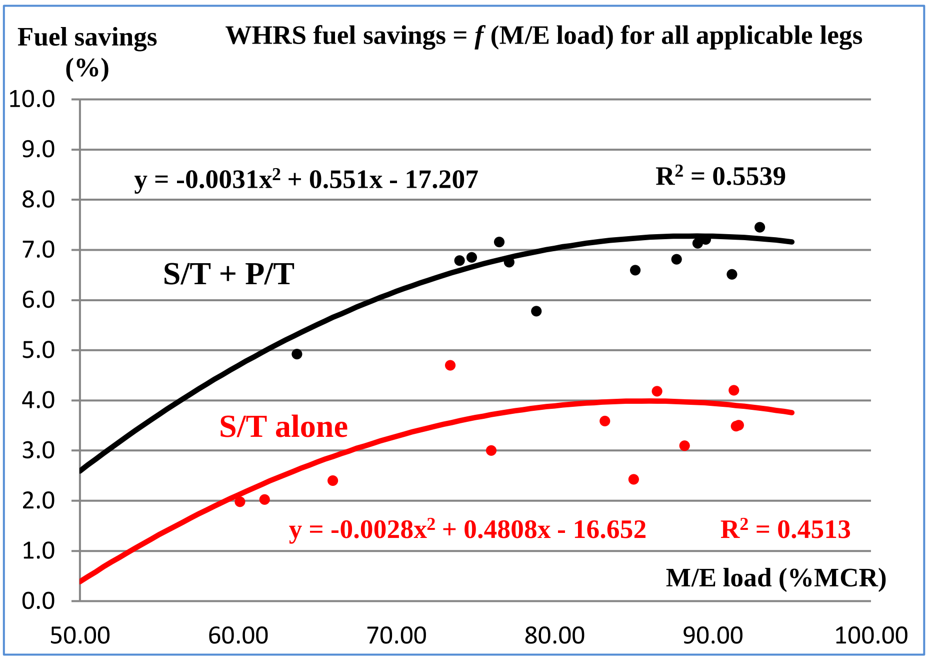


**Figure 4. 15:** Comparison of WHRS fuel savings with high M/E load (≥ 50% MCR) and different mode of operation

From the Figure 4.15 can be observed, that fuel savings (electrical power produced by T/G compared with same power to be produced by A/Es) are having decreasing trend after crossing 88% MCR of M/E. It is caused by main EGE safeguards, which are opening secondary exhaust gas by-pass in order to protect main exhaust gas economizer from increasing thermal stresses, thus causing minor decrease in steam production.

The reason why the Figure 4.15 is divided into two parts is that during time period of data collection (1.5 year), power turbine become inoperable (beginning of voyage 1630). In order to be able to present reliable data and its analysis, the division into two separate curves was necessary.

From the view point of ship's owner and operator relationship between potential fuel savings, while using WHRS, and ship's speed was established. It is presented in this thesis only as a theoretical relationship with curve, which should help ship owner and operator in estimation of transportation costs and possible fuel savings. The relationship is presented on Figure 4.16.

