Developing Criteria for Advanced Exergoeconomic Performance Analysis of Thermal Energy Systems: Application to A Marine Steam Power Plant

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Abstract:

Advanced exergoeconomic analysis is a powerful tool to evaluate the economic improvement potential of a system, but it lacks providing information on the required investments to be made to improve the system and its components while considering cost-benefit assessments. In this paper novel criteria are introduced as an extension to fulfill the shortcomings of mentioned analysis and provide further insight about investment feasibility of components as well as the whole system including but not limited to the amount of avoided exergy destruction per unit renovating cost, the renovating cost to improve the efficiency, the amount of profit after renovation. The criteria are applied to a marine steam power plant to evaluate the system and its components. The results show that boiler has the highest avoidable exergy destruction cost of 77.4 $/h while the third stage of low-pressure turbine (LPT3) has the highest recovered exergy destruction per dollar invested. On the other hand, by investing in boiler, the saving potential is 36.8 $/h and on LPT3 it is 6.5$/h. It has been observed that the overall system has avoidable exergy destruction cost of 101$/h, while a 52.7 $/h part of it could be saved with the improvement investments made.

Keywords:

Advanced exergoeconomic analysis, Advanced exergoeconomic performance criteria, marine power plant, energy systems, exergy based evaluation

Nomenclature

Abbreviations

IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
GHG	Green House Gas

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ORC	Organic Rankine cycle
LCiTA	Life cycle integrated thermoeconomic assessment
HPT	High pressure turbine
LPT	Low pressure turbine
IPT	Intermediate pressure turbine
FWPH	Feed water preheater
CDP	Condensed feed water pump
FWP	Feed water pump
FWMP	Feed water main pump
DEAER	Deaerator
LCI	Life Cycle Integrated
LHV	Lower Heating Value [kJ/kg]
MOPSA	Modified Productive Structure Analysis

Symbols

CCI	Capital cost for improvement [$]
AEC	Cost of avoidable exergy destruction [W/$]
EIC	Exergy efficiency improvement cost [$/%]
$Z\dot{C}I$	Levelized investment, operation and maintenance costs for improvement [$/h]
CAV	Over life time investment, operation and maintenance costs of avoidable exergy destruction [$/kWh]
SPP	Specific profit potential [$/kWh]
$\dot{C}P$	Cost profit [$/h]
$\dot{C}$	Cost of exergy stream[$/h]
c	Specific cost of exergy stream [$/kWh]
$\dot{E}x$	Exergy of stream [kW]

$\dot{Z}$	Levelized investment, operation and maintenance costs [$/h]
$\dot{m}$	Mass flow rate [kg/s]
P	Pressure [kPa, bar]
T	Temperature [K, °C]
$\dot{W}$	Power [kW]

Subscripts

j	Any working fluid stream
k	Any investigated component
F	Fuel
P	Product
D	Destruction
tot	Overall system

Superscripts

AV	Avoidable
UN	Unavoidable
EN	Endogenous
EX	Exogenous
*	Modified

Greek Letters

ε	Exergy efficiency
Δ	Difference
η	Isentropic efficiency

1. Introduction

The sustainability of healthy air is a global goal that has been approved by the Paris agreement [1]. International Maritime Organization’s (IMO) Marine Environment Protection Committee (MEPC) takes responsibility to issue resolutions to protect the environment with the reduction of Green House Gas (GHG) emissions from ships [2]. Emission limits are generally defined as the ratio of generated GHG emissions over the produced power. Hence, improving the efficiency of the system will lead to more power with the same amount of fuel, therefore, decreasing specific emissions. Moreover, if efficiency is improved, specific fuel consumption will also decrease. Thus, one of the heaviest economic burden, namely the fuel cost, will follow this decrease which is a great interest to ship owners [3]. However, to achieve the improvement of a system, the required investment cost is very important. Ship owners pay attention to the payback time of the new investments on the vessels. The aim should then be that of an efficiency increase with a relatively low cost or even with a profit.

Decreasing the exergy destruction of a system, and further knowledge of how far it would be decreased, provide crucial information to understand the improvement boundaries for the development of an investigated system. The exergy destruction decreasing potential known as avoidable exergy destruction is the key to producing the same amount of power with less fuel consumption. Advanced exergy analysis is a technique to reveal the aforementioned potential. It has been applied to several different thermal systems as well as to marine power production systems [4-20]. Generally, to avoid exergy destruction, an investigated component should be either replaced by a better and more efficient one or repaired to correct the operational and timely degradation and also to reduce wearing and malfunctions. Either replacing or repairing the components brings an economic burden. Hence, to improve the efficiency of the investigated component, an investment must be considered together with recovering a part of exergy destruction. As a result, advanced exergoeconomic analysis is introduced for the economic evaluation of energy systems. That is, conventional exergoeconomic analysis suggests that exergy destruction of a component or overall system has a cost, and advanced exergoeconomic analysis proposes that by avoiding a part of the exergy destruction, some of the cost could be saved. This approach has been used to analyze the financial terms of a variety of energy conversion systems. Petrakopoulou et al. used advanced exergoeconomic analysis to analyze a combined cycle power plant and showed that the combustion chamber within the system has the highest avoidable and unavoidable exergy destruction costs while the gas turbine has mostly avoidable exergy destruction cost, and it is the second highest [21]. Wei et al proposed calculation methods for avoidable and unavoidable exergy and associated costs of a distillation system components namely, distillation columns, and heat exchangers as well as a savings indicator, and applied the method to a case study and concluded that exergy- and cost-savings potential can be a good indicator for comparing different system components [22]. Petrakopoulou et al evaluated chemical loop combustion included power plant with advanced exergoeconomic analysis and concluded that the combustion reactor is determined as the component with the highest avoidable exergy destruction cost [23]. Janghorban Esfahani et al. optimized a desalination system with the genetic algorithm via two objective functions and evaluated it by applying advanced exergy and exergoeconomic analyses [24]. Gungor et al employed advanced exergoeconomic analysis to evaluate the performance of a gas engine heat pump that is used for three different plants drying processes and they found out that the improvement potential for the investment costs of the systems are low in comparison with avoidable exergy destruction costs while the highest avoidable exergy destruction costs belong to condenser and drying ducts [25]. Koroglu and Sogut used conventional and advanced exergy and exergoeconomic analyses to compare conceptual organic Rankine cycles (ORCs) with two different configurations and five different organic working fluids that utilize the waste heat of a marine Diesel engine and, under given conditions, they concluded that the optimal system works with saturated steam ORC with the optimal working fluid of R141b [3]. Koroglu and Sogut, investigated a marine Diesel engine waste heat recovery system that includes a turbogenerator with pump outlet pressure as parameter by splitting the costs into avoidable and unavoidable parts and concluded that 7 bar maximum pressure system is the best option in terms of advanced exergoeconomic analysis while the cheapest would be of 7.5 bar and the most efficient and powerful one is 6 bar pressurized systems [26]. Moharamian et al. analyzed a complicated system of biomass integrated and natural gas co-fired combined cycles with hydrogen injection and hydrogen production by applying advanced exergy and exergoeconomic analyses. It has been concluded that the gas turbine has the highest avoidable exergy destruction cost to recover. Moreover, the analysis has shown that improvements regarding the results would also lead to a decrease of fossil fuel requirement as well as emissions [27]. Ansarinasab and Mehrpooya investigated a combined cooling, heating, and power system that includes a molten carbonate fuel cell, gas turbine, and Stirling engine, H2O-Li/Br absorption refrigeration cycle by advanced exergy, exergoeconomic analyses [28]. They used strategies based on advanced exergy based analyses and concluded that decreasing the capital investment cost of the pumps is more important than improving the combustion chamber. Heat exchangers have improvement potential according to the advanced exergoeconomic analysis. Açıkkalp et al.

introduced new indices by integrating lifecycle to advanced exergoeconomic analysis and applied to a simple building heating system [29] based on LCiTA method introduced by Kanbur et al [30]. Mehrpooya et al. introduced a new set of strategies to evaluate energy systems and their components based on advanced exergy and exergoeconomic analyses. The strategies use the results of the analyses, namely results of the avoidable cost of exergy destruction to reveal whether the improving the component itself and replacing it with more efficient one or improving the system structure and the other components in the system is a better option. They applied the analyses to several systems [31-33]. Ansarinasab et al evaluated a newly developed process configuration used for recovering helium from natural gas based on flash separation with a three stage propane refrigeration cycle by applying advanced exergy and exergoeconomic analyses and showed that compressors have high importance as expected [34]. More studies of advanced exergoeconomic analyses on different systems can be found in the literature [35-41]. Some selected papers in focus of the current study with their key findings are summarized and given in Table 1.

Table 1. Some selected papers in focus with key findings.

Ref	System	Analysis	Key findings
[21]	Combined cycle power plant (gas and steam)	Advanced exergoeconomic analysis with the total avoidable cost approach based on conventional exergoeconomic analysis	• The results are dependent of assumptions, but they yield independent conclusions. • to improve a system, component interactions should be considered together with their avoidable exergy destruction, cost, or environmental impact • advanced methods not only reveal the effects of component interactions but also the improvement priority is based strictly on the avoidable part of the total amount of exergy destruction/cost/ environmental impact
[23]	CO_2 capture in a combined-cycle power plant	Application of conventional and advanced exergoeconomic analyses.	• The investment cost and the cost of exergy destruction, the interactions among components, are of lower importance and the endogenous part of the costs is significantly larger for most of the components.
[26]	Marine diesel engine steam Rankine Cycle waste heat recovery system	Conventional exergoeconomic and advanced exergoeconomic analysis are carried out.	• The most of the costs are unavoidable, and the avoidable costs are lower in component-based comparison.
[28]	An integrated combined cooling heating and power plant	conventional and advanced exergy and exergoeconomic analyses are performed.	• Based on the results of advanced exergoeconomic analysis, three strategies are introduced to decrease the inefficient cost: • Strategy A: Improving the efficiency of the kth component or replacing it with a more efficient one • Strategy B: Improving efficiency of the remaining process components • Strategy C: Optimizing the structure of the overall process
[29]	The analyzed building heating system includes generation, distribution, heating, and building envelope stages.	the advanced exergoeconomic analysis is extended to include the advanced Life Cycle Integrated (LCI) exergoeconomic analysis which presents the relationship between thermodynamic inefficiencies and the cost and environmental effect of the product.	• An opportunity arises for a deeper investigation of any heating system by using the proposed analysis and indices. • Suggested indicators lead to detailed analyses of interactions between the components and possible improvement potentials.
[35]	the supercritical carbon	Conventional and advanced exergoeconomic analyses are performed.	• Improving the cycle thermal performance may not be feasible at all times due to the trade-off between the thermal and cost performances of the system.

	dioxide recompression Brayton cycle		• the advanced exergoeconomic analysis can locate improvement potential, present the improvement limit, and rank the components to gain the highest profit. • Advanced exergoeconomic analysis would alter under the assumption of conventional and MOPSA approach as the MOPSA method splits thermomechanical exergy as thermal and mechanical exergies. Hence, differences occur in the fuel and product definitions of the components which yield alterations for the split exergy destruction and investment costs.
[37]	a gas turbine cycle located in Inchon/South Korea	Conventional and advanced exergoeconomic analyses are performed. In addition, the modified productive structure analysis (MOPSA) is used on the costing of exergy destruction.	
[41]	The conceptual hybrid concentrated solar power-biomass Organic Rankine Cycle (ORC) plant based on a real plant in Ottana, Italy.	Conventional and advanced exergoeconomic analysis are carried out with different auxiliary costing approaches, one of which is based on the quality of energy.	• The study suggests modifying the auxiliary exergy costing method in the advanced exergoeconomic analysis, to include the stream energy quality. • the modified auxiliary costing approach gives more practical results. • the literature has shown that the advanced exergoeconomic methodology is applicable and capable for thermodynamic system analysis.
[45]	Cogeneration system.	The concept of avoidable exergy destruction and avoidable costs constitutes the background of the advanced exergy based analyses.	• The advanced exergoeconomic analysis can present a realistic image of the potential cost savings in the component and ranks the components in this respect. • The determination of avoidable investment costs requires some decisions and assumptions that include operational conditions that can be realized in recent technological and economic limitations. These decisions and assumptions may not significantly affect the conclusions of the analysis.

