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FROM ENERGY FLOWS TO MONETARY FLOWS – AN INNOVATIVE WAY OF ASSESSING SHIP PERFORMANCES THROUGH THERMO-ECONOMIC ANALYSIS

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ABSTRACT
Recent events concerning world economy, environmental policies and resources depletion have grown a large interest in the matter of reducing energy consumption. Unfortunately, even if several cost-effective measures could bring to sensible reductions in fuel consumption, shipping industry is often much reluctant to act in this direction.
It is in the opinion of the authors, based on recent studies on the subject (Johnson, 2012),(Johnson, 2011), that a primary reason for this behavior lays in the lack of clear and effective tools for including these matters in the decision making processes. Therefore, the aim of this paper is to propose a new and innovative methodology for improving communication between technical and management departments of a shipping company when dealing with ship fuel consumption analysis. This will be done by making use of Sankey diagrams as graphical support and by converting energy flows to monetary flows, thus showing how energy is being used by different components or wasted to the environment in a much tangible manner. A case study will be presented in order to support the analysis with numerical values.

Key Words: Energy Efficiency, Sankey, Shipping, Energy Audit, Energy Review

1. INTRODUCTION

Focus on the emissions of greenhouse gases have been growing sharply during last years. The awareness of the looming danger to the environment caused by two centuries of exploitation of fossil fuels, together with the upcoming depletion of these same resources, raised a growing interest in methods and technologies for reducing the environmental impact of current society (Houghton et al., 1990), (Bentley, 2002).

Among all different sectors affected by this process shipping has been left apart for years, due to its high fuel efficiency and relatively low contribution to global emissions, as respectively shown in Figure 1 and Figure 2. However, seaborne trade volumes have been growing sharply in past years and are expected to follow this trend in the future. The impact of such a scenario on global CO2 emissions is shown in Figure 3. Even if the expected global emission trend largely depends on the scenario, as described by Buhag et al., none of the proposed trends shows a decrease or even a stabilization of CO2 emissions

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from shipping (Buhaug et al., 2009).

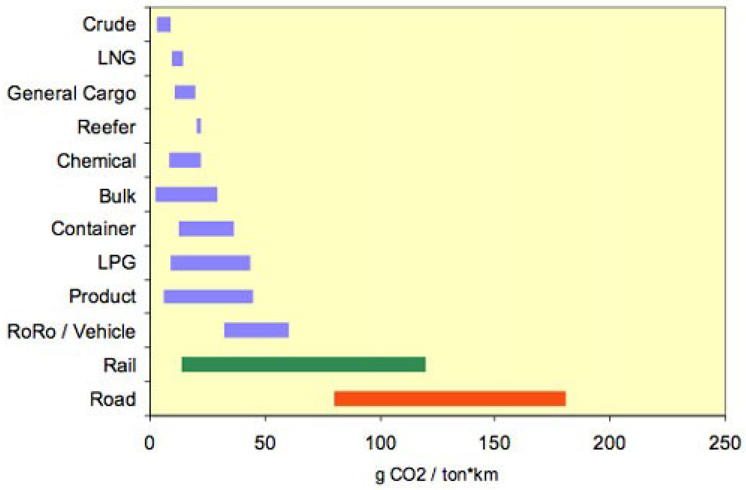

Figure 1: Range of typical CO_2 efficiencies for various cargo carriers (Buhaug et al., 2009)

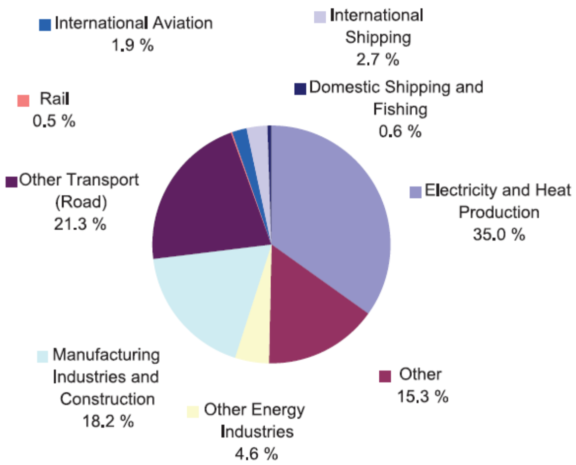

Figure 2: Contribution from different sectors to global CO_2 emissions (Buhaug et al., 2009)

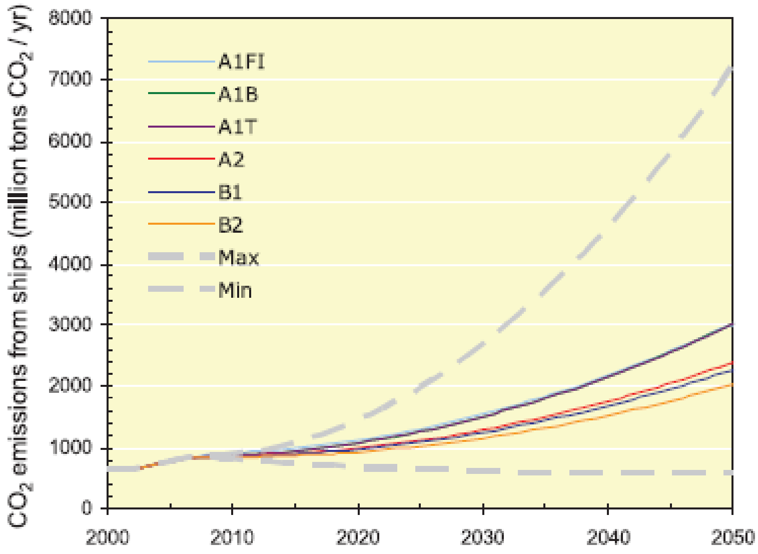

Figure 3: Expected global emissions trend (Buhaug et al., 2009)

Coming regulations on sulphur emissions, as well as expected political actions on other pollutants and greenhouse gases (GHG), together with concerns about fuel availability (Kjärstad and Johnsson, 2009) (Tsoskounoglou et al., 2008), will lead to a sharp increase in fuel costs for shipowners. Despite its mentioned high transportation efficiency, the potential for savings of greenhouse gas emissions in the international fleet is high. Buhag et al. (Buhaug et al., 2009) estimate this potential being in the range of 25% to 75%, while Eide et al.(Eide et al., 2009) get to an estimation of the same potential being of above 50% with the implementation of cost effective measures alone. However, as it has been demonstrated in dedicated research (Johnson, 2011),(Johnson, 2012), (Veenstra and Ludema, 2006), several barriers exist that prevent the introduction of a number of both technological and operational measures that would significantly decrease fuel consumption.

For various reasons, in fact, the shipping industry has until now seen few incentives to either build energy efficient ships or strive to operate existing ships in an energy effective manner. Even if this behavior has been historically connected to low fuel prices, this could not be regarded as the only explanation, especially since prices have been growing fast in the last decade. Shipping is an old, global and conservative industry characterized by fragmentation, global competition and high capital intensity (Stopford, 2009). In most segments the vessel types and sizes have been standardized leading to low differentiation in customer proposals (Veenstra and Ludema, 2006). Entry barriers for new capacity are very low leading to a very cyclical business. Most ship-owners see their vessels more as assets rather than production means with little focus on life cycle cost analysis. The shipbuilding industry is also quite fragmented where the competition is based more on price and delivery capacity rather than product qualities and guarantees. Few shipyards invest in product development, and they should be compared more to real estate construction firms rather than product firms such as truck manufacturers (Solesvik, 2007). In the latter case the industry is consolidated and considerable sums are invested in product development spread over a large number of delivered products with more or less life cycle guarantees.

