This is a peer-reviewed, accepted author manuscript of the following research article: Koroglu, T & Sogut, OS 2018, 'Conventional and advanced exergy analyses of a marine steam power plant', Energy, vol. 163, pp. 392-403. https://doi.org/10.1016/j.energy.2018.08.119

Conventional and Advanced Exergy Analyses of a Marine Steam Power Plant

Abstract:

Stricter rules and regulations about emissions for marine vessels and escalating fuel prices have motivated researchers and engineers to study further on improving fuel efficiency. Thus, it has become crucial to estimate the improvement potential and the sources of irreversibilities within energy systems. In this paper conventional and advanced exergy analyses are applied to a marine steam power plant to reveal insights which may help designers to make decisions on component renewal issues. The results of the study showed that the highest exergy destruction is within the boiler due to chemical reactions. Moreover, it has the highest avoidable exergy destruction. Pumps in the system contribute to the destruction in small percentages. Turbines have more importance compared to the heat exchangers. The findings for avoidable endogenous exergy destructions indicated that the improvement efforts should be focused essentially on boiler, turbines, condenser and pump equipment respectively, and that feed water heaters could be improved externally by improving other components. It is also concluded that the overall system has a 10% improvement potential of the exergy efficiency, of which almost three out of four is due to two components namely, boiler (6%), and low pressure turbine (1.3%), other components have smaller room for improvement.

Keywords: Steam power plant, marine energy systems, advanced exergy analysis, Energy Efficiency Design Index

Highlights:

- A marine steam power plant is simplified for advanced exergy analysis and its accuracy is validated with the real data from literature.
- Overall system has a 10% exergy efficiency improvement potential.
- Improvements in boiler, and 3rd stage of low pressure turbine could recover 73% of overall efficiency improvement potential.

Nomenclature

Abbreviations

CDP: condensed feed water pump

CO2: Carbon dioxide

COGAS: Combined Gas and Steam

COND: Condenser

EI: Efficiency Improvement (%)

EEDI: Energy Efficiency Design Index

EEOI: Energy Efficiency Operational Indicator

FWMP: feed water main pump

FWP: feed water pump

FWPH: Feed Water Preheater

GHG: greenhouse gas

HPT: High Pressure Turbine

IMO: International Maritime Organization

IPT: Intermediate Pressure Turbine

LHV: Lower Heating Value

LNG: Liquified Natural Gas

LPT: Low Pressure Turbine

ORC: Organic Rankine Cycle

SEEMP: Ship Energy Efficiency Management Plan

TEU: Twenty-Foot Equivalent Unit

WHR: Waste Heat Recovery

Symbols

ex : specific exergy, kJ/kg

$\dot{Ex}$: exergy flow rate, kW

h : enthalpy, kJ/kg

$\dot{m}$: mass flow rate, kg/s

P: Pressure, kPa

s : entropy, kJ/kgK

T: Temperature, K

$\dot{W}$: Power, kW

Greek letters

ε: exergy efficiency

η: 1st law efficiency

Subscripts

D: destruction

F: Fuel

j: any jth stream

k: any kth component

L: loss

P: Product

tot: overall system

0: environmental condition

Superscripts

AV: Avoidable

AVEN: Avoidable Endogenous

AVEX: Avoidable Exogenous

EN: Endogenous

EX: Exogenous

UN: Unavoidable

UNEN: Unavoidable Endogenous

UNEX: Unavoidable Exogenous

*: new, modified

1. Introduction

Maritime fleet continuously rise due to explicit growth of seaborne trade [1]. New vessels as well as old ones carry the efficient fuel consumption and emission problem forward to be tackled. International Maritime Organization (IMO) has taken actions against the increase of greenhouse gas (GHG) emissions within regulations, the key indicators defined are the Energy Efficiency Design Index (EEDI) for new ships, the Energy Efficiency Operational Indicator (EEOI) and Ship Energy Efficiency Management Plan (SEEMP) for vessels in operation [2, 3] to increase the energy efficiency of vessels even their GHG share is relatively small compared to other sectors [4]. Hence improvement approaches of marine power plants to reduce the fuel consumption gain high level of importance not only for designers but also for operators and ship-owners.

Marine vessels have been driven by different types of power systems in history. The utilization of power plants in propulsion started with the low-efficient and bulky steam engines, then with the advancements in the turbine technology, the steam engines have been replaced by steam turbines [5]. Although the leadership in propulsion power has been overtaken by diesel engines, which are in use dominantly, a portion of marine vessels such as LNG and oil carriers, naval and cruise ships still have steam power plants as prime mover alone or in combination with other engines [5-7]. Moreover, a high portion of two stroke cycle diesel engines, which are utilized in 85% of the world fleet [8], have a steam cycle as auxiliary power production unit namely turbo-generator and/or waste heat recovery (WHR) systems [9-11]. It can be concluded that, steam power plants are still here as an option to produce power and drive the propeller of marine vessels.

Energy analysis is used to determine the efficient use of energy throughout all marine power production systems including steam power plants. It has been observed that energy analysis has shortcomings of determining cause, location and magnitude of irreversibilities in components and processes [12].Consequently, exergy analysis has been emerged to tackle with aforementioned situations. In the literature, several applications of energy and exergy analyses to main or auxiliary marine steam power plants have been carried out. Poljak et al. [13] investigated a marine steam plant by exergy analysis with respect to the variation of shaft speed for an LNG carrier and they revealed that at the lower speed of the shaft, exergy flow is the highest in services and it gradually decreases while flow in the main turbine increases with respect to the speed. Mrzljak et al. [14] conducted energy and exergy analyses on marine steam generators of LNG carrier steam power plant with different types of fuel, different engine loads. It has been shown that energy and exergy efficiencies of steam generators vary in a small interval with respect to the propeller speed while CO_2 emission decreases proportionally to the increase of shaft speed. Mrzljak et al. [15] also applied these analyses to turbo-generators and steam turbines driving the main feed water pump on LNG carrier with respect to turbine types, ambient temperature and shaft speed. They revealed that power of the steam turbine is almost constant while power of turbo generators varies. The change of efficiencies in turbo-generators are higher than in the steam turbine. Exergy destruction for both systems have high oscillations in terms of shaft speed. Recently, they analyzed the high pressure feed water heater of a marine steam power plant by applying energy and exergy analyses, and reported that the energy and exergy efficiencies of the heater vary in a relatively small range while exergetic power loss, and power of heater vary more by propeller speed [16]. Attah and Bucknall [17] evaluated different engine options for LNG carriers via EEDI comparison with their suggestion of EEDI calculation approach and results show that steam powering has slightly higher EEDI results comparing to EEDI baseline and dual fuel diesel electric propulsion. Olszewski [18] analyzed combined diesel engine-steam turbine possibilities as waste heat recovery system thermodynamically based on different diesel engines and disclosed that combination could raise efficiency and also the power output over 5%. In a following study, Dzida and Olszewski [19] compared gas turbine-steam turbine combination possibilities to diesel-steam engine with an improvement of double pressure steam cycle, and concluded that almost 50% improvement could be achieved for gas turbines and dual pressure system produces slightly more power compared to single pressure system for both diesel engines. Jefferson et al. [20] published an article on analysis of combined gas and steam turbine system based on a thermodynamic model for dynamic computer simulation. Theotokatos and Livanos [11] presented energy, EEDI and economic analyses for single pressure WHR after two and four stroke diesel engines in range of 50% to 100% engine load, they suggested an approach to calculate EEDI of dry cargo bulk carriers, and concluded that two stroke engine with WHR steam cycle is the best option. Mito et al. [21] considered utilizing scavenge air cooler heat to improve the performance of steam turbine WHR systems namely single and double pressure systems. Energy, exergy and economic analyses are applied to the aforementioned systems with several parameters such as operating pressure. They concluded that exergy destruction decreases for all models with increasing operating pressure, and that costs of fuel saved, cost of steam generator and CO_2 emission reduction are almost identical. Ma et al. [10] conducted a conceptual design and performance analysis of power turbine and turbo-generator WHR system for a 10000 TEU container ship and results showed that power production potential of suggested system is around 5 MW. Benvenuto et al. [22] evaluated different plant layouts with a two-stroke diesel engine and WHR systems for a crude oil carrier according to economic aspects, fuel savings and EEDI. They suggested an approach to calculate EEDI of crude oil carriers and results showed that system with shaft generator, power-turbine and turbo-generator is the most appropriate layout. Haglind [6] reviewed COGAS studies in his three-parted-article series.