The literature in the focus of the current study which is shown in Table 1, reveals that advanced exergoeconomic analysis has been studied and applied not only by its own but also with different approaches regarding the introduction of new criteria and costing considerations. However, the analysis comes short even with the suggested extensions and approaches of enlightening the following issues [42]:

(i) There is no direct connection between the investment made for the improvement and the avoidable exergy destruction.

(ii) In the case of increasing the exergy efficiency of the investigated component, the renovation cost to increase the exergy efficiency by 1% has not been specified in the system.

(iii) Most importantly, it has not been assessed how much a component contributes to the exergy efficiency of the overall system in terms of saving the avoidable exergy destruction, that is, a 1% increase of the system efficiency by improving the investigated component.

(iv) During the lifetime of the system, the cost of investment, operation, and maintenance required for unit exergy destruction that could be avoided in the component under investigation is not calculated.

(v) The cost of component for avoiding exergy destruction which is paid for the life of the system has not been taken into account, with the potential for saving by means of prevention of the exergy destruction.

(vi) Potential profit in the system over its lifetime due to the improvement to be made on a component is not shown. Therefore, as the result of avoiding a part of exergy destruction, if the avoided cost of exergy destruction is higher than the investment cost of the component improvement, this effort is profitable and investment will be acceptable.

Based on the mentioned inferences, the novelty of the paper is to introduce new economic performance criteria to utilize the results of advanced exergoeconomic analysis and provide a decision support tool for the thermal energy system designers, engineers, and operators. Even though the advanced exergoeconomic analysis reveals invaluable information with the techniques mentioned in the literature review, designers, engineers, and owners would like to invest the renovation money on the components and processes that they achieve a sound and solid profit in the end. Hence, the aim of the introduced novel economic performance criteria as a decision support tool is to show and reveal the information and improve the knowledge about the overall system and its components in brief as follows:

(i) The amount of avoided exergy destruction per unit renovating cost.
(ii) The renovating cost to improve the efficiency by 1%.
(iii) The amount of economic profit after renovation.
(iv) Rank the components regarding their economic profit potential.

In this paper, the results of an advanced exergoeconomic analysis are evaluated and further employed in forming decision criteria which have been introduced as advanced exergoeconomic performance criteria. The developed criteria are an extension based on the known methods to evaluate the results of the investigated system for a decision support tool. The analysis and the criteria are applied to a 17 MW steam power plant of a very large crude oil carrier [12]. Results of the advanced exergoeconomic analysis and the performance criteria as a component renovation decision support are discussed and evaluated.

2. Theoretical Method

In this section, the methodology of the application of conventional and advanced exergoeconomic analyses will be presented first. Later, the introduction of novel exergoeconomic performance criteria and their calculation procedures will be presented.

2.1. Conventional and advanced exergoeconomic analyses

Exergoeconomic analysis is not only based on conventional exergy analysis by assigning specific exergy costs to all matter and exergy streams as given in Eq.1, but also on economics to define exergoeconomic balances with the investment costs of components [43].

$$\dot{C}_j = c_j \dot{E}x_j \tag{1}$$

Where, $\dot{C}_j$, c_j and $\dot{E}x_j$are the cost of the exergy stream j, the specific cost of exergy stream j, and exergy of the stream j, respectively. Exergoeconomic balance equation is given with the fuel and product approach as follows [44]:

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \tag{2a}$$

$$c_{P,k}\dot{E}x_{P,k} = c_{F,k}\dot{E}x_{F,k} + \dot{Z}_k \tag{2b}$$

Where $\dot{Z}_k$ denotes levelized investment, operation, and maintenance costs over the component's life time, and subscripts F and P represent fuel and product, respectively. Moreover, one of the objectives of the exergoeconomic analysis is to reveal the cost of exergy destruction, $\dot{C}_{D,k}$, which is defined as the amount of cost due to irreversibilities of the investigated component and/or overall system. Cost of exergy destructions is related to the specific exergy cost of fuel while exergy of product is kept constant, hence it is calculated as follows [44]:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}x_{D,k} \tag{3}$$

Subscript D is the representative of the exergy destruction. With the aid of advanced exergy analysis, cost of exergy destruction could be divided into *avoidable (*$\dot{C}^{AV}_{D,k}$*), unavoidable (*$\dot{C}^{UN}_{D,k}$*), endogenous (*$\dot{C}^{EN}_{D,k}$*), exogenous (*$\dot{C}^{EX}_{D,k}$*)* parts and the combination of these four as *avoidable endogenous (*$\dot{C}^{AV,EN}_{D,k}$*), avoidable exogenous (*$\dot{C}^{AV,EX}_{D,k}$*), unavoidable endogenous (*$\dot{C}^{UN,EN}_{D,k}$*)* and *unavoidable exogenous (*$\dot{C}^{UN,EX}_{D,k}$*)* costs of exergy destruction as defined below [21, 22, 45]:

$$\dot{C}^{AV}_{D,k} = c_{F,k}\dot{E}^{AV}_{D,k} \ \ and \ \ \dot{C}^{UN}_{D,k} = c_{F,k}\dot{E}^{UN}_{D,k} \tag{4a, b}$$

$$\dot{C}^{EN}_{D,k} = c_{F,k}\dot{E}x^{,EN}_{D,k} \ \ and \ \ \dot{C}^{EX}_{D,k} = c_{F,k}\dot{E}x^{EX}_{D,k} \tag{5a, b}$$

$$\dot{C}^{AV,EN}_{D,k} = c_{F,k}\dot{E}x^{,AV,EN}_{D,k} \ \ and \ \ \dot{C}^{AV,EX}_{D,k} = c_{F,k}\dot{E}x^{,AV,EX}_{D,k} \tag{6a, b}$$

$$\dot{C}^{UN,EN}_{D,k} = c_{F,k}\dot{E}x^{,UN,EN}_{D,k} \ \ and \ \ \dot{C}^{UN,EX}_{D,k} = c_{F,k}\dot{E}x^{,UN,EX}_{D,k} \tag{7a, b}$$

The avoidable cost of exergy destruction represents the amount of cost when all avoidable exergy destruction is recovered by applying renovation or repairs to the investigated component. Thus, the unavoidable cost of exergy destruction is the part that could not be further regained due to technological and industrial limitations. The location of exergy destruction cost can be determined by utilizing endogenous and exogenous parts where the endogenous cost of exergy destruction is the representative of the costs related to the component conditions while the exogenous cost of exergy destruction shows the effects of other components and simultaneous working conditions of the overall system on the incremental cost of the investigated component. Combined costs are utilized to determine the sources of the avoidable and unavoidable costs of exergy destruction as such if the part of the avoidable cost of exergy destruction can be recovered with the improvements within the investigated component, it is called avoidable endogenous cost of exergy destruction. However, if the exergy destruction cost of the investigated component can be avoided with the changes in the other components of the system, it is named as avoidable exogenous cost of exergy destruction.

2.2. Novel exergoeconomic performance criteria

A novel decision support tool regarding exergoeconomic performance criteria based on the results of advanced exergoeconomic analysis is introduced. The calculation, as well as the evaluation procedure, are given in the following paragraphs.

The required renovation cost or capital cost for improvement of the investigated component is denoted by CCI_k. On the other hand, the cost of avoidable exergy destruction of the investigated component, AEC_k, indicates how much of the exergy destruction is avoided for unit renovation cost of the component as follows :

$$AEC_k = \frac{\dot{E}x_{D,k}^{AV}}{CCI_k} \tag{8}$$

AEC_kvalue could also be used as the required cost of overall system exergy efficiency improvement under the influence of the investigated component as it is used on the new modified exergy efficiency of the overall system [12]. It is useful to sort the components of the system with respect to the profitability by unit renovation cost.

EIC_k is the exergy efficiency improvement cost of the investigated component. It is defined as the cost to improve the exergy efficiency of the component by 1 percent. It is employed to compare system components in a way that how much exergy efficiency improvement could be achieved with a lower cost:

$$EIC_k = \frac{CCI_k}{\varepsilon_k^* - \varepsilon_k} \tag{9}$$

where ε_k^* and ε_k is the modified and real exergy efficiency of the investigated component, respectively [12].

A more important criterion is the exergy efficiency improvement cost of the overall system under the influence of the investigated component, EIC_{tot}^k. It is useful not only to evaluate the direct effect but also the financial burden of the investigated component on the overall system. It is defined as the component renovation cost to improve the exergy efficiency of the overall system as percentage:

$$EIC_{tot}^k = \frac{CCI_k}{\varepsilon_{tot}^{*,k} - \varepsilon_{tot}} \tag{10}$$

where $\varepsilon_{tot}^{*,k}$ and ε_{tot} is the new modified exergy efficiency under the influence of investigated component *k* and real exergy efficiency of the overall system, respectively [12].

Besides the renovation cost for improvement, there is a financial burden of improvement over the component's life time as levelized investment, operation, and maintenance costs for improvement renovation, $\dot{ZCI}_k$. Over life time investment, operation, and maintenance costs of avoidable exergy destruction of the investigated component, CAV_k, is calculated as follows:

$$CAV_k = \frac{\dot{ZCI}_k}{\dot{Ex}_{D,k}^{AV}} \tag{11}$$

In the perspective of economical profit, CAV_k is expected to be small in comparison with $c_{F,k}$ because, for the same amount of avoided exergy destruction, while the latter represents the specific amount of money that could be recovered, the former stands for the specific amount of money that must be investigated over the component's life time. Hence, the specific profit potential of the investigated component, SPP_k, can be defined as the difference between the specific profit, $c_{F,k}$, and loss, CAV_k:

$$SPP_k = c_{F,k} - CAV_k \tag{12}$$

SPP_k might not be adequate on its own to decide whether the improvement should be made on the investigated component without the avoidable exergy destruction. Ultimately, the most crucial criterion for the decision is called cost profit, $\dot{CP}_k$, which is the amount of money that could be: (i) gained if it is positive, (ii) lost if it is negative, and (iii) break even if it is zero by improving the investigated component. It could also be expressed in other words when the avoidable cost of exergy destruction is higher than the investment, operation, and maintenance costs of renovation, it is practical and profitable to make the changes on the system component. Otherwise, it may give little information to focus on that component for improvement.

$$\dot{CP}_k = SPP_k\, \dot{Ex}_{D,k}^{AV} = \dot{C}_{D,k}^{AV} - \dot{ZCI}_k \tag{13}$$

Components of the investigated system could be compared by applying cost profit potential criteria and the most important component in the system which provides the highest profit with renovation could be determined and components could be listed with the rank of importance.

3. Application

New modified exergy efficiency criteria are applied to a 17 MW marine steam power plant, that has been studied previously with conventional and advanced exergy analyses [12]. The system is briefly described and the application procedure with the balance equations of the conventional and advanced exergoeconomic analyses as well as advanced exergoeconomic performance criteria are given in the following sections.

3.1. System Description

The investigated system has a high-pressure turbine (HPT) with two stages, an intermediate-pressure turbine (IPT), and a low-pressure turbine (LPT) with three stages. Four different feed water preheaters (FWPHs) heat the feed water upto the inlet temperature of the boiler by using bleeding steam, while three pumps namely, condensed feed water pump (CDP), feed water pump (FWP), and feed water main pump (FWMP) increase the pressure level up to the inlet pressure of the boiler. The condensed water is heated with an external oil-fired heater after CDP. Before FWMP, feed water degasified in the deaerator (DEAER). The system is modelled by compiling the data of the system working in real, steady state and continuous power generation conditions. Sample data could be seen in Table 2. The layout of the investigated system is shown on Fig. 1 and the thermodynamic properties of the streams and the accuracy of the system could also be found in Ref [12]. The initial conditions of the system components are given Table 3.

