



Assessment of novel Kalina power system through exergoenvironmental perspective

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Abstract

A novel power generation system suitable to recover waste heat from a renewable source at medium temperature level is investigated in the present work. In a regenerative system, saturated vapour is supplied to one of the heat exchangers by a secondary solar collector, which raises the temperature of the boiler as a whole. The main advantage of this method is the reduction in irreversibility in the mixing chamber M3, which encourages a higher flow rate to the turbine. Preheating the circulating solution and completely evaporating the basic stream are used to achieve this. The performance of the system is investigated in energy aspects along with detailed exergy analysis. Environmental impact as a result of the working conditions is essential to propose the optimum decision variables. Exergy analysis in both conventional and advanced methods proposes the system components which need improvements in themselves and associated with other components more properly. Exergoenvironmental analysis using the Life cycle assessment method is examined in the system under the hot sink conditions. Exergy analysis reveals that the component with a high source will yield more losses resulting in higher irreversibility. Hence, turbine and heat exchanger 4 (HE4) need investigation in improving the system's performance. Exergoenvironmental investigation suggests that the highest impact results same components identified by the advanced exergy analysis. Exergoenvironmental analysis on the proposed Kalina power generation system is carried out under hot sink conditions. The exergy destruction and destruction cost rate of 29.23 kW and 0.478 \$ h⁻¹ at turbine inlet conditions of 185 °C and 45 bar. The exergoenvironmental factor fb and the relative difference rb reveal that the components with high environmental impact have to be minimized. Turbine and HE4 are the components resulting in higher total exergy and devise related impact on the environment.

Keywords Power generation · Kalina cycle · Exergoeconomic · Exergoenvironment · Investment cost · Medium temperature

List of Symbols

m Mass flow rate (kg s⁻¹)
 h Specific enthalpy (kg kJ⁻¹)

x Mass fraction of ammonia (kg/kg mixture)
 T Temperature (°C)
 W Work output (kW)
 G Generator
 M Mechanical
 P Pressure, bar
 Q Heat supplied (kW)
 s Specific entropy (kJ kg⁻¹ K⁻¹)
 I Irreversibility (kJ kg K)
 ex Specific exergy (kJ kg)
 E Exergy (kJ)
 $\dot{E}x$ Exergy rate, (kW)
 0 Environment condition
 HE Heat exchanger
 MXT Mixture turbine
 B Exergoenvironmental impact rate (Pts h⁻¹)
 b Unit environmental impact (mPts GJ⁻¹)
 SEP Separator

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CND	Condenser
F	Vapour fraction
M	Mixing chamber
S	Separator
Y	Exergy destruction ratio (%)
C	Cost rate ($\$ \text{h}^{-1}$)
CRF	Capital recovery factor
N	Annual unit operation hours
\dot{Z}	Investment cost rate of components ($\$ \text{h}^{-1}$)
z	Investment cost of components ($\$$)
r	Relative cost difference (%)
LMTD	Logarithmic mean temperature difference (K)
U	Overall heat transfer coefficient ($\text{kW m}^{-2} \text{ }^\circ\text{C}^{-1}$)

Subscripts

P	Pump
S	Supply
v	Vapour
l	Liquid
cwin	Cooling water inlet
cwout	Cooling water outlet
D	Destruction
F	Fuel
P	Product
tot	Total
CI	Capital investment
OM	Operating maintenance
c	Specific exergy cost ($\$ \text{GJ}^{-1}$)
w	Specific work (kJ kg^{-1})
q	Specific heat (kJ kg^{-1})
R	Reference cost

Greek symbols

η	Efficiency
\mathcal{E}	Exergetic efficiency (%)
φ	Maintenance factor

Superscripts

AV	Avoidable
CH	Chemical
EN	Endogenous
EX	Exogenous
UN	Unavoidable

Introduction

One of the prominent challenges of the present population condition is to produce and supply continuous energy, limiting global climatic changes associated with improvised industrial activities and exergoenvironmental aspects most needed for sustainable improvement. More advancements are required in power generation and cogeneration systems to generate and supply electricity without interruption.