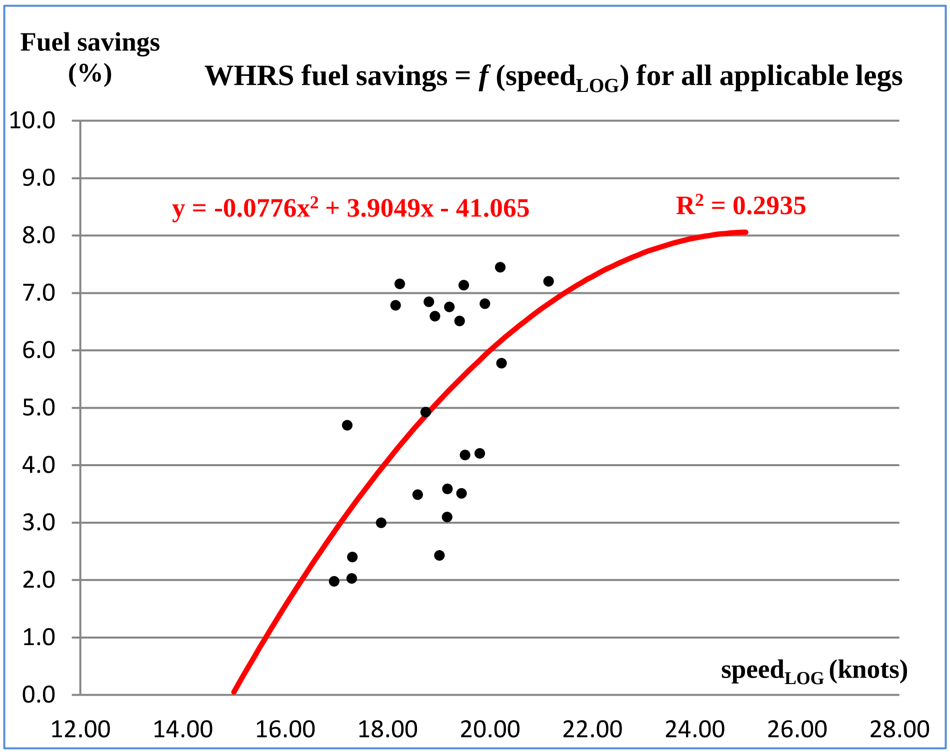


**Figure 4. 16:** WHRS fuel savings with high M/E load (≥ 50% MCR) for ship’s plausible speeds

## 4.4 Possible modifications of WHRS operational profiles to increase energy efficiency

Practically WHRS is to be used for electrical power generation at M/E loads over 50% MCR. Beneath that load it can be used for heating steam generation. In order to increase energy efficiency, shaft generator (S/G) is installed on board case ship. Shaft generator can be engaged for electrical power generation at more than 42 RPM of M/E (approximately ≥ 25% MCR of M/E).

Analogically to section 4.3, selection of collected data from case ship is presented in Table 4.13. Complete database is presented in excel file as Appendix II. Calculations of fuel savings obtained by usage of T/G and S/G to produce electrical power in kg/h and as percentage compared towards ships total fuel consumption per hour per relevant legs are presented in Table 4.13 as well. All fuel savings of T/G electrical power generation are calculated relative to A/Es electrical power generation fuel consumption and all fuel savings of S/G electrical power generation are calculated as a difference between M/E electrical power generation fuel consumption and A/Es electrical power generation fuel consumption (difference between M/E SFOC and A/Es SFOC). Data taken under consideration are from voyages and legs where WHRS and S/G were running in parallel. S/G in PTO mode. M/E ISO SFOC for each leg in each voyage is calculated in complete database. A/Es ISO SFOC @ 50% MCR is 214.615 g/kWh.