Although exergy analysis is a useful tool to expose losses of investigated processes or components, it has limited capability on leading the engineer which improvement steps would be taken. Hence advanced exergy analysis is introduced to overcome stated problems such as the real sources and improvement potentials of systems. In 1996, Feng et al. [23] presented a new exergy method for system analysis which introduced avoidable and inevitable exergy loss (destruction) analysis and commented that improvement efforts should be on the avoidable parts of exergy losses (destructions) of the components. This was the first approach of advanced exergy analysis. Then, Feng and Zho [24] applied this approach to a more complex system with combined pinch and exergy analysis. Later on, Tsatsaronis [25] showed that exergy destruction of a component depends not only on its exergetic efficiency but also on exergetic efficiencies of other components. Then he defined endogenous and exogenous exergy destructions which depend on component itself and other components respectively. On this background, advanced exergy analysis is defined as splitting exergy destruction into avoidable/unavoidable and endogenous/exogenous exergy destructions and their combinations [26]. The method is applied to a range of different energy utilizing and producing systems such as comparison of different gas turbine cycles [27], organic Rankine cycle (ORC) WHR system for an internal combustion engine [28], jet engines with after burner [29], combined cycle power plants [30, 31], aircraft gas turbine engines [32], an existing boiler of an industrial plant [33] and ultra-super critical power plant [34, 35]. Moreover, Fu et al applied splitting exergy destruction into endogenous and exogenous parts to define malfunctions and performance degradations in components, and applied their approach to an ultra-super critical steam power plant [36]. Trinidade et al, analyzed a steam power plant with incineration of solid waste as energy provider in Brazil [37]. They have presented that, the boiler has the highest share of exergy destruction and of which is mostly unavoidable endogenous. The turbine mostly has avoidable exergy destructions as significant and the higher share of exergy destruction is of avoidable exogenous. Pump has 48% of avoidable exergy destruction while huge amount of it is endogenous. Finally, most of the exergy destruction of the overall system is unavoidable. However, applications of the advanced exergy analysis on marine systems are relatively new. Koroglu and Sogut [38] investigated a steam WHR system for a very large crude carrier's two stroke diesel engine with respect to the ahead lever position and the feed water pressure. The results show that improvement efforts should be focused on different components than those determined by the conventional exergy analysis, and that WHR addition would lower the emissions up to 15% regarding to ship telegraph position. Later, they analyzed a superheated ORC WHR system of a marine power plant with four different organic fluids and four different lever positions, and results revealed that R113 is the most suitable fluid among others due to lower total unavoidable exergy destruction and higher exergy efficiency [4]. Afterwards, they applied the advanced exergy and advanced exergoeconomic analyses to two different ORC WHR systems of a marine power plant with superheated and saturated five different organic fluids [39]. The analyses resulted that saturated ORC system with R141B is a better option compared to superheated system.

In this paper, an advanced exergy analysis of a 17MW steam power plant of a crude oil carrier is carried out to provide detailed information on the improvement potential by using avoidable exergy destructions, the component performance effects by using endogenous exergy destruction and the component-to-component effects by using exogenous exergy destructions defined for the whole system. Also, combined exergy destructions will be evaluated to discover potential improvement related to component itself and inter-relations of components in depth. Finally, overall modified exergy efficiency and overall efficiency improvement percentage are introduced to provide better insight for improvement potential of the overall system under the influence of the investigated component.

2. Theoretical Method

2.1. *Conventional exergy analysis*

Exergy is the maximum theoretical useful work that could be obtained from a system that interacts only with its environment until thermodynamic equilibrium is achieved between the system and the environment or alternatively, exergy is the minimum theoretical useful work that could bring a system from environmental state to a specified state [12]. Exergy and specific exergy can be shown for a stream *j* as follows, when potential and kinetic exergies are neglected [39]:

$$\dot{Ex}_j \cong \dot{m}_j\left[\left(h_j - h_0\right) - T_0\left(s_j - s_0\right)\right] \; and \; ex_j = \dot{Ex}_j/\dot{m}_j, \quad (1a, 1b)$$

To analyze any component, fuel and product concept for exergy is applied, which described as the exergy of product is the desired exergetic change or output of the component or system and the exergy of fuel is required exergetic change or input to produce desired output. It is assumed that exergy loss only occurs at system level [12]:

$$\dot{Ex}_{F,tot} = \dot{Ex}_{P,tot} + \sum \dot{Ex}_{D,k} + \dot{Ex}_{L,tot}, \quad (2)$$

Thus, sum of exergy destructions of the components in the system is the total exergy destruction of the investigated system. So that, exergy destruction of a component *k* could be obtained as:

$$\dot{Ex}_{D,k} = \dot{Ex}_{F,k} - \dot{Ex}_{P,k}, \quad (3)$$

And exergy efficiency in general and can be calculated as:

$$\varepsilon = \frac{\dot{Ex}_P}{\dot{Ex}_F} \quad (4)$$

2.2. *Advanced exergy analysis*

Conventional exergy analysis could come short to highlight the real improvement potential of a whole system while evaluating each component and/or the interactions among different system components [34, 40]. Advanced exergy analysis has the potential to fill these types of gaps in all kinds of exergetic methods.

Due to technological limits and availability and cost of materials or manufacturing processes, there is a part of exergy destruction that cannot be decreased which is called *unavoidable exergy destruction*. Hence, there is also a part of exergy destruction which could be avoided and named *avoidable exergy destruction* [40]. For a component *k* avoidable exergy destruction could be calculated as:

$$\dot{Ex}_{D,k}^{AV} = \dot{Ex}_{D,k} - \dot{Ex}_{D,k}^{UN} \quad (5)$$

Building a cycle based on the theoretical cycle of a system that incorporates all the components at their unavoidable conditions would help to obtain unavoidable exergy destruction. The ratio of exergy destruction to product exergy for the component considered should be obtained first, while component is at unavoidable condition; then real product exergy of the component should be multiplied by this ratio to calculate the unavoidable exergy destruction of the component as follows [34]:

$$\dot{Ex}_{D,k}^{UN} = \dot{Ex}_{P,k}\left(\frac{\dot{Ex}_{D,k}}{\dot{Ex}_P}\right)_k^{UN} \quad (6)$$

Exergy destruction could occur due to imperfections and irreversibilities of component itself or under the influence of other components and overall system. *Endogenous exergy destruction* is calculated by hybrid cycles, that is when all components of whole system run at their theoretical conditions while investigated component is at its real condition. *Exogenous exergy destruction* is caused by interactions between investigated component and others and calculated as follows [33]:

$$\dot{E}x_{D,k}^{EX} = \dot{E}x_{D,k} - \dot{E}x_{D,k}^{EN} \quad (7)$$

Avoidable, unavoidable, endogenous and exogenous exergy destructions could be combined with each other, and named e.g. *unavoidable endogenous, avoidable endogenous*, *avoidable exogenous*, and *unavoidable exogenous* exergy destructions [26, 34]. Unavoidable endogenous exergy destruction is the inevitable part of endogenous exergy destruction, which cannot be eliminated by improving the investigated component.

$$Ex_{D,k}^{UN,EN} = \dot{E}_{P,k}^{EN} \left(\frac{\dot{E}x_{D,k}}{\dot{E}_P}\right)_k^{UN} \quad (8)$$

Avoidable endogenous exergy destruction is the avoidable part of exergy destruction due to component's improvement potential.

$$\dot{E}x_{D,k}^{AV,EN} = \dot{E}x_{D,k}^{EN} - \dot{E}x_{D,k}^{UN,EN} \quad (9)$$

Unavoidable exogenous exergy destruction is the effect of other components on the kth component, which is inevitable even all other components are improved.

$$\dot{E}x_{D,k}^{UN,EX} = \dot{E}x_{D,k}^{UN} - \dot{E}x_{D,k}^{UN,EN} \quad (10)$$

Avoidable exogenous exergy destruction is the avoidable exergy destruction due to improvements of other components.

$$\dot{E}x_{D,k}^{AV,EX} = \dot{E}x_{D,k}^{EX} - \dot{E}x_{D,k}^{UN,EX} \quad (11)$$

A new parameter which is called as the modified exergy efficiency is defined on the basis of the determined gain by advanced exergy analysis. Component-wise, it has been applied in several studies and it could be calculated as [4, 38, 41, 42]:

$$\varepsilon_k^* = \frac{\dot{E}x_{P,k}}{\dot{E}x_{F,k} - \dot{E}x_{D,k}^{AV}} \quad (12)$$

This efficiency could be used to observe the effect of avoided exergy destruction on the component itself. It can also be utilized to show the ultimate improvement in the overall system:

$$\varepsilon_{tot}^* = \frac{\dot{E}x_{P,tot}}{\dot{E}x_{F,tot} - \sum \dot{E}x_{D,k}^{AV}} \quad (14)$$

