Energy and exergy analysis of ship energy systems – the case study of a chemical tanker

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Abstract:

Shipping is already a relevant contributor to global carbon dioxide emissions, and its share is expected to grow together with global trade in the coming years. At the same time, bunker prices are increasing and companies start to feel the pressure of growing fuel bills in their balance sheet. In order to address both challenges, it is important to improve the understanding of how ship energy consumption is generated, through a detailed analysis of its energy systems. In this paper, a method for the analysis of ship energy systems is proposed and applied on one year of operations of a chemical tanker, for which both measurements and mechanistic knowledge of ship systems were available. Energy analysis applied to the case-study vessel allowed comparing different energy flows and therefore identifying system components and interactions critical for ship energy consumption. Exergy analysis allowed instead identifying main inefficiencies and evaluating waste flows. This last information was then processed in order to estimate the potential for waste energy recovery under different conditions. Results showed that propulsion is the main contributor to ship energy consumption (70%), but that also auxiliary heat (16.5%) and power (13.5%) needs are relevant sources of energy consumption. The potential for waste heat recovery is relevant, especially in the exhaust gas, which contains an exergy flow sized 18% of engine power output.

Keywords:

Energy analysis, Exergy analysis, Shipping, Energy efficiency

1. Introduction

As shipping is facing a number of challenges related to increased fuel costs and stronger focus on environmental impact energy efficiency is more and more a subject of study. In this condition, however, detailed studies on energy generation, use and losses on board, together with similar evaluations related to exergy, are lacking in existing scientific literature.

1.1. Background

International trade is the core of today's economy and lifestyle. Its size, compared to 1950, is today more than 100 times larger in terms of volume and value of goods transported [1]. In this picture shipping, which is responsible for between 80% and 90% of the overall global trade [2], has a crucial role in global economy and, more in general, in all human activities.

However, shipping is now subject to a large number of important challenges. Bunker fuel prices are today three times higher than they were in the 80's [3], and fuel costs are estimated to account for between 43% and 67% of total operating costs depending on vessel type [4]. Moreover, upcoming environmental regulations on sulphur oxides, nitrogen oxides and greenhouse gases will exert an additional leverage on fuel costs [5]. This phenomenon will be more pronounced in emission controlled areas, i.e. USA coastal waters, the Baltic Sea, and the North Sea, where regulations will be stricter.

Various fuel saving solutions for shipping are available and currently implemented. Operational measures include improvements in voyage execution, engine monitoring, reduction of auxiliary power consumption, trim/draft optimization, weather routing, hull/propeller polishing, slow-steaming. Design related measures can relate to the use of more efficient engines and propellers, improved hull design, air cavity lubrication, wind propulsion, fuel cells for auxiliary power generation, waste heat recovery, liquefied natural gas as fuel, pump frequency converters, cold ironing [6]. Several scientific studies have been conducted on these technologies, and a more detailed treatise would be out of the scope of this work.

Even if efforts have been put in order to evaluate the benefits associated with the use of each of these solutions and of their combined effect [6, 7], it has also been acknowledged that the world fleet is heterogeneous; from the perspective of a ship owner or operator, measures need to be evaluated on a ship-to-ship basis [8]. In this process, a deeper understanding of energy use on board of the specific ship is vital.

1.2. Previous work

Some studies presenting the analysis of ship energy systems can be found in literature. Thomas et al.[9] and Basurko et al. [10] worked on energy auditing fishing vessels; Shi et al. [11, 12] proposed models for predicting ship fuel consumption in design and off-design conditions; Balaji and Yaakob [13] analysed ship heat availability for use in ballast water treatment technologies. However, a more thorough, holistic thermodynamic analysis of a ship, such as that proposed by Nguyen et al. [14] for oil platforms, is, to the best of our knowledge, lacking in scientific literature. The work proposed by Zaili and Zhaofeng [15], though looking in the right direction, still does not represent the required level of detail.

Analysis purely based on the First law of thermodynamics lack insight of the irreversibilities of the systems, as well as of the different quality of heat flows, since they do not account for the additional knowledge provided by the Second law of thermodynamics [16]. Exergy analysis, which is based on both the First and the Second laws of thermodynamics, can help addressing this shortcoming. Widely used in other industrial sectors, exergy analysis in not commonly employed in maritime technology studies, and is mostly related to waste heat recovery systems [17, 18] and refrigeration plants [19, 20].

1.3. Aim

The aim of this paper is to present a methodology to analyse the energy and exergy flows of an entire ship based on real ship operations. The scope of the analysis is to provide a better understanding of how energy is used on board and where the largest potential for improvement is located. Compared to what can be found in literature, the elements of novelty introduced in this paper can be summarized as follows:

- Is based on a combination of measurements and design information.
- Embraces all ship energy systems.
- Analyses energy input, output, and internal energy flows.
- Focuses on both energy and exergy analysis, hence including considerations about energy quality.