**Table 4. 13:** Case ship collected data and WHRS modes with S/G, increase of energy efficiency calculations

| Leg | Voy. no. | M/E load | S/G savings | T/G savings | S/G + T/G savings | Leg | Voy. no. | M/E load | S/G savings | T/G savings | S/G + T/G savings |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [-] | [-] | [%MCR] | [%] | [%] | [%] | [-] | [-] | [%MCR] | [%] | [%] | [%] |
| 1 | 1545 | 38.69 | 3.04 | 0.00 | 3.04 | 6 | 1545 | 53.87 | 3.22 | 0.00 | 3.22 |
|  | 1605 | 78.86 | 0.23 | 5.77 | 6.00 |  | 1605 | 43.11 | 3.22 | 0.00 | 3.22 |
|  | 1618 | 43.25 | 2.07 | 2.65 | 4.72 |  | 1618 | 74.00 | 0.42 | 6.78 | 7.21 |
|  | 1630 | 71.83 | 0.00 | 0.00 | 0.00 |  | 1630 | 61.69 | 2.34 | 2.02 | 4.36 |
|  | 1642 | 65.35 | 1.59 | 0.00 | 1.59 |  | 1642 | 36.03 | 4.69 | 0.00 | 4.69 |
|  | 1701 | 65.28 | 0.00 | 0.00 | 0.00 |  | 1701 | 66.00 | 1.70 | 2.40 | 4.09 |
| 2 | 1545 | 63.73 | 0.77 | 4.92 | 5.69 | 7 | 1545 | 39.20 | 2.48 | 6.13 | 8.61 |
|  | 1605 | 89.58 | 0.04 | 7.20 | 7.24 |  | 1605 | 27.02 | 2.81 | 10.48 | 13.30 |
|  | 1618 | 74.79 | 0.39 | 6.84 | 7.23 |  | 1618 |  |  |  |  |
|  | 1630 | 92.18 | 0.00 | 0.00 | 0.00 |  | 1630 | 20.35 | 4.41 | 0.00 | 4.41 |
|  | 1642 | 76.01 | 0.51 | 2.99 | 3.51 |  | 1642 | 33.71 | 4.14 | 0.00 | 4.14 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1701 | 37.76 | 0.00 | 0.00 | 0.00 | | 1701 | 35.32 | 3.75 | 2.67 | 6.42 |
| 3 | 1545 | 45.22 | 1.63 | 0.00 | 1.63 | 8 | 1545 | 34.49 | 2.81 | 2.84 | 5.64 |
| | 1605 | 72.75 | 0.61 | 9.19 | 9.80 | | 1605 | 25.38 | 3.85 | 0.00 | 3.85 |
| | 1618 | 47.36 | 0.85 | 8.13 | 8.98 | | 1618 | 92.99 | 0.00 | 7.44 | 7.44 |
| | 1630 | 85.02 | 0.28 | 2.42 | 2.70 | | 1630 | 60.14 | 1.93 | 1.97 | 3.90 |
| | 1642 | 83.20 | 0.00 | 3.58 | 3.58 | | 1642 | 55.65 | 0.00 | 0.00 | 0.00 |
| | 1701 | 71.15 | 0.00 | 0.00 | 0.00 | | 1701 | 27.25 | 2.34 | 7.86 | 10.20 |
| 4 | 1545 | 87.72 | 0.12 | 6.81 | 6.92 | 9 | 1545 | 14.58 | 0.00 | 0.00 | 0.00 |
| | 1605 | 77.15 | 0.22 | 6.75 | 6.97 | | 1605 | 17.59 | 4.24 | 0.00 | 4.24 |
| | 1618 | 76.51 | 0.43 | 7.15 | 7.59 | | 1618 | 27.15 | 0.00 | 0.00 | 0.00 |
| | 1630 | 91.50 | 0.11 | 3.48 | 3.59 | | 1630 | 40.57 | 2.40 | 0.00 | 2.40 |
| | 1642 | 91.34 | 0.00 | 4.20 | 4.20 | | 1642 | 27.33 | 0.00 | 0.00 | 0.00 |
| | 1701 | 86.49 | 0.62 | 4.18 | 4.80 | | 1701 | 19.44 | 3.22 | 0.00 | 3.22 |
| 5 | 1545 | 89.06 | 0.09 | 7.13 | 7.22 | | | | | | |
| | 1605 | 85,11 | 0.04 | 6.59 | 6.63 | | | | | | |
| | 1618 | 91,24 | 0.03 | 6.51 | 6.54 | | | | | | |
| | 1630 | 88,23 | 0.00 | 3.09 | 3.09 | | | | | | |
| | 1642 | 91,66 | 0.00 | 3.50 | 3.50 | | | | | | |
| | 1701 | 73.43 | 0.20 | 4.69 | 4.89 | | | | | | |

Based on the collected data. calculations are graphically presented as Figures 4.17 and 4.18. Each of the graphical representation is consisting of three curves – STG alone (in figures presented by black color) and S/G PTO alone (in figures presented in red color) fuel savings curves as a function of M/E load and third curve is a geometric sum of both (in figures presented in blue color).