In addition, it is also necessary to determine the effect of the investigated component k on the overall system. For this purpose, the new modified exergy efficiency under the influence of the investigated component could be expressed as follows:

$$\varepsilon_{tot}^{*,k} = \frac{\dot{E}x_{P,tot}}{\dot{E}x_{F,tot} - \dot{E}x_{D,k}^{AV}} \quad (15)$$

Also, it is useful to see the contribution of the investigated component on the overall system efficiency. Hence, the percentage of the overall efficiency improvement could be obtained as:

$$EI = \frac{\varepsilon_{tot}^{*,k} - \varepsilon_{tot}}{\varepsilon_{tot}} \quad (16)$$

3. Marine power plant description

The investigated marine power plant belongs to a crude oil carrier, and produces 17MW of power and it is used to propel the vessel [43]. The system is based on the data provided for a crude oil carrier by Otto Geisler [44]. The steam power plant is considered to be operating at full load design conditions. Moreover, some of produced steam is designed to be utilized for domestic purposes. The power plant is shown on Fig. 1. It has three main turbines, namely high pressure (HPT), intermediate pressure (IPT) and low-pressure turbines (LPT). HPT has two and LPT has three stages and bleeding steam extraction points. System has a fresh water condenser and three pumps, namely, condensed feed water pump (CDP), feed water pump (FWP) and feed water main pump (FWMP). The plant has been simplified to let itself for theoretical analysis, while accommodating the essential available data of the real power plant. Some modifications include such as; combining two FWPHs, a deaerator is included for gas removal purposes and the boiler of the system has also a reheating duty. Finally, to satisfy the balance of system pressures, several valves have been added to the power plant layout. The system is re-organized and simulated in Ebsilon Professional Software for analyses, which is a commercial software that can be used to design, simulate, evaluate and optimize power systems [45].

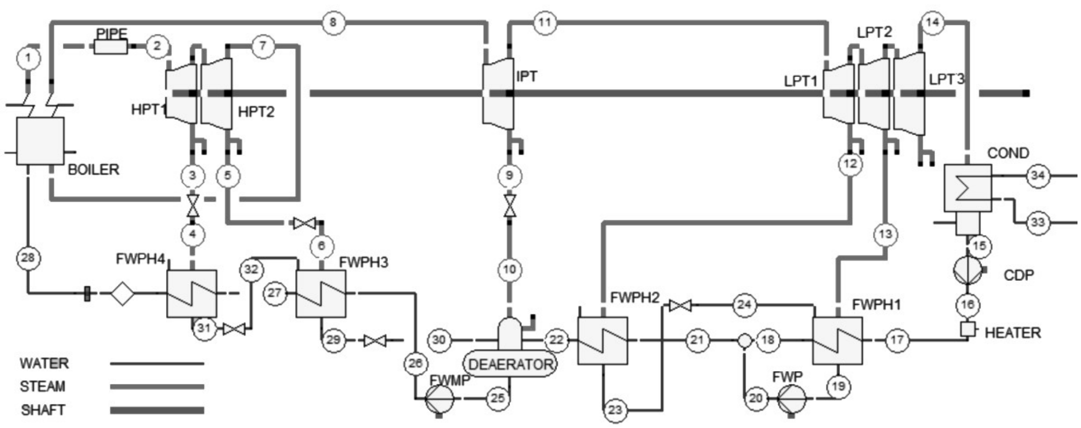

Figure 1: Layout of the investigated system

In Fig.1, water is heated to produce steam in the boiler (1) and by passing through the transfer pipe it loses some energy (2), then it is expanded in the first stage of high pressure turbine. The bleeding portion of steam (3) is sent to FWPH4 and the rest is continued to expand in the second stage. After bleeding steam extracted (5), the rest is reheated in the boiler (7). The reheated steam (8) produces power in IPT, and after expansion some of it is directed to the deaerator (9) and remaining part flows to the first LPT stage (11). At the end of first and second stage, some steam is extracted, and used as heating medium in FWPH2 and FWPH1, (12) and (13) respectively. Condenser cools the steam coming from the LPT third stage (14) by utilizing fresh water. CDP pumps condensed water through heater to FWPH1 (17) while bleeding steam is condensed and heated the feed water mixed with throttled outlet of FWPH2. FWP supplies power to saturated water and are connected to the feed water line before FWPH2 (18). Deaerator mixes and removes gases out of throttled steam coming from IPT, feed water from FWPH2 and throttled outlet of FWPH3. FWMP delivers deaerated feed water through FWPH3 and FWPH4, (26) and (27) where feed water receives more heat from first and second stage HPT bleeds and then the cycle is completed. The thermodynamic data of the investigated system can be seen on Table 1, where $\dot{m}$, *P, T, ex* are mass flow rate, pressure, temperature and specific exergy respectively.

Table 1: Thermodynamic properties of streams

Stream	$\dot{m}$ kg/s	P kPa	T K	ex kJ/kg	Stream	$\dot{m}$ kg/s	P kPa	T K	ex kJ/kg
1	15.593	10300	786.00	1497.53	18	10.947	520	354.23	28.09
2	15.593	10100	783.00	1491.73	19	1.491	60	358.93	31.43
3	1.055	3870	671.01	1259.32	20	1.491	520	358.98	31.93
4	1.055	3770	670.26	1256.02	21	12.438	520	354.80	28.54
5	1.679	2260	599.95	1119.12	22	12.438	520	392.37	64.75
6	1.679	2120	598.46	1111.01	23	0.808	240	399.07	72.23
7	12.859	2260	599.95	1119.12	24	0.808	60	358.93	64.97
8	12.859	2030	783.00	1343.40	25	15.593	520	426.32	107.74
9	0.421	560	614.95	975.13	26	15.593	10300	428.03	119.28
10	0.421	520	614.56	965.37	27	15.593	10300	483.35	208.33
11	12.438	560	614.95	975.13	28	15.593	10300	514.87	269.56
12	0.808	240	522.92	774.63	29	2.734	2120	488.35	210.75
13	0.683	60	399.97	503.93	30	2.734	520	426.32	197.13
14	10.947	5	305.88	138.53	31	1.055	3770	519.87	275.44
15	10.947	5	305.88	2.13	32	1.055	2120	488.35	271.57
16	10.947	520	305.92	2.66	33	3223.6	300	297.00	0.78
17	10.947	520	315.80	5.69	34	3223.6	300	298.90	1.04

Simplified system data has been closely adopted from reference [44], except mass flow rates of some streams for utility purposes. Since, domestic use of hot water also adds extra heat load to the original system, it is neglected in the simplified system. Moreover, the system is optimized topologically for component connections and positions. Some components are assumed to be free of pressure drop. Thus, some properties differ from the original values. Table 2 shows accuracy of some properties in the the simplified system .

Table 2: Accuracy of some properties in the simplified system

Property	Simplified	Original [44]	Property	Simplified	Original [44]
HPT inlet T	783 K	783 K	Boiler inlet T	515 K	520 K
HPT inlet P	10100 kPa	10100 kPa	FWMP outlet T	428 K	430 K
LPT inlet T	614.95 K	615 K	Specific Fuel Consumption	0.189 kg/kWh	0.232 kg/kWh
LPT inlet P	560 kPa	560 kPa	Produced Power	17MW	17 MW

4. Analysis

Energy analyses are carried out using thermodynamic data given in Table 1 to determine the operating conditions such as pressure drop, temperature difference, boiler efficiency and isentropic efficiency. Moreover, marine fuel oil is burnt in the boiler and heater, and efficiencies of aforementioned components are taken from the reference system [43]. Unavoidable conditions are determined from literature and some of them are based on expert opinion [33, 34, 46]. Theoretical conditions are given either at zero exergy destruction or minimum exergy destruction conditions [34] and given in Table 3 for real and unavoidable conditions.

Table 3: Real, Unavoidable and theoretical conditions of components [34, 46].