Shipowners who want to invest into innovative and energy efficient vessels must therefore have the will, competence and resources to drive the development themselves. For the above reasons the development of new ships has stagnated and, even if a few promising cases of efficient design can be documented, most ships built today are based on traditional design concepts. Some improvements can be observed in single components, such as engines and propellers, but this does not apply to the ship as a whole system. Now the industry is struggling with overcapacity, too many ships have been built but unfortunately they also consume unnecessary much fuel.

Most shipping firms divide their cost structure into financial costs, daily operating cost and voyage costs. Since the shipping industry has to compete on prices, a lot of effort is put into reducing financial and daily cost. However, the voyage cost is mostly seen as consequential to the voyage and often covered by the customer, and the firm's governance of the voyage cost is therefore much weaker as compared to the financial and daily costs. This is despite the fact that the fuel bill alone is today mostly higher than the total daily costs. The typical ship owning firm has therefore spent until now little time and resources to monitor and control the energy use on board their ships.

In this scenario, the authors identified in the lack of communication between technical and management departments one of the issues that should be addressed. Johnson cites lack in knowledge of energy matters and absence of a systematic approach as two of the main barriers to energy efficiency in shipping (Johnson, 2011).

The objective of this paper is to propose a simple and easily understandable approach for the evaluation of ships energy performances to be used as a decision-making tool in the process of assessment and improvement of ships energy performances and as part of the implementation of energy management systems.

Two main tools will be used for this purpose: the Sankey diagram as graphic representation of results, and the conversion from energy to monetary flows as improvement in their comprehension.

2. METHODOLOGY

2.1. Graphic presentation: The Sankey diagram

The first tool to be used is connected to results graphic representation. When presenting the outcome of a survey process, it is extremely important to make the analysis be clear and easily accessible. For this reason the Sankey diagram will be hereafter introduced, and used in the continuation of the text.

Developed in the 19th century by the Irish engineer Riall Sankey, Sankey diagrams are used to provide an easy visualization of flow quantities in systems (Sankey, 1897). They put a visual emphasis on the major transfers or flows within a system, therefore helping in locating dominant contributions to an overall flow and in identifying inefficiencies (Schmidt, 2008). An example for a typical Sankey diagram of the energy flows in a marine Diesel engine is given in Figure 3

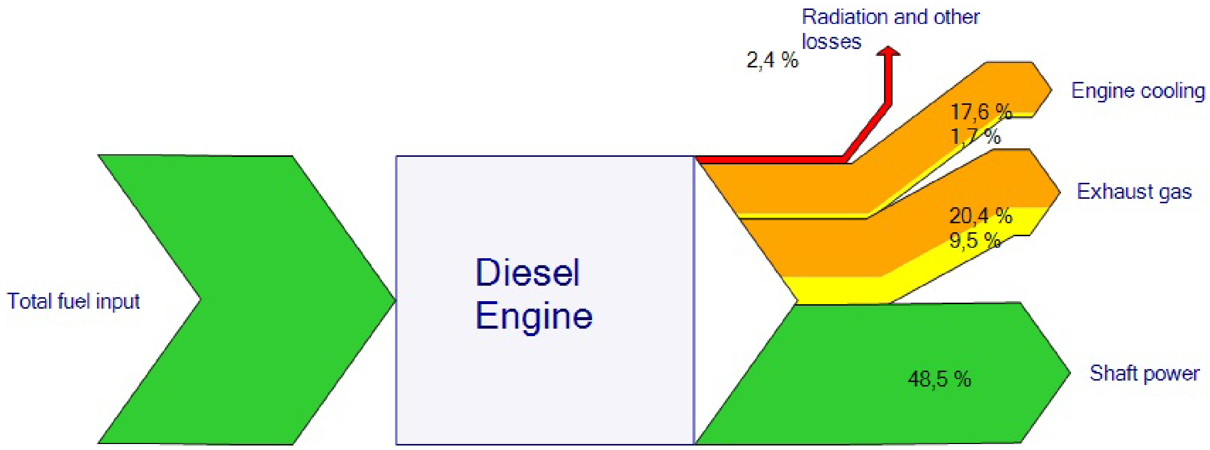

Figure 4: Example of a Sankey diagram for a Diesel engine

Here, as in all Sankey diagrams that will be used in the continuation of this work, a color legend was introduced for enhancing the visualization of energy quality. Four colors were used:

- **Useful energy: green -** Flow in the form of mechanical, electric, or chemical energy. Flows in the required form for their final use, such as steam for tank cleaning, are also included.
- **Recoverable wasted energy: yellow/orange** The part of the energy lost to the environment in form of theoretically recoverable heat. This part is further subdivided in two categories, according to stream's temperature: a larger yellow part of the arrow means higher temperature, and therefore higher quality waste heat[2], that is more easily to recover and that has a higher potential to produce additional mechanical or electrical power. This subdivision is used in order to have a faster and clearer visualization of which extent wasted flows can be reused yo
- **Unrecoverable wasted energy: red:** Energy lost to the environment and impossible to recover

2.2. Energy flows and monetary flows

In a scientific environment, energy balances are commonly used for studying machinery systems performances. However, when communicating outside the peculiarly scientific environment of physics, this analysis can becomes less appropriate; Joule and kWh are not intuitive units of measure, even for experienced scientists, and they lack the connection with the everyday life that makes tables and figures easy to interpret at a first glance.

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[2] In strictly scientific terms, the subdivision of a heat flow into two parts according to flow energy quality refers to the second law of thermodynamics and, more specifically, on the definition of exergy and anergy. The distinction between these two properties is a thermodynamic concept often applied when dealing with energy efficiency and heat recovery. Given a defined heat flow at a defined temperature, exergy is defined as the maximum fraction of the aforementioned flow that can theoretically be converted to work under ideal conditions. The remaining fraction of the original flow is then called anergy. Under specific assumptions, such as ideal gas behavior and constant specific heat values, exergy and anergy can be calculated for any given energy flow in the form of heat, and only depend on flow's temperature. This concept will not be further devolped, and more details on the subject can be find in dedicated literature (Moran and Sciubba, 1994).

For this reason, the concept of transforming energy flows to monetary flows will be explored in this paper. The use of a very intuitive and broadly used unit of measure, as US Dollars are, will make the interpretation of results to become much more direct and straight-forward.

This conversion will be performed based on the use of fuel thermal properties and prices, in close relationship with the broadly used technique of thermoeconomic analysis (Tsatsaronis, 1993). This procedure, involving the coupling between thermodynamics concepts and economic analysis for cost optimization, has often been used in several industrial sectors, such as CHP installations (Athanasovici et al., 2000).

Fuel energy content can be described by the Lower Heating Value (LHV), which identifies the amount of energy released after its complete combustion. Though it can vary sensibly between different fuels and even between different stocks of the same kind of fuel, a reference value of 40.7 MJ/kg (Bengtsson et al., 2011) will be used in the rest of the paper[3]. A reference price of 668 $/mt, representing the 25/01/2012 value for IFO 380 Rotterdam price, will be taken into account.

The first and main idea that comes after a conversion from energy to monetary flows is that of applying this concept to the evaluation of the potential earnings related to performance improvement in different parts of the ship. This number could then be used as a first estimation of the yearly savings needed for the calculation of the payback time of different actions and measures towards higher energy efficiency. However, in order to calculate the cost of the lost energy, we need to know how much fuel has been consumed to produce that amount of energy. The calculation of this value involves being aware of all the components located between the fuel inlet and the loss itself, and taking their efficiencies into account. This concept can easily be grasped intuitively, but it needs to be translated numerically.