2. Methodology

In this section, the methods of energy and exergy analysis are described for the application to ship energy systems. Their application to a case-study vessel is proposed.

2.1. Combined top-down and bottom-up approach

Analyses of energy systems are often categorised as either Top-down or Bottom-up. Top-down approaches relate to the analysis of extensive sets of measured data and on their use for predictive purposes. Such approaches are accurate and have a good ability of reflecting real operations, but can do only little good in improving the analysis when some variables are not measured [21, 22]. On the other hand, bottom-up approaches make use of mechanistic knowledge of the system in order to simulate its behaviour. Bottom-up approaches are less accurate, but provide a larger insight of the system, as well as allow a safer extrapolation of the results [21, 23, 24].

The methodology employed in this work proposes a flexible mix of both empiric and mechanistic knowledge. In the specific case of the ship under study large amounts of measured data were used to generate the core of the analysis, while mechanistic knowledge of the system, based on the use of technical documentation, was used in order to produce the analysis of those flows for which it was not possible to get measurements. The main source of data for the Top-down part of the analysis is a continuous monitoring system (CMS) installed on board. Technical documentation was available for on board machinery and was used as input for numerical regressions. Heat and electric balance of the ship were provided by the shipyard. Ship sea trials performed by the shipyard when the ship was first sailed and direct communication with on board and onshore personnel were also available.

2.2. Ship description

In order to give a practical demonstration of the applicability of the proposed methodology, operational data from a real ship are used in this study. The selected ship is a Panamax chemical / product tanker. Relevant ship features are provided in Table 1, while Figure 1 conceptually represents the ship energy systems.

The ship is propelled by two 4-stroke Diesel engines (ME) rated 3840 kW each. The two engine shafts are connected to a common gearbox (GB). One of the gears reduces the rotational speed from 600 rpm to 105.7 rpm, the design speed for the controllable pitch propeller. Another shaft from the gearbox connects it to the electric generator (SG) which provides 60 Hz current to the ship. Additionally, two auxiliary engines rated 682 kW each can provide electric power when the MEs are not in operation, or whenever there is a failure in the SG. Auxiliary heat needs are fulfilled by the exhaust gas economisers (EGE) or by auxiliary boilers when the MEs are not running or heat demand is higher than what provided by the EGEs.

Main engine power is calculated according to Equation 1.

$$P_{ME} = \frac{\left(\frac{P_{prop}}{\eta_S} + \frac{P_{SG}}{\eta_{SG}}\right)}{\eta_{GB}}, \qquad (1)$$

Where the variables P and η refer to power and efficiency and subscripts, prop and S respectively refer to the propeller and the propeller shaft. P_{SG} and P_{prop} are available from the CMS; η_S is assumed equal to 0.99, as suggested by Shi et al. [11]; η_{GB} is assumed equal to 0.983 as reported by the shipyard. As the SG often operates at very low load, its efficiency dependence on load needs is modelled using a polynomial regression calibrated on the experimental points reported by Hau [25] and based on a design efficiency of 95%, as reported on technical documentation. Finally, for the determination of engine efficiency, main engine fuel consumption is measured via flow meters and available through the CMS. Inlet air conditions are determined using a polynomial regression for compression ratio in the turbocharger based on engine technical data; air temperature in the engine room, before the turbocharger, is assumed equal to 35°C.

Table 1. Main ship features

Ship feature	*Value*	*Unit*
Deadweight	47 000	ton
Installed power (Main Engines)	7 700	kW
Installed power (Auxiliary Engines)	1 400	kW
Shaft generator design power	3 200	kW
Exhaust boilers design steam gen.	1 400	kg/h
Auxiliary boilers design steam gen.	28 000	kg/h