Comp	Real	Unavoidable	Theoretical	Comp	Real	Unavoidable	Theoretical
PIPE	$\Delta P = 100$ $\Delta T = 3$	$\Delta P = 100$ $\Delta T = 1$	$\Delta P = 0$ $\Delta T = 0$	FWPH1	$\Delta T = 4.7$	$\Delta T = 2.5$	$\Delta T = 0$
HPT1	$\eta = 0.65$	$\eta = 0.8$	$\eta = 1$	FWP	$\eta = 0.83$	$\eta = 0.91$	$\eta = 1$
HPT2	$\eta = 0.89$	$\eta = 0.92$	$\eta = 1$	FWPH2	$\Delta T = 6.7$	$\Delta T = 4.5$	$\Delta T = 0$
IPT	$\eta = 0.85$	$\eta = 0.9$	$\eta = 1$	FWMP	$\eta = 0.80$	$\eta = 0.87$	$\eta = 1$
LPT1	$\eta = 0.83$	$\eta = 0.88$	$\eta = 1$	FWPH3	$\Delta T = 5$	$\Delta T = 2.5$	$\Delta T = 0$
LPT2	$\eta = 0.83$	$\eta = 0.88$	$\eta = 1$	FWPH4	$\Delta T = 5$	$\Delta T = 2.5$	$\Delta T = 0$
LPT3	$\eta = 0.70$	$\eta = 0.84$	$\eta = 1$	HEATER	$\eta = 0.91$	$\eta = 0.96$	$\eta = 1$
COND	$\Delta T = 6.98$	$\Delta T = 3$	$\Delta T = 0$	BOILER	$\Delta P = 230$ $\eta = 0.91$	$\Delta P = 100$ $\eta = 0.96$	$\Delta P = 0$ $\eta = 1$
CDP	$\eta = 0.82$	$\eta = 0.87$	$\eta = 1$				

Theoretical and unavoidable cycles are generated with respect to conditions given in Table 3. Hybrid cycles as well as theoretical and unavoidable cycles are simulated while produced power is kept constant [38].

Assumptions have been made to analyze the system. Pressure drops on components are neglected. Lower heating value (LHV) is assumed as 43038 kJ/kg [43, 44] and exergy of fuel oil is assumed as LHV multiplied by 1.07 as in previous works [47, 48]. Mass flow rates of the consumed fuel are calculated via energy analysis for both of heater and boiler. Environmental conditions are assumed as 288 K and 100 kPa [48]. Secondary stream outlet, known as bleeding steam outlet is assumed as saturated water for all conditions. Deaerator and valves are assumed as dissipative components, because they do not have an adjustable parameter in the system.

Fuel and product exergy equations for investigated components are given in Table 4.

Table 4: Fuel and product exergy equations for each investigated component

Comp	$\dot{E}x_F$	$\dot{E}x_P$
PIPE	$\dot{E}x_1$	$\dot{E}x_2$
HPT1	$\dot{E}x_2 - \dot{m}_2 ex_3$	$\dot{W}_{HPT1}$
HPT2	$(\dot{m}_2 - \dot{m}_3)ex_3 - (\dot{E}x_5 + \dot{E}x_7)$	$\dot{W}_{HPT2}$
IPT	$\dot{E}x_8 - (\dot{E}x_9 + \dot{E}x_{11})$	$\dot{W}_{IPT}$

LPT1	$\dot{E}x_{11} - (\dot{m}_{11}ex_{12})$	$\dot{W}_{LPT1}$
LPT2	$(\dot{m}_{11} - \dot{m}_{12})(ex_{12} - ex_{13})$	$\dot{W}_{LPT2}$
LPT3	$(\dot{m}_{11} - \dot{m}_{12} - \dot{m}_{13})ex_{13} - \dot{E}x_{14}$	$\dot{W}_{LPT3}$
COND	$\dot{E}x_{14} - \dot{E}x_{15}$	$\dot{E}x_{34} - \dot{E}x_{33}$
CDP	$\dot{W}_{CDP}$	$\dot{E}x_{16} - \dot{E}x_{15}$
FWPH1	$(\dot{E}x_{13} + \dot{E}x_{24}) - \dot{E}x_{19}$	$\dot{E}x_{18} - \dot{E}x_{17}$
FWP	$\dot{W}_{FWP}$	$\dot{E}x_{20} - \dot{E}x_{19}$
FWPH2	$\dot{E}x_{12} - \dot{E}x_{23}$	$\dot{E}x_{21} - \dot{E}x_{22}$
FWMP	$\dot{W}_{FWMP}$	$\dot{E}x_{26} - \dot{E}x_{25}$
FWPH3	$(\dot{E}x_{6} + \dot{E}x_{32}) - \dot{E}x_{29}$	$\dot{E}x_{27} - \dot{E}x_{26}$
FWPH4	$\dot{E}x_{4} - \dot{E}x_{31}$	$\dot{E}x_{28} - \dot{E}x_{27}$
HEATER	$1.07(\dot{m}_{f,H})LHV_f/\eta_B$	$\dot{E}x_{17} - \dot{E}x_{16}$
BOILER	$1.07(\dot{m}_{f,B})LHV_f/\eta_B$	$(\dot{E}x_{1} - \dot{E}x_{28}) + (\dot{E}x_{8} - \dot{E}x_{7})$

5. Results and Discussion

5.1. Conventional exergy analysis

Table 5 shows the findings of marine steam power plant for conventional exergy analysis. The main exergy input is in the boiler; hence it has the highest fuel exergy. Pumps have the smallest exergy of fuel due to pumping water, which has relatively small specific volume. Moreover, they have the smallest exergy destructions in the system. Among these, FWMP has the highest share of fuel, product exergy and exergy destruction due to pumping the highest mass flow rate of the working fluid.

Table 5: Conventional exergy analysis results of the investigated system

Component	$\dot{E}x_F$ [kW]	$\dot{E}x_P$ [kW]	$\dot{E}x_D$ [kW]	ε [%]
PIPE	23350.98	23260.62	90.361	99.6130
HPT1	3624.11	2926.09	698.013	80.7397
HPT2	2038.30	1923.98	114.313	94.3917
IPT	4735.57	4368.35	367.225	92.2454
LPT1	2493.90	2243.46	250.400	89.9579
LPT2	3148.33	2737.97	410.363	86.9657
LPT3	4000.04	2862.05	1137.99	71.5506
COND	1493.12	853.011	640.107	57.1295
CDP	6.928	5.741	1.187	82.8637
FWPH1	350.012	245.275	104.737	70.0761

FWP	0.8504	0.7366	0.1137	86.6181
FWPH2	567.470	450.310	117.160	79.3539
FWMP	207.707	179.927	27.780	86.6252
FWPH3	1576.11	1388.61	187.503	88.1034
FWPH4	1034.06	954.767	79.293	92.3318
Boiler	49432.61	22031.69	27400.92	44.5691
Heater	531.532	33.188	498.344	6.2439
TOTAL	49964.12	17061.90	32125.84	34.1483

Fig. 2 shows the amount of produced power and exergy destructions of turbine stages as stacks. Top points of stacks represent exergy of fuel for each turbine stage.

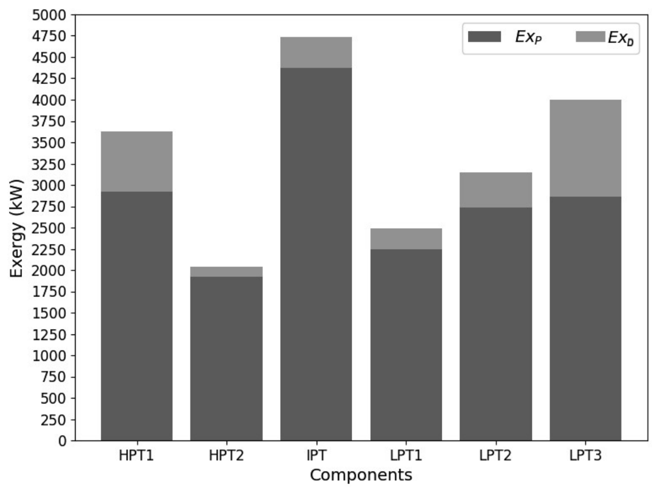

Figure 2: Produced powers and exergy destructions of turbine stages

It is clear that IPT has the highest power production together with an average exergy destruction. Compared to HPTs, it has higher efficiency than HPT1 and its inlet temperature is higher that HPT2 in spite of its efficiency is lower. Inlet-outlet pressure ratio of the LPT3 is the highest, hence its power production is higher than HPT2, LPT1 and LPT2. Moreover, its exergy destruction is the highest due to having lower isentropic efficiency. Although, the lowest isentropic efficiency belongs to HPT1, it produces slightly higher power than LPT3 due to having high temperature and pressure steam with high mass flow rate. The lowest exergy destruction belongs to HPT2. The reason for that it has the highest isentropic efficiency.

Fig. 3 represents the exergy of product and destruction of FWPH network. Top points of the stacks are equal to the exergy of fuel for each FWPH.

