Conventional and Advanced Exergy-Exergoeconomic-Exergoenvironmental Analyses of an Organic Rankine Cycle Integrated with Solar and Biomass Energy Sources: Postprint

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Abstract

Considering the massive consumption of traditional energy and the growing demand for electricity, the development of renewable energy is essential. This paper proposes an energy system integrating biomass energy, solar energy, and a two-stage organic Rankine cycle (ORC), which utilizes the stable energy output of biomass energy to compensate for the volatility of solar modules. The proposed system comprises a biomass boiler, photovoltaic-thermal panels (PV/T), evaporators, condensers, working fluid pumps, turbines, a preheater, and an air preheater. Furthermore, conventional and advanced exergy, exergoeconomic, and exergoenvironmental (3E) analyses are conducted. Conventional 3E analyses identify two components requiring priority improvement: Evaporator 1, which exhibits the largest exergy destruction (708.2kW) and exergy destruction environmental impact rate (775.3 mPt/h), and Evaporator 2, which has the largest exergy destruction cost rate (19.15/*h*). *Theresultsofadvanced3Eanalysesshowthatthelargestavoidableendogenousexergydestructioniscon*
Additionally, Condenser 1 shows the largest avoidable endogenous exergy destruction environmental impact rate (196.1mPt/h). This indicates that these components possess significant potential for improvement in terms of reducing exergy destruction, saving costs, and protecting the environment. However, the avoidable endogenous exergy destruction, cost, and environmental impact rates of Evaporator 2 are negative, indicating that Evaporator 2 is not a suitable priority component for improvement, which contradicts the conclusions of conventional 3E analyses. It is found that conventional 3E analyses can only identify the components with the greatest exergy destruction, but cannot indicate whether these components have the greatest potential for improvement. However, advanced 3E analyses can reveal the improvement potential of

each component through enhancements in its own performance and external conditions. Therefore, it is necessary to conduct advanced 3E analyses.

Full Text

Preamble

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Abstract

Considering the massive consumption of traditional energy sources and the rising demand for electricity, the development of renewable energy systems has become imperative. This paper proposes an energy system that integrates biomass energy, solar energy, and a two-stage organic Rankine cycle (ORC). The system leverages the stable energy output from biomass to compensate for the inherent volatility of solar modules. The proposed system comprises a biomass boiler, photovoltaic-thermal panels (PV/T), evaporators, condensers, working fluid pumps, turbines, a preheater, and an air preheater. Both conventional and advanced exergy, exergoeconomic, and exergoenvironmental (3E) analyses are conducted. Conventional 3E analyses identify two components requiring priority improvement: Evaporator 1, which exhibits the largest exergy destruction (708.2 kW) and exergy destruction environmental impact rate (775.3 mPt/h), and Evaporator 2, which shows the highest exergy destruction cost rate $(19.15/h).Theresultsofadvanced3Eanalysesshowthatthelargestavoidableendogenousexergydestructioniscon$ Additionally, Condenser 1 demonstrates the largest avoidable endogenous exergy destruction environmental impact rate (196.1 mPt/h), indicating significant potential for improvement in reducing exergy destruction, saving costs, and protecting the environment. However, the avoidable endogenous exergy destruction, cost, and environmental impact rates for Evaporator 2 are negative, suggesting it is unsuitable as a priority component for improvement—a conclusion that contradicts conventional 3E analysis results. Conventional 3E analyses can only identify the location of maximum exergy destruction but cannot determine whether components with the greatest exergy destruction offer the greatest improvement potential. In contrast, advanced 3E analyses reveal the improvement potential of each component through enhancements in its own performance and external conditions. Therefore, conducting advanced 3E analyses is essential.

Keywords: Exergoenvironmental analysis, Exergoeconomic analysis, Advanced exergy, Two-stage ORC

1 Introduction

The massive consumption of fossil fuels and the associated environmental impact of greenhouse gas emissions have become critical global concerns, prompting efforts to identify environmentally friendly renewable energy alternatives [1,2]. Due to decreasing costs of solar power generation technology and the advantages of biomass energy—including direct storage, transportability, and widespread availability [3]—both sources hold substantial potential for future renewable energy development. However, solar energy is significantly affected by climate variability, with solar irradiance differing across regions, resulting in lower reliability [4]. Biomass energy, conversely, is a storable and transportable renewable energy source that represents another form of solar energy, existing in solid, liquid, or gaseous states. Furthermore, the carbon dioxide emitted during biomass combustion is offset by the CO_2 absorbed during biomass growth, making it a carbon-neutral renewable energy source [3]. By combining these characteristics, the integrated application of biomass and solar energy can effectively compensate for the unstable output of solar energy caused by weather conditions.