For this reason, the choice of introducing a coefficient, here named “cascade factor”, was made. This value is obtained by reciprocating the product of the efficiencies of all the components located before a specific point on an energy flow. By using the cascade factor for losses at a specific location of the ship energy system it is always possible to calculate how much fuel would be saved thanks to an improvement applied to that specific component. Figure 5 and equation 1 give an example of cascade factor calculation. The application of this value is that if a 1 $ reduction in energy losses in a component located after the shaft can be achieved, they will turn out in a 2.09 $ reduction in fuel cost.

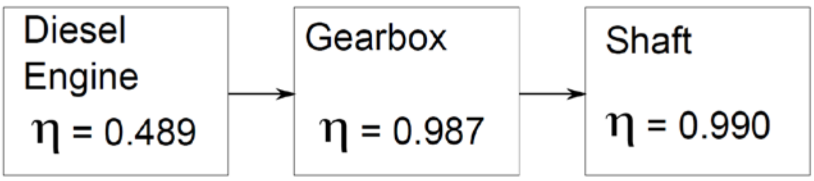

Figure 5: Example of cascade factor

$$C_f = \frac{1}{0.489 \cdot 0.998 \cdot 0.990} = 2.09 \quad (1)$$

2.3. Case study

Tools presented in the previous two sections are supposed to be applied to a specific ship

[3] The small oscillations of this value (generally ranging between 40 and 43 MJ/kg) are considered to be negligible for the sake of the study and will therefore be ignored.

or ship class on a well-defined time interval. Since the method presented is rather new and innovative, a case study will be hereafter introduced in order to give a practical demonstration on how the method can be employed in a specific case. However, for obvious reasons, numerical results from the presented analysis are relevant only for this specific ship. The analysis should therefore be considered as an application example rather than a presentation of relevant numerical results.
The case study ship will be a chemical tanker, whose main features are listed in table 1.

Table 1: Case study main features

Length	182.74 m
Width	32.18 m
Tonnage	46 764
Draft	12.18 m
Main engines rated power	2 x 3 840 kW
Auxiliary engines rated power	2 x 650 kW

A chemical tanker is normally characterized by rather low operating speed (around 14 knots) and by having propulsion as main energy consumer. A few elements constitute distinctive features for a chemical tanker in terms of energy use onboard: the heat use connected to tank cleaning and cargo heating, and the power needed by nitrogen compressors. For those variables and parameters for which a clear, definite value could not be derived from given measurements, realistic values will be applied according to literature in the subject.

2.4. Components categorization

There are several different systems on a ship involving the use and conversion of energy.
Even if from a scientific point of view it would only be correct to talk about energy conversion, for the sake of clarity components available on board will be subdivided in three main categories, according to their main function relating to energy use onboard.

1. **Energy producers:** In this group, components such as engines and boilers will be listed. All of them share the feature of performing the conversion from a non-directly usable form of energy (fuel, wind, radiation) to a usable one (work, electric power, heat).
2. **Energy transmitters and energy converters:** Under this category, components such as the shaft generator and the gearbox will be listed. These components share the feature of either physically allowing the use of some kind of energy in a different location from where it is produced, or converting energy between two different forms, such as from mechanical to electrical.
3. **Energy consumers:** Under this category, components such as the propeller, fans, pumps, and heaters will be found. All of them share the feature of using energy in order to perform a specific function (ship propulsion, ventilation, flow generation, heating) different from energy transmission or conversion. Components belonging to this category will be further subdivided in three sub-categories: main consumers, connected to propulsion, auxiliary power consumers, and auxiliary heat consumers.

For the case study under consideration, three main energy producers (1) will be taken into account:

I. **Main engines:** Case study ship is equipped with 2 medium speed 4-strokes engines, each one providing a maximum rated power of 3860 kW. They are mainly used for providing energy for the propulsion and less frequently for port operations.

II. **Auxiliary engines:** Case study ship is equipped with two auxiliary engines of 682 kW of design power. They are mainly used in port, where the main engine is shut down and, therefore, there is no more contribution from the shaft generator to electric power production.

III. **Boilers:** Case study ship is equipped with two auxiliary boilers designed for the production of 14 tons per hour of 14 bar steam. Their use is mostly connected to tank cleaning, where a very high amount of steam is needed for preparing the tank to accommodate the next cargo, and cargo heating, which is needed for some specific types of liquid cargoes that are too viscous at ambient temperature. Boiler energy can also be used for other purposes, such as accommodation heating and bunker heating, even if these heat requirements are usually lower[4].

Energy transmitters and converters (2) are connected to a ship's need to convert energy to the most convenient form and to transport it from one side to the other of the ship.

I. **Shaft generator:** The cast study ship is equipped with a shaft generator, converting a part of the mechanical energy produced by the main engine to electric power. Auxiliary engines are also provided with an analogue component.

II. **Gearbox:** The case study ship is equipped with a gearbox located between the engine and the propeller shaft. This component is required since the ship is equipped with a medium-speed engine, rotating at 600 rpm, while the propeller has an optimal rotating speed of around 100 rpm.

III. **Propeller shaft:** The propeller shaft is in itself a device for power transmission, from the gearbox to the propeller, with the associated friction losses.

IV. **Electric wires and switchboard:** Electric power is produced onboard in the engine room, while its consumption occurs on the whole ship. For this reason electric wires are needed for the transmission of such power, leading to losses that generally depend on the thickness of the wires, the amount of transmitted power, and the voltage of the grid. The switchboard also includes some power losses that should be taken into account in the overall balance.

Energy consumers (3) are subdivided in three main categories: propulsion, auxiliary power consumers, and auxiliary heat consumers.

I. **Propulsion:** The propeller is the component that transforms mechanical work coming from the engines to thrust, thus providing ship motion. Losses connected to an inefficient operation of the ship, including hull and propeller fouling, non-optimal trim and rudder, are gathered in an "operational inefficiencies" sub-category. Finally the external influence of waves, wind, and currents, is considered thorough a "sea margin" term. Propulsion is generally the main figure for energy consumption on board of a ship.

II. **Auxiliary power consumers:**

[4] The ship is also equipped with an exhaust gas boiler. However, no measured data are available of its yearly use, and it will be therefore ignored in the follow-up of the study. It is clear however that, not only in this case but for every kind of ship component, having complete information about its energy use and performance is of key importance for the application of the presented method.

- Cooling pumps: Fresh and sea water cooling pumps, mainly connected to main engine operations, constitute the major contribution to engine room power need.
- Nitrogen compressors: Even though they are not used in a continuous way, nitrogen compressors constitute a considerable part of ship power consumption. Installed power is of 280 kW.
- Other Engine Room consumers**:** Components in the engine room that do not belong to any of the previous two categories. The main components belonging to this category are the working air compressors, starting air compressors, fuel and lubricating oil separators, fuel and lubricating oil transfer pumps, and bilge treatment equipment (pumps, separators).
- Air conditioning provision plant: Components related to air conditioning: compressors and ventilators, fans, and electric heaters.
- Other electric power consumers: This category includes all components consuming electric power onboard which do not belong to any of the previous categories

III. **Auxiliary heat consumers:** non-electric consumption is mainly provided by the boiler and the exhaust gas boiler, and is mainly used for cargo heating and tank cleaning.

For all categories, systems to be considered highly depend on the ship taken into consideration and its operation pattern. For instance, nitrogen compressors are only significant in tankers, while they are not even installed in most of other ship types. This analysis should therefore be performed in a very case-dependent way.