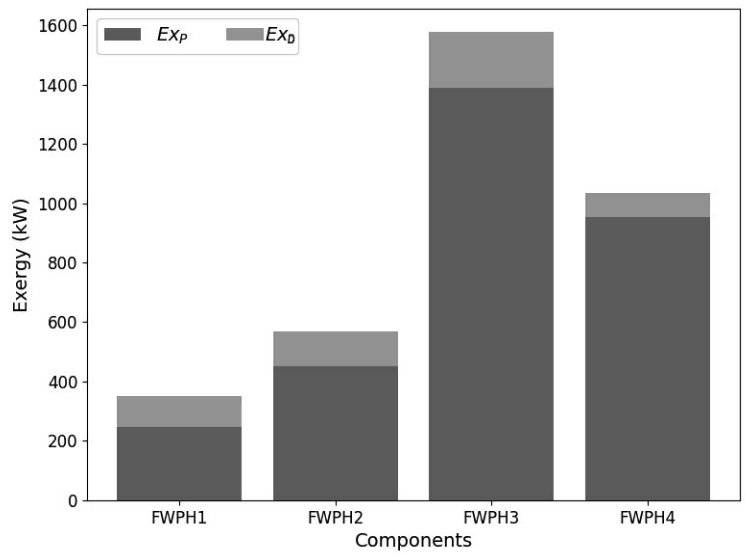

Figure 3: Exergy given to the feed water and exergy destruction of FWPHs

The exergy transferred to the feed water is the highest at FWPH3 due to the highest temperature increase of the feed water, however it is the component with the highest exergy destruction due to mixing of two secondary inlets. FWPH1 has the lowest exergy transfer, because of temperature difference of the secondary stream inlet and primary stream outlet is relatively small. The lowest exergy destruction is observed in the FWPH4 related to the lowest temperature change between the primary inlet and outlet.

Fig. 4 shows the exergy destruction ratio of investigated components. It is clear that Boiler has the highest exergy destruction ratio of around 85% due to chemical reactions within. The second highest exergy destruction ratio is 3.5% in LPT3 because of expanding of the low quality steam and also the turbine having low isentropic efficiency. And the rest of the exergy destruction ratios has the total of 11.5% and the order from the highest is as HPT1, COND, Heater, LPT2, IPT, LPT1, FWPH3, FWPH2, HPT2, FWPH1, PIPE, FWPH4, FWMP, CDP and FWP, respectively. Exergy destruction ratios of CDP and FWP are too small to be seen in Fig. 4. Exergy destructions for pumps and turbines are essentially due to their isentropic efficiencies, which represent the direct effect of design considerations and the wear and tear of components. Similarly, design considerations have utmost influence on the efficiency of heat transfer in heat exchangers. Increasing the heat transfer surface area of heat exchangers can lead more efficient heat transfer, but the design must take economic and spatial constraints into account, especially for marine vessels.

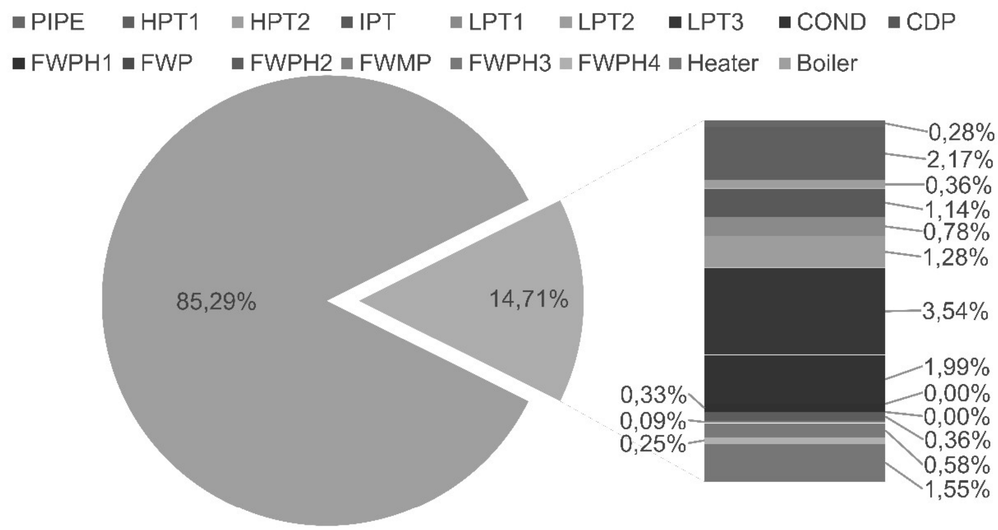

Figure 4: Exergy destruction percentages of investigated components

Finally, the lowest exergy efficiency is observed in the Heater. This is because of the fact that saturated water has higher entropy, and also the heater efficiency is 91%. There is a great difference between the first and the second lowest exergy efficiencies. Despite of chemical reactions, Boiler has an exergy efficiency of 44%. It could be concluded in the same reasoning as steam has smaller entropy. In contrast, the highest efficiency belongs to pipe due to smaller exergy destruction related to its fuel exergy. The second highest exergy efficiency calculated for the HPT2 as it has the highest isentropic efficiency. Exergy efficiencies of other components vary between 57-92% as can be seen on Table 5. Exergy efficiency of the marine steam power plant system is 34.15%, which indicates a room for improvement.

5.2. Advanced exergy analysis

The results of the conventional exergy analyses can be considered as input to the advanced exergy analysis. Hence, they are applied in sequence. Table 6 represents the results of advanced exergy analysis of the marine steam power plant.

Table 6: Advanced exergy analysis results of the marine steam power plant [kW]

Comp	$\dot{Ex}_{D,k}^{UN}$	$\dot{Ex}_{D,k}^{AV}$	$\dot{Ex}_{D,k}^{EN}$	$\dot{Ex}_{D,k}^{EX}$	$\dot{Ex}_{D,k}^{UNEN}$	$\dot{Ex}_{D,k}^{UNEX}$	$\dot{Ex}_{D,k}^{AVEN}$	$\dot{Ex}_{D,k}^{AVEX}$	$\varepsilon_{tot}^{*,k}$[%]	EI [%]
PIPE	32.390	57.971	73.845	16.515	26.470	5.9200	47.375	10.595	34,188	0,116
HPT1	328.66	369.36	618.14	79.874	291.07	37.585	327.07	42.289	34,402	0,744
HPT2	83.14	31.171	91.822	22.492	62.562	20.581	29.260	1.9104	34,169	0,062
IPT	237.89	129.34	324.79	42.440	205.67	32.218	119.12	10.222	34.236	0.259
LPT1	177.33	73.106	203.25	47.193	133.54	43.794	69.706	3.3991	34.198	0.146
LPT2	290.81	119.55	322.80	87.563	211.76	79.056	111.04	8.5073	34.230	0.239
LPT3	513.40	624.58	888.89	249.10	401.03	112.38	487.86	136.72	34.580	1.265
COND	400.44	239.67	457.80	182.31	286.39	114.05	171.41	68.259	34.312	0.482
CDP	0.8007	0.3865	0.9353	0.2518	0.6308	0.1698	0.3045	0.0820	34.148	0.000
FWPH1	96.261	8.4759	80.805	23.933	75.981	20.281	4.8238	3.6521	34.154	0.017

FWP	0.0573	0.0564	0.1041	0.0096	0.0525	0.0049	0.0516	0.0048	34.148	0.000
FWPH2	101.93	15.229	68.278	48.882	73.537	28.394	-5.2591	20.488	34.158	0.030
FWMP	17.269	10.511	22.577	5.2035	14.035	3.2347	8.5423	1.9688	34.155	0.021
FWPH3	174.33	13.176	142.92	44.580	143.27	31.056	-0.3478	13.524	34.157	0.026
FWPH4	67.511	11.782	41.976	37.317	46.244	21.267	-4.2676	16.050	34.156	0.023
Boiler	24597.1	2803.7	22919.9	4481.0	20567.3	4029.7	2352.5	451.25	36.178	5.945
Heater	470.75	27.590	393.75	104.59	371.73	99.029	22.024	5.5665	34.167	0.055
TOTAL	27590.1	4535.7	26652.5	5473.2	22911.3	4678.7	3741.2	794.49	37.557	9.984