The electrical efficiency of solar photovoltaic panels is inversely correlated with panel temperature. Photovoltaic-thermal panels (PV/T) improve power generation efficiency by absorbing heat from the photovoltaic panels while simultaneously producing low-grade thermal energy [5]. Additionally, biomass combustion represents an effective method for large-scale biomass utilization [6,7]. Given the low energy density of biomass, the low-grade heat generated by PV/T and biomass boilers can be recovered using an Organic Rankine Cycle (ORC). The ORC effectively converts low-grade thermal energy into high-grade electricity, making it a viable approach for medium- and low-temperature heat source recovery. This cycle employs low-boiling-point organic fluids as the working medium, unlike the conventional Rankine cycle that uses water, enabling ORC systems to recover heat sources ranging from 65–400°C [8]. In 2022, Atiz et al. [9] developed a PV/T-ORC coupling model suitable for residential loads, achieving cogeneration through comprehensive heat source utilization. In the same year, Ding et al. [10] compared the economics of biomass gasification and biomass combustion for heating, demonstrating that the total cost of biomass gasification technology is approximately 1.63 times that of biomass combustion, thereby confirming the feasibility of coupling biomass combustion with ORC systems.

To improve the comprehensive performance of ORC systems, numerous researchers have modified the basic cycle based on its working principles, developing recuperative organic Rankine cycles [11,12], pumped recuperative organic Rankine cycles [13], reheating-regenerative-internal recuperation organic Rankine cycles [14], and dual organic Rankine cycles [15]. Zeng et al. [15] compared three ORC configurations—basic ORC, tandem ORC, and double ORC—under cold, conventional, and tropical conditions, revealing that the double ORC exhibits the best thermodynamic and economic performance under cold and conventional conditions, while the tandem ORC performs best in tropical environments. In summary, improved tandem and dual ORC configurations outperform the basic ORC in both thermodynamic performance and cost-effectiveness. Li et al. [16] designed an energy system integrating geothermal energy, proton exchange membrane fuel cells, and a two-stage organic Rankine flash cycle, cleverly utilizing different heat source temperatures to increase system exergy efficiency and significantly improve net power output. Therefore, a two-stage ORC can be designed to accommodate the two distinct heat sources from biomass and solar outputs, facilitating temperature cascading and yielding superior energy output.

Most current assessments of hybrid energy systems incorporate conventional exergy and exergoeconomic analyses [17–19], with few studies including the exergoenvironmental analysis proposed by Meyer in 2009 [20]. These conventional exergy, exergoeconomic, and exergoenvironmental (3E) analyses can determine the improvement potential of each system component by dividing outputs into exergy destruction and useful energy, then calculating the economic and environmental impacts associated with each. This enables targeted optimization of energy systems. In 2023, Wang et al. [21] performed conventional 3E analyses of a biomass gasifier and solid oxide fuel cell integrated energy system, employing a multi-objective particle swarm optimization algorithm to optimize three distinct dual-objective functions. In 2023, Ali et al. [22] conducted energy and exergy analyses on a combined cooling, heating, and power generation system integrated with an improved Kalina cycle and supercritical CO_2 power cycle, evaluating the system based on energy and exergy efficiencies. Khoshgoftar Manesh et al. [23] designed a polygeneration system powered by solar energy and natural gas, analyzing its energy, exergy, exergoeconomic, and exergoenvironmental performance before applying multi-objective optimization.

However, conventional 3E analyses possess certain limitations. They only indicate the general magnitude of energy losses during component operation without specifying whether and to what extent these losses can be reduced. Consequently, numerous researchers [24–26] have enhanced conventional 3E analyses, proposing advanced exergy, advanced exergoeconomic, and advanced exergoenvironmental analyses. Advanced 3E analyses decompose exergy destruction, exergy destruction cost, and exergy destruction environmental impact into endogenous/exogenous and avoidable/unavoidable components, thereby helping to determine improvement potential through both component efficiency optimization and external condition modification.

In 2019, Moharramian et al. [27] conducted conventional and advanced exergy and exergoeconomic analyses of a biomass-photovoltaic hydrogen production integrated energy system, discussing module parameter settings using exergy efficiency and exergoeconomic factor as evaluation metrics. Their findings revealed inconsistencies between conventional and advanced analysis conclusions, suggesting that conventional exergy analysis can identify components with maximum exergy destruction but cannot assess their improvement potential. In 2020, Oyekale et al. [28,29] performed conventional and advanced exergy and exergoeconomic analyses of a solar-biomass-ORC cogeneration system, describing two improvement methods for exergoeconomic analysis that provide references for system enhancement. In 2020, Khoshgoftar Manesh et al. [30] evaluated a biomass gasification combined cycle using conventional and advanced 3E analyses, exploring the improvement potential of each component. In 2021, Al-Sayyab et al. [31] assessed a PV/T-driven ejector heat pump system using conventional and advanced exergy and exergoeconomic analyses, finding similar improvement recommendations from both conventional and advanced exergy analyses. The contrasting results of Moharramian and Al-Sayyab suggest that conventional and advanced exergy analyses may yield different conclusions for different energy systems. In 2021, Wang et al. [32] detailed the advanced exergy analysis process for an ORC using the thermodynamic cycle method, comparing the gap between conventional and advanced exergy analysis and demonstrating that advanced exergy analysis pinpoints components with the greatest improvement potential. Hu et al. [33] conducted conventional and advanced exergy analyses of a cascade high-temperature heat pump system based on experimental data, determining component improvement priorities. In 2022, Dilek Nur et al. [34] analyzed an LNG-powered generation system using conventional and advanced exergy and exergoeconomic analyses, identifying components with the greatest improvement potential. In 2022, Gürbüz et al. [35] performed an exergoenvironmental analysis of a geothermal-driven two-stage ORC system, dividing environmental impacts into endogenous/exogenous and avoidable/unavoidable components to obtain information on component interactions and improvement potential from an environmental perspective. In 2023, Zahra et al. [36] designed a geothermal-powered triple-generation system and performed conventional and advanced exergy analyses to establish component improvement priorities. In 2023, Li et al. [37] proposed a geothermal-driven organic Rankine flash cycle and applied conventional and advanced exergy and exergoeconomic analyses to determine individual component improvement potential. In the same year, Tian et al. [38] conducted conventional and advanced exergy analyses of an ORC for low-temperature cold energy recovery, finding that the expander's avoidable endogenous exergy destruction constitutes the highest proportion of total exergy destruction, indicating its superior improvement potential.