Table 2. Sample data of some properties in the investigated system [12].

Property	Value	Property	Value
HPT inlet T	783 K	Boiler inlet T	515 K
HPT inlet P	10100 kPa	FWMP outlet T	428 K
LPT inlet T	614.95 K	Specific Fuel Consumption	0.189 kg/kWh
LPT inlet P	560 kPa	Produced Power	17MW

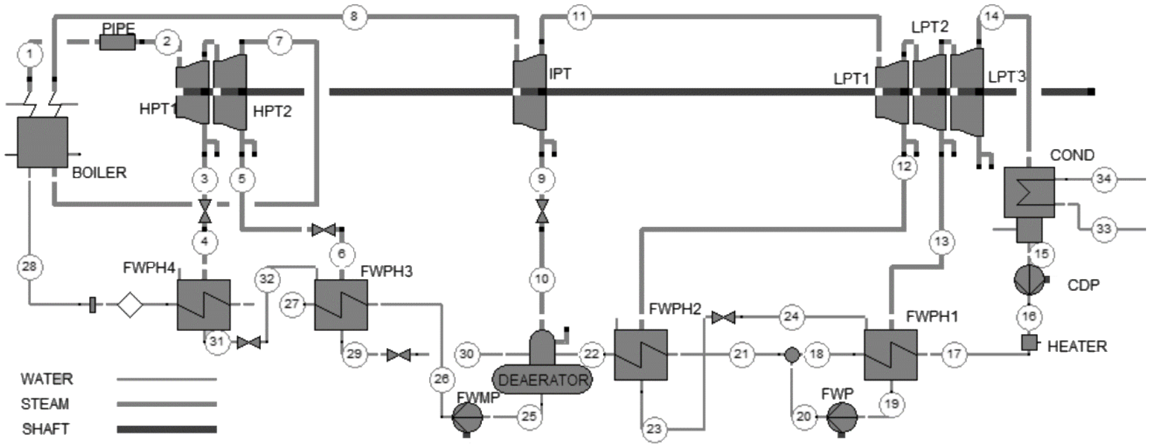

Figure 1. Layout of the investigated system [12]

Table 3. Initial Conditions of the components [12].

Comp	Condt	Comp	Condt	Comp	Condt	Comp	Condt
HPT1	$\eta = 0.65$	LPT1	$\eta = 0.83$	FWPH1	$\Delta T = 4.7$	FWMP	$\eta = 0.80$
HPT2	$\eta = 0.89$	LPT2	$\eta = 0.83$	FWPH2	$\Delta T = 6.7$	HEATER	$\eta = 0.91$
IPT	$\eta = 0.85$	LPT3	$\eta = 0.70$	FWPH3	$\Delta T = 5$	BOILER	$\Delta P = 230$ $\eta = 0.91$
FWP	$\eta = 0.83$	CDP	$\eta = 0.82$	FWPH4	$\Delta T = 5$		

3.2. Conventional and Advanced Exergoeconomic Analyses

Since the capital costs of the components have to be determined before the application of the exergoeconomic analyses, the cost calculations are made using the equations given in the literature [46, 47]. The costs of pipes are neglected in the calculations. In feed water preheaters, the steam entering the preheater is often superheated, so preheaters are modeled as two sections namely: a precooler to convert the hot steam into saturated steam with feed water, and then a preheater to transfer the heat of the saturated steam to the feed water. For all heat exchangers in the system, universal heat transfer coefficients by type have been determined according to the literature [48-50]. The assumptions for the investigation of the system by conventional and advanced exergoeconomic analyses are given in Table 4.

Table 4. Assumptions for conventional and advanced exergoeconomic analyses

Parameter	Value	Parameter	Value
service life of the system	30 years	cost of fuel	378.5 $/ t
the annual interest rate	12.75%	LHV of fuel [12]	43038 kJ/kg
the annual working period	6720 hours	Environmental conditions [51].	15°C and 100 kPa
maintenance operation and repair cost (Maintenance factor)[31]	6% of the capital investment cost		

Following the calculated investment costs of the components, exergoeconomic balance equations could be established by employing equations given in Table 5, and a coefficient matrix could be created with the aid of auxiliary equations. Afterward, advanced exergoeconomic analyses could be applied by using the results of conventional exergoeconomic analysis and advanced exergy analysis.

It should be noted that the system runs in a steady state regime and the kinetic and potential exergies are neglected. The cost effect of the pipes has not been taken into account. In the literature, the cost analysis of the pipe has been made only for a system with a fixed geometric design for a building, where the pipes are used for heating purposes [29]. Moreover, piping systems and layouts onboard a ship vary widely due to geometric requirements within the expertise of the designer, and that must be optimized for each system. Furthermore, the main focus of this study is to demonstrate the utility of the new criteria.

Table 5. Exergoeconomic balance equations for the investigated system

Component	$\dot{C}_F$	$\dot{C}_P$
HPT1	$c_2\dot{E}x_2 - c_3\dot{m}_2 ex_3$	$c_w\dot{W}_{HPT1}$
HPT2	$c_3(\dot{m}_2 - \dot{m}_3)ex_3 - (c_5\dot{E}x_5 + c_7\dot{E}x_7)$	$c_w\dot{W}_{HPT2}$
IPT	$c_8\dot{E}x_8 - (c_9\dot{E}x_9 + c_{11}\dot{E}x_{11})$	$c_w\dot{W}_{IPT}$
LPT1	$c_{11}\dot{E}x_{11} - c_{12}(\dot{m}_{11}ex_{12})$	$c_w\dot{W}_{LPT1}$
LPT2	$(\dot{m}_{11} - \dot{m}_{12})(c_{12}ex_{12} - c_{12}ex_{13})$	$c_w\dot{W}_{LPT2}$
LPT3	$c_{13}(\dot{m}_{11} - \dot{m}_{12} - \dot{m}_{13})ex_{13} - c_{14}\dot{E}x_{14}$	$c_w\dot{W}_{LPT3}$
COND	$c_{14}\dot{E}x_{14} - c_{15}\dot{E}x_{15}$	$c_{34}\dot{E}x_{34} - c_{33}\dot{E}x_{33}$
CDP	$c_w\dot{W}_{CDP}$	$c_{16}\dot{E}x_{16} - c_{15}\dot{E}x_{15}$
FWPH1	$\left(c_{13}\dot{E}x_{13} + c_{24}\dot{E}x_{24}\right) - c_{19}\dot{E}x_{19}$	$c_{18}\dot{E}x_{18} - c_{17}\dot{E}x_{17}$
FWP	$c_w\dot{W}_{FWP}$	$c_{20}\dot{E}x_{20} - c_{19}\dot{E}x_{19}$
FWPH2	$c_{12}\dot{E}x_{12} - c_{23}\dot{E}x_{23}$	$c_{21}\dot{E}x_{21} - c_{22}\dot{E}x_{22}$
DEAER	$c_{10}\dot{E}x_{10}$	$\left(c_{22}\dot{E}x_{22} + c_{30}\dot{E}x_{30} - c_{25}\dot{E}x_{25}\right)$
FWMP	$c_{10}\dot{W}_{FWMP}$	$c_{26}\dot{E}x_{26} - c_{25}\dot{E}x_{25}$
FWPH3	$\left(c_6\dot{E}x_6 + c_{32}\dot{E}x_{32}\right) - c_{29}\dot{E}x_{29}$	$c_{27}\dot{E}x_{27} - c_{26}\dot{E}x_{26}$
FWPH4	$c_4\dot{E}x_4 - c_{31}\dot{E}x_{31}$	$c_{28}\dot{E}x_{28} - c_{27}\dot{E}x_{27}$
HEATER	$c_B\left(1.07\left(\dot{m}_{f,H}\right)LHV_f/\eta_B\right)$	$c_{17}\dot{E}x_{17} - c_{16}\dot{E}x_{16}$
BOILER	$c_B\left(1.07\left(\dot{m}_{f,B}\right)LHV_f/\eta_B\right)$	$\left(c_1\dot{E}x_1 - c_{28}\dot{E}x_{28}\right) + (c_8\dot{E}x_8 - c_7\dot{E}x_7)$

3.3. Advanced Exergoeconomic Performance Criteria Analysis

Once the results of advanced exergy and exergoeconomic analyses are obtained, criteria analysis can be conducted. The required results of advanced exergy analysis from the previous study of the authors are given in Table 6. As it is mentioned in the Theoretical method section, avoidable exergy destruction, cost of avoidable exergy destruction, specific cost of fuel, modified exergy efficiency as well as real exergy efficiency of each component of the investigated system should be employed for advanced exergoeconomic performance criteria analysis. Capital cost for improvement CCI_k could be determined as the investment to renovate or repair the component or the difference between the new investment cost of the component and the salvage value of the old component. $\dot{ZCI}_k$ can be calculated over the component's life time by utilizing CCI_k as invested money with the addition of operation and maintenance costs.

Table 6. Results of advanced exergy analysis from the previous study [12]

Component	$\dot{Ex}_{D,k}^{AV}$	ε [%]	$\varepsilon_{tot}^{*,k}$[%]
HPT1	369.36	80.7397	34.402
HPT2	31.171	94.3917	34.169
IPT	129.34	92.2454	34.236
LPT1	73.106	89.9579	34.198
LPT2	119.55	86.9657	34.230
LPT3	624.58	71.5506	34.580
COND	239.67	57.1295	34.312
CDP	0.3865	82.8637	34.148
FWPH1	8.4759	70.0761	34.154
FWP	0.0564	86.6181	34.148
FWPH2	15.229	79.3539	34.158
FWMP	10.511	86.6252	34.155
FWPH3	13.176	88.1034	34.157
FWPH4	11.782	92.3318	34.156
Boiler	2,803.7	44.5691	36.178
Heater	27.590	6.2439	34.167
TOTAL	4,535.7	34.1483	37.557

4. Results and Discussion

In this section, the results of conventional and advanced exergoeconomic analyses will be given and discussed. Afterward, the results of the criteria analyses will be evaluated.

4.1. Conventional and Advanced Exergoeconomic Analyses

The results of the conventional and advanced exergoeconomic analyses are given in Table 7. The calculated costs of the components are in the first column ($), the hourly costs ($ / h) throughout the life of the components are in the second column, the specific fuel exergy costs derived from the specific exergetic costs assigned to each material and energy stream determined as a result of exergoeconomic analysis is in the third column (\$ / kWh) and other columns have hourly costs (\$ / h) of exergy destructions calculated with advanced exergy analysis in the previous study [12].

The exergy destruction cost percentages of the components are presented in Fig.2. It can be observed in Fig. 2 and in the 3rd column of Table 7 that the highest cost of exergy destruction is in the boiler where the highest exergy destruction occurred is around 91% and the second in the line is LPT3, and the heater is in the third position.