Fig. 5 shows the avoidable and unavoidable exergy destruction percentages of the investigated components. Component-wise, it could be seen that the unavoidable part of the exergy destruction is higher than 50% for most of the components. Only 15% of the total exergy destruction of the marine steam power plant is avoidable. The highest unavoidable exergy destruction percentage belongs to heater, however its avoidable exergy destruction amount is higher than seven other components namely, CDP, FWPHs, FWP, and FWMP. Similar case can be observed with the Boiler, even its avoidable percentage is low, it has the highest avoidable exergy destruction value, which is more than half of the total avoidable exergy destruction of the marine steam power plant. With respect to boiler and heater, controlling the chemical reactions and the heat transfer phenomenon are not an easy task, hence their unavoidable exergy destruction percentages are high. Nevertheless, the improvement efforts should focus on the Boiler first. Alternative chemical reactions and systems such as chemical loop combustion are recommended to lower the unavoidable part in both heater and boiler. Moreover, heat transfer in the boiler and heater could be improved by improving materials. FWP has the smallest avoidable exergy destruction as seen on Table 6. PIPE has the highest avoidable exergy destruction percentage. In reality, it has 58 kW to be recovered by insulating and smoothing the roughness of the investigated pipe. LPT3 has the second highest improvement potential, almost twice than HPT1, which has the third highest avoidable exergy destruction. Improvement of turbines could be obtained by improving their operating conditions, i.e. inlet temperature and pressure, and design and construction materials for turbine blades The focus of improvement should be on the rest of the components as, COND, IPT, LPT2, LPT1, PIPE, HPT2, Heater, FWPH2, FWPH3, FWPH4, FWMP, FWPH1, CDP and FWP respectively. Heat exchangers such as Condenser and FWPHs could be improved by changing the materials used within components, and increasing their heat transfer surface area. It may be recommended to replace pumps with more efficient alternatives, which are optimal for operating conditions. Overall, if any leakages occur in the system components, they should be sealed to avoid pressure drops, working fluid and energy loss.

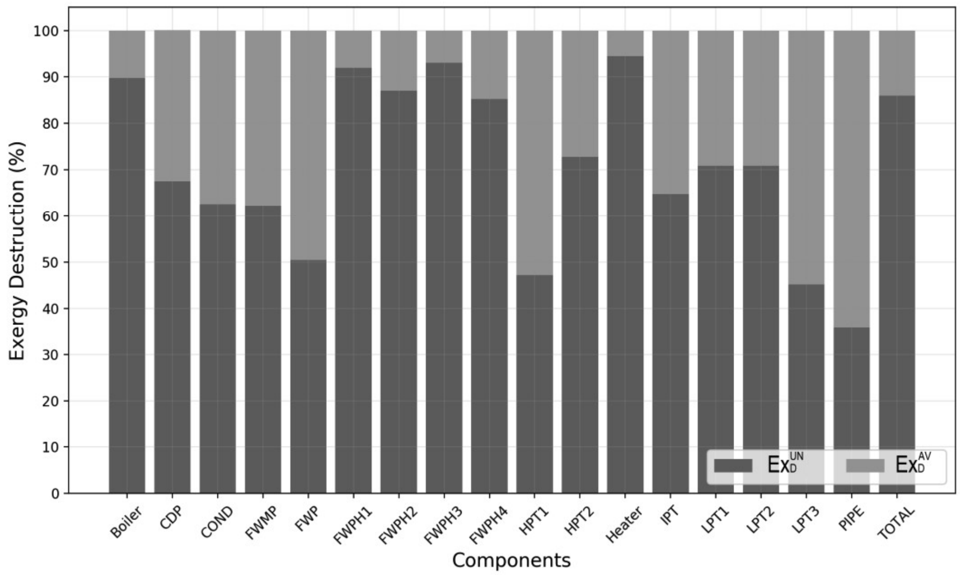

Figure 5: Avoidable and Unavoidable exergy destruction percentages of components

Fig. 6 shows the percentages of endogenous and exogenous exergy destructions of the investigated components. It can be seen that for the most of the components, consequently for whole of the system, the higher percentage of exergy destruction is endogenous. Interactions among components have lower effect on the components and the system. FWP has the highest endogenous exergy destruction percentage (91%). In contrast, FWPH4 has the lowest (52%). Focusing on the Boiler suggests also to improve endogenous exergy destruction with the highest rate at 22920 kW. Moreover, the highest exogenous exergy destruction belongs to this component which is almost 8 times more than the closest value of exogenous exergy destruction of LPT3. Second highest endogenous and exogenous exergy destructions belong to LPT3. While COND have less endogenous exergy destruction than that of HPT1, it has more exogenous exergy destruction. This could be explained as COND is under the influence of the other components, especially by LPT3, more than HPT1, while HPT1 is barely under the influence of the Boiler. FWP, on the other hand, has the lowest endogenous and exogenous exergy destructions.

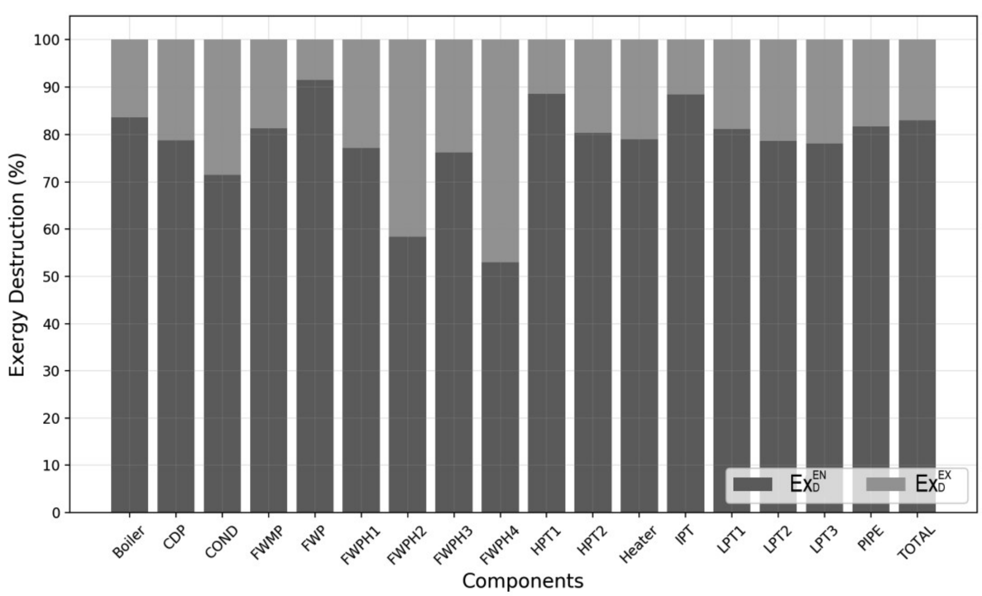

Figure 6: Endogenous and exogenous exergy destruction percentages of components

Finally, Fig. 7 shows the combined exergy destruction percentages while Fig. 8 shows the endogenous and exogenous shares of avoidable exergy destruction of the investigated components as well as the overall system. On Fig. 7, if no comparison of alternative systems is made, the engineer should focus on red and green bars, which are avoidable endogenous and avoidable exogenous exergy destructions of the investigated components and the overall system, respectively. It represents the influences of irreversibilities of the component itself and the rest of the components on improving potential for the investigated component. The portion of avoidable exogenous exergy for the overall system is the smallest compared to other constituents. In general, one should focus on components themselves instead of improving the overall plant layout. Although, the share of avoidable endogenous exergy destruction for the marine steam power plant is smaller compared to unavoidable portions, it is still higher than avoidable exogenous portion. Component-wise, pipe has the highest percentage of the avoidable endogenous exergy destruction compared to all other components. The avoidable effect of the boiler as exogenous exergy destruction percentage over the pipe is smaller. Almost nothing could be avoided from the Heater with either internal or external improvements. Internal improvement such as improving the isentropic efficiency of the FWP would recover a high percentage of the exergy destruction as it can be seen in Fig. 7, but according to Table 6, it has the smallest improvement potential either internally or externally.