Evidently, conventional and advanced 3E analyses yield valuable results for renewable energy system optimization. However, limited literature addresses both conventional and advanced 3E analyses comprehensively. Many studies examine only one or two aspects of conventional and advanced exergy, exergoeconomic, and exergoenvironmental analyses [28,31,39]. As environmental concerns grow, environmental impact has become as critical as cost in energy system design and optimization. Furthermore, conventional and advanced 3E analyses can determine the reducible exergy destruction for each component and identify reduction strategies, providing valuable references for comprehensive energy system optimization. Therefore, comprehensive conventional and advanced 3E analyses are essential. The main contributions and novelties of this paper are summarized as follows:

- Design of a multi-energy complementary system integrating biomass and solar energy, employing a two-stage organic Rankine cycle as a waste heat recovery device for both the biomass boiler and PV/T.
- Performance of conventional 3E analyses on the energy system, particularly the less frequently conducted exergoenvironmental analysis.
- Conducting advanced 3E analyses to provide detailed improvement recommendations for the proposed energy system.

2 System Description

[Figure 1: see original paper] illustrates a schematic diagram of the proposed system, which primarily consists of two parts: an organic Rankine cycle driven by boiler pressurized hot water, and an organic Rankine cycle driven by PV/T output hot water.

Biomass fuel and air preheated by an air preheater undergo complete combustion in the biomass boiler, transferring heat to water to produce pressurized hot water. This pressurized hot water enters Evaporator 1, where it exchanges heat with the organic working fluid R245fa in ORC 1. After heat exchange, the pressurized hot water returns to the biomass boiler for reheating, forming a biomass boiler pressurized hot water cycle. The R245fa at Evaporator 1 outlet is first pressurized by Pump 1, then absorbs heat in Evaporator 1 to become a high-temperature, high-pressure organic fluid. This fluid enters Turbine 1, expands rapidly, and drives the turbine to generate electricity. After expansion, the fluid retains residual heat and is designed to enter the Preheater to preheat the high-pressure working fluid of ORC 2 while reducing its own temperature, thereby decreasing the cooling water flow required for Condenser 1. Condenser 1 condenses the working fluid from the Preheater outlet into liquid before sending it to Pump 1 for pressurization. The pressurized organic working fluid then enters Evaporator 1 for evaporation, completing the ORC 1 cycle. ORC 2 operates similarly to ORC 1, except that the heat source for Evaporator 2 originates from PV/T output hot water. The PV/T is a solar cogeneration system—an excellent option for small-scale residential applications. By adding thermal conduction channels on the PV/T backside and circulating cold fluid, the system not only reduces photovoltaic panel temperature to improve cell efficiency but also captures low-grade thermal energy. However, PV/T operation is significantly weather-dependent. To stabilize ORC 2 operation, the design feeds high-pressure organic working fluid—pressurized by Pump 2 and preheated by the Preheater—into Evaporator 2. The electricity generated by Turbine 1, Turbine 2, and the PV/T components constitutes the system's primary output.

3 Mathematical Model

This section establishes mathematical models for energy, conventional exergy, conventional exergoeconomic, conventional exergoenvironmental, advanced exergy, advanced exergoeconomic, and advanced exergoenvironmental analyses. Engineering Equation Solver and TRNSYS were used for simulation and calculation. To simplify the model, the following assumptions are made [40,41]:

1. System operation is steady-state;
2. Power consumption of cooling water pumps is ignored;
3. Heat loss and pressure drop in components and piping are ignored;
4. Ambient temperature is 293.15 K, and ambient pressure is 101.325 kPa;
5. Isentropic efficiency of turbines and working fluid pumps is 0.85.

3.1 Energy Analysis

Biomass combustion is the process of burning biomass fuel in a burner. The fuel used is biomass pellet fuel, with elemental analysis shown in Table 1. The thermal efficiency of the biomass pressurized hot water boiler is 0.9 [42], with a given heat load of 650 kW. The biomass boiler heat balance calculation [43] is as follows:

where is the given heat load of the biomass pressurized hot water boiler, is the mass flow rate of biomass pellet fuel, is the lower heating value of biomass pellet fuel $(/h).Theresultsofadvanced3Eanalysesshowthatthelargestavoidableendogenousexergydestructioniscond$ [43], is the heat transferred from the biomass boiler to pressurized hot water, and is the thermal efficiency of the biomass boiler.