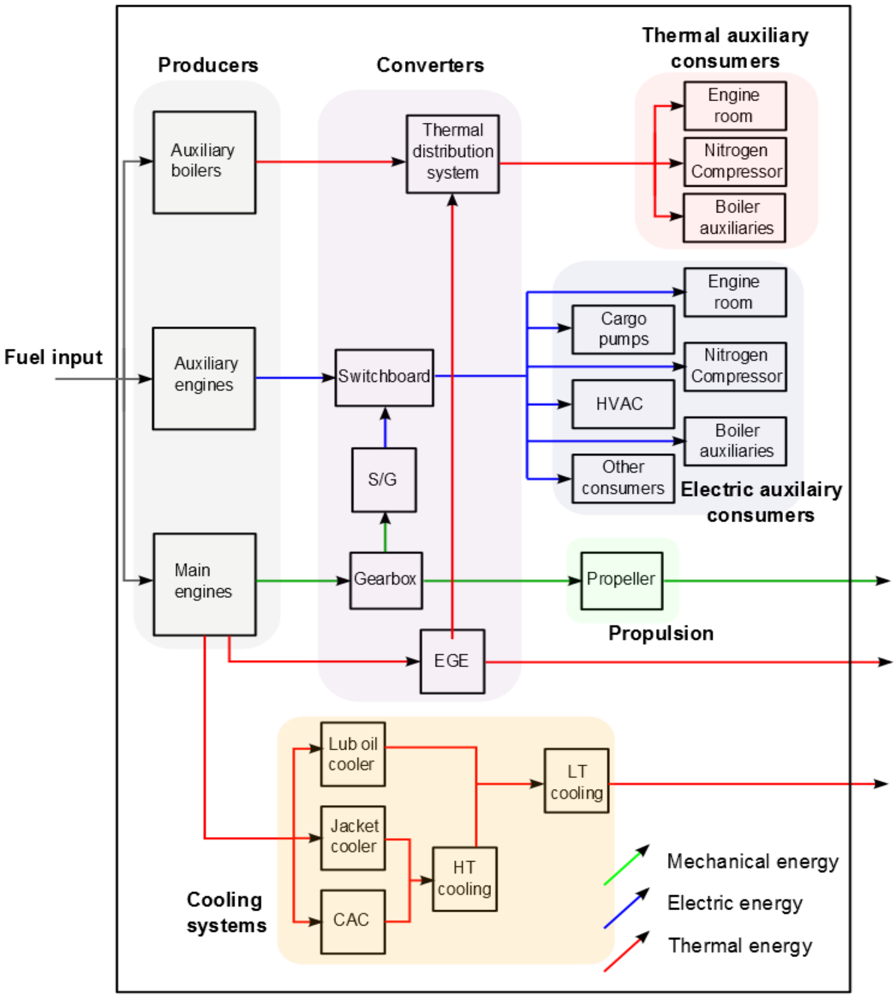

Fig. 1. Conceptual representation of ship energy systems

Air is cooled after the turbocharger in order to increase its density through a charge air cooler (CAC); the air temperature before the charge air cooler is calculated assuming a polytropic compression, whose efficiency is based on a polynomial regression; the air temperature after the charge air cooler is assumed equal to 55°C according to common practice on the selected ship; the air mass flow is calculated assuming unitary Volumetric efficiency. The heat exchanged to the cooling system in the charge air cooler can therefore be calculated as:

$$P_{CAC} = \dot{m}_{air} c_{air} \Delta \mathrm{T}_{CAC}, \qquad (2)$$

The temperature of the exhaust gas is estimated through a polynomial regression, while the mass flow is obtained adding air and fuel flows. The energy content in the exhaust flow is therefore calculated from the temperature difference with ambient temperature, assuming a constant $c_{eg}$of 1.08 kJ/kgK. Heat flows to engine jacket water (JW) cooling, lubricating oil (LO) and radiation are estimated from design values available from technical documentation, under the assumption that their share of the total energy input, once engine power, CAC cooling, and exhaust gas output are subtracted, does not change with load.

The engine is connected to a double-level cooling system, composed of a low-temperature (LT) and a high-temperature (HT) part. JW heat is transferred to the HT circuit, while heat from the CAC is subdivided among the two circuits. Based on data available from the technical documentation and related to the design point, it was assumed that 22.4% of the charge air cooling heat is transferred to the low-temperature circuit, while the remaining part is transferred to the high-temperature circuit. Mass flows in the HT cooling, LT cooling and LO circuit are assumed to be constant with engine load as they are operated by engine-driven pumps. LT circuit inlet temperature, HT circuit outlet temperature, and LO circuit inlet temperature are respectively assumed equal to 34°C, 85°C, and 60°C according to operative experience coming from communication with on board technical personnel.

Technical documentation for the auxiliary engines was limited to the efficiency at design. The efficiency at off-design conditions is calculated as a polynomial regression of available data points and corrected according to ISO standards point [26, 27], while the residual energy is subdivided among charge air cooling, jacket water, lubricating oil, and radiation according to values at design point.