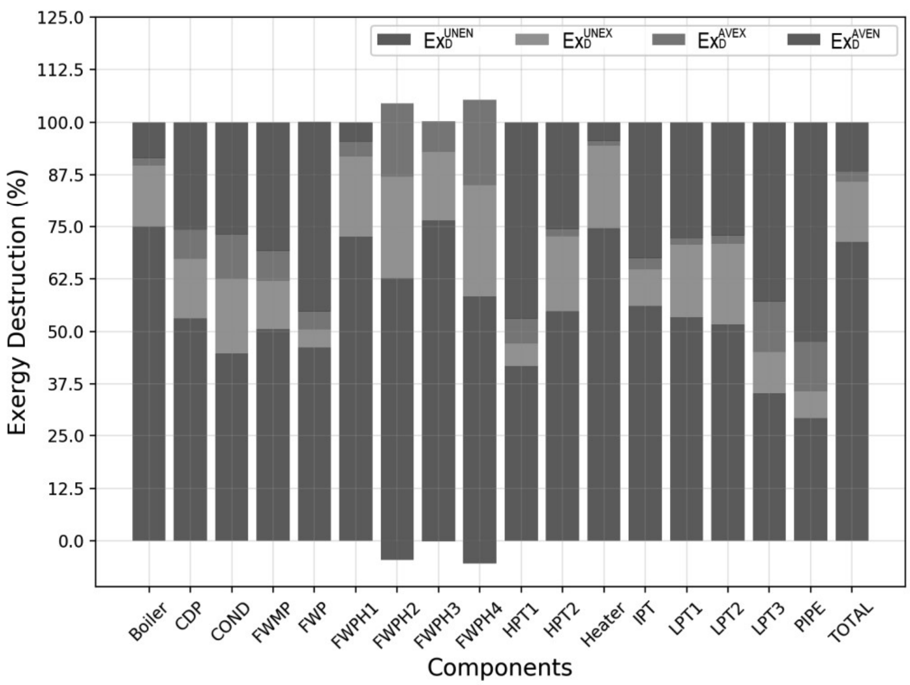

Figure 7: Percentages of combined exergy destructions of components and the system

Though the Boiler seems to have relatively small percentages of the room for improvement, also smaller influence to the other components, it has the highest share of endogenous and also exogenous avoidable exergy destruction among all, which are 82.5% and 17.5% of the avoidable exergy destruction respectively. LPT has the second highest avoidable endogenous and exogenous exergy destructions, furthermore, 78% of the avoidable exergy destruction of the mentioned component is avoidable. Endogenous share of the avoidable exergy destruction as percentage belongs to LPT1 with 95%. Improving interactions among components would improve the LPT1 by only 5%. Improvement of FWPH1 is almost equally shared by both endogenous and exogenous avoidable exergy destructions. Other FWPHs have negative avoidable endogenous exergy destructions as it could be seen on both Table 6, Fig. 7 and Fig. 8. This situation occurs due to the change of mass flow rates between the conditions. Furthermore, it also shows that the influence of other components to recover the exergy destructions of FWPHs is far more influential than component's own improvements. The focus should be on the components for internal improvement as Boiler, LPT3, HPT1, COND, IPT, LPT2, LPT1, PIPE, HPT2, Heater, FWMP, FWPH1, CDP, FWP, respectively.

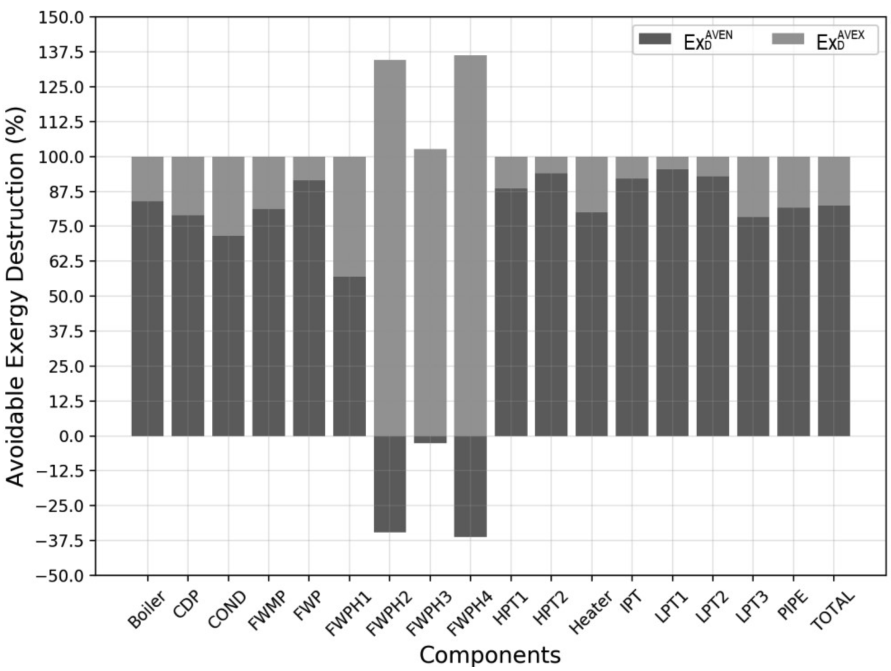

Figure 8: Shares of endogenous and exogenous parts in avoidable exergy destruction

The last two columns in Table 6 represent the introduced new overall modified exergy efficiency influenced by investigated components and efficiency improvement potential percentage of the overall system to put the contribution of this study in perspective. The overall system has almost 10% of exergy efficiency improvement. Almost 6% of the efficiency improvement potential belongs to boiler. It is followed by LPT3 with 1.3%. Other components have smaller effects on overall system which are lower than 1% individually. Hence the improvement efforts should be on boiler and LPT 3 to observe direct efficiency increase of the overall system. Other components have relatively low influence with a similar order of avoidable exergy destruction results.

6. Conclusions

This study reports the conventional and advanced exergy analyses of a steam power plant of a crude oil carrier to reveal the inefficiencies, sources and improvement potentials of components, and of the overall system. The system is simplified to carry out a thermodynamic analysis with available data.

Conventional exergy analysis revealed that the highest exergy destruction belongs to the boiler of the marine steam power plant. Other components share the rest of destruction. The results suggest that the improvement efforts should be focused on Boiler, LPT3, HPT1, COND, Heater, LPT2, IPT, LPT1, FWPH3, FWPH2, HPT2, FWPH1, PIPE, FWPH4, FWMP, CDP and FWP respectively.

The results of advanced exergy analysis show that the most of the exergy destruction in the components are unavoidable. 86% of the total exergy destruction in the marine steam power plant is unavoidable. Due to the highest share of exergy destruction, 89% of the exergy destruction of the boiler is unavoidable. Nevertheless, it still has the highest avoidable exergy destruction among all. After the first four mutual components as Boiler, LPT3, HPT1, COND, the focus to improve the system is to be on IPT, LPT2, LPT1, PIPE, HPT2, Heater, FWPH2, FWPH3, FWPH4, FWMP, FWPH1, CDP and FWP respectively.

When the exergy destruction sources are considered, all of the components, consequently the overall system have more endogenous than exogenous exergy destruction. Thus, interactions among components have lower influence than components themselves in general. The subject of interest for the engineer is combination of avoidable exergy destruction with its sources as avoidable endogenous and avoidable exogenous exergy destructions.

Efficiency improvement percentage revealed that overall system has a 10% improvement potential and almost three quarter of this potential could be recovered by improving two components namely boiler and LPT3 with 6% and 1.3% respectively. Improving exergy efficiency of the overall system will lead to decreasing the total exergy of fuel, hence the fuel consumption. Consequently, it will help to meet obligatory regulations of IMO.

To conclude, it can be said that the advanced exergy analysis which reveals the avoidable exergy destructions for each component enhanced with the ability of determining the effect of improving an individual component on the efficiency improvement potential of the overall system provides more insight than conventional exergy analysis to analyze power production systems.

7. Acknowledgements

Authors would like to thank the reviewers for their invaluable comments to improve the quality of the article.

8. References

1. UNCTAD. Review of Maritime Transport 2016. Switzerland: 2016 UNCTAD/RMT/2016 Contract No.: UNCTAD/RMT/2016.
2. Bazari Z, Longva T. Assessment of IMO mandated energy efficiency measures for international shipping. International Maritime Organization. 2011.
3. Buhaug Ø, Corbett J, Endresen Ø, Eyring V, Faber J, Hanayama S, et al. Second IMO GHG Study. International Maritime Organization (IMO), London, UK. 2009.
4. Koroglu T, Sogut OS. Advanced exergy analysis of an organic Rankine cycle waste heat recovery system of a marine power plant. Journal of Thermal Engineering. 2017;3(2):1136-48. 10.18186/thermal.298614.
5. Morsy El-Gohary M. Overview of past, present and future marine power plants. Journal of Marine Science and Application. 2013;12(2):219-27. 10.1007/s11804-013-1188-8.