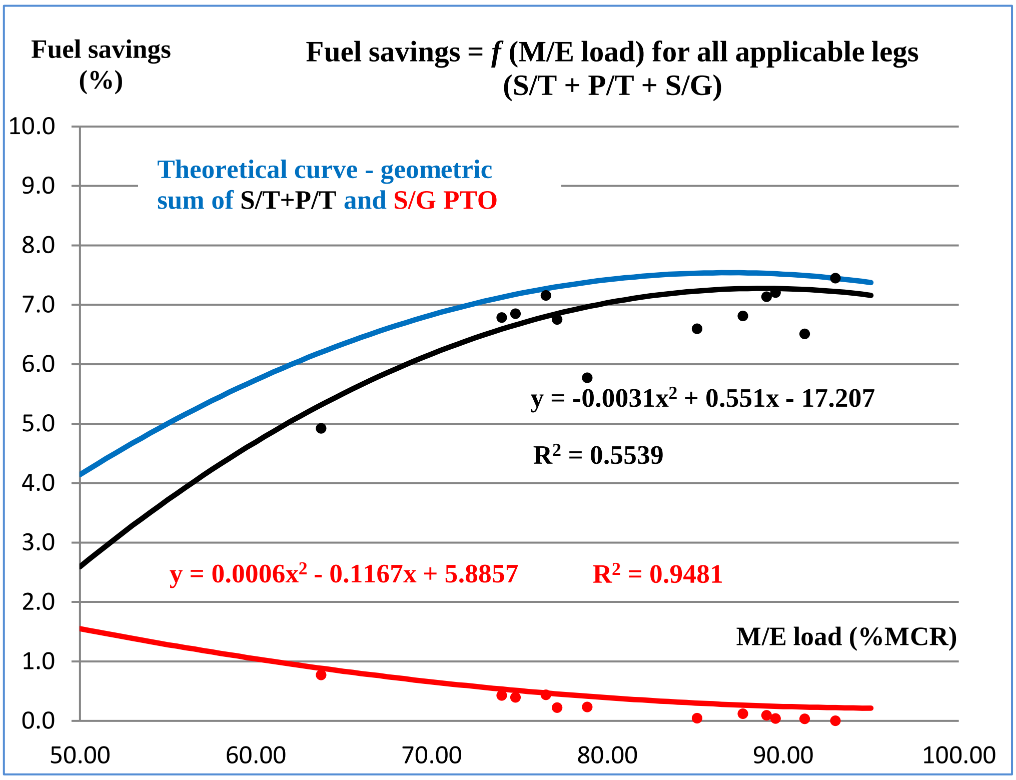


**Figure 4. 17:** Comparison of WHRS fuel savings dependent on mode of operation (S/T + P/T and S/G) and M/E load

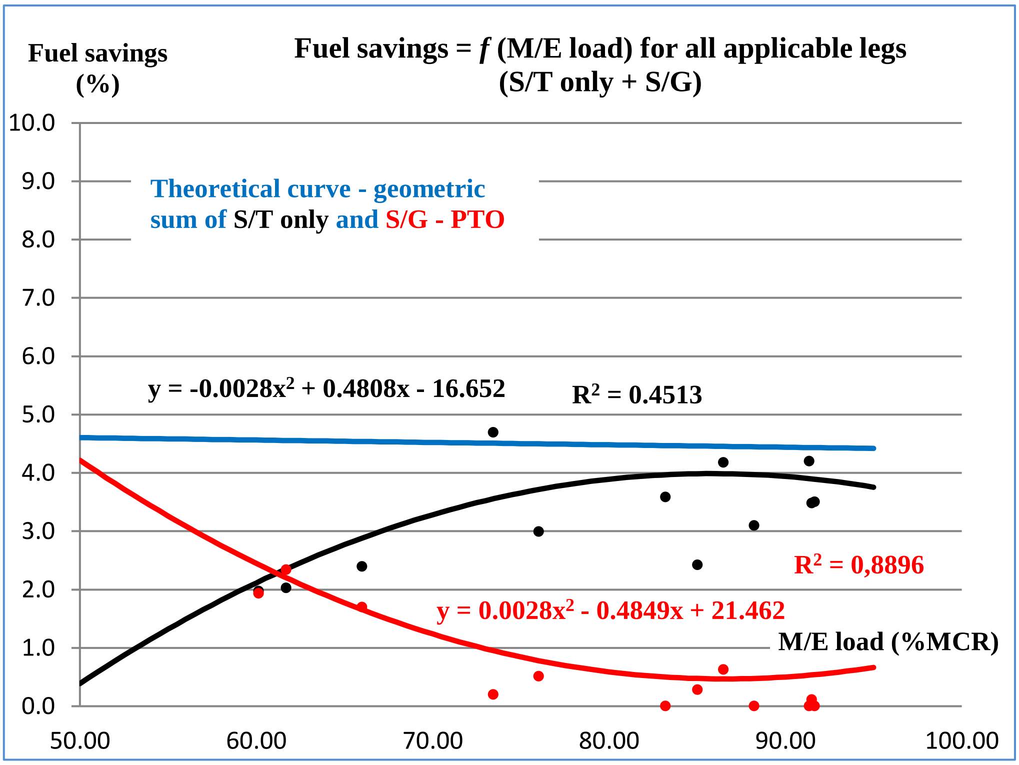


**Figure 4. 18:** Comparison of WHRS fuel savings dependent on mode of operation (S/T and S/G) and M/E load

When analyzing Figures 4.17 and 4.18 major difference between both theoretical curves (in figures presented in blue color). The difference is in using or not using power turbine. As mentioned above, the power turbine was damaged after first three voyages and was not in operation during last three voyages.

Whilst using STG as steam turbine with power turbine supported by shaft generator in PTO mode, the fuel savings were reaching up to 7.5% of total fuel consumption (Figure 4.17). Comparing to the situation when using STG as steam turbine only supported by shaft generator in PTO mode, the fuel savings were reaching up to 4.6% only (Figure 4.18). The difference in fuel savings, which was caused by usage of power turbine, was 2.9%.

This is giving ship owner / operator solid information whether to, in this case, arrange for repair of mentioned power turbine, or simply leave it as it is – in nonfunctional condition. The potential increase by 2.9% in fuel savings should be strong enough motivator to proceed with repairs as soon as possible. For simple calculation leg 4 in voyage 1642 should be presentable. Total consumption of fuel (ISO) per the leg was 1540.31 metric tons. According to above presented figures, if the power turbine would have been used, the fuel savings could have been 44.66 mt of fuel. As to translation to financial benefits, at average price (from May 2017) of 280 US$ per mt of FO, the potential savings could have been 12500 US$ per that particular voyage.

# 5 Principal findings and conclusions

## Attained EEI and GHG emission reduction

The comparison between required and attained EEDI of case ship (detailed description in section 2.1) is implying that the ship has been constructed as "green". The required EEDI value is 15.888 $g_{(CO2)}/t\cdot nm$ and attained EEDI value is 6.309 $g_{(CO2)}/t\cdot nm$. From those figures can be concluded that ship has GHG reduction potential, in numbers by almost 60% compared to legally required. Next step, which was applied by ship owners, is introduction of dual fuel engines and boilers. All engines and oil fire boilers on board case ship are LNG ready. Upon changing over to LNG fuel, the reduction of GHG will be even larger than it is already in present.