Table 7. Results of conventional and advanced exergoeconomic analyses (in \$/h)

Component	$\dot{Z}_k$	c_F (\$/kWh)	$\dot{C}_{D,k}$	$\dot{C}_{D,k}^{UN}$	$\dot{C}_{D,k}^{AV}$	$\dot{C}_{D,k}^{EN}$	$\dot{C}_{D,k}^{EX}$	$\dot{C}_{D,k}^{UNEN}$	$\dot{C}_{D,k}^{UNEX}$	$\dot{C}_{D,k}^{AVEN}$	$\dot{C}_{D,k}^{AVEX}$
HPT1	37.73	0.01	10.04	4.73	5.31	8.89	1.15	4.19	0.54	4.71	0.61
HPT2	34.11	0.01	1.40	1.02	0.38	1.13	0.28	0.77	0.25	0.36	0.02
IPT	40.52	0.02	7.26	4.70	2.56	6.42	0.84	4.07	0.64	2.36	0.20
LPT1	35.50	0.01	3.35	2.38	0.98	2.72	0.63	1.79	0.59	0.93	0.05
LPT2	37.20	0.01	6.11	4.33	1.78	4.81	1.30	3.15	1.18	1.65	0.13
LPT3	37.56	0.01	14.33	6.46	7.86	11.19	3.14	5.05	1.41	6.14	1.72
COND	8.59	0.01	8.06	5.04	3.02	5.76	2.29	3.61	1.44	2.16	0.86
CDP	0.42	0.03	0.04	0.02	0.01	0.03	0.01	0.02	0.01	0.01	0.00
FWPH1	2.10	0.01	1.33	1.22	0.11	1.02	0.30	0.96	0.26	0.06	0.05
FWP	0.29	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FWPH2	2.05	0.01	1.57	1.37	0.20	0.91	0.65	0.99	0.38	-0.07	0.27
DEAER	11.08	0.02	1.39	1.15	0.24	0.63	0.76	0.94	0.21	-0.30	0.55
FWMP	4.67	0.03	0.85	0.53	0.32	0.69	0.16	0.43	0.10	0.26	0.06
FWPH3	2.77	0.01	2.75	2.55	0.19	2.09	0.65	2.10	0.45	-0.01	0.20
FWPH4	2.66	0.01	1.14	0.97	0.17	0.60	0.54	0.67	0.31	-0.06	0.23
Boiler	109.38	0.03	756.67	679.25	77.43	632.93	123.74	567.97	111.28	64.96	12.46
Heater	29.78	0.03	13.76	13.00	0.76	10.87	2.89	10.27	2.73	0.61	0.15

The lowest exergy destruction cost belongs to FWP and is about 10 times lower than CDP with the cost of exergy destruction. According to the results of the conventional exergoeconomic analysis, improvement efforts should focus on the boiler which has the largest exergy destruction costs among the remaining, respectively. The rest is sequenced as LPT3, Heater, HPT1 which have \$ 10 / h per hour and above; condenser, IPT, LPT2, LPT1, FWPH3, FWPH2, HPT2, deaerator, FWPH1, FWPH4 which have 1 \$ / h and above, pumps are below 1 \$ / h as FWMP, CDP, FWP. In light of the information given, the results of exergoeconomics analysis in comparison with the conventional exergy analysis provide different results [12]. This situation, which is a result of the costing of the exergy streams, occurred due to the exergoeconomic assumptions and it is considered that exergoeconomic analysis gives more meaningful results because the cost is included in the exergy analysis.

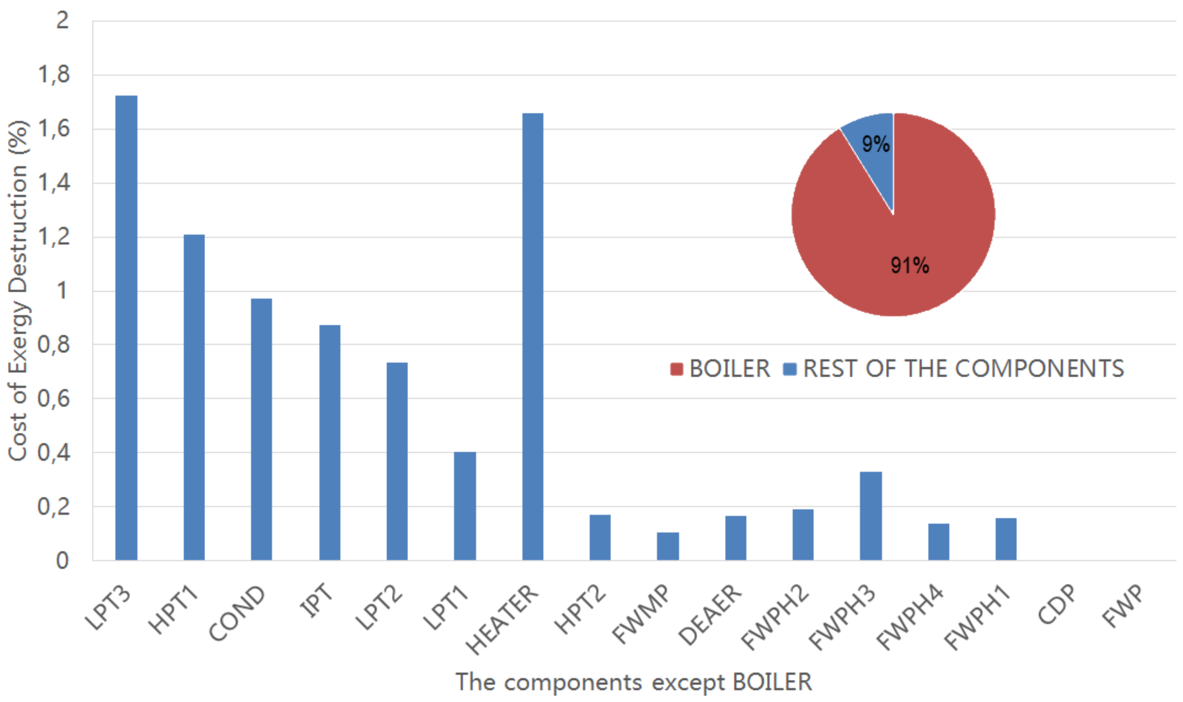

Figure 2. Exergy destruction cost percentages of the components.

In order to evaluate the results of advanced exergoeconomic analysis, avoidable and unavoidable exergy destruction costs and percentages can be seen in Table 7 and Fig. 3, respectively. For all components, except LPT3, HPT1, and FWP, most of the cost of exergy destruction is unavoidable. Albeit FWP has an equal level of avoidable and unavoidable exergy destruction cost, its improvement potential of it is not important as the lowest cost of exergy destruction occurs in this component. Although the lowest avoidable exergy destruction cost percentage occurs in the heater, the value of this mentioned cost is higher than the avoidable exergy destruction costs of the other nine components, HPT2, FWMP, deaerator, FWPH2, FWPH3, FWPH4, FWPH1, CDP, and FWP, respectively. In general, the avoidable exergy destruction costs of feed water preheaters are over 85%. Despite the fact that the avoidable exergy destruction cost percentage is around 10% for the boiler, the cost of avoidable exergy destruction is the highest due to the high cost of exergy destruction and is 10 times more than the cost of avoidable exergy destruction of LPT3, which is the closest component. In order to reduce costs due to the reduction of exergy destruction, the improvement list should further include HPT1, condenser, IPT, LPT2, and LPT1, respectively. The avoidable part of exergy destruction of the deaerator originates from the mixing and it is important to improve the condition of the flows entering into the component.

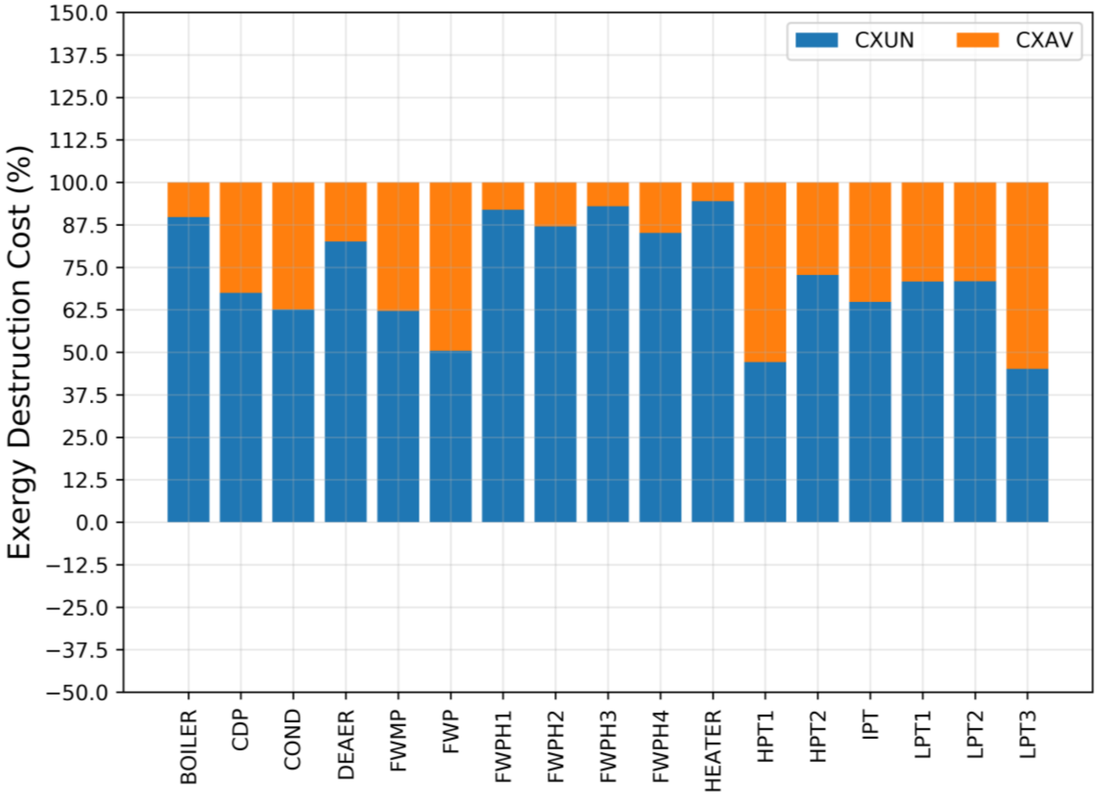

Figure 3. Avoidable and unavoidable exergy destruction cost percentages of the components.

The percentages of endogenous and exogenous exergy destruction costs, which represent the determination of the sources of exergy destruction costs, can be seen in Fig. 4. The cost of exergy destruction of all components except the deaerator is endogenous. Thus, cost interactions between components are low in terms of exergy destruction costs. The deaerator with exogenous exergy destruction cost, which is larger than the endogenous one, is under the influence of other components as mentioned before, but the reason for the internal origin is due to the formation of a mixture of exergy. When the exergy destruction cost of the boiler is examined, the amount of \$ 633 / h is endogenous and it is approximately 60 times the cost of the closest component, LPT3. The costs of exogenous exergy destruction of all components, except the boiler, remained below \$ 4 / h. The highest percentage of endogenous exergy destruction is in FWP. HPT1 and IPT have almost the same percentage, and the third is the boiler. It should be noted that the percentages of the endogenous and exogenous exergy destructions are beneficial to determine whether the cost of exergy destruction occurs within the component itself or due to irreversibilites of affecting components not only for the analysis of the component but also for the overall system.