6. Haglind F. A review on the use of gas and steam turbine combined cycles as prime movers for large ships. Part II: Previous work and implications. Energy Conversion and Management. 2008;49(12):3468-75. https://doi.org/10.1016/j.enconman.2008.08.004.
7. Somes AD. Advances in Steam Turbines for Marine Propulsion. Journal of Engineering for Power. 1961;83(1):108-18. 10.1115/1.3673088.
8. Wärtsilä. Solution for merchant vessels. In: Corporation Wr, editor. 2010.
9. MAN Diesel&Turbo. Waste heat recovery system (WHRS) for reduction of fuel consumption, emissions and EEDI. MAN Diesel, Augsburg, Germany, 2014 August. Report No.
10. Ma Z, Yang D, Guo Q. Conceptual design and performance analysis of an exhaust gas waste heat recovery system for a 10000 TEU container ship. Polish Maritime Research. 2012;19(2):31-8.
11. Theotokatos G, Livanos G. Techno-economical analysis of single pressure exhaust gas waste heat recovery systems in marine propulsion plants. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment. 2013;227(2):83-97. 10.1177/1475090212457894.
12. Bejan A, Moran MJ, Tsatsaronis G. Thermal design and optimization: Wiley. com; 1996.
13. Poljak I, Mrzljak V, Blažević S, editors. Change of exergy motion in the marine steam plant with main shaft speed variation. XXV International Scientific Conference trans & MOTAUTO'17; 2017 28 Jun - 01 Jul; Burgas, Bulgaria.
14. Mrzljak V, Poljak I, Medica-Viola V. Dual fuel consumption and efficiency of marine steam generators for the propulsion of LNG carrier. Applied Thermal Engineering. 2017;119(Supplement C):331-46. https://doi.org/10.1016/j.applthermaleng.2017.03.078.
15. Mrzljak V, Poljak I, Mrakovčić T. Energy and exergy analysis of the turbo-generators and steam turbine for the main feed water pump drive on LNG carrier. Energy Conversion and Management. 2017;140(Supplement C):307-23. https://doi.org/10.1016/j.enconman.2017.03.007.
16. Mrzljak V, Poljak I, Medica-Viola V. Thermodynamical analysis of high-pressure feed water heater in steam propulsion system during exploitation. Brodogradnja. 2017;68(2):45-61.
17. Ekanem Attah E, Bucknall R. An analysis of the energy efficiency of LNG ships powering options using the EEDI. Ocean Engineering. 2015;110(Part B):62-74. https://doi.org/10.1016/j.oceaneng.2015.09.040.
18. Olszewski W. Possible use of combined Diesel engine/steam turbine systems in ship power plants. Zeszyty Naukowe/Akademia Morska w Szczecinie. 2011:88-94.
19. Dzida M, Olszewski W. Comparing combined gas tubrine/steam turbine and marine low speed piston engine/steam turbine systems in naval applications. Polish maritime research. 2011:43-8.
20. Jefferson M, Zhou P, Hindmarch G. Analysis by computer simulation of a combined gas turbine and steam turbine (COGAS) system for marine propulsion. Journal of Marine Engineering & Technology. 2003;2(1):43-53.
21. Mito MT, Teamah MA, El-Maghlany WM, Shehata AI. Utilizing the scavenge air cooling in improving the performance of marine diesel engine waste heat recovery systems. Energy. 2018;142(Supplement C):264-76. https://doi.org/10.1016/j.energy.2017.10.039.
22. Benvenuto G, Campora U, Trucco A. Comparison of ship plant layouts for power and propulsion systems with energy recovery. Journal of Marine Engineering & Technology. 2014;13(3):3-15. 10.1080/20464177.2014.11658117.

23. Feng X, Zhu X, Zheng J, editors. A practical exergy method for system analysis. Energy Conversion Engineering Conference, 1996 IECEC 96, Proceedings of the 31st Intersociety; 1996: IEEE.
24. Feng X, Zhu XX. Combining pinch and exergy analysis for process modifications. Applied Thermal Engineering. 1997;17(3):249-61. http://dx.doi.org/10.1016/S1359-4311(96)00035-X.
25. Tsatsaronis G. Strengths and limitations of exergy analysis. Thermodynamic optimization of complex energy systems: Springer; 1999. p. 93-100.
26. Morosuk T, Tsatsaronis G. A new approach to the exergy analysis of absorption refrigeration machines. Energy. 2008;33(6):890-907.
27. Fallah M, Siyahi H, Ghiasi RA, Mahmoudi SMS, Yari M, Rosen MA. Comparison of different gas turbine cycles and advanced exergy analysis of the most effective. Energy. 2016;116(Part 1):701-15. https://doi.org/10.1016/j.energy.2016.10.009.
28. Galindo J, Ruiz S, Dolz V, Royo-Pascual L. Advanced exergy analysis for a bottoming organic rankine cycle coupled to an internal combustion engine. Energy Conversion and Management. 2016;126(Supplement C):217-27. https://doi.org/10.1016/j.enconman.2016.07.080.
29. Balli O. Advanced exergy analyses to evaluate the performance of a military aircraft turbojet engine (TJE) with afterburner system: Splitting exergy destruction into unavoidable/avoidable and endogenous/exogenous. Applied Thermal Engineering. 2017;111(Supplement C):152-69. https://doi.org/10.1016/j.applthermaleng.2016.09.036.
30. Boyaghchi FA, Molaie H. Sensitivity analysis of exergy destruction in a real combined cycle power plant based on advanced exergy method. Energy Conversion and Management. 2015;99(Supplement C):374-86. https://doi.org/10.1016/j.enconman.2015.04.048.
31. Petrakopoulou F, Tsatsaronis G, Morosuk T, Carassai A. Conventional and advanced exergetic analyses applied to a combined cycle power plant. Energy. 2012;41(1):146-52.
32. Şöhret Y, Açıkkalp E, Hepbasli A, Karakoc TH. Advanced exergy analysis of an aircraft gas turbine engine: Splitting exergy destructions into parts. Energy. 2015;90(Part 2):1219-28. https://doi.org/10.1016/j.energy.2015.06.071.
33. Vučković GD, Stojiljković MM, Vukić MV. First and second level of exergy destruction splitting in advanced exergy analysis for an existing boiler. Energy Conversion and Management. 2015;104(Supplement C):8-16. https://doi.org/10.1016/j.enconman.2015.06.001.
34. Yang Y, Wang L, Dong C, Xu G, Morosuk T, Tsatsaronis G. Comprehensive exergy-based evaluation and parametric study of a coal-fired ultra-supercritical power plant. Applied Energy. 2013;112:1087-99.
35. Zhu Y, Zhai R, Peng H, Yang Y. Exergy destruction analysis of solar tower aided coal-fired power generation system using exergy and advanced exergetic methods. Applied Thermal Engineering. 2016;108:339-46. https://doi.org/10.1016/j.applthermaleng.2016.07.116.
36. Fu P, Wang N, Wang L, Morosuk T, Yang Y, Tsatsaronis G. Performance degradation diagnosis of thermal power plants: A method based on advanced exergy analysis. Energy Conversion and Management. 2016;130:219-29. https://doi.org/10.1016/j.enconman.2016.10.054.
37. Trindade AB, Palacio JCE, González AM, Rúa Orozco DJ, Lora EES, Renó MLG, et al. Advanced exergy analysis and environmental assesment of the steam cycle of an incineration system of municipal solid waste with energy recovery. Energy Conversion and Management. 2018;157:195-214. https://doi.org/10.1016/j.enconman.2017.11.083.

38. Koroglu T, Sogut OS. Advanced exergy analysis of a Marine Diesel Engine waste heat recovery system. In: Turan O, Day S, Incecik A, Banks C, Demirel YK, Howett B, editors. International Conference on Shipping in Changing Climates; 24-26th November; Glasgow. Glasgow Scotland United Kingdom: University of Stratclyde; 2015. p. 521-33.
39. Koroglu T, Sogut O. Advanced Exergoeconomic Analysis of Organic Rankine Cycle Waste Heat Recovery System of a Marine Power Plant. International Journal of Thermodynamics. 2017;20(3):140-51.
40. Tsatsaronis G, Morosuk T. Understanding and improving energy conversion systems with the aid of exergy–based methods. International Journal of Exergy. 2012;11(4):518-42.
41. Kelly S. Energy systems improvement based on endogenous and exogenous exergy destruction. Berlin: Technische Universität Berlin; 2008.
42. Vučković GD, Vukić MV, Stojiljković MM, Vučković DD. Avoidable and unavoidable exergy destruction and exergoeconomic evaluation of the thermal processes in a real industrial plant. Thermal Science. 2012;16(suppl. 2):433-46.
43. Çiçek AN. Exergy analysis of a crude oil carrier steam plant [MSc]. Istanbul: Istanbul Technical University; 2009.
44. Geisler O. Schiffsdampfanlagen. Hamburg: Technische Universitat Hamburg-Harburg; 1990.
45. STEAG. EBSILON®Professional. 11 ed. Essen, Germany: STEAG Energy Services GmbH; 2015.
46. Tsatsaronis G, Morosuk T, Koch D, Sorgenfrei M. Understanding the thermodynamic inefficiencies in combustion processes. Energy. 2013;62:3-11. https://doi.org/10.1016/j.energy.2013.04.075.
47. Kotas TJ. The exergy method of thermal plant analysis. Florida, USA: Krieger Publishing Company; 1995.
48. Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical, and metallurgical processes: Hemisphere; 1988.