Auxiliary power consumption measurements are available from the CMS. In order to give an estimation of the power needed by different consumers, data from the electric balance was used. Since the measured consumption is different from design figures, this operation required a number of assumptions:

- For seagoing mode (loaded), it is assumed that the power consumption is subdivided according to the electric balance. Therefore, proportions between different consumers are maintained. For all points were auxiliary load is larger than 500 kW nitrogen compressors are assumed to account for the difference between with actual consumption. Nitrogen compressors are needed for keeping an inert atmosphere into the cargo tanks when inflammable liquids are transported.
- For seagoing mode (ballast) the same repartition is assumed as for seagoing mode (loaded) if auxiliary power is lower than 500 kW. If power consumption is higher the difference is assumed to be connected to the operations of nitrogen compressors and boilers auxiliaries (in connection to tank cleaning), which are subdivided according to their respective design power.
- For manoeuvring the same assumptions as for seagoing mode (loaded) are employed.
- For cargo loading and unloading all consumption going over 500 kW is allocated to nitrogen compressors and cargo pumps, with repartition according to maximum installed power. It should be noted that cargo loading operations normally do not require the use of cargo pumps, as port storage facilities can provide the needed overpressure for loading the cargo.
- For waiting time the same proportions as reported in the ship electric balance are used, with the exception of engine room consumption, which is halved, since when waiting in port only auxiliary engines are used.

Fuel heating is needed because of high fuel viscosity, and is computed starting from the design heat balance and using sea water temperature and outer air temperature measurements. Hotel facilities needs are calculated assuming a linear correlation between calculated values given in the heat balance, assumed at an outer temperature of 2°C, depending on outer air temperature. Heat consumption for fresh water generation is calculated including service water for machinery and cooling systems and consumption for the crew according to common practice [28]. Since the generation of fresh water is connected to the (LT) cooling systems, the value of heat of vaporisation for water was taken at 50°C and equal to 2382 kJ/kg.

During ballast legs, steam is needed for tank cleaning, which requires the operation of the auxiliary boilers. Energy use for tank cleaning is derived from the aggregated boiler fuel consumption, under the assumption of 90% boiler efficiency accounting for combustion losses and heat flow in the exhaust gas, limited at 200°C to prevent sulphuric acid condensation in the funnel. Auxiliary boilers are also used when the main engines are not in operation. In this condition, as boilers are operated at very low load, a reduced efficiency of 80% was assumed instead. A summary of the main auxiliary consumers is shown in Table 2.

Table 2. Summary of auxiliary consumers

Electrical energy consumers	*Thermal energy consumers*
Nitrogen compressors	Fuel Handling
Cargo pumps	Hotel facilities
HVAC	Tank cleaning
Engine room	
Boiler auxiliaries	
Miscellaneous	

2.3. Exergy analysis

When dealing with energy flows of different nature, energy analysis alone can lead to misleading results, as it does not account for energy quality. This problem can be partially overcome by the use of exergy analysis.

Exergy is defined as the maximum shaft work that can be done by the a system in a specified reference environment [16]. The exergy content of a flow depends on the quality of the energy content. Additionally, differently from energy, exergy is not conserved and can be destroyed, representing the deterioration of energy quality. For electrical, potential, kinetic, and mechanical energy, exergy and energy flows coincide. In the case of chemical exergy, substantial differences can be found when analysing systems involving a more advanced chemistry; in this case combustion is the only chemical reaction taken into account, and it is assumed that the specific chemical exergy of the fuel coincides with its lower heating value. In the case of thermal energy, the exergy content of a given amount of matter is defined as showed in Equation 3.

$$EX = m\,[(h - h_0) + T_0(s - s_0)], \qquad (3)$$

EX, h, and s respectively stand for exergy, specific enthalpy, and specific entropy, while the subscript 0 refers to reference conditions, which in this work coincide with measurements of seawater temperature. Exergy flows calculated according to Equation 1 can be divided in three main categories [16]:

- *Input* ($\dot{E}X_{in}$): the flow of exergy entering the component.
- *Output* ($\dot{E}X_{out}$): the flow of exergy leaving the component.
- *Irreversibility rate* ($\dot{I}$): the amount of exergy lost in the component operation (also known as exergy distruction). This part represents energy quality deterioration and is defined as $\dot{I} = T_0\dot{S}_{gen}$, where $\dot{S}_{gen}$ represents the rate of entropy generation in the component.

In this study, four different quantities measuring efficiency according to exergy analysis will be used [16]:

- *Exergy efficiency* is defined in this study as $\eta_{ex} = \frac{\dot{E}X_P}{\dot{E}X_{in}}$, where the subscripts *p* and *in* respectively refer to products and inputs. In the case of heat exchangers, the alternative definition of $\eta_{ex} = \frac{\Delta EX_c}{\Delta EX_h}$ is used, where subscripts *c* and *h* respectively refer to the cold and the hot fluid. The definitions of the ΔEX are adapted depending on whether the component is meant for cooling or heating. Exergy efficiency gives an estimation of how efficient the component is in the generation of useful products.
- *Irreversibility ratio* is used according to the definition proposed by Kotas et al. [29], i.e. $\lambda = \frac{\dot{I}}{\dot{E}X_{in}}$. The irreversibility ratio gives an estimation of how much energy quality is lost in the component.