Among the low-temperature power generation systems, Kalina cycle is one of the most prominent cycles that generate energy efficiently. In KC, the waste heat is recovered in the boiler and condenser as the working component is a zeotropic mixture [1]. The performance strategy resulted in low-temperature power generation systems being much better [2]. KC is one of the low-temperature systems considered as bottoming cycle in the combined power and cooling systems [3]. The energy utilized from the low-temperature heat source is comparably higher in the amount in KC than the organic Rankine cycle (ORC). One among the competitors in the conversion of low-grade heat sources is organic flash cycle and transcritical ORC [4]. The economic performance of KC is higher than ORC [5]. KC using an expander in place of the throttle valve recovers loss resulting due to exergy in the throttling device since the expander accepts two-phase expansion [6]. 3E analyses were devised on a multigeneration system with the Kalina cycle as a power generation system [7]. The KC used in the proposed cycle is suitable for recovering heat from a low-temperature source. Brayton cycle run by renewable energy sources is considered as the topping cycle which provides input to the KC as bottoming cycle hence producing more power [8]. The 4E analysis is carried out to specify the impact of working fluid including environmental analysis along with energy, exergy and economic analysis. The waste heat from the geothermal stream is utilized in evaporating the KC working fluid in the assessment of exergy analysis [9]. With the increment in the temperature ($346 \text{ }^\circ\text{C}$) inlet to the turbine of a medium temperature configuration, a higher amount of power can be generated [10]. The power produced by KC has resulted in high compared to ORC in a low enthalpy geothermal source [11]. KC is implemented as a bottoming cycle in a combined gas turbine and absorption chiller for generating power and cooling. The performance investigation of the cogeneration system is assessed through surface methodology [12]. KC is more efficient in recovering waste heat from the flue gas resulting from stack ejectors in reducing the iron oxide process [13]. KC is integrated with a compressed air system in which performance investigation is presented [14]. Recovery of waste heat by the KC is more efficient when it is equipped as a bottoming cycle. Through variable decision variables, investigation on KC recovering waste heat from the cement industry is investigated [15]. The exergy destruction in the KC components is lower than ORC and trilateral flash cycles. The environmental investigation by life cycle assessment (LCA) is considered an analysis tool for the complete assessment of KC along with the thermo-economic investigation [16]. The component's impact on the environment in a thermal system is evaluated by the exergoenvironmental investigation [17]. The ECO-Indicator is utilized for assessing the impact of the input stream with the plant component on the environment [18]. Exergoenvironmental investigation

provides detail about the location, size and resources which impact the environment [19]. In compression ignition engines, an exergoenvironmental investigation is presented [20]. The environmental impact of the poly-generation system components has been reduced in the summer season [21]. The optimization of exergoenvironmental assessment is carried out by a genetic algorithm similar to the exergy analysis [22]. Exergoenvironmental investigations have been carried out even in aircraft engines [23].

The literature review reveals that most of the exergoenvironmental analyses performed on the power generation systems are adopted with low-temperature power generation temperatures and with low sink temperatures. The proposed system can produce electricity from sources with medium temperatures. The proposed system is capable of operating at 200 °C. To raise the temperature of the boiler as a whole in a regenerative system, the system uses a secondary solar collector to supply saturated vapour to one of the heat exchangers. The fundamental benefit of this system is that the irreversibility in the mixing chamber M2 is minimized, which promotes an increased flow rate to the turbine. This is accomplished by preheating the recirculating solution and fully evaporating the basic stream. Organic Rankine cycle-based power generation system has received more exergoenvironmental studies, whereas very minimum numbers are presented in Kalina cycle systems. Exergoenvironmental investigations on Kalina systems suitable for medium temperature applications are not much more presented in the literature studies. The main objective of this present work is to assess conventional exergy, exergoeconomic analysis, advanced exergy, and exergoenvironmental analysis for medium-temperature power generation systems. The proposed novel system has resulted in a higher amount of mass to the turbine at the given input condition. Environmental analysis is receiving noticeable attention in power generation and cogeneration systems. The thermodynamic property values of the proposed system are investigated using Python.

Novel Kalina system

A novel power generation system suitable to utilize the heat from renewable energy sources for generating electricity is shown in Fig. 1. The system uses a zeotropic mixture as a working component. The use of ammonia-water mixture results in lowering the irreversibility caused by the boiler and condenser. The proposed system is a novel system suitable for generating power at medium temperature sources. The proposed system operates up to a temperature and pressure levels of 190 °C and 45 bar. The system supplies saturated vapour to one of the heat exchangers by a supplementary solar collector to enhance the temperature to the boiler as such in a regenerative system. In addition,