Elemental analysis of biomass pellet fuels.

The amount of air required for combustion and the amount of flue gas emitted by the biomass boiler are calculated based on the data in Table 1 [43]:

where represents the amount of air entering the boiler and the amount of individual gases emitted by the boiler, represents mass flow rate, is the excess air coefficient ($ Air preheater Biomass boiler Condenser 1 Condenser 2 Evaporator 1 Evaporator 2 Preheater Pump 1 Pump 2 Turbine 1 kkZCR-FZN=(1)(1)1nrrnriiCRFi+=+−„,kckkDkLkZfZCC=++,outkC,inkC,wkC,QkCckZNCRFrin,ckf,DkC13151416 Turbine 2 Exergoenvironmental analysis is similar to exergoeconomic analysis, and both need to be calculated on the basis of exergy analysis. The main goal of exergoenvironmental analysis is to obtain components with the greatest environmental impact over the life cycle of the system and components with high environmental impact caused by exergy destruction. It can evaluate components with pollutant emissions. Exergoenvironmental analysis balance equation is as follows [20]: where are the environmental impact rate of the output exergy stream and input exergy stream of the component k, is the environmental impact of the component itself, is the environmental impact rate of pollutants, is the specific environmental impact rate, , and are the environmental impact rates generated during the component creation, operation and maintenance and disposal process, is the exergoenvironmental factor, and is the exergy destruction environmental impact rate.

Table 5 shows the exergoenvironmental balance equations and auxiliary equations for each component of the system, and Table 6 shows the environmental impact values of each component of the system.

Table 5 Equation for exergoenvironmental analysis for each component.

Component Environmental impact balance relation Auxiliary equation Air preheater Biomass boiler Condenser 1 62722turCZCC+=+0.7524750()turturZW= „PFinkkkoutkBYBB++=kkkB 0BEBEB==1917161813bioBBBYBB+++=+25.4545/0.004889/CObfbmPtkgbmPtkg==3231424conBBYBB 0BEBEB== Condenser 2 Evaporator 1 Evaporator 2 Preheater Pump 1 Pump 2 Turbine 1 Turbine 2 Table 6 The environmental impact values of each component of the system [58–60].

Component Material Unit component-related environmental impact /mPt/kg Build Operation and maintenance Recycle Points/mPt/kg Air preheater Steel(25%), steel high alloy(75%) Biomass boiler Steel(20%), steel high alloy(70%), steel low alloy(10%) Condenser 1 Steel(100%) Condenser 2 Steel(100%) Evaporator 1 Steel(100%) Evaporator 2 Steel(100%) Preheater Steel(25%), steel high alloy(75%) Pump 1 Pump 2 Steel(35%), cast iron(65%) Steel(35%), cast iron(65%) Solar glass(44%), silicon(2%), polyethylene(1%), copper(24%), 2582826conBBYBB++=+778825 0BEBEB==5181119evaBBYBB++=+18181919BEBE=10112126evaBBYBB++=+11111212BEBE=29310preBBY 0PVTsunBBEEBWB−−==11220turBYBB+=+1122BEBE=62722turBYBB+=+6677BEBE= PUR(6%), aluminum(15%), galvanized iron(8%) Turbine 1 Steel(25%), steel high alloy(75%) Turbine 2 Steel(25%), steel high alloy(75%)

3.3 Advanced 3E analyses

The difference between advanced exergy analysis and conventional exergy analysis is that advanced exergy analysis divides exergy destruction into endogenous/exogenous, avoidable /unavoidable exergy destruction on the basis of conventional exergy analysis. Through advanced exergy analysis, we can quantitatively analyze the causes of exergy destruction, so that we can judge which exergy destruction of components are worth taking measures to reduce.

Endogenous exergy destruction is exergy destruction caused by the component itself.

Exogenous exergy destruction is exergy destruction caused by the interaction between components. The sum of these two parts is the exergy destruction of the component under operating conditions [61]. where the superscripts represent endogenous and exogenous, is the endogenous exergy destruction of component k. It is obtained by setting the component k in the model to the real working condition, and the other components are set to operate under ideal working conditions. is the exogenous exergy destruction, which is the difference between Unavoidable exergy destruction is an irreversible loss due to technical limitations.

Avoidable exergy destruction is an irreversible loss that can be avoided by technical means.