- *Irreversibility share* is defined as the ratio between the exergy destroyed in the component "i" and the total rate of exergy destruction in the whole system, i.e. $\delta = \frac{\dot{I}_i}{\dot{I}_{tot}}$
- Task efficiency is defined as the ratio between the irreversibility in an ideal exchange at constant temperature difference (here arbitrarily fixed to 10 K) and the irreversibility in the actual process, i.e. $\eta_{task} = \frac{\dot{I}_{i,ideal}}{\dot{I}_{i,real}}$. The Task efficiency gives an estimation of the proximity of the performance of a component to an ideal process.

Ship flows between components are computed in terms of both their energy and exergy contents. The connections in the system can be seen in Figure 1. The results from the energy analysis are reported using respectively Sankey and Grassmann diagrams, which represent flows as weighted arrows [30].

3. Results

In this section the results of the energy and exergy analysis of the case-study ship are presented and analysed. Results are presented in Figures 2 and 3, and commented in the text. All details about the numerical results are listed in Appendix A.

3.1. Energy analysis

Figure 2 shows the Sankey diagram of ship energy systems. Propulsion represents the main source of energy consumption, as it accounts for 70% of the yearly ship energy demand. This also translates in the main engines consuming the largest share of the overall energy input of the system (89%). Hence, efforts directed towards the reduction of propulsive power are highly justified for the ship under study.

Both auxiliary engines and auxiliary boilers (respectively representing 8.0% and 2.6% of ship energy input) on one side, and auxiliary power and heat consumers (16% and 14% of ship energy output) on the other, should be given significant attention. Boiler auxiliary electric demand should also be taken into account as it also represents a significant share of the total output (2.7%). Auxiliary boilers are run at low load most of the time, leading to low efficiency.