The parameter which has influence over generation of GHG is fuel consumption. Decreased fuel consumption means decreased GHG generation. One of the steps how to achieve decreased fuel consumption (beside speed reduction) is installation of WHRS. On board case ship two WHR subsystems are installed – main and auxiliary (both described in detail in section 3.3). Installation of WHRS saves fuel of heating steam production and in case of main WHR subsystem also in addition to heating steam production, fuel of electrical power production as well.

Analysis of EEOI for different legs of different voyages provided several interesting conclusions (section 4.1). E.g. the higher the mass of cargo, the more reliable EEOI values grouped tightly together are observed (Figure 4.4 and 4.5). The less cargo carried on board, the EEOI values are more scattered (e.g. Figure 4.9).

Analysis of EEOI for all recorded legs and voyages provided very conclusive results. Analyzing figure 4.10, the exponential regression based curve for all legs and voyages lies below required EEDI line (for all plausible DWT). Implication might be, even though case ship has only one value of required and attained EEDI (based on ships DWT), that energy efficiency and GHG reduction potential is very high.

Analysis of case ship collected data and calculated EEOI for pre-determined period of time is conclusively proving that attained energy efficiency is very good and thus potential for GHG reduction analogically is very high. Majorly further reduction of GHG and increase in energy efficiency (within technical limits of case ship) depends on chosen ship's operational profile by ship owner / operator and ship's command (vastly based on nautical conditions).

## Possible impacts of WHRS on vessel's design and safety

As described in detail in section 3.2 of this work, in fact, two WHR subsystems are installed on board case ship. Both comprises of source of waste heat (heat machine – engine) and heat utilization equipment, in both cases the equipment is economizer (exhaust boiler). Such equipment as exhaust gas boiler requires space on board, usually in engine casing or funnel area. Designer of the vessel must predict the spatial requirements in the phase of project and must consult with ship owner and equipment maker in order to establish the future spatial needs of such equipment. As any boiler, exhaust gas economizer is pressurized equipment and as such, it must be constructed according relevant norms and regulations, supervised, verified and tested according adopted procedures.

Next item which ship's designer must take under consideration is auxiliary equipment which is to operate and support WHRS which is designated as auxiliary WHR subsystem – for heating steam generation only:

- feed water and steam pipelines,
- circulation equipment, most often pumps where forced circulation is predicted,
- automation and electrical connections, cables and their electrical insulation,
- thermal insulation of water, steam and exhaust pipes,
- safeguards, such as boiler safety valves, assorted interlocks preventing "dry run" of boilers,
- supervisory equipment, such as thermometers, pressure gauges, etc.

As to the main WHR subsystem goes, in addition to above mentioned auxiliary equipment, additional systems are required, because of installed turbo generating set as an element which transforms waste heat energy to electrical energy. Additional auxiliary equipment can be:

- all necessary systems operating turbo generating set – lube oil pumps, cooling systems, valves, advanced automation, etc.
- safeguards and interlocks
- reliable communication system between M/E, main EGE, T/G set, power management system and ship's supervisory system

In regards to the vessel's safety, installation of WHRS is not a large obstacle, as to the applying new safety features or additional safety systems. Almost all components of main and auxiliary WHR subsystem are already covered from the design and safety side and similar equipment is in some degree already installed on board – boilers, pumps, pipelines, electrical cables, automation, etc.

The largest challenge, from the view point of ship's safety and WHRS, is turbo generating set. This equipment is not yet installed on board and requires improved operational and maintenance procedures, which must be supplied from maker, together with ship's delivery. The T/G set has installed multiple safety features, safeguards and interlocks already from maker, however improper operation can render these safety items inoperable, which might in future present itself as danger to personnel and property. Therefore, proper training of the operators has utmost importance in regards to ship's safety.