The sum of these two parts is also the exergy destruction of the component under operating conditions [61]: where the superscripts represent unavoidable and avoidable. is the unavoidable exergy destruction of component k, which is obtained after the model runs under unavoidable conditions, and is the avoidable exergy destruction, which is the difference between „,ENEXDkDkDkEEE=+ENEX,ENDkE,EXDkE,DkE,ENDkE„,UNAVDkDkDkEEE=+()„„UNUNDkPkDkPkEEEE= UNAV In addition, the exergy destruction can be further divided to obtain the avoidable endogenous exergy destruction , the unavoidable endogenous exergy destruction , the avoidable exogenous exergy destruction and the unavoidable exogenous exergy destruction . Among them, avoidable endogenous exergy destruction is a measure of a component's ability to improve by improving itself. It provides a powerful reference for system optimization. These four exergy destruction can be calculated as follows [61]:

Advanced exergoeconomic analysis and advanced exergoenvironmental analysis are similar to advanced exergy analysis. It is carried out on the basis of conventional exergoeconomic analysis and conventional exergoenvironmental analysis. The exergy destruction cost rate and exergy destruction environmental impact rate are divided into endogenous/exogenous and avoidable and unavoidable. Advanced exergoeconomic analysis and exergoenvironmental analysis can avoid the high cost and pollution caused by the pursuit of efficient performance. According to the analyses result of the two, the system efficiency, economy and environmental protection can be better balanced. The expressions of the advanced exergy destruction cost rate and exergy destruction environmental impact rate of each component are shown in Table 7 . And they satisfy the following relationships: „AVENDkE„UNENDkE„AVEXDkE„UNEXDkE„„„„„,UNENAVENUNEXAVEXDkDkDkDkDkEEEEE=+++ Table 7 Advanced exergy destruction cost rate and environmental impact rate [62,63].

Exergy destruction cost rate Exergy destruction environmental impact rate Endogenous (EN) Exogenous (EX) Avoidable (AV) Unavoidable (UN) Avoidable endogenous (AV,EN) Avoidable exogenous (AV,EX) Unavoidable endogenous (UN,EN) Unavoidable exogenous (UN,EX)

4 Results and discussion

This section validates the proposed system. And the results of conventional and advanced exergy, exergoeconomic, and exergoenvironmental analyses of the proposed system are given.

The improvement potential of individual components in the system are analyzed.

4.1 Validation

In order to verify the correctness of the established biomass-fired, the ORC model and the PV/T model, the parameters of literature [42] and literature [50] are brought into the established system model. The net power of the system, electrical efficiency were used as the verification objectives and compared with the data in the literatures. The results are shown in Table 8 . We observed good agreement between the results obtained in this model and those in the literatures.

Table 8 Comparison of present model results with references.

Parameters ORC[42] Reference Present study Error (%) Organic working medium R245fa R245fa Evaporation temperature /K „,ENENDkFkDkCcE= „,ENENDkFkDkBbE= „,EXEXDkFkDkCcE= „,EXEXDkFkDkBbE= „,AVAVDkFkDkCcE= „,AVAV Condensation temperature /K Heat source temperature /K Biomass boiler efficiency /% Power output /kW Electrical efficiency /% PV/T [50] Solar radiation intensity (W/m2) Area of PV/T (m2) Temperature coefficient of photovoltaic efficiency (%) Power output (kW)

4.2 Energy analysis

Table 9 shows the input data and energy analysis results of the designed system. R245fa was selected as the working medium for two-stage organic Rankine cycle, and different evaporation temperatures were set for the ORC 1 and the ORC 2 according to the heat source temperatures. The solar radiation intensity of 800W/m2 was selected, and the basic input data of biomass-fired was set according to the research of Zhu et al. [42]. The energy analysis results show that the designed system can produce 205kW of electricity, and its energy efficiency is 14.14%. Conventional and advanced 3E analyses were performed on the system under these conditions.

Parameters Table 9 Input data and energy analysis results.

Organic working medium Evaporation temperature of the ORC 1 /K Evaporation temperature of the ORC 2 /K Condensation temperature of the ORC 1 and ORC 2 /K Heat source temperature of the ORC 1 /K Biomass boiler efficiency /% Solar radiation intensity (W/m2) Area of PV/T (m2) Cell efficiency (%) Power output (kW) Energy efficiency (%) Value R245fa

4.3 Conventional 3E analyses

Exergy efficiency and exergy destruction rate are the main criteria to measure the thermodynamic properties of each component. Conventional exergy analysis can obtain the exergy destruction rates and exergy efficiencies of each component, which point the direction for system improvement. Figure 2 [Figure 2: see original paper] shows the proportion of exergy destruction for each component in the proposed system. Among them, evaporator 1 has the highest exergy destruction ( ), accounting for 50.8% of the total exergy destruction of the system. This is followed by the PV/T (25.4%) and evaporator 2 (16.7%). The exergy destruction rates of the air preheater, condenser 1, condenser 2, turbine 1, turbine 2, pump 1, pump 2, and preheater are minimal. The sum of the exergy destruction rates of these components only accounts for 3.1% of the total exergy destruction rate of the system. Therefore, from the perspective of reducing the exergy destruction rate to improve system performance, evaporator 1, the PV/T and evaporator 2 have great potential for improvement.

Figure 3 [Figure 3: see original paper] shows the exergy efficiency of each component in the proposed system.