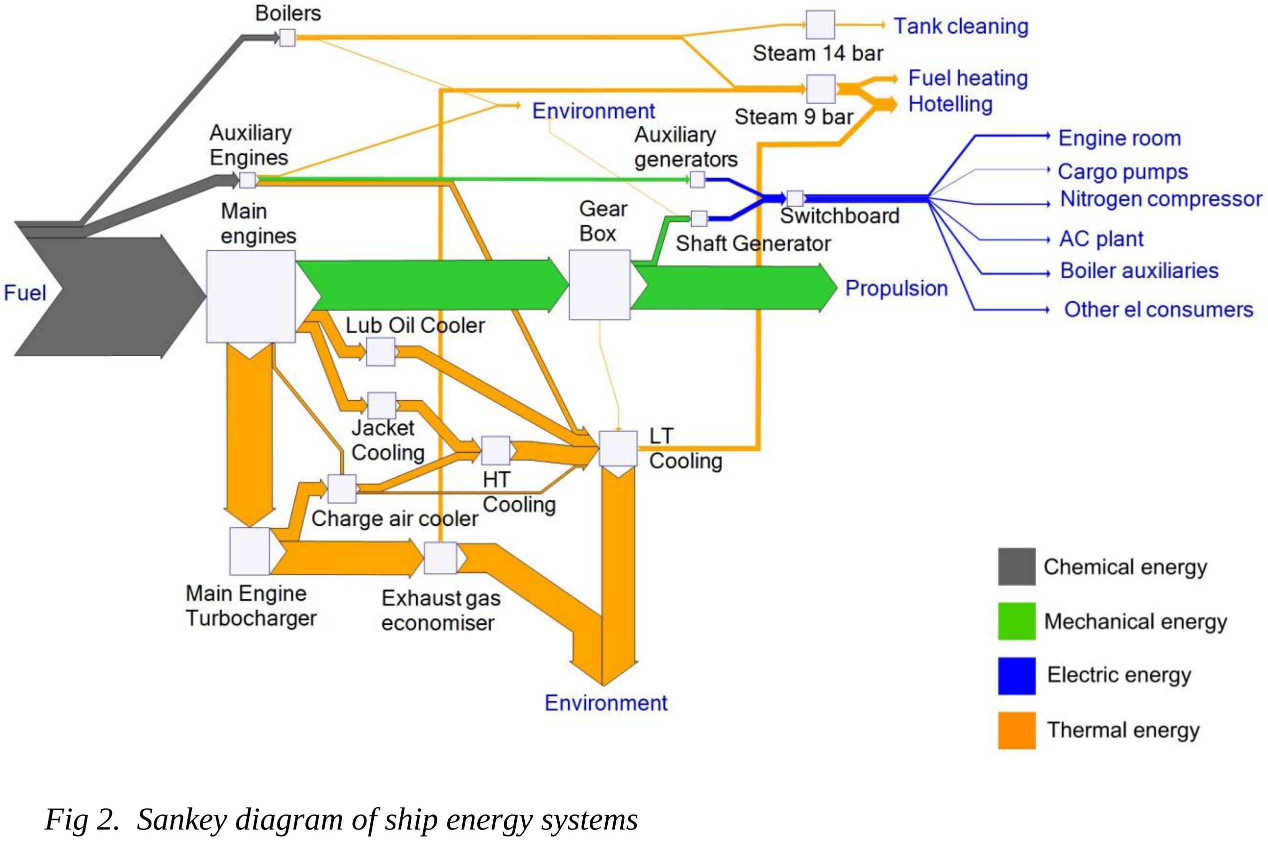

Fig 2. Sankey diagram of ship energy systems

Fuel heating also represents a surprisingly high share of the overall ship energy consumption (7.8%). This high influence of auxiliary needs is partly connected to the ship spending large amount of time in port, when there is no propulsion power demand.

Finally, a large amount of energy is wasted to the environment through the exhaust gas (41% of main engines power output), the CAC (20%), JW cooler (22%) and the LO cooler (24%). This suggests that there is potential for the recovery of these waste flows. The amount of energy recovered in the EGE and in the fresh water generator for fulfilling auxiliary heat needs only represents a small percentage of the total waste energy flows (7%).

3.2. Exergy analysis

The results from the exergy analysis are presented in Figure 3. Figure 3 can be helpful in the evaluation of different waste flows with respect to both energy quantity and quality. It is here shown that the exhaust gas is a much larger source of potentially recoverable heat than the cooling systems, contrarily to what could be deducted from Figure 2. When looking at the results of the exergy analysis, the exergy flow in the exhaust gas and in the cooling flows is respectively reduced from 41% to 18% and from 66% to 15% of the engine power output. In the case of the cooling systems, it should also be noted that every additional heat exchanger decreases the recovery potential; as an example, the exergy flow entering the jacket cooling alone is almost the same size as that flowing into the heat exchanger between LT systems and sea water. These results show how exergy gives a much more realistic estimation the amount of energy that can actually be recovered from the analysed waste flows, also accounting for their quality. In particular, waste heat recovery (WHR) systems are often proposed for enhancing marine propulsion systems efficiency [31-33]. In this context exergy analysis, compared to energy analysis, provides a more accurate estimate of the amount of power that could be generated through a WHR system.