3. EXAMPLE OF METHODOLOGY APPLICATION TO THE CASE STUDY

3.1 Sankey diagram application: identification of energy flows

In this section, the results from the energy analysis of the case study ship are shown. Sankey diagrams as well as pie charts will be employed for results visualization. Results from this case study should not be taken as a reference for the whole shipping sector: quantitative results will vary strongly on ship and on its operating conditions. The case study should be rather seen as an example of how the proposed method can be used for performing the energy analysis of a real ship.

The ship taken into consideration for the analysis is a chemical tanker sailing the whole year round between North, Central and South America. Figure 6 shows fuel consumption for one year of ship operations (excluding idling time and maintenance), averaged on data measured between November 2004 and December 2010. The overall fuel consumption is then subdivided according to ship operation (loaded legs, ballast legs, port operations). No distinction is made between heavy fuel oil (HFO) and Diesel oil (DO) consumption, since DO use is negligible compared to that of HFO.

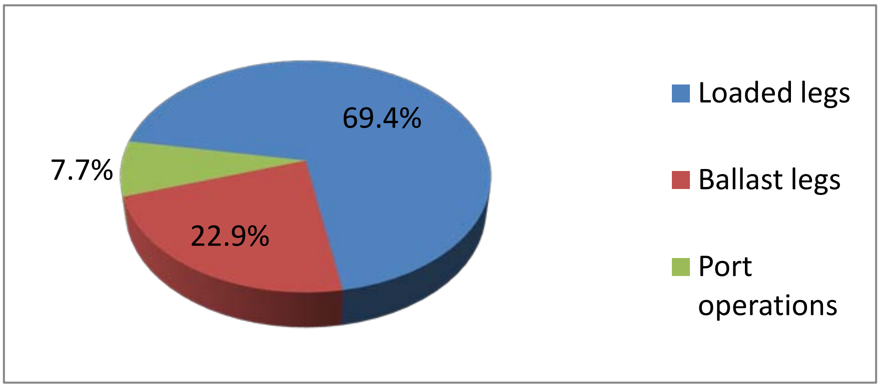

Figure 6: Yearly fuel consumption, subdivided by ship operational mode

Sailing operations account for around 92% of yearly energy consumption, making them the most interesting operative condition to study. It is clear indeed that introducing some major energy saving measures applicable while at sea would have the highest impact on overall fuel consumption. Moreover, any improvement coming from the voyage planning optimization, thus connected to the idea of reducing time spent in port, would increase the accountancy of loaded and ballast trips even more.

In order to get to the final aim of representing monetary flows, energy flows should be calculated first. This operation should be performed making use of available data, prioritizing those featuring the highest accuracy. In the presented analysis this is done according to assumptions on engines and boilers performances taken from direct measures on ship performances, from manufacturers' technical papers and from literature[5]. Main engine efficiency is taken from averaging data from noon-reports, while cooling, exhaust gas and radiation are calculated after rescaling the data available on main engine project guide; auxiliary engines efficiency is assumed according to (Heywood, 1988), where thermal losses are rescaled starting from values for the main engines; boiler efficiency is assumed after (Petersson, 2012).

The observation of figure 7 can lead to some interesting thoughts and conclusions. Percentage values are given for all losses, in order to increase the focus on where energy is wasted. It can be seen how the largest part of the energy use during sea passages is connected to the prime movers, which should therefore be the first focus for any kind of measure to improve the efficiency of energy use on board. Possible results from this observation are that measures such as engine maintenance and cleaning, performance monitoring, and fuel quality should be prioritized for maximizing efficient results, while efforts on auxiliary engines and boilers should be undertaken only in a second moment, given their low contribution to the overall fuel consumption. The fact that around 9% of the total fuel input could theoretically be recovered for the production of additional power from the exhaust gas alone (see yellow arrow for exhaust gas, Figure 7) should bring up to the discussion the possibility of the installation of systems for waste heat recovery (WHR). All this can be deducted from the Sankey diagram at a first glance, in a fast and clear way.

[5] Details on the calculation of results will not be presented here, since they do not represent the main purpose of this study and they are based on common knowledge.

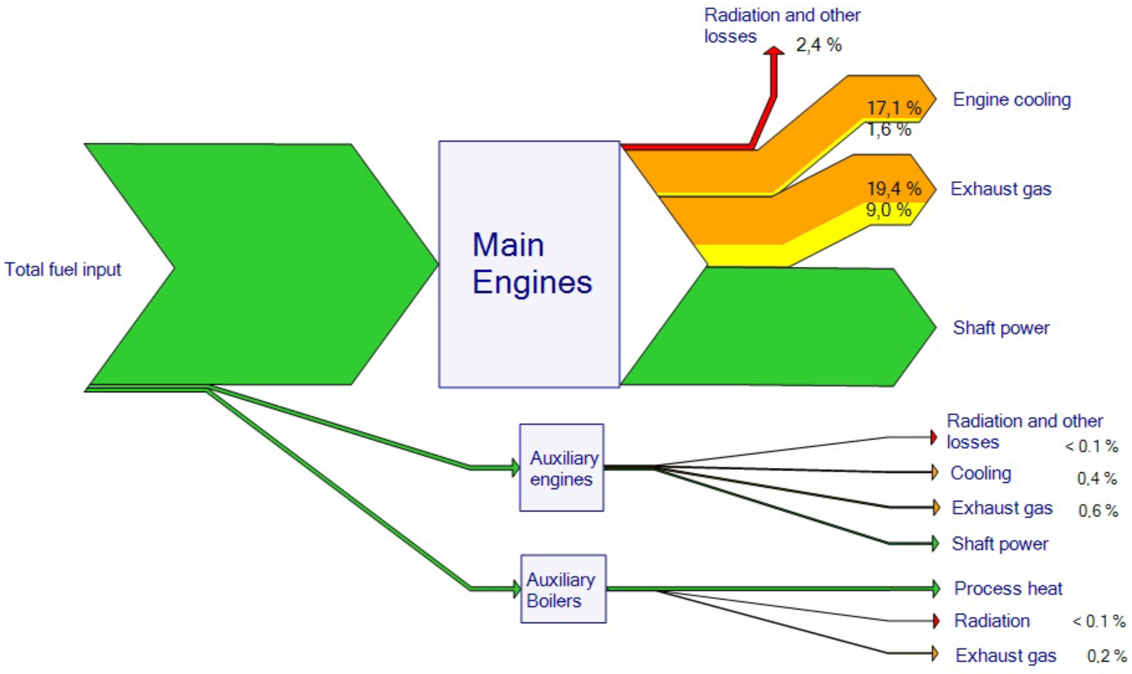

Figure 7: Sankey diagram for energy producers

In table 2 typical efficiencies for different transmission and conversion facilities are shown, taken from manufacturers (gearbox efficiency), from technical papers (shaft generators,(MAN)) or assumed according to literature (switchboard and shaft efficiencies,(Shi et al., 2010))[6].

In order to give a more easily understandable interpretation of these values, the amount of energy passing through these components is also shown, together with the correspondent energy losses. Efficiencies for these components, though being only assumed, are very well known parameters and inaccuracies are negligible.