Condenser 1 has the lowest exergy efficiency (1.628%), followed by evaporator 2 (6.712%), condenser 2 (7.121%), air preheater (9.857%), and evaporator 1 (10.96%). Exergy efficiency is the ratio of product exergy to fuel exergy, Table 10 shows the exergy destruction, product exergy and fuel exergy of each component in the system. Although the exergy destruction rate of condenser 1 is small compared to other components, the fuel exergy of the condenser 1 is mostly destroyed, and only a small part is converted into product exergy. Therefore, the exergy efficiency of condenser 1 is low. The reasons for the low exergy efficiency of condenser 2 are similar to those of the condenser 1. Combined with the results of exergy efficiency and exergy destruction rate, evaporator 1 and evaporator 2 have great potential for improvement.

Figure 4 [Figure 4: see original paper] shows the exergy, unit exergy cost, and unit exergy environmental impact of fuel stream and product stream for each component in the system. According to Figure 4(a), the biomass boiler has the highest fuel stream and product stream exergy. And the fuel exergy of biomass boiler is close to the exergy of the product. These indicate that the exergy destruction of the component is small. Therefore, the exergy efficiency of the biomass boiler is higher (93.65%). Secondly, the fuel exergy and product exergy of preheater, turbine 1, turbine 2, pump 1 and pump 2 are also close. Therefore, their exergy efficiencies are also higher, 89.07%, 86.11%, 85.96%, 85.63%, 85.62%, respectively. ,1708.2DevaEkW= Figure 2 The proportions of exergy destruction of each component.

Figure 3 Exergy efficiency of each component. Table 10 Results of the exergy analysis of the energy system.

Component Air preheater Biomass boiler Condenser 1 Condenser 2 Evaporator 1 Evaporator 2 Preheater Pump 1 Pump 2 Turbine 1 Turbine 2 ,()DkEkW,()PkEkW,()FkEkW,(%)exk Figure 4 (a) Exergy of the fuel and product, (b) Cost of fuel and product, (c) Environmental impacts of fuel and product streams of components.

Table 11 presents the results of conventional exergoeconomic analysis. Figure 5 [Figure 5: see original paper]-6 show the exergy destruction cost rates and investment cost rates of each component. Obviously, evaporator 2 has the highest exergy destruction cost rate, followed by evaporator 1 and condenser 2, which the exergy destruction cost rates are 19.15)[44], $represents density$(/h and 6.609\$) [42]. The subscript represents the theoretical value, represents the actual value, and represents the flue gas emitted from the boiler.

The heat source for the air preheater is the high-temperature flue gas emitted from the biomass boiler, with a flue gas outlet temperature of 439.65 K [45]. The energy balance equation for the air preheater is:

where represents specific heat capacity, represents temperature, and the numerical subscripts correspond to the state points in Figure 1.

The PV/T is a solar cogeneration system—an excellent choice for small-scale residential energy applications. By adding thermal conduction channels on the PV/T backside and circulating cold fluid, the system reduces photovoltaic panel temperature to improve cell efficiency while simultaneously absorbing heat as low-grade thermal energy. The total radiation and electricity production by the photovoltaic panels are calculated as follows [46–48]:

where is the instantaneous irradiation intensity per unit area, is the total surface area of the PV/T, is the PV/T absorption rate, is the packing factor, is the cell efficiency at temperature , is the reference temperature for cell efficiency (\$/h.

This is because solar energy as a free fuel supplies the PV/T, so that the fuel stream cost for the PV/T is 0. According to the formula Eq (28), the exergy destruction cost rate of the PV/T is calculated to be 0.

Table 11 shows the exergoeconomic factors for each component of the system. The exergoeconomic factors reflect the relationship between component efficiency and economy.

The PV/T has the highest exergoeconomic factor, and its value is 1. This is due to the fact that solar energy is free. Therefore, the economic evaluation of the PV/T can only start from the investment cost of the component itself. Secondly, turbine 1 (89.5%), turbine 2 (82.96%), and preheater (81.1%) have a higher exergoeconomic factor. These show that the investment cost rate of these components is high, but their exergy destruction cost rate is low. Therefore, the investment cost rates of these components can be appropriately reduced to obtain better economy. In addition, the exergoeconomic factors of the remaining components are less than 50%. Among them, condenser 1 (2.28%), condenser 2 (1.25%), evaporator 1 (0.44%), evaporator 2 (0.45%) have an exergoeconomic factor of less than 1%. It is due to the high exergy destruction cost rates of these four components. Therefore, it is possible to consider sacrificing some of the economy to improve the performance of these four components.

Figure 4(b) shows unit fuel stream cost and unit product stream cost. It's not hard to see that condenser 2 has the highest unit exergy cost associated with both input and output streams.

Among them, output stream of condenser 2 has the highest unit product exergy cost, followed by condenser 1, pump 2 and turbine 2, which are 0.0048$ K) [49], is the cover transmittance of the PV/T glass ($/kJ, 0.0012$) [49], is the temperature coefficient of solar cell efficiency ($/kJ. Therefore, from the aspect of reducing the unit exergy cost of product stream, condenser 2, condenser 1, pump 2 and turbine 2 can be optimized to improve the economy of the system.

Figure 5 The exergy destruction cost rate and investment cost.