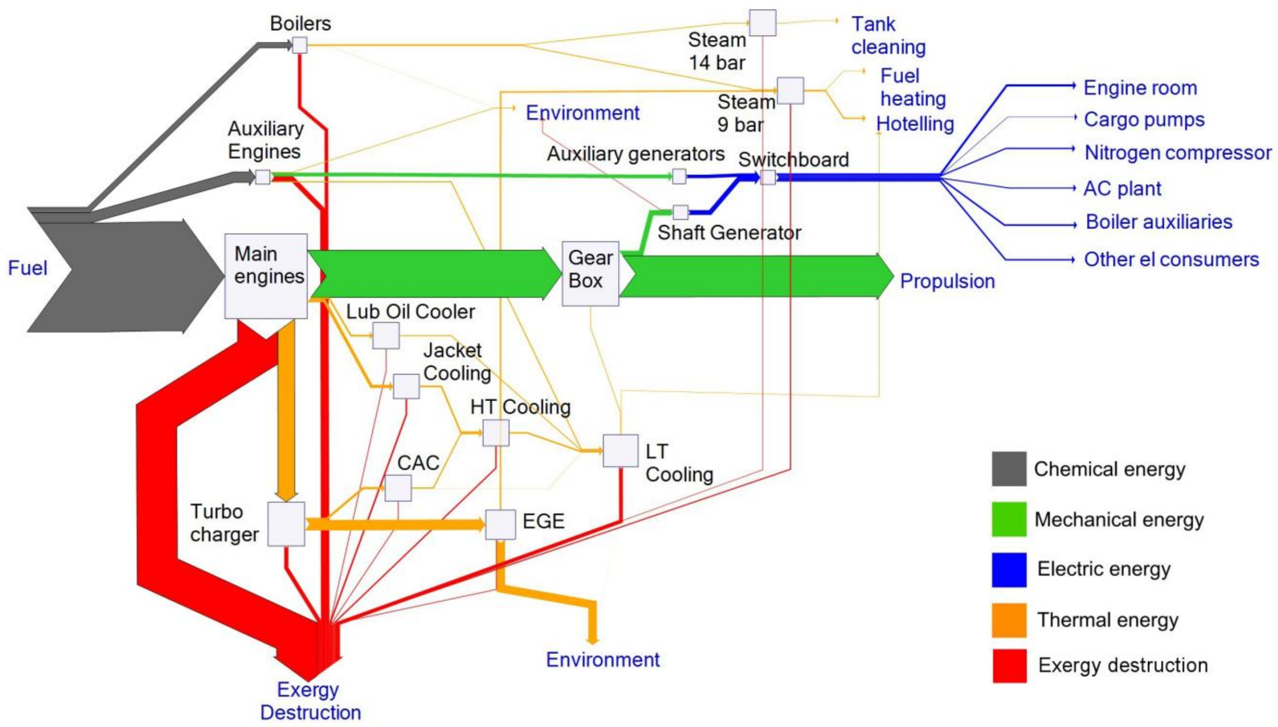

Fig 3. Grassmann diagram of ship energy systems

The exergy analysis also provides information about the efficiency of individual components. The exergy efficiency (η_{ex}) quantifies the ability of a component to generate its required output with low exergy losses or destruction. Low values of η_{ex} correspond to high losses in energy quality. It can be seen, for example, that according to this definition, boilers ($\eta_{ex} = 0.30$) are much less efficient than both main ($\eta_{ex} = 0.43$) and auxiliary engines ($\eta_{ex} = 0.36$). In the case of heat exchangers, the utilisation of the irreversibility ratio as a figure of merit can be misleading: a heat exchanger located on a large exergy flow (e.g. on the exhaust gas) could have very high η_{ex} only because of its low heat exchange area.

Looking at task efficiencies instead allows the identification of which components could be improved in order to perform the same task while reducing exergy destruction. In the cooling systems this is particularly true for the CAC ($\eta_{task} = 0.27$) and the EGE ($\eta_{task} = 0.048$). From the point of view of energy consumers, the very low efficiency of all auxiliary heat consumers (tank cleaning, hotelling, and fuel heating respectively have task efficiencies of 0.074, 0.072 and 0.091) indicates that it would be possible to generate the same heat requirements while using much lower heat-grade sources. This could be done, for example, by using a different heat transfer fluid or, in alternative, steam at a lower pressure. Fuel handling and hotelling, for instance, only require temperatures as low as 70-80°C (a part from fuel heaters before the engine, which warm HFO up to around 90-100°C), which could be provided at much lower temperature than by 9 bar steam.

These considerations can also be quantified: assuming to improve the η_{task} of the CAC, LO cooler, EGE, tank cleaning, hotelling and fuel heating to the maximum measured in the analysis (0.5 for the jacket water cooler), it would be possible to increase the amount of the total recoverable exergy by 8.6%. In practice, however, this improvement would in most cases be reached using larger heat exchanger, at the cost of an increased capital investment. This worked focused on the purely thermodynamic analysis of ship energy systems; methods for thermoeconomic analysis and optimisation have been proposed in literature and should be employed in further developments of this work (e.g. by Szargut and Sama [34]).

4. Discussion

The implications of the hypotheses made in this study will be here further discussed, together with the generalizability of the results.

4.1. Generalizability of the results

Even though the main interest of this work lies in the application of a method, the results of its application to the case study are also a subject of interest. However, their generalizability (or external validity) should be discussed. The numerical results presented in the energy and exergy analysis are expected to be representative of the selected vessel and its sister ships: as aggregated data over one year of operation were used any voyage-specific feature (weather influence on propulsive power, sea water temperature, etc.) is supposed to be cancelled out when accounting for longer periods of time. It should be noted, however, that some phenomena can be observable only under longer time perspectives. In particular, today's low markets and high fuel prices have pushed down the operative speed of the vessel, and it is reasonable to expect that the share of propulsive power would be larger (together with recoverable energy) if the vessel were to operate at higher speed. The validity of the results can also be extended to vessels of similar scope, even if of different sizes. It is legitimate to expect that while quantities will vary sensibly from ship to ship, the conclusions and considerations derived from the analysis of this ship can still be accounted as valid.

4.2. Input data

One strength of the procedure employed lies in the variety of input data that can be used in order to elaborate the structure of on board energy flows. Input data for calculations were obtained from the CMS, manufacturers technical documentation, shipyard technical documentation, and reported measurements from the crew. This mixture of different data sources made it possible to use all available information, with the drawback of reduced consistency in data sources and accuracy. More accurate data concerning boiler fuel consumption, temperatures across the engines and the different cooling flows, as well as more detailed information about all different auxiliary needs, would make the analysis much more consistent and accurate. However, since this information was not available, it was decided that employing all usable data, even if coming from different sources, was the best solution for getting the highest amount of insight on the system under study. It is clear, however, that the higher the quality of the input data, the higher the accuracy of the analysis. Having access to measurements of individual auxiliary components electric power demand through the CMS would bring, for example, a better understanding of those systems.