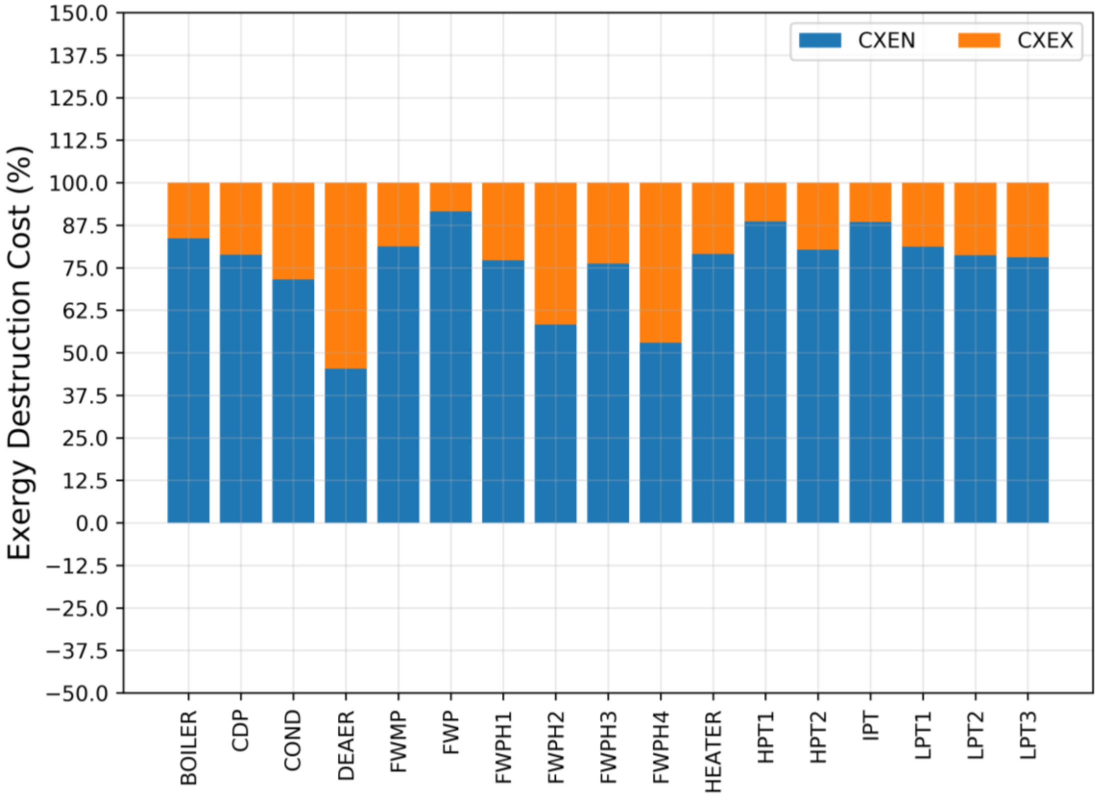

Figure 4. Endogenous and exogenous exergy destruction cost percentages of the components.

The most important items in the use of exergy destruction costs for evaluation purposes are the values of the combined exergy destruction costs which are given in Table 7, and the percentages of those are shown in Fig. 5. It is clear that the cost of avoidable exergy destruction is exogenous for the deaerator. FWPH2 and FWPH4 are likewise under the influence of other components. In terms of cost, FWPH3 has a percentage of trace amounts of negative avoidable endogenous exergy destruction cost. In other components, the avoidable endogenous exergy destruction costs are higher than the exogenous part. The cost of unavoidable endogenous exergy destruction is also higher than the unavoidable exogenous part for each component. That means the irreversibilities in the investigated component are more dominant than the irreversibilities of other components. Therefore, the improvement efforts on the investigated component play an important role in reducing the exergy destruction cost, except for the four components mentioned before. From this point of view, as predicted, the highest avoidable exergy destruction cost value is in the boiler with \$ 65 / h. The second highest component is LPT3 with \$ 6 / h avoidable endogenous exergy destruction cost and then HPT1 comes with \$ 4.7 / h. The cost of avoidable endogenous exergy destruction is 5 times greater than the exogenous cost for the boiler and still has the highest value.

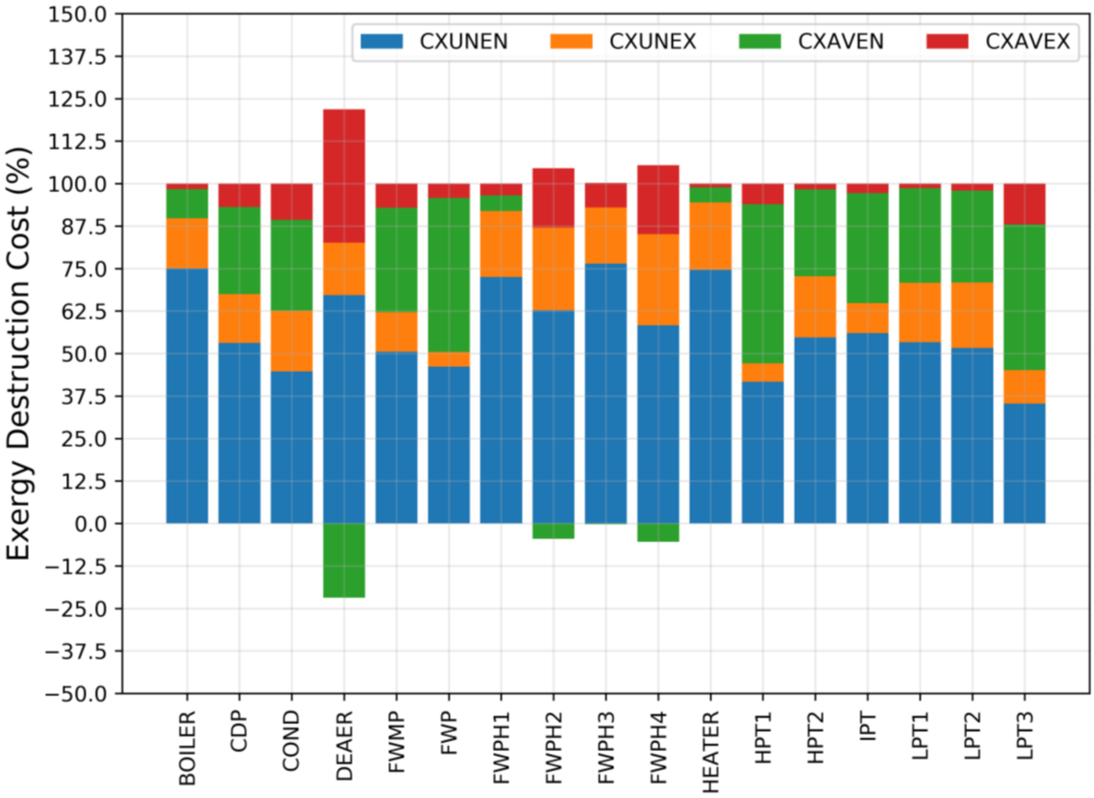

Figure 5. Combined exergy destruction cost percentages for the investigated components

The total amount lost due to exergy destruction during the operation of the system was calculated as 830 $ / h. Only 12.3% of this is a preventable cost, and the prevention of all exergy destruction in the system corresponds to the prevention of a cost of around $ 100 per hour. $ 83 / h of this amount is due to the improvements on the components' own conditions and the rest to the interaction between the components. As a result, one should focus on the components that are important in terms of decreasing the exergy destruction costs by their avoidable exergy destruction costs. The improvements on the simultaneous operation and topology of the system can be recommended as a secondary improvement step.

4.2. Advanced Exergoeconomic Performance Criteria Analysis

Table 8 provides the results of the advanced exergoeconomic performance criteria analysis based on advanced exergoeconomic analyses carried out in the current study. The reason why the deaerator is not rated in Table 8 is that the cost of the improvement is negative due to the fact that the deaerator is under the heavy influence of other components. Therefore, a lower capacity deaerator is required by improving other components. The second column in Table 8, AEC_k, shows the exergy destruction of the investigated component that can be avoided by per dollar invested. The most important evaluation is recovering the maximum amount of exergy destruction with minimum investment on the component, hence LPT3 provides the criteria with approximately 10W/$ and IPT is the second unit on the list with 8 W/$.

Table 8. Results of the advanced exergoeconomic performance criteria analysis

Comp	AEC_k[W/$]	EIC_k [$/%]	EIC_{tot}^k [$/%]	CAV_k [$/kWh]	SPP_k [$/kWh]	$\dot{CP}_k$ [$/h]
HPT1	4.97	8,113.02	292,293.62	0.004	0.010	3.777
HPT2	2.13	9,972.40	685,768.30	0.010	0.003	0.080
IPT	8.23	6,068.90	177,366.93	0.003	0.017	2.233
LPT1	3.20	8,401.49	456,132.99	0.007	0.007	0.507
LPT2	5.50	6,330.28	265,308.98	0.004	0.011	1.332
LPT3	9.58	4,925.33	150,848.92	0.002	0.010	6.514
COND	1.94	11,318.24	751,160.56	0.011	0.002	0.461
CDP	0.97	81.09	150,3035.05	0.021	0.010	0.004
FWPH1	1.83	2,660.39	798,535.44	0.011	0.001	0.012
FWP	1.20	7.63	1,217,239.89	0.017	0.014	0.001
FWPH2	5.71	1,219.50	256,318.14	0.004	0.010	0.149
FWMP	0.71	3,204.87	2,059,468.28	0.029	0.002	0.017
FWPH3	3.35	5,297.74	436,835.78	0.006	0.009	0.112
FWPH4	2.40	4,605.85	608,526.31	0.009	0.006	0.068
BOILER	1.43	732,718.17	967,219.23	0.015	0.013	36.825
HEATER	3.79	21,317.79	386,249.43	0.006	0.022	0.611

Exergy destructions that can be avoided from the improvement of components per unit investment can be seen in Fig. 6. In the third rank of the list, FWPH2 and then LPT2 and HPT1 are listed with values close to each other with 5.7W/$, 5.5W/$, and 5W/$, respectively. It is thought-provoking that four of the top five components for investment are turbines. On the basis of this situation, it can be said that the avoidable part of the exergy destruction is high and the development costs are lower than the other components. It could be concluded that a small amount of money invested in turbine renovation could have a great opportunity to recover more exergy destruction.

Pumps are components with the lowest importance due to approximately 1W avoidable exergy destruction in response to unit development cost. Although the boiler had the highest avoidable exergy destruction, it was found to be fourth in terms of finance because it provides 1.4W recovery for the unit improvement cost. Therefore, it can be said that the boiler does not provide the expected performance against the investment made.

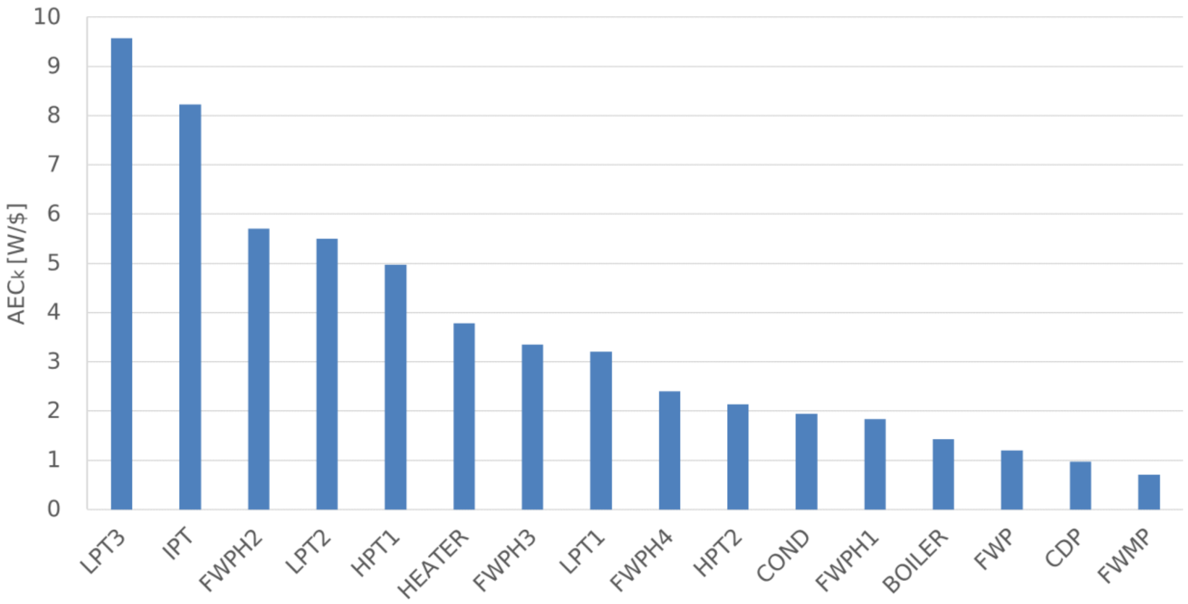

Figure 6. Exergy destructions that can be avoided from the unit cost of improvement of components.