Table 2: Efficiencies, energy flows and energy losses through main transmitters/converters

	Efficiency	**Energy flow**	**Energy Loss**	**Cascade factor**
	[%]	MWh	MWh	
Gearbox	98.7	29 914	389	2.05
Shaft	99	28 530	285	2.07
Shaft generator (ME)	92	1 384	111	2.05
Shaft generator (AE)	92	380	30	2.63
Switchboard	98	1 623	32	2.28
TOTAL	-		848	

6 A measure for the overall amount of power produced by the shaft generator was not available, thus a value had to be given as assumption. However, after a close observation of monthly reports coming from different ships belonging from the same class as the case study ship, it appears that 400 kW is the most common figure for shaft generator power production. This value, multiplied by the total amount of hours of shaft generator operations, provides a good assumption on the total amount of energy yearly flowing through this component. All main engine power flows through the gearbox, while the amount of energy being transferred to the shaft generator was deduced in order to get the energy flow through the propeller shaft.

Results shown in table 2 make it easy to understand that, even if these losses are rather small in percentage, they can become an important figure on the overall yearly operations. Yearly losses in the boilers, as a term of comparison, account for 123 MWh/year.

Energy transformers contribute, in percentage, only to a very small amount of the total energy flow on the ship, therefore making the Sankey diagram inappropriate for this kind of representation.

The energy consumption on board of the case study ship is composed by three main figures: propulsion, auxiliary electric power and auxiliary heat consumption.

The required power for propelling the ship is given by:

$$P_{prop} = P_{th} \left(1 + \varepsilon_{oi} + \varepsilon_{sm}\right) \tag{2}$$

Where P_{prop} is the required power for propulsion, P_{th} is the theoretical propulsive power needed in ideal conditions, ε_{oi} is the influence of operational inefficiencies and ε_{sm} is the sea margin, as defined in section 2.4.

Under these assumptions, P_{th} also includes propeller and hull efficiencies. Even if these two values are of primary importance for ship energy consumption, they are both hard to measure and difficult to improve. For this reason, the boundaries of both the thermodynamic and economic analysis will stop at shaft power. However, operational inefficiencies will be taken into account, since it represents losses that can be reduced with correct ship operations.

A value for sea margin of 15% is here used (MAN), even if precise measurements could help getting a clearer figure, while for the operational inefficiencies an hypothetical value of 10% was used. However for a correct use of this method, real measurements should be taken in order to give a better estimation and to separate different influences. Optimal trim test should be conducted, and trim should be recorded for every trip, while ship resistance should be accurately assessed and its operational measurements should be compared to baseline data. The issue of lack of investments in measurement systems in shipping is an old problem (Drinkwater, 1967), that has not been completely solved yet. Comparing the expected consumption from the sea trials to the actual one could be a good method to establish, with low effort and qualitative results, an operational value for the cumulated effect of operational inefficiencies and sea margin.

Under these assumptions, operational margin represents a remarkable energy loss, as shown in Figure 8, where percentages are referred to the total energy flow after the energy transformers. Since they are located after propeller and hull in the energy cascade, two reference values will be used for these efficiencies, respectively 66% and 98.6 % (Shi et al., 2010), in order to calculate the cascade factor for the final propulsive energy flow. This latter therefore results equal to 3.22.

It is easy to notice how large losses connected to the additional ship resistance here identified as “operational margin” are, corresponding to 7.5% of the energy used. Trim optimization, weather routing, and effective anti-fouling maintenance can lead to major improvements. These losses are located at the end of the energy cascade of ship’s energy system, making it clear that, if this specific aspect of ship maintenance was handled with needed care, large improvements in ship performances and fuel consumption could be achieved, as shown by the high cascade factor associated to these losses.

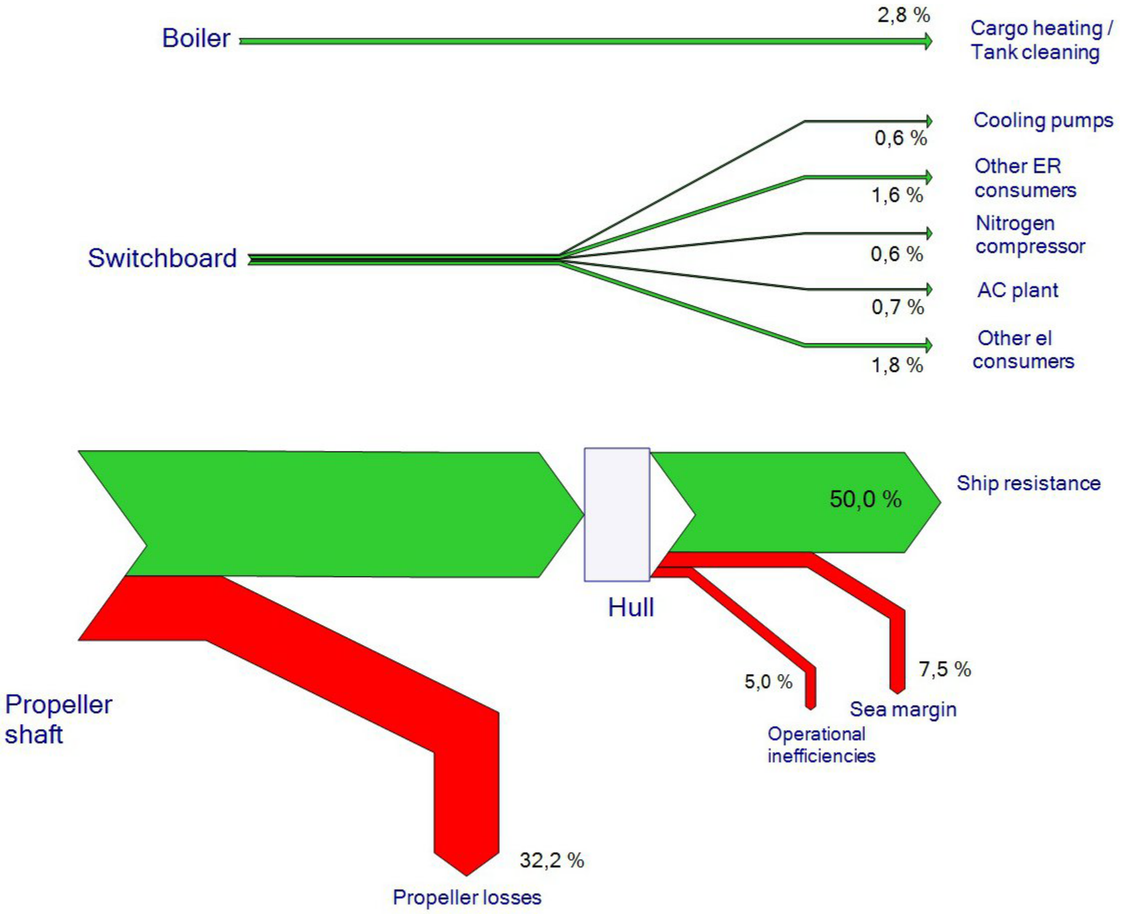

Figure 8: Sankey diagram for energy consumers

From the observation of the Sankey diagram showed in Figure 8, it can be noticed how the consumption for ship propulsion represents the most relevant figure for the case under study. This observation, which mainly depends on ship type, can again lead to interesting considerations. Propeller and hull polishing should be prioritized, as well as a correct optimization for the trim. On the other hand, efforts directed towards an increased efficiency in auxiliary energy consumption should be considered only in a second moment, given their low impact on overall energy consumption. Once again, this can be easily deducted from the observation of the Sankey diagram representation, which includes all the needed information to support the decision making process.

Finally, the Sankey diagram for the overall ship is showed in figure 9. This figure gives a summary of the energy flows of the ship as a whole, and connects the previous two figures. The observation of this diagram alone is sufficient for planning future decisions for interventions towards the increase of ship energy efficiency.