Figure 6 [Figure 6: see original paper] The proportions of exergy destruction cost of each component.

Table 11 Results of the exergoeconomic analysis of the energy system.

Component Air preheater 0.36×10-6 0.33×10-5 Biomass 0.31×10-5 0.33×10-5 ,()DkEkW,($) [50], and is the photovoltaic cell temperature.

The organic Rankine cycle is a critical component of the proposed system. The energy analysis equations for components in ORC 1 and ORC 2 are presented in Table 2.

Energy analysis equations for organic Rankine cycles.

3.2 Conventional 3E Analyses

Exergy refers to the available portion of energy. Only part of the energy in a system is available; the remainder is typically lost through exergy destruction. The purpose of exergy analysis is to calculate the exergy destruction of each component, identify energy quality across components, locate maximum exergy destruction points, and provide references for system performance optimization [51]. According to the second law of thermodynamics, the exergy balance equation is [39,51]:

where represents exergy, represents the exergy destruction rate, is the output exergy, is the heat released by chemical reaction, and is the input exergy, with subscript referring to the component.

When considering component exergy balance, in addition to input and output exergy, exergy can be categorized as fuel exergy and product exergy. The fuel-product exergy balance equation is [37]:

where subscripts and represent fuel and product, respectively, and represents the external exergy destruction rate of component . The specific exergy calculation formula is:

where represents the specific exergy of component , represents the physical specific exergy, represents the chemical specific exergy, subscript represents the environmental state, and and are the restricted state potential and final dead state potential, respectively. Most components in the proposed system do not involve chemical reactions; only the biomass boiler involves combustion. Therefore, the chemical exergy of all components except the biomass boiler is zero. The flue gas emitted from the biomass boiler is a gas mixture, with chemical exergy calculated as:

where represents the molar fraction of each gas and is the universal gas constant.

Additionally, the exergy of biomass fuel [42] and solar energy [52] is calculated as:

where represents biomass fuel exergy, is the chemical exergy coefficient, and is the solar exergy.

Exergy destruction rate and exergy efficiency are critical indicators for evaluating system performance in exergy analysis. Exergy efficiency is the ratio of product exergy to fuel exergy. When external exergy losses are neglected, exergy destruction equals the difference between fuel exergy and product exergy. Therefore, exergy efficiency directly reflects the component's ability to convert fuel into useful energy. The calculation formulas for exergy destruction rate and exergy efficiency of each system component are shown in Table 3 . The exergy efficiency formula is [53]:

Conventional exergoeconomic analysis builds upon exergy analysis to avoid poor economic performance caused by pursuing high exergy efficiency alone. Exergoeconomic analysis identifies the cost rate resulting from exergy destruction and component investment costs, providing references for component optimization from both economic and efficiency perspectives. The exergoeconomic balance equation is [54]:

where and are the exergoeconomic costs of the output and input exergy streams of component , and are the exergoeconomic costs of output work and input heat, is the cost per unit exergy of each stream, is the total cost rate related to capital investment and operation and maintenance, is annual operating hours, is the capital recovery factor, is the interest rate, is system lifetime, is the exergoeconomic factor, and is the exergy destruction cost rate.

The cost balance equations and investment cost equations for each component are shown in Table 4 .

Exergy destruction significantly affects the exergy destruction cost rate. According to the analysis, most of the fuel exergy in Evaporator 2 and Evaporator 1 is lost, with only a small portion converted to product exergy, resulting in high exergy destruction cost rates for these components. The remaining components exhibit low exergy destruction cost rates, while the PV/T shows values of $0/)PkckJ, (/\text{kJ}, 0.002/)kZh, (/\text{kJ}, \text{and } 0.00067/AVENDconCh =, , 12.246/\text{kJ}.$

presents the conventional exergoenvironmental analysis results. Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper] illustrate the exergy destruction environmental impact rate and component-related environmental impact rate. Evaporator 1 exhibits the highest exergy destruction environmental impact rate (775.3 mPt/h), followed by Condenser 1 (218.4 mPt/h), accounting for 58.29% and 16.42% of the total exergy destruction environmental impact rate, respectively. The remaining components show low exergy destruction environmental impact rates, with the PV/T rate being 0 mPt/h. This occurs because solar energy serves as the PV/T fuel source, and solar energy carries no environmental impact, resulting in zero fuel stream environmental impact for the PV/T and consequently zero exergy destruction environmental impact according to Eq (33).

Table 12 shows the exergoenvironmental factors for each system component. These factors reflect the relationship between component efficiency and environmental performance. The PV/T achieves the highest exergoenvironmental factor of 1, attributable to solar energy's zero environmental impact. Therefore, environmental assessment of the PV/T must focus solely on component-related environmental impact. The biomass boiler also exhibits a very high exergoenvironmental factor (99.94%), indicating high boiler-related environmental impact rates and necessitating efforts to reduce component-related environmental impact to improve overall system environmental performance. However, the other components show exergoenvironmental factors below 15%, indicating high exergy destruction environmental impact rates but low component-related environmental impact rates. Consequently, improving the efficiency of these components can appropriately reduce environmental impact caused by exergy destruction. Specifically, Condenser 1, Condenser 2, Evaporator 1, Pump 1, and Pump 2 exhibit exergoenvironmental factors below 1%, making them priority candidates for environmental performance improvement to reduce exergy destruction environmental impact.