If the priority is more important to increase the exergy efficiency of the component, the third column in Table 8 gives the required investment cost for a unit exergy efficiency increase of the component under consideration, EIC_k. The cost of investment required to increase the unit exergy efficiency of components is shown in Fig. 7. In this case, it is beneficial to have the lowest cost for unit efficiency increase. From this point of view, FWP is at the top with a cost of $ 7.6 per 1% increase. This component has a cost of approximately twelve times lower than the closest component, it may be appropriate to improve this component as the investment to increase its exergy efficiency at a lower cost. CDP then comes second with a cost of $ 81 per 1% increase. It is noteworthy that the gap between FWP and CDP was further extended between the CDP and FWPH2, which costs $ 1219.5 in third place. When considering the boiler, the highest cost for unit efficiency increase is 732718.2 $ in the boiler and this value is 34 times greater than the nearest component. In such a case, investing in increasing the exergy efficiency of the boiler does not seem to be a wise recommendation. The sequence of all remaining components can be observed in Fig. 7. When evaluated under these conditions, increasing the efficiency of the heater is very costly. The condenser, which is the closest component to the heater, seems to be as efficient as a heat exchanger at half the cost. The heater and boiler having such high values cannot be seen as a coincidence. Due to the fact that both have similar duties as providing heat, they have higher costs due to the inclusion of complex systems within, such as incineration systems and heat exchangers.

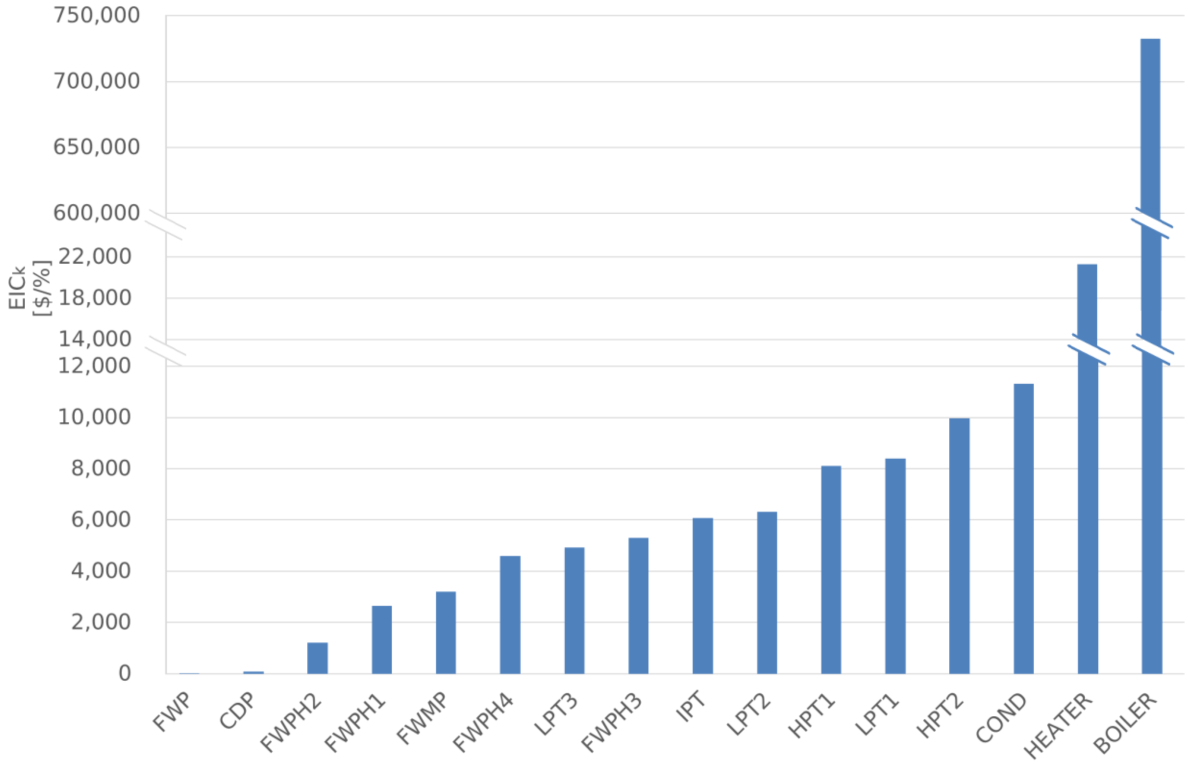

Figure 7. Cost of investment required to increase the unit exergy efficiency of components.

Then, the required improvement cost values for the unit exergy efficiency increase of the entire system under the effect of the investigated component, EIC_{tot}^{k}, is in the fourth column of Table 8. It is important to note that these values given for the percentage increase in unit efficiency are limited to the amount of avoidable exergy destruction. Investment in components to increase the exergy efficiency of the system is shown in Fig. 8. Therefore, the highest value of the exergy efficiency of the overall system that can be increased with the improvement of a component is limited, and investing more money does not allow to cross the limit. The unit efficiency percentage increase is employed here to ensure that all components are compared at the same base.

The component causing the increase in efficiency of the entire system with the lowest improvement cost is LPT3 as can be seen in Figure 8. Subsequently, IPT is in second place and their values are below $ 200.000. These two components provide a relatively high efficiency increase at a lower cost. The highest cost per unit exergy efficiency improvement of the system belongs to FWMP. That is due to their small effect on increasing the exergy efficiency of the entire system. Although the highest avoidable exergy destruction value is in the boiler, the cost required to improve the boiler for the increase of unit exergy efficiency is the fourth highest cost. For FWPH1, its contribution to efficiency increase is lower than FWMP, but it has a lower

EIC_{tot}^{k} value than pumps and the boiler due to the low cost of improvement. Although the condenser could provide a higher efficiency increase, it is found itself at the end of the improvement focus list with a relatively high cost due to the high cost of improvement.

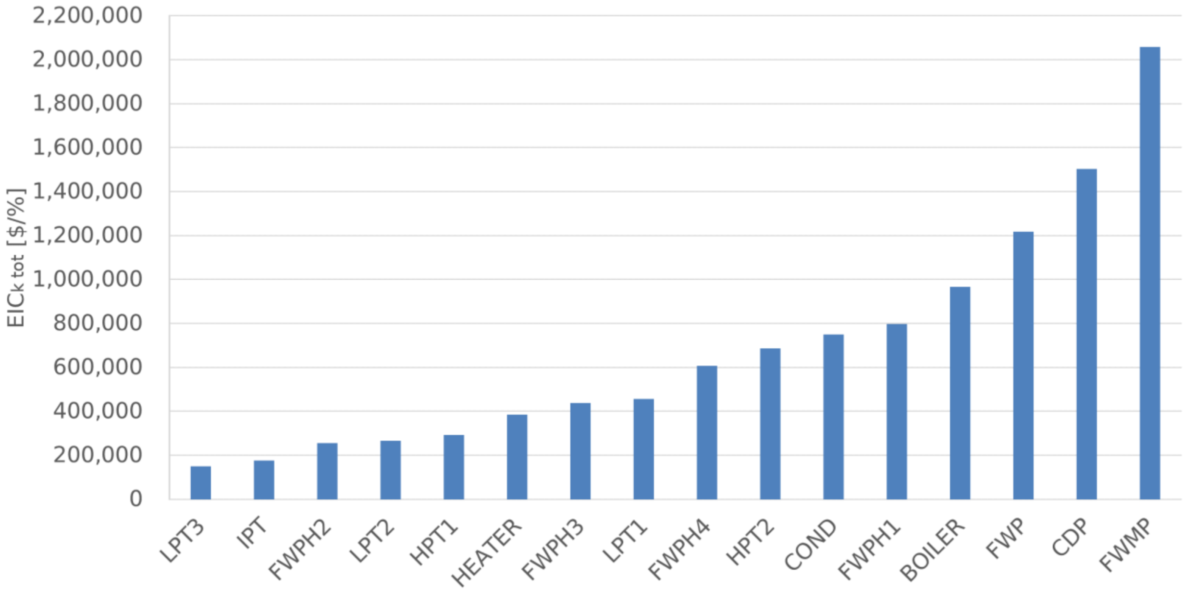

Figure 8. Investment in components to increase the exergy efficiency of the system.

Calculated levelized investment, operation, and maintenance costs over the lifetime of the components per unit avoidable exergy destruction, CAV_k, can be seen on the fifth column of Table 8 and sequentially in Fig. 9. It is important to have the smallest value of CAV_k. The lowest value is determined in LPT3 according to the data which is evaluated as the lowest investment cost throughout its lifetime in unit avoidable exergy destruction. Thus, this component appears to be the most attractive in terms of investment. IPT comes in sequence with a very small difference and it is possible to accept the importance of these two components approximately at the same level. The difference between FWPH2 in the third rank and the following LPT2 is similar to the first two components, but their costs are almost 1.5 times the costs of the first two components. The maximum lifetime cost per unit of avoidable exergy destruction is calculated for FWMP. Therefore, this component has the highest cost of improvement in unit time related to the exergy destruction that can be recovered and its value is 13 times more than the LPT3. the boiler is fourth in the order, it is only better than the renovation costs of the pumps.

What is noteworthy here is that the component order of the $EIC_{tot}^{k}$and AEC_k values and the CAV_k values are the same. Basically, the same avoidable exergy destruction and component cost of improvement are used in both equations, so the sequence of the components is expected to be similar.

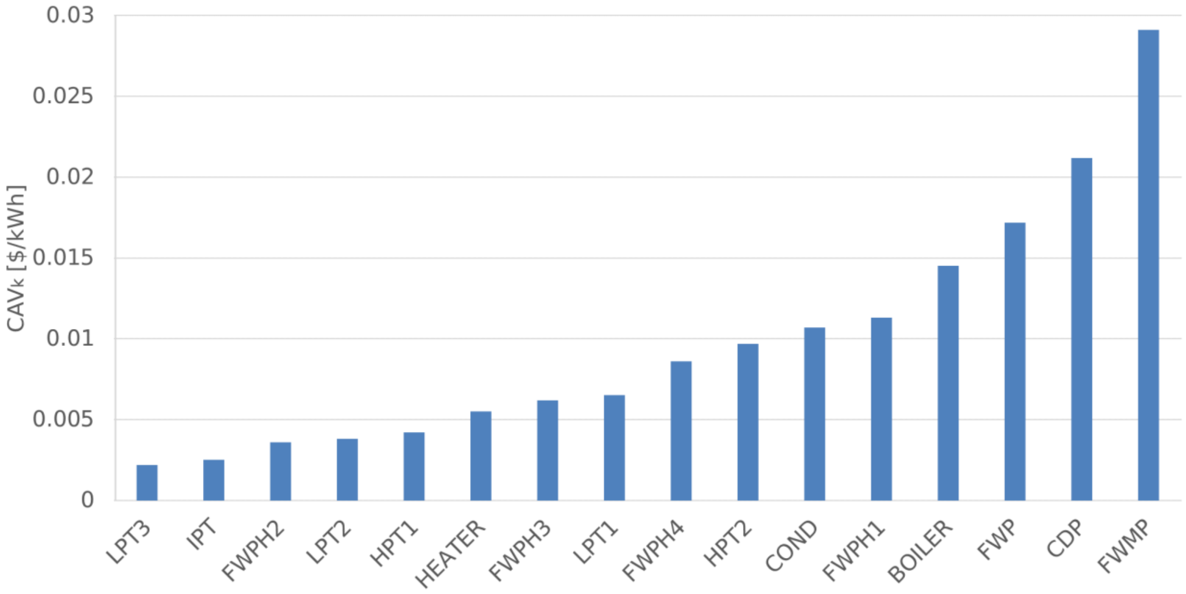

Figure 9. The cost calculated over the lifetime of the component per avoidable exergy destruction.