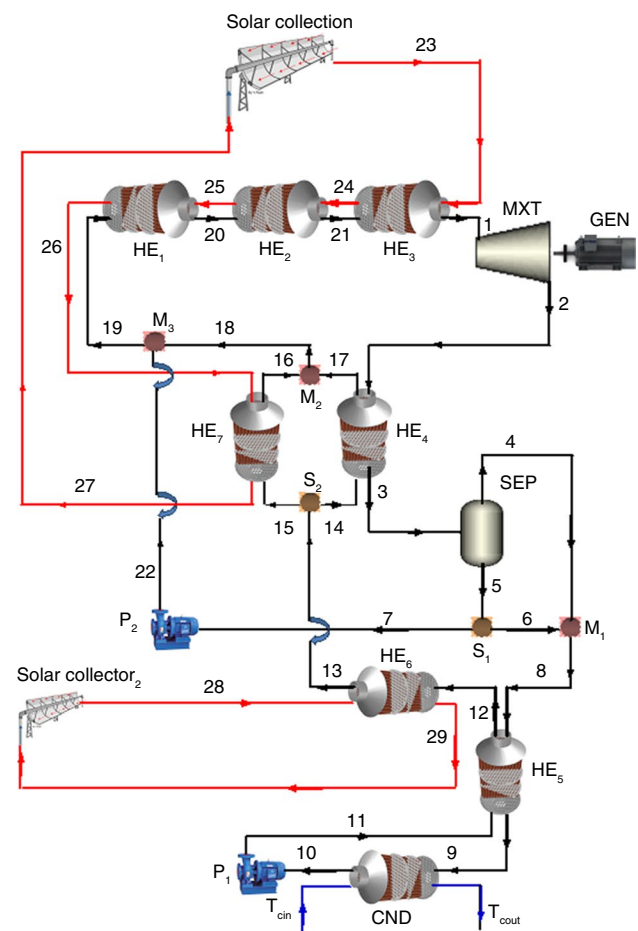


Fig. 1 Kalina power generation system operable at medium temperature applications. MXT: mixture turbine; GEN: generator; CND: condenser; P: condensate feed pump; HE: heat exchanger; SEP: separator; S: splitting chamber; M mixing chamber

the irreversibility in the mixing chamber M2 is reduced which favours an increased flow rate to the turbine. The energy efficiency of the proposed system is 4% higher than with the single solar collector. The primary solar collector supplies energy to the heat exchangers for energizing the working component. The secondary solar collector provides additional heat to the working component entering the heat exchangers HE1, HE2, HE3 and HE7. As per to the conventional Kalina cycle system suitable for medium temperature, applications have single solar collector. Here, with the addition of two systems, the irreversibility in the heat exchangers receiving heat from the primary solar collector is reduced, higher performance. For a unit mass flow considered in the condenser, the system claims a higher flow rate to the turbine. This is due to a portion of the lean mixture separated at S1 being recirculated through the M3. In the KC, the lean mixture from the separator is mixed with the enriched vapour mixture to lower the concentration of the working mixture at the condenser. The enriched vapour

Table 1 Input parameter required for calculating the properties of the proposed Kalina cycle

Parameter	Unit	Value
Reference pressure, P_0	Bar	1.01325
The reference temperature, T_0	°C	25
Mass flow rate at HE6, m_8	Kg s^{-1}	1
Pump isentropic efficiency, $\eta_{m,pump}$	%	75
Turbine isentropic efficiency, $\eta_{m,tur}$	%	75
Electrical generator efficiency, η_{gen}	%	95
Pinch point in evaporator, $\Delta T_{PP,EVA}$	°C	5
Approach point in evaporator, $\Delta T_{AP,EVA}$	°C	5
Terminal temperature difference, TTD_{SH}	°C	10
Turbine inlet pressure	Bar	45
Hot source temperature	°C	200
Ammonia water mixture concentration at separator inlet, X_3	Kg/kg mixture	0.80

from the separator if sent to the condenser without mixing with the lean liquid mixture, condensation at the pressure level is not possible.

Table 1 provides the input decision variables considered in this work for evaluating the system performance.

Energy and exergy modelling

An energy balance to the components is applied to identify the unknown variables. The properties of the working component are obtained through Python coding [24].

On applying the lever rule to separator,

$$F = \frac{X_3 - X_5}{x_4 - x_5} \quad (1)$$

Turbine and pump work,

$$W_T = m_1 (h_1 - h_2) \eta_{m,tur} \eta_{gen} \quad (2)$$

$\eta_{m,tur}$ and η_{gen} are the isentropic efficiency of the turbine and generator efficiency.

Work input to pump,

$$W_{P1} = \frac{m_{11} (h_{11} - h_{10})}{\eta_{m,pump}} kW \quad (3)$$

$$W_{P2} = \frac{m_{22} (h_{22} - h_7)}{\eta_{m,pump}} kW \quad (4)$$

$\eta_{m,pump}$ is the isentropic efficiency of the pump.
Net output of Kalina cycle,

$$W_{net} = [W_T - (W_{P1} + W_{P2})] KW \quad (5)$$

Net heat transfer,

$$Q = Q_{HE1} + Q_{HE2} + Q_{HE3} + Q_{HE7} \quad (6)$$

Kalina cycle efficiency

$$\eta_{KC} = \frac{W_{net}}{Q} \times 100 \quad (7)$$

Conventional exergy correlations

Exergy analysis is carried out to identify the losses resulting due to irreversibility involved in the components. Evaluating physical exergy and chemical exergy is the primary step to estimating the total exergy at every state point. Equations 8, 9, and 10 provide the physical exergy, chemical exergy and total exergy correlations [33]. [34].

$$\dot{E}x_{Ph,i} = [\dot{m}_i (h_i - h_0) - T_0 (s_i - s_0)] \quad (8)$$

In Eq. (8), h_0 is specific enthalpy, s_0 is specific entropy and T_0 is the temperature at ambient conditions.