Figure 4(c) shows the unit fuel stream environmental impact and unit product stream environmental impact. Notably, Condenser 1 (0.1717) and Condenser 2 (0.0352) exhibit large unit product stream environmental impacts, indicating that optimizing these condensers can enhance system environmental performance by reducing unit product stream environmental impact.

4.4 Advanced 3E Analyses

Conventional 3E analyses identify components requiring improvement but do not quantify the extent of possible improvement. Advanced 3E analyses can partition exergy destruction rate, exergy destruction cost rate, and exergy destruction environmental impact rate into endogenous/exogenous and avoidable/unavoidable components based on model outputs under real, ideal, and unavoidable operating conditions. The avoidable endogenous exergy destruction rate, exergy destruction cost rate, and exergy destruction environmental impact rate are the primary focus, representing the potential to reduce these metrics through technical constraint adjustments and component efficiency improvements.

Table 13 reveals that, except for Evaporator 2 and the Preheater, all other components exhibit higher endogenous exergy destruction rates than exogenous exergy destruction rates. The total endogenous exergy destruction accounts for 93.2% of total system exergy destruction, indicating that most exergy destruction stems from component inefficiencies. Therefore, the energy system can be improved by enhancing component efficiencies. For Evaporator 2 and the Preheater, where exogenous exergy destruction exceeds endogenous exergy destruction, exergy destruction can be reduced by improving associated components. Meanwhile, the system's avoidable exergy destruction constitutes 7.95% of total exergy destruction, indicating relatively small improvement potential. However, Evaporator 1 and the PV/T exhibit high avoidable exergy destruction, representing another improvement direction. Additionally, Condenser 1, Condenser 2, the Preheater, Turbine 1, and Turbine 2 show avoidable exergy destruction greater than unavoidable exergy destruction, indicating good improvement potential. For remaining components where avoidable exergy destruction is less than unavoidable exergy destruction, improvements will have limited system impact.

Avoidable endogenous exergy destruction represents the potential to reduce exergy destruction through component efficiency and technical condition improvements. Evaporator 1 and the PV/T exhibit high avoidable endogenous exergy destruction, indicating substantial potential for reduction through technical improvements and efficiency increases. Furthermore, the avoidable endogenous exergy destruction of the Air Preheater, Biomass Boiler, Condenser 1, Condenser 2, Pump 1, Pump 2, Turbine 1, and Turbine 2 exceeds their exogenous avoidable exergy destruction, indicating these components also possess improvement potential regarding their own efficiency and technical limitations.

Results of advanced exergy analysis for the proposed system.

Table 14 presents the endogenous/exogenous and avoidable/unavoidable exergy destruction cost rates for each system component. Except for Evaporator 2 and the Preheater, all other components show higher endogenous exergy destruction cost rates than exogenous rates, indicating that exergy destruction cost rates are significantly affected by irreversibility while component interactions have minimal impact. Therefore, besides Evaporator 2 and the Preheater, other components can be improved through efficiency enhancements. Regarding avoidable versus unavoidable exergy destruction cost rates, all components except Condenser 1, Condenser 2, the Preheater, Turbine 1, and Turbine 2 exhibit greater unavoidable than avoidable exergy destruction cost rates. Based on avoidable endogenous exergy destruction cost rate calculations, the Air Preheater, Biomass Boiler, Condenser 1, Condenser 2, Evaporator 1, Pump 1, Pump 2, Turbine 1, and Turbine 2 show higher avoidable endogenous than exogenous exergy destruction cost rates, making component efficiency improvements worthwhile for reducing exergy destruction cost rates. Condenser 2 exhibits the highest avoidable endogenous exergy destruction cost rate $(/)DkCh, (/\mathrm{h})$, indicating the greatest improvement potential, followed by Condenser 1 $(/)EXDkCh, (/\mathrm{h})$.

Results of advanced exergoeconomic analysis for the proposed system.

Table 15 shows the endogenous/exogenous and avoidable/unavoidable exergy destruction environmental impact rates for each system component. The avoidable endogenous exergy destruction cost rate of Evaporator 2 is negative, indicating it essentially lacks improvement potential through efficiency and condition optimization. Meanwhile, Evaporator 1 exhibits the highest avoidable endogenous exergy destruction and avoidable endogenous exergy destruction environmental impact rate, while Condenser 2 shows the highest avoidable endogenous exergy destruction cost rate. These results indicate that Evaporator 1 and Condenser 2 should be prioritized for optimization.

The findings demonstrate that improving Evaporator 1 and Condenser 2 represents an effective and rational approach to optimizing the proposed system. However, this study's conventional and advanced 3E analyses were based solely on simulation results. Future work should emphasize performing these analyses based on experimental data. Additionally, research should focus on improving evaporators and condensers, including selecting appropriate models, designing reasonable parameters, and optimizing operating conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Note: Figure translations are in progress. See original paper for figures.