The specific profit potential, SPP_k, calculated due to the avoidable part of exergy destruction results are given in the sixth column of Table 8, and components are shown sequentially in Fig. 10. As can be seen, the highest saving potential is in the heater. This is mainly due to the fact that the fuel cost of fuel specific to the heater comes directly from the cost of heavy diesel fuel, and the cost of the improvement investment is relatively low. Although the cost of the unit exergy destruction is high in the boiler, the fuel cost has a direct impact, thus, it is ranked fourth in the cost saving potential ranking. Interestingly, since the calculated specific fuel exergy of FWP was considered to be directly equal to the specific cost of the generated power (c_w), the effect of the high cost of unit avoidable exergy destruction is reduced and the specific profit potential to avoid a part of the exergy destruction is higher than the boiler. Similar to other criteria, IPT has been identified as the second-most potential component, due to the fact that it has the lowest second cost per unit exergy destruction and a relatively high specific fuel exergy cost. On the basis of unit avoidable exergy destruction, there are seven components with a small savings potential above $ 0.01 and nine components below $ 0.01. FWPH1 is the last in the list as the component with the lowest potential because the cost of avoidable exergy destruction is very close to the cost of fuel exergy for the component. Since the FWMP has the highest cost per unit avoidable exergy destruction, with a close value of $ 0,0002 / kWh to FWPH1; There is also a condenser with a difference of $ 0.0005 / kWh compared to FWPH1. Using the specific profit potential for the next step, more information will be provided about the entire system to show the benefits of the system components' renovation.

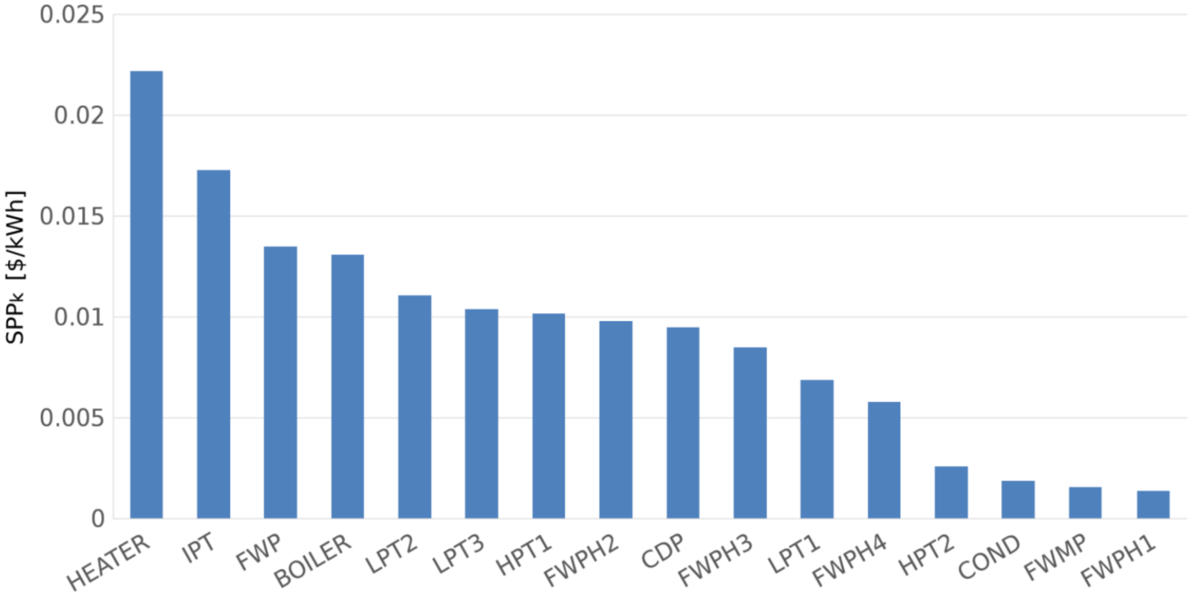

Figure 10. Specific profit potentials of the investigated components.

Cost profit, $\dot{CP}_k$, could be seen in the last column of Table 8 and is shown in sequential order in Fig. 11. Although the potential of the boiler is lower than that of the heater, IPT, and FWP, it has the highest avoidable exergy destruction, resulting in the highest savings of about \$ 36.8 / h. It is approximately six times more than the closest component LPT3. LPT3 is second to the cost profit due to having a higher amount of avoidable exergy destruction, although it has lower savings potential than the boiler, FWP, IPT, and the heater. As improvements on the first five components, boiler, LPT3, HPT1, IPT, LPT2 can save above \$ 1 / h. In total, it is possible to save \$ 52.7 / h in the entire system by improving all components. 70% of this value only belongs to the boiler. The other four components namely LPT3, HPT1, IPT, LPT2 have 12.3%, 7%, 4%, and 2.5%, respectively. FWP has the lowest cost profit since it has very small avoidable exergy destruction despite having the third highest savings potential. In general terms, the turbines have a higher cost of benefit than heat exchangers. The only exception of this case is HPT2, which follows condenser, FWPH2, and FWPH3 in the ranking. The reason for this is that it has one of the lowest SPP_k values and relatively low avoidable exergy destruction.

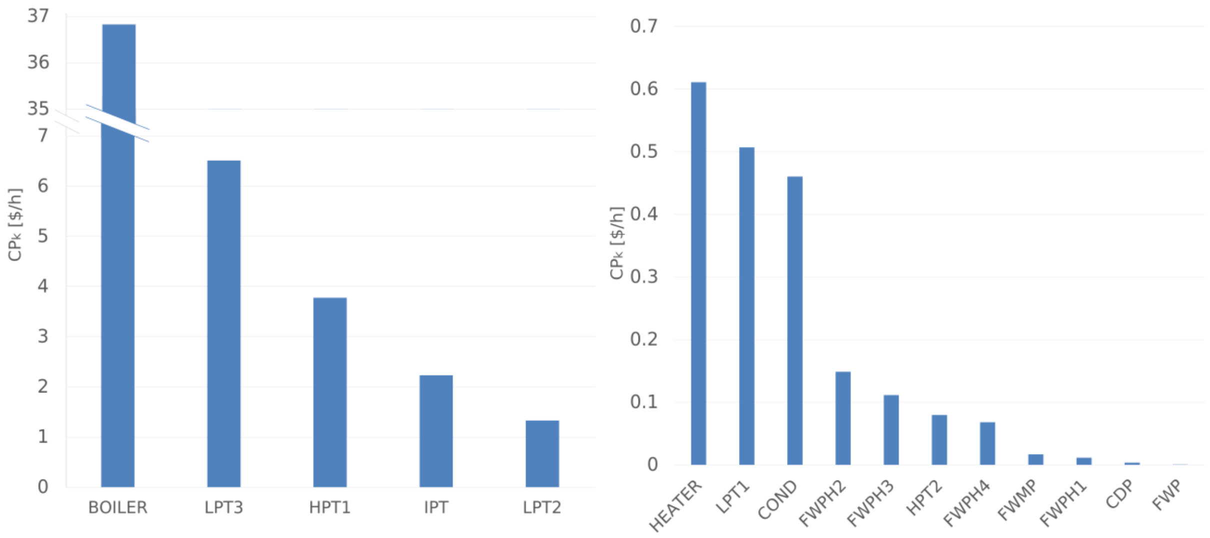

Figure 11. Cost profits, savings potentials of the investigated components.

Considering the results, the priorities of the engineer show importance. An engineer who keeps the exergy efficiency of the system regardless of the cost should strive to improve the components that have the highest value, i.e. the ones that have the most impact on the increase of system efficiency. Where the cost is at the forefront, the engineer should give priority to the recovery of the maximum avoidable exergy destruction per unit cost of improvement, or to the improvement of the components that provide the minimum investment cost required for the unit efficiency increase in the system. Increasing the efficiency of the components at minimum cost should be directed towards development approaches by considering the engineer EIC_k values. CAV_k values give similar ranking results to EIC_{tot}^k and AEC_k, but it is appropriate to use this criterion where the cost per unit time per unit avoidable exergy destruction is important. The savings potential of each component depends on the operating conditions and costs. The SPP_k values represent the engineer as an important concept, as it shows how potentially the costs of components can be saved. However, since each component's potential saving is limited to its avoidable exergy destruction, the cost profits, $\dot{CP}_k$ symbolize the maximum savings that a component can provide for the system. In cases where the savings are of the utmost importance, the engineer should consider directing investments in terms of investment, maintenance, operation, and repair costs for the components that can provide the highest savings in order.

In general, the conclusions that are drawn out of the results of the decision support criteria will be helpful to improve the system and to direct the engineer toward a better working system with a smaller monetary loss.

5. Conclusion

In this paper, novel advanced exergoeconomic performance criteria for energy systems are introduced to shed light on the demands of investors, which could be applied to evaluate whether an investment is feasible. Advanced exergoeconomic analysis is applied to a marine steam power plant and the system components are evaluated by using aforementioned criteria. The results of advanced exergoeconomic analysis revealed that the highest avoidable exergy destruction cost belongs to the boiler with 77.4 \$/h. On the other hand, criteria analysis yield that investing in the boiler will recover 1.4 W/\$. That is small among all components. However, the most crucial information which is the amount of profit that could be recovered by investing on the boiler is 36.8 \$/h and it is the maximum profit among all. The highest avoidable exergy destruction per investment cost with the lowest hourly cost per avoided exergy destruction belongs to LPT3 with values of 9.6 W/\$ and 0.0022 \$/kWh, respectively. Moreover, it has a potential to recover 7.9 \$/h and have savings potential, $\dot{CP}_k$, of 6.5 \$/h as the second feasible component in the system. HPT1 comes the third on investment feasible list with the 3.8 \$/h profit potential. Although the investment feasible components list is the same for the first three components, it starts to diversify afterward. Though IPT has a lower avoidable exergy destruction than the condenser, it can provide more profit as 2.2 \$/h when invested. This case is also valid for LPT2 with 1.3 \$/h cost profit. Similarly, LPT1 has avoidable exergy destruction cost as 0.98\$/h, while the heater has 0.76 \$/h, but the heater has more savings potential compared to LPT1 with respect to $\dot{CP}_k$ values. To sum up, the system has 101\$/h avoidable exergy destruction cost when all destructions are recovered, but $\dot{CP}_k$ reveals that the system could save more than half of that value as 52.7 \$/h with respect to the costs made for the improvements.

It has been seen that advanced exergoeconomic analysis provides valuable information to evaluate the improvement potential of the system due to avoidable exergy destruction costs. However, developed criteria cover the shortcomings of the aforementioned method and constitute the next step as an extension of the advanced exergoeconomic analysis by providing the profit potential of the system that is the highest recovery of avoidable costs with a unit investment on the system.

It should be noted that the novel criteria as decision support for the improvement have only limitations of the advanced exergoeconomic analysis, which are stated in the literature as technologic, economic, and environmental constraints. Moreover, the results of the advanced exergoeconomic analysis are obtained by the application of component parameters in real, theoretical, and unavoidable conditions regarding mentioned limitations. Nevertheless, it is expected that the careful interpretation of economic performance criteria would enhance the results, and alterations of the assumptions regarding the expertise of the engineer and/or designer should not affect the yielded general conclusions pictured by the novel criteria.

With the criteria proposed here, it is aimed to provide a decision support tool to the plant designer or engineer. It is foreseen that these decision support criteria can make an important contribution and be a useful tool as a result of their application to other thermal systems.

Further consideration should be given to assess the environmental impact of thermal systems through decision support tool such as presented in this study. Moreover, environmental impact and economic concerns could be combined together with new objective functions to assess and optimize thermal systems in a more economic and environmentally friendly way.