5. Conclusions

The paper presented the energy and exergy analysis of a chemical / product tanker, based on a mixed top-down and bottom-up approach applied to one year of ship operation. The exergy analysis was used as a basis for evaluating the potential for waste heat recovery on the vessel.

The application of the proposed method to the case study ship led to an improved understanding of onboard energy use and of inefficiencies in the system, obtained through the estimation of energy and exergy flows. Energy analysis allows estimating the main consumers, producers, and hence allows understanding where most of the energy goes and were losses are located. Exergy analysis, on the other hand, improves the understanding of the potential for WHR, and helps in the identification of inefficiencies in the handling of waste heat.

In addition to showcasing the application of the proposed methodology, the numerical results related to the case-study ship can also be of interest. The analysis showed, as expected, that propulsion power is the major energy consumption (70%), while also demonstrating that auxiliary demands of both electric power (14%) and heat (16%) are not negligible. A large amount of energy is wasted to the environment through the engine cooling and the exhaust gas. Using exergy analysis, the potential for WHR from these losses was estimated. The largest exergy losses are connected to the exhaust (18% of engine output), and to engine cooling systems (15%). Large amounts of exergy are destructed in the boiler and in the cooling systems, as exchanges are not optimised for conserving energy quality.

The availability of such amounts of waste heat would suggest further investigating the possibility of installing WHR systems; future work can be directed towards the design and optimization of WHR cycles for the generation of auxiliary power, such as steam-based and Organic Rankine cycles, which have been extensively treated in literature (e.g. Larsen et al. [33]). In addition to the aforementioned technologies, complementary uses for waste heat from Diesel engines for shipping application have been extensively reviewed by Shu et al. [35].

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Appendix A

Table A.1 Summary of ship energy flows

Producers	$\%_{prod}$	*Consumers*	$\%_{cons}$
Main Engines	88.2	Propulsion	70
Auxiliary Engines	7.8	Auxiliary power	14
Auxiliary Boilers	4.0	Auxiliary heat	16

Table A.2 Summary of second-law based efficiencies for ship energy system main engines

	η_{ex}	λ	δ	η_{task}
Engine	0.420	0.390	0.660	-
Turbocharger	0.360	0.240	0.060	-
Exhaust gas economizer	0.670	0.065	0.010	0.048
Charge air cooler	0.660	0.067	0,011	0.280
Lubricating oil cooler	0.580	0.200	0,011	0.410
Jacket water cooler	0.510	0.160	0.024	0.510
HT/LT heat exchanger	0.54	0.140	0.020	0.330
LT/SW heat exchanger	0.021	0.84	0.047	0.350

Table A.3 Summary of second-law based efficiencies for ship energy system auxiliary consumers

	η_{ex}	λ	δ	η_{task}
Auxiliary engines	0.360	0.380	0.058	-
Boilers	0.300	0.640	0.053	-
Tank cleaning	0.250	0.610	0.008	0.047
Hotelling	0.160	0.620	0.007	0.081
Fuel heating	0.260	0.620	0.017	0.091

Table A.4 Energy and exergy analysis of ship waste heat flows

Waste flows	Energy		Exergy	
	$\%_{rec}$	$\%_{ME,out}$	$\%_{rec}$	$\%_{ME,out}$
Exhaust gas	38	41	54	17.7
Charge air cooler	19	20	14	4.6
Jacket water cooler	21	22	20	6.7
Lubricating oil cooler	22	24	12	3.8

Nomenclature

c	specific heat, J/(kg K)
ex	specific exergy, J/kg
EX	exergy, J
$\dot{EX}$	exergy flow, W
h	specific enthalpy, J/kg
$\dot{I}$	irreversibility rate, W
m	mass, kg
s	specific entropy, J/(kg K)
$\dot{S}_{gen}$	entropy generation rate, W/K
T	Temperature, K,^{o}C

Acronymes

CAC	charge air cooler
HT	high temperature
LO	lubricating oil
LT	low temperature
ME	main Engine
SG	shaft generator
WHR	waste heat recovery

Greek letters

δ	irreversibility share
η_{ex}	exergy efficiency
η_{task}	task efficiency
λ	irreversibility ratio
Δ	finite difference

Subscripts

c	cold
eg	exhaust gas
$cons$	consumer

h	hot	*prod*	producer
i	generic component	*tot*	total
in	inlet flow	*0*	reference state
out	output flow		
p	product		

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