## Technical aspects of WHRS, maintenance and reliability

Construction of WHRS, main and auxiliary, with exception of turbo generating set, is very common and can be described as standard. Boilers, pumps, pipelines, electrical cables, automation etc. are from view point of technical aspects basic and unified with other equipment and elements on board. All technical aspects are described in detail in each relevant instruction manual and drawings.

As the challenging aspect, turbo generating set might be presented. This particular T/G set comprises of several shafts, each with different rotational speed, two turbines – one steam and other exhaust gas, two reduction gears, one clutch and one generator. All of these components must be selected and assembled with high precision. All applicable standards, procedures and legislation must be strictly followed during design and construction stage. Assembled machinery must be then verified, tested and approved.

Auxiliary WHR subsystem, from view point of maintenance and reliability, can be considered as extremely reliable and virtually maintenance free. In regular intervals the exhaust side of economizers must be cleaned, pumps must be inspected and boiler safety features must be inspected, tested and verified for functionality.

Main WHR subsystem, from view point of reliability can be considered highly reliable. Minor issues with economizer and turbo generating set are to be expected. The most troubled part of main WHR subsystem was identified on board case ship as power turbine and its inlet exhaust gas piping (from M/E exhaust gas receiver to P/T inlet valves). Troubles were caused by humidity reacting with sulphuric sediments inside piping, creating sulphuric acid. This acid then inflicted damage to gaskets and expansion bellows (corrosion).

Also, it has created issues with movability of P/T inlet valves as they were stuck in closed position without possibility of operating them, thus rendering power turbine inoperable.

Main WHR subsystem, from view point of maintenance, can be considered low maintenance demanding. Except minor issues with P/T (described above), standard maintenance works on exhaust gas boiler and steam system in regular intervals can be expected, such as:

- main EGE exhaust side cleaning,
- soot blowers inspection and maintenance,
- safety features inspection and functional checks,
- occasional inspection of HP and LP drums internal condition.

Turbo generating set, from view point of maintenance, can be considered minor maintenance demanding. Inspections in regular intervals are to be carried out in accordance with maker's recommendations and continuous monitoring of operational parameters is to be established. The most maintenance demanding element is power turbine, which during operation requires regular dry cleaning of turbine rotor.

## General recommendations

### Verification and confirmation of T/G set theoretical output curve presented by its maker as function of M/E load

T/G set theoretical output curves are presented in figures 3.20, 3.21 and 3.22 – for ISO, tropical and winter conditions. The theoretical curves are presented as steam turbine plus power turbine and steam turbine alone. Analogically the characteristic from case ship's recorded logs has been created and is presented on Figure 5.1 (S/T + P/T are presented in black color and S/T alone in red color).

From comparison between theoretical curves and real curves build upon data from recorded logs, conclusion can be made, that turbo generating set reaches physically during ship's operation values which can be placed between theoretical curves for winter and ISO conditions. The tropical conditions curves have not been reached during ship's operation.