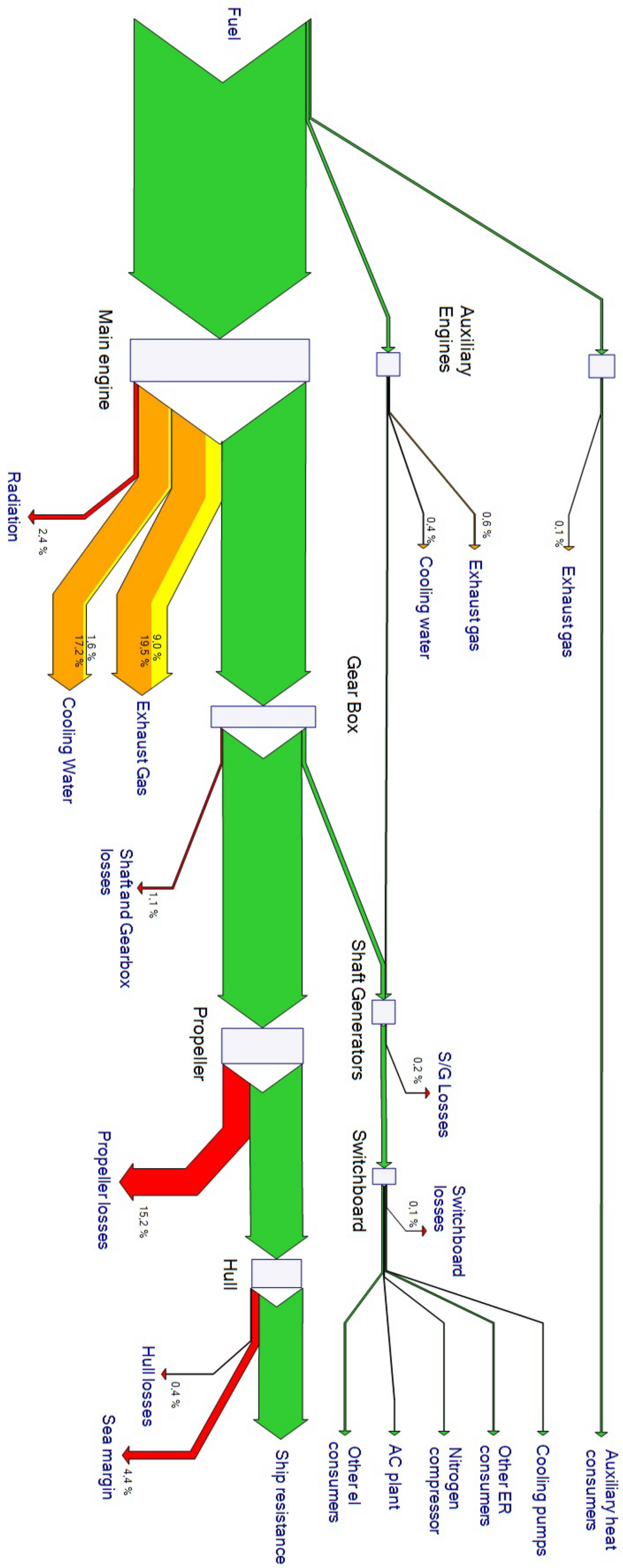

Figure 9: Sankey diagram for whole ship

3.2 Conversion from energy flows to monetary flows

In the previous section, a technical methodology for the evaluation of ships energy consumption has been introduced based on typically easily available measurements onboard. This section was introduced in order to give the reader the scientific basis on which the following part starts from, while having a clear supporting graphic representation based on the already mentioned Sankey diagram.

Up to this point, flows were estimated in terms of energy units. In this section, the application of the conversion from energy to monetary flows will be analyzed in order to give a clear understanding of how much money is spent for different ship functions. The cascade factors, as introduced in section 2.2, will be also introduced and taken into account in the analysis. Figure 10 shows the cascade factors for all previously mentioned components.

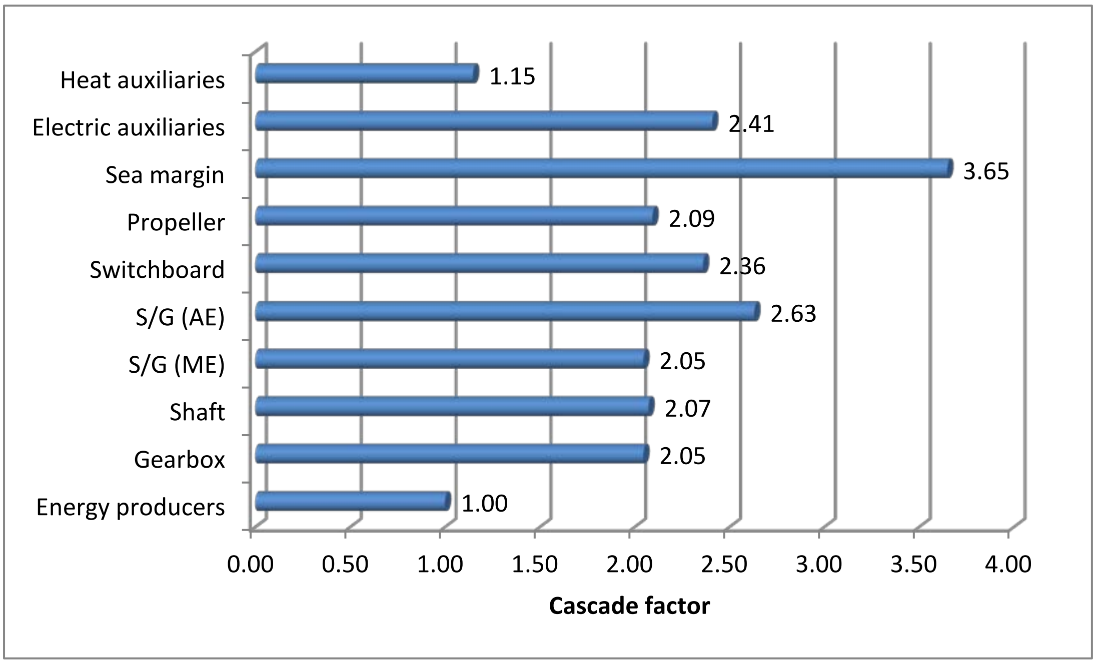

Figure 10: Cascade factors for considered ship components

In order to show the use of the conversion from energy to monetary flows, figures showing economic losses connected to different components onboard on a yearly-operation basis will be showed. All values take into consideration the cascade factor connected to each specific component, so that the loss that is showed in the figure represents the economic loss in fuel consumption.

Every year the selected ship, while at sea, consumes more than 3 M$ for fuel, which are almost entirely used by the primary main engines. In order to have a grasp on where this money goes Figure 11 gives a graphical representation of the result of the conversion from energy to monetary losses. From this figure the dimension of these concepts appears clear. For the case under study almost 1 million dollars of fuel energy is wasted through the exhaust gas, while around 600 000 $ are discharged into sea water cooling system. The conversion from energy to monetary flows can be useful, in this case, to put some more light on the size of the energy losses that take place in the engine and have an estimation of the savings compared to the capital cost of a certain measure. Investing money in engine tuning, whose benefits to engine efficiency are expected to be in the order of 1 g/kWh (MAN, 2009), would bring in this case to estimated savings of 18 000 $/year.