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References

[1] *Paris Agreement*. ; http://unfccc.int/process-and-meetings/the-paris-agreement. 2015. [accessed 26 December 2017].

[2] MARPOL IMO, *Consolidated Edition 2006, MARPOL Annex VI: Regulations for the prevention of air pollution from ships.* London: International Maritime Organization, 2006.

[3] Koroglu, T. and O.S. Sogut, *Advanced Exergoeconomic Analysis of Organic Rankine Cycle Waste Heat Recovery System of a Marine Power Plant.* International Journal of Thermodynamics, 2017. **20**(3): p. 140-151.

[4] Bühler, F., et al., *Energy, exergy and advanced exergy analysis of a milk processing factory.* Energy, 2018. **162**: p. 576-592.

[5] Gholamian, E., P. Hanafizadeh, and P. Ahmadi, *Advanced exergy analysis of a carbon dioxide ammonia cascade refrigeration system.* Applied Thermal Engineering, 2018. **137**: p. 689-699.

[6] Fallah, M., S.M.S. Mahmoudi, and M. Yari, *A comparative advanced exergy analysis for a solid oxide fuel cell using the engineering and modified hybrid methods.* Energy Conversion and Management, 2018. **168**: p. 576-587.

[7] Mortazavi, A. and M. Ameri, *Conventional and advanced exergy analysis of solar flat plate air collectors.* Energy, 2018. **142**: p. 277-288.

[8] Trindade, A.B., Palacio, J. C. E., González, A. M., Orozco, D. J. R., Lora, E. E. S., Renó, M. L. G., 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**: p. 195-214.

[9] He, Q., Liu, H., Hao, Y., Liu, Y., Liu, W. *Thermodynamic analysis of a novel supercritical compressed carbon dioxide energy storage system through advanced exergy analysis.* Renewable Energy, 2018. **127**: p. 835-849.

[10] Jain, V., G. Sachdeva, and S.S. Kachhwaha, *Comparative performance study and advanced exergy analysis of novel vapor compression-absorption integrated refrigeration system.* Energy Conversion and Management, 2018. **172**: p. 81-97.

[11] Koroglu, T. and O.S. Sogut, *Advanced exergy analysis of an organic Rankine cycle waste heat recovery system of a marine power plant.* Journal of Thermal Engineering, 2017. **3**(2): p. 1136-1148.

[12] Koroglu, T. and O.S. Sogut, *Conventional and advanced exergy analyses of a marine steam power plant.* Energy, 2018. **163**: p. 392-403.

[13] Koroglu, T. and O.S. Sogut. *Advanced exergy analysis of a Marine Diesel Engine waste heat recovery system*. in *International Conference on Shipping in Changing Climates*. 2015. Glasgow: University of Stratclyde.

[14] Ehyaei, M.A., A. Ahmadi, and M.A. Rosen, *Energy, exergy, economic and advanced and extended exergy analyses of a wind turbine.* Energy Conversion and Management, 2019. **183**: p. 369-381.

[15] Dibazar, S.Y., G. Salehi, and A. Davarpanah, *Comparison of Exergy and Advanced Exergy Analysis in Three Different Organic Rankine Cycles.* Processes, 2020. **8**(5).

[16] Mohammadi, Z., M. Fallah, and S.M.S. Mahmoudi, *Advanced exergy analysis of recompression supercritical CO2 cycle.* Energy, 2019. **178**: p. 631-643.

[17] Cao, Y., Rostamian, F., Ebadollahi, M., Bezaatpour, M., & Ghaebi, H., *Advanced exergy assessment of a solar absorption power cycle.* Renewable Energy, 2022. **183**: p. 561-574.

[18] Ebrahimi, M., Carriveau, R., Ting, D. S. K., McGillis, A, *Conventional and advanced exergy analysis of a grid connected underwater compressed air energy storage facility.* Applied Energy, 2019. **242**: p. 1198-1208.

[19] Yuan, B., Zhang, Y., Du, W., Wang, M., Qian, F., *Assessment of energy saving potential of an industrial ethylene cracking furnace using advanced exergy analysis.* Applied Energy, 2019. **254**: p. 113583.

[20] Liao, G., Jiaqiang, E., Zhang, F., Chen, J., & Leng, E., *Advanced exergy analysis for Organic Rankine Cycle-based layout to recover waste heat of flue gas.* Applied Energy, 2020. **266**: p. 114891.

[21] Petrakopoulou, F., Tsatsaronis, G., Morosuk, T., & Carassai, A., *Advanced exergoeconomic analysis applied to a complex energy conversion system.* Journal of Engineering for Gas Turbines and Power, 2012. **134**(3): p. 031801.

[22] Wei, Z., Zhang, B., Wu, S., Chen, Q., & Tsatsaronis, G., *Energy-use analysis and evaluation of distillation systems through avoidable exergy destruction and investment costs.* Energy, 2012. **42**(1): p. 424-433.

[23] Petrakopoulou, F., G. Tsatsaronis, and T. Morosuk, *Evaluation of a power plant with chemical looping combustion using an advanced exergoeconomic analysis.* Sustainable Energy Technologies and Assessments, 2013. **3**: p. 9-16.

[24] Janghorban Esfahani, I., S. Lee, and C. Yoo, *Evaluation and optimization of a multi-effect evaporation–absorption heat pump desalination based conventional and advanced exergy and exergoeconomic analyses.* Desalination, 2015. **359**: p. 92-107.

[25] Gungor, A., Tsatsaronis, G., Gunerhan, H., & Hepbasli, A., *Advanced exergoeconomic analysis of a gas engine heat pump (GEHP) for food drying processes.* Energy Conversion and Management, 2015. **91**: p. 132-139.

[26] Koroglu, T. and O.S. Sogut. *Splitting costs of a marine diesel engine waste heat recovery system into avoidable and unavoidable parts*. in *The International Maritime Association of the Mediterranean 2017 Conference*. 2017. Lisbon, Portugal: CRC Press, Taylor & Francis Group.

[27] Moharamian, A., Soltani, S., Rosen, M. A., Mahmoudi, S. M. S., *Advanced exergy and advanced exergoeconomic analyses of biomass and natural gas fired combined cycles with hydrogen production.* Applied Thermal Engineering, 2018. **134**: p. 1-11.

[28] Ansarinasab, H. and M. Mehrpooya, *Investigation of a combined molten carbonate fuel cell, gas turbine and Stirling engine combined cooling heating and power (CCHP) process by exergy cost sensitivity analysis.* Energy Conversion and Management, 2018. **165**: p. 291-303.

[29] Açıkkalp, E., Hepbasli, A., Yucer, C. T., Karakoc, T. H., *Advanced life cycle integrated exergoeconomic analysis of building heating systems: An application and proposing new indices.* Journal of Cleaner Production, 2018. **195**: p. 851-860.

[30] Kanbur, B. B., Xiang, L., Dubey, S., Choo, F. H., Duan, F., *Life cycle integrated thermoeconomic assessment method for energy conversion systems.* Energy Conversion and Management, 2017. **148**: p. 1409-1425.

[31] Mehrpooya, M., Sharifzadeh, M. M. M., Zonouz, M. J., Rosen, M. A., *Cost and economic potential analysis of a cascading power cycle with liquefied natural gas regasification.* Energy Conversion and Management, 2018. **156**: p. 68-83.

[32] Mehrpooya, M., Ansarinasab, H., Sharifzadeh, M. M. M., & Rosen, M. A., *Conventional and advanced exergoeconomic assessments of a new air separation unit integrated with a carbon dioxide electrical power cycle and a liquefied natural gas regasification unit.* Energy Conversion and Management, 2018. **163**: p. 151-168.

[33] Mehrpooya, M., M.M.M. Sharifzadeh, and H. Ansarinasab, *Investigation of a novel integrated process configuration for natural gas liquefaction and nitrogen removal by advanced exergoeconomic analysis.* Applied Thermal Engineering, 2018. **128**: p. 1249-1262.

[34] Ansarinasab, H., M. Mehrpooya, and M. Pouriman, *Advanced exergoeconomic evaluation of a new cryogenic helium recovery process from natural gas based on the flash separation – APCI modified process.* Applied Thermal Engineering, 2018. **132**: p. 368-380.

[35] Liu, Z., Liu, Z., Cao, X., Luo, T., Yang, X., *Advanced exergoeconomic evaluation on supercritical carbon dioxide recompression Brayton cycle.* Journal of Cleaner Production, 2020. **256**.

[36] Ambriz-Díaz, V. M., Rubio-Maya, C., Ruiz-Casanova, E., Martínez-Patiño, J., Pastor-Martínez, E., *Advanced exergy and exergoeconomic analysis for a polygeneration plant operating in geothermal cascade.* Energy Conversion and Management, 2020. **203**.

[37] Uysal, C. and A. Kecebas, *Advanced exergoeconomic analysis with using modified productive structure analysis: An application for a real gas turbine cycle*. Energy, 2021. **223**.

[38] Wang, Y., Liu, Y., Liu, X., Zhang, W., Cui, P., Yu, M. et al., *Advanced exergy and exergoeconomic analyses of a cascade absorption heat transformer for the recovery of low grade waste heat.* Energy Conversion and Management, 2020. **205**.

[39] Liu, Z., Liu, Z., Yang, X., Zhai, H., Yang, X., *Advanced exergy and exergoeconomic analysis of a novel liquid carbon dioxide energy storage system.* Energy Conversion and Management, 2020. **205**.

[40] Dai, B., Zhu, K., Wang, Y., Sun, Z., Liu, Z.Dai, B.M., et al., *Evaluation of organic Rankine cycle by using hydrocarbons as working fluids: Advanced exergy and advanced exergoeconomic analyses.* Energy Conversion and Management, 2019. **197**.

[41] Oyekale, J., M. Petrollese, and G. Cau, *Modified auxiliary exergy costing in advanced exergoeconomic analysis applied to a hybrid solar-biomass organic Rankine cycle plant.* Applied Energy, 2020. **268**: p. 114888.

[42] Koroglu, T., *Developing Criteria For Advanced Exergoeconomic Performance Analysis of the Thermal Systems*, in *Graduate School of Science, Engineering and Technology*. 2018, Istanbul Technical University: Istanbul, Turkey.

[43] Tsatsaronis, G. and M. Winhold, *Exergoeconomic analysis and evaluation of energy-conversion plants—I. A new general methodology.* Energy, 1985. **10**(1): p. 69-80.

[44] Bejan, A., M.J. Moran, and G. Tsatsaronis, *Thermal design and optimization*. New York: John Wiley & Sons, Inc.; 1996.

[45] Tsatsaronis, G. and M.-H. Park, *On avoidable and unavoidable exergy destructions and investment costs in thermal systems.* Energy Conversion and Management, 2002. **43**(9): p. 1259-1270.

[46] Turton, R., R.C. Bailie, and W.B. Whiting, *Analysis, Synthesis, and Design of Chemical Processes*. 4th Ed. ed. Upper Saddle River, NJ: Pearson Education International; 2012.

[47] Wang, L., *Thermo-economic Evaluation, Optimization and Synthesis of Large-scale Coal-fired Power Plants*, in *Institut für Energietechnik.* 2016, Technische Universität Berlin: Berlin.

[48] VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen, *VDI Heat Atlas*. 2 ed. VD-Buch., Berlin Heidelberg: Springer-Verlag Berlin Heidelberg. 2010

[49] Coleman, M.J., *Ship Weight Reduction and Efficiency Enhancement Through Combined Power Cycles*. 2013, Florida State University: Tallahassee, Florida.

[50] Çengel, Y.A. and A.J. Ghajar, *Heat and mass transfer : fundamentals & applications*. New York: McGraw-Hill Education; 2015.

[51] Szargut, J., D.R. Morris, and F.R. Steward, *Exergy analysis of thermal, chemical, and metallurgical processes*. New York: Hemisphere; 1988.