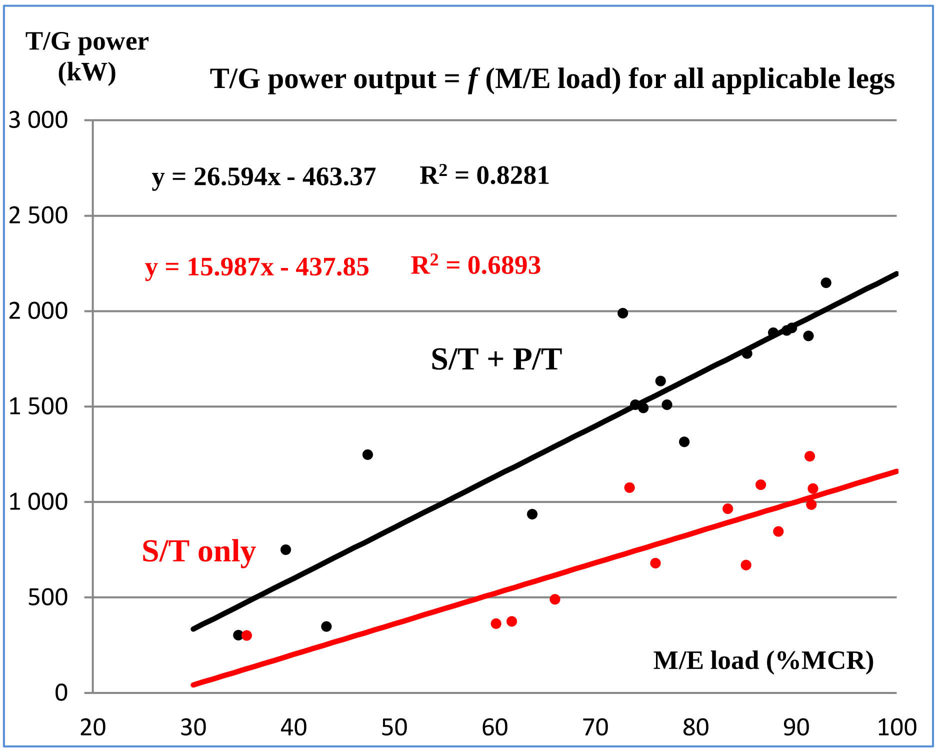


**Figure 4. 19:** Effective T/G output dependent to M/E load and different means of propulsions (S/T + P/T and S/T alone)

### Loading conditions (cargo weight) influence on ship's EEOI as function of its speed, suggestions for increasing energy efficiency during different loading conditions

Attained curves – EEOI as function of ship's speed has been divided into three segments based on ship's loaded conditions (figures 4.12, 4.13 and 4.14):

- more than 75% DWT,
- 50% ÷ 75% DWT,
- up to 50% DWT.

Each of mentioned loading conditions has characteristic shape and function. Whilst ship is loaded more than 75% DWT, the grouping of attained EEOI points is very close and it can be observed that with increasing speed, EEOI increases as well. Similar shape has characteristic for loading condition between 50% and 75% DWT, although grouping of calculated EEOI points is more scattered and EEOI values are higher.

The most interesting is characteristic for loading condition of less than 50% DWT – this curve has opposite progress than above functions. With increasing speed, EEOI decreases (whilst loading condition of less than 50% DWT).

From presented data (Figure 4.12) conclusion can be made that lowest EEOI was achieved when ship was loaded more than 75% DWT and sailing with speed around 13.2 knots. This can be verified using summarizing Figure 4.11. However theoretical exponential regression based curve is to be considered as strictly theoretical and informative.

### WHRS influence on fuel savings as a function of ship's speed

This can be presented on Figure 4.15 – WHRS fuel savings as function of ship's speed. From the curve can be observed that from certain point (around 15 knots), whilst using WHRS, fuel savings are increasing almost up to the point, where the case ship is reaching maximum designed speed. So, the ship owner / operator can estimate based on presented data, the fuel savings on legs, where WHRS will be in operation. Amount of fuel savings also depends on nautical conditions, weather conditions and loading conditions, however as strictly informative, the curve can give certain input and provide guidance.

### Possible modifications of WHRS operational profiles and theirs influence on fuel savings as a function of M/E load

Possible modifications of WHRS operational profile, including utilization of shaft generator are graphically presented in Figures 4.17 and 4.18. Major difference between both theoretical curves (in figures presented in blue color) can be observed. The difference is in using or not using power turbine.

Whilst using T/G set as steam turbine with power turbine supported by shaft generator in PTO mode, the fuel savings were reaching up to 7.5% of total fuel consumption (Figure 4.17). Comparing to the situation when using T/G set as steam turbine only supported by shaft generator in PTO mode, the fuel savings were reaching up to 4.6% only (Figure 4.18).

The difference in fuel savings, which was caused by usage of power turbine, was 2.9%.

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# List of Figures

# List of Tables