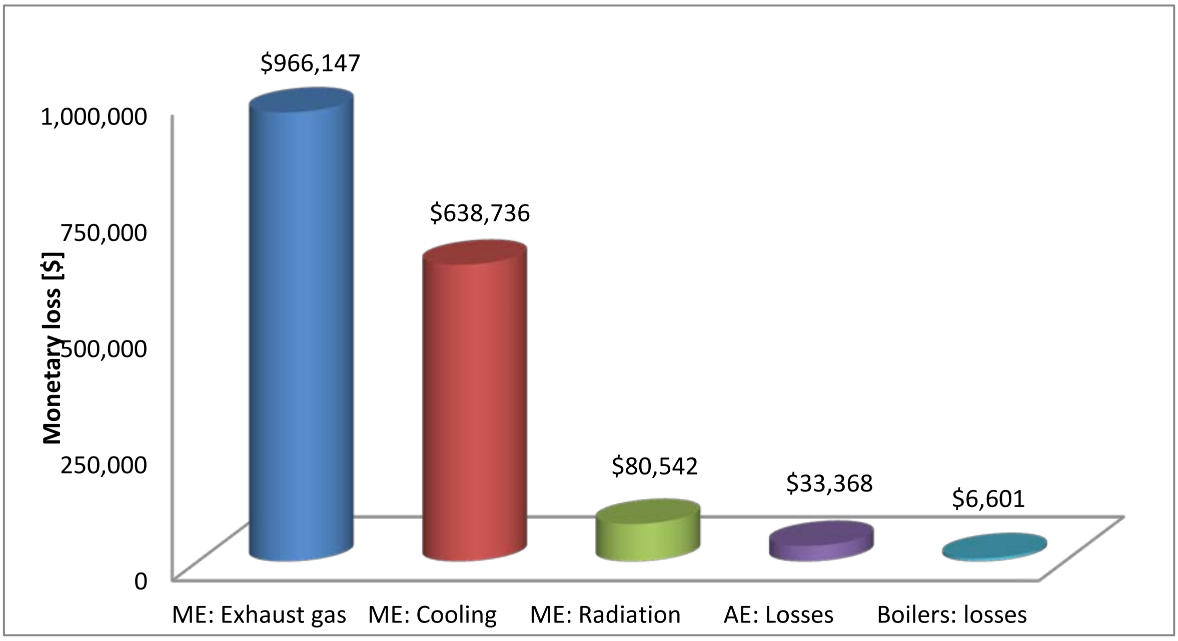

Figure 11: Monetary losses in energy producers

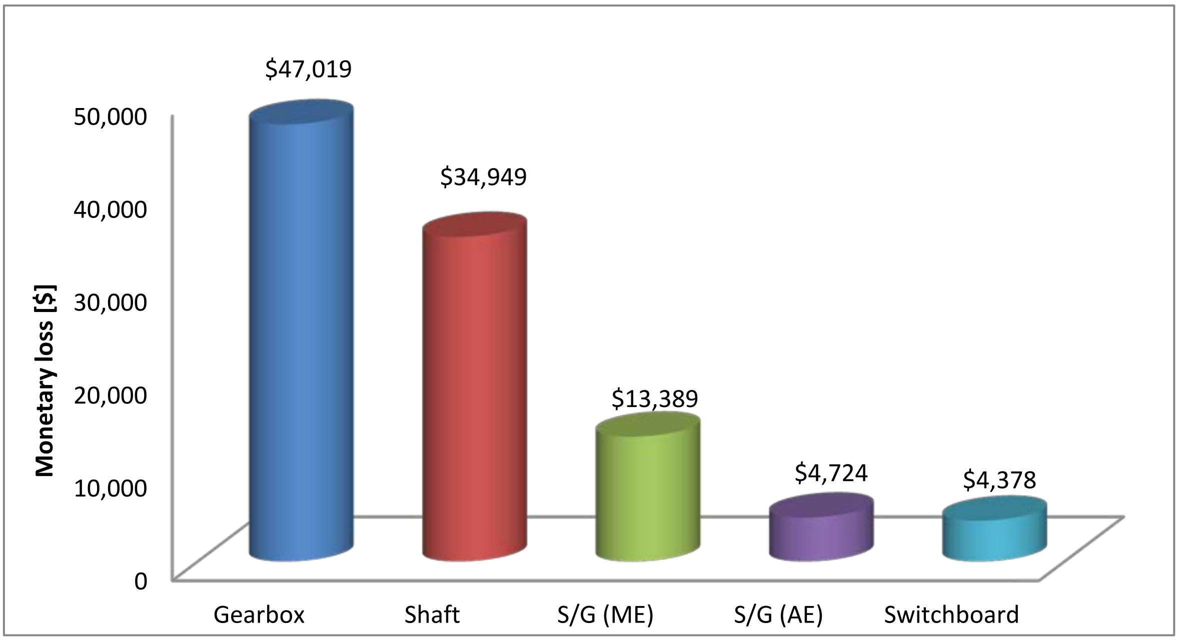

Figure 12: yearly losses in converters and transmitters

Figure 12 shows energy losses in conversion / transmission components converted to monetary losses.

These figures are quite important and often underestimated. On one hand, most of these components are quite efficient and improvements are not always easy to achieve. But, on the other hand, monetary losses can be quite important. For instance, the annual savings coming from the improvement of the gearbox from 98.7% to 99% can be calculated. Gearbox losses at 98.7% efficiency account for 47 000 $/year, while the same figure at 99% efficiency accounts for 36 200 $/year. Therefore, knowing that such a measure would bring an estimated saving of 10 800 dollars per year and per ship could be a good incentive in investing more on this component. Auxiliary engines shaft generators instead, according to this analysis, are involved in a very small energy flow and should be considered for improvement only in a second stage. All these values should be used taking into account ship's expected life, thus comparing investment costs with expected savings over a fixed amount of time.

From the energy consumers' point of view the high cascade factor for the operational inefficiencies underlines how big the impact of potential improvements in this part would be. Hull fouling effect on fuel consumption can depend very much on several parameters, first of all hull polishing frequency, but if a value of 40% increase was to be compared to the 10% reference, the correspondent increase in fuel consumption to be accounted would be of 790 000 $/year, which largely justifies not only a more frequent investment in hull cleaning, but also points out how important it is to be able to monitor propulsion performance.

Finally, Figure 13 shows monetary flows for auxiliary energy consumers[7]. These values could be used once again for estimating saving potential. As an example, studies showed how energy savings up to an estimated 50% could be attained by optimizing cooling pumps operations (Petersson, 2012). This would mean, applying the presented method, a yearly saving of 13 100 $.

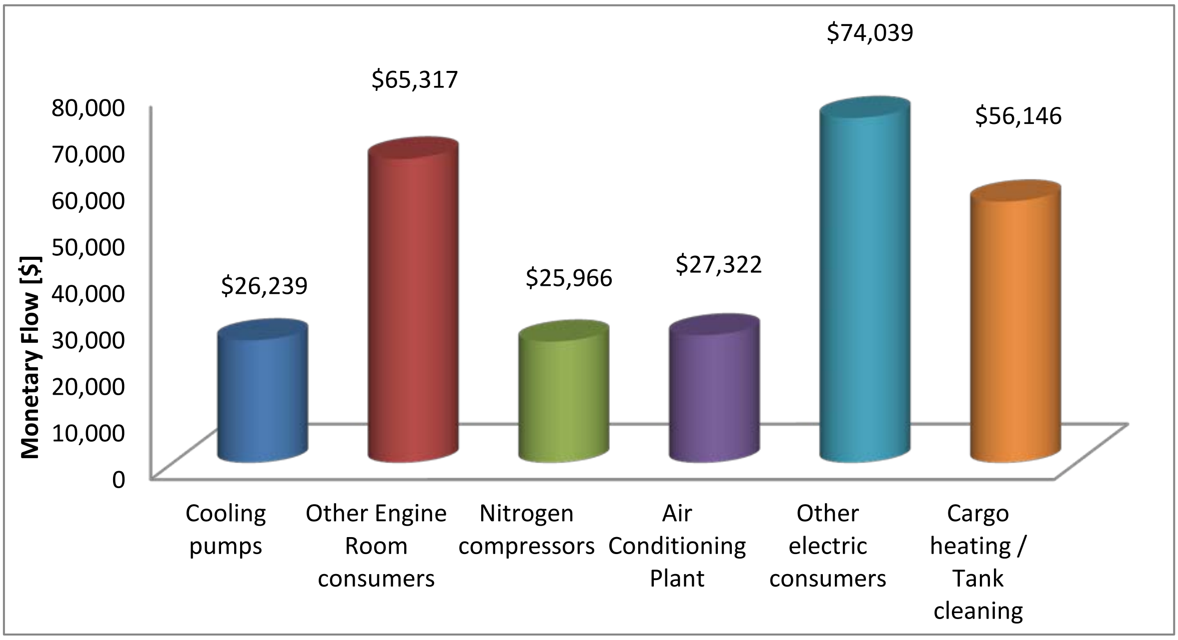

Figure 13: Monetary flows in auxiliary energy consumers

7. CONCLUSION

In this paper a method for analyzing ship energy performances and presenting the analysis in a clear, efficient, and easily understandable way was presented. This was done by introducing two main tools: the Sankey diagram as a graphic representation of energy flows and processes onboard, and the conversion from energy to monetary flows, together with the introduction of a cascade factor, as an easily understandable figure of energy use

[7] It should be noted that, since no satisfactory value was found for auxiliary components efficiency, here monetary flows are shown, instead of losses.

and losses. The combined use of these solutions proved to efficiently show where most of the losses take place and, therefore, where efforts should be directed in order to maximize the outcome, measured in fuel savings, while minimizing the time and resources spent in identifying correct measures to apply.

The results of the analysis show how, thanks to the use of the Sankey diagram, the interpretation of ship performances becomes clear, resulting in a limited number of diagrams that allow not only to understand ship energy flows with little effort, but also to isolate the main sources of energy inefficiency.

In a third step energy flows previously calculated were converted into dollars as unit of measure, according to a reference fuel price. The analysis that followed allowed giving an estimation of how much financial resources are used for different processes onboard and are wasted in different parts of the ships, therefore allowing to help in the decision of where efforts should be focused on in order to implement the most cost-effective measures. Some examples were given in order to show how these numbers could be employed in a real decision-making process. Results will be dependent on the parameters that have been assumed in the case study, i.e. the ship used, its use and the economic situation, but the methodology can be applied to any kind of ship.

The result of this paper is therefore that of giving visual and numerical instruments to facilitate the implementation of energy savings in the decision process of shipping companies' management boards.

The main limitation to this method is the dependence on rather extensive and accurate measured data. Even if the calculations, as showed in the case study, can be performed with fuel consumption and manufacturers data alone, the accuracy of the analysis largely depends on the use of operational data, that can give a clear picture of how the ship behaves, and can be compared with the expected performance from the ship, according to sea trials or manufacturer data. The need of investments in efficient measurement equipment and logging systems is here underlined, as a way to give access to the required information needed to assess ship performances and, therefore, to act towards optimization. A further remark should be connected to the usage of proposed methodology: if it can be a quick and clear insight on energy use onboard and on possible ways to improve ship efficiency, a deeper and more detailed analysis should follow in order to have a more accurate estimation of potential benefits. This instrument, even if of large use in the initial stage of the energy review, is not sufficient, if used alone, to direct the owner to the definitive solution.

Further work on the subject should involve a deeper understanding of the interaction between different components onboard and on the influence of more parameters on their performance, such as seawater and ambient temperature. Energy systems in shipping feature a larger complexity then what presented in this study. Thus, for a higher degree of the accuracy in the analysis, this issue should be taken into account, both in the operation and design phase.

REFERENCES

Athanasovici, V., Le Corre, O., Brecq, G. & Tazerout, M. Thermoeconomic analysis method for cogeneration plants. ECOS 2000 from Thermo-Economics to Sustainability, 2000 Enschede. vol 1, pp 157-164.

Bengtsson, S., Andersson, K. & Fridell, E. 2011. A comparative life cycle assessment of marine fuels: liquified natural gas ahd three other fossil fuels. Proceedings of the

Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment, Vol 225, Iss 2, pp 97-110.
Bentley, R. W. 2002. Global oil and gas depletion: An overview. Energy Policy, 30, 189-205.
Buhaug, O., Corbett, J. J., Endersen, O., Eyring, V., Faber, J., Hanayama, S., Lee, D. S., Lee, D., Lindstad, H., Markowska, A. Z., Mjelde, A., Nilsen, J., Palsson, C., Winebrake, J. J., Wu, W. & Yoshida, K. 2009. Second IMO GHG Study 2009. London, UK: International Maritime Organization (IMO).
Drinkwater, J. W. 1967. Measurement of ship performance. Journal of Scientific Instruments, Vol 44, pp 702-708.
Eide, M. S., Endresen, Ø., Skjong, R., Longva, T. & Alvik, S. 2009. Cost-effectiveness assessment of CO2 reducing measures in shipping. Maritime Policy and Management, 36, 367-384.
Heywood, J. N. 1988. Internal Combustion Engine Fundamentals, McGraw-Hill.
Houghton, J. T., Jenkins, G. J. & Ephraums, J. J. 1990. Climate change: the IPCC scientific assessment. Climate change: the IPCC scientific assessment.
Johnson, H. 2011. The energy efficiency gap in shipping - barriers to improvement. IAME. Santiago de Chile.
Johnson, H. 2012. Barriers for improving energy efficiency in short sea shipping - A case study. Short Sea Shipping. Lisbon - Portugal.
Kjärstad, J. & Johnsson, F. 2009. Resources and future supply of oil. Energy Policy, 37, 441-464.
Man Shaft Generators for the MC and ME Engines. Copenhagen, Denmark: MAN B&W Diesel A/S.
Man 2009. "Green Ship" Project Exploits Existing Technology. DieselFacts.
Petersson, C. 2012. Energy optimization of an engine room. Gothenburg: Chalmers Publication Library.
Sankey. Minutes of Proceedings of The Institution of Civil Engineers. Session 1897-98. Part IV, 1897. Vol. CXXXIV.
Schmidt, M. 2008. The Sankey diagram in energy and material flow management: Part I: History. Journal of Industrial Ecology, pp 82-94.
Shi, W., Grimmelius, H. T. & Stapersma, D. 2010. Analysis of ship propulsion system behavior and the impact on fuel consumption. International Shipbuilding progress, Iss 57, pp 35-64.
Solesvik, M. Z. A collaborative design in shipbuilding: Two case studies. 2007. 299-304.
Stopford, M. 2009. Maritime Economics, New York, Routeledge.
Tsatsaronis 1993. Thermoeconomic analysis and optimization of energy systems. Progress in energy and combustion science, Vol 19, Iss 3, pag 227-257.
Tsoskounoglou, M., Ayerides, G. & Tritopoulou, E. 2008. The end of cheap oil: Current status and prospects. Energy Policy, 36, 3797-3806.
Veenstra, A. W. & Ludema, M. W. 2006. The relationship between design and economic performance of ships. Maritime Policy and Management, 33, 159-171.