The maximum work obtained in bringing the system to a dead state from an environmental state is termed chemical exergy.

The system under investigation is brought to a dead state from an environmental state that is chemical exergy.

$$\dot{E}x_{Ch,i} = m_i \left(\left[\frac{ex_{ch,NH_3}^0}{M_{NH_3}} \right] x_i + \left[\frac{ex_{ch,H_2O}^0}{M_{H_2O}} \right] (1 - x_i) \right) \quad (9)$$

where ex_{ch,NH_3}^0 , ex_{ch,H_2O}^0 are the specific chemical exergy of NH3 and H2O at standard conditions [25],

$$\dot{E}x_{Tot,i} = \dot{E}x_{Ph,i} + \dot{E}x_{Ch,i} \quad (10)$$

Fuel exergy and product exergy are the results due to net resources united to produce a product and the one developed in components.

Exergy destruction ($\dot{E}x_{D,i}$), exergetic efficiency (ϵ) and exergy destruction ratio ($Y_{D,i}$) are the decision variables for assessing the individual component's irreversibility, performance, and comparison of identical components.

$$\dot{E}x_{D,i} = \dot{E}x_{Fuel,i} - \dot{E}x_{Product,i} \quad (11)$$

$$\epsilon = \frac{\dot{E}x_{P,i}}{\dot{E}x_{F,i}} \times 100 \quad (12)$$

$$Y_{D,i} = \frac{\dot{E}x_{D,i}}{\dot{E}x_{D,Tot}} \tag{13}$$

The components exergy destruction and exergetic efficiency are provided in Table 2.

Thermoeconomic analysis

The exergy analysis, economic analysis, and exergy costing are carried out in the thermodynamic analysis. The capital cost, the relative cost difference of a component, exergy destruction cost, and exert economic factor are the decision variables performed through thermoeconomic evaluation. The system’s cost-effectiveness is enhanced by minimizing the amount of exergy destruction cost in a component that is

exergy costing. The exergy costing value is concerned with each exergy stream in the components of the system. Exergy is the basic need for assigning a cost to an energy carrier.

In Eq. 14, the cost equation is evaluated from the present year; hence, the error coefficient is provided to convert the cost into the present year value ($\dot{Z}_i, 1996$ to $\dot{Z}_i, 2021$). The error coefficient is introduced by the Chemical Engineering Plant Cost Index (CEPCI) to estimate the error coefficient value. Eq. (15) provides the corrected cost function [27],

$$J = \frac{CEPCI_{2021}}{CEPCI_{2000}} \tag{14}$$

$$\dot{Z}_{i, 2021} = J \dot{Z}_{i, 2020} \tag{15}$$

Table 2 Conventional exergy parameters correlation [26]

Component	Fuel exergy, kW ($\dot{E}x_{F,i}$)	Product exergy, kW ($\dot{E}x_{P,i}$)	Exergy of destruction, kW $\dot{E}x_{D,i} = (\dot{E}x_{F,i} - \dot{E}x_{P,i})$	Exergetic efficiency, % $\epsilon = \dot{E}x_{P,i} / \dot{E}x_{F,i}$
MXT	$\dot{E}x_{total,1} - \dot{E}x_{total,2}$	W_{Tur}	$\dot{E}x_{total,1} - \dot{E}x_{total,2} - W_{Tur}$	$\frac{W_{Tur}}{\dot{E}x_{total,1} - \dot{E}x_{total,2}}$
HE ₁	$\dot{E}x_{total,25} - \dot{E}x_{total,26}$	$\dot{E}x_{total,20} - \dot{E}x_{total,19}$	$(\dot{E}x_{total,25} - \dot{E}x_{total,26}) - (\dot{E}x_{total,20} - \dot{E}x_{total,19})$	$\frac{\dot{E}x_{total,20} - \dot{E}x_{total,19}}{\dot{E}x_{total,25} - \dot{E}x_{total,26}}$
HE ₂	$\dot{E}x_{total,24} - \dot{E}x_{total,25}$	$\dot{E}x_{total,21} - \dot{E}x_{total,20}$	$(\dot{E}x_{total,24} - \dot{E}x_{total,25}) - (\dot{E}x_{total,21} - \dot{E}x_{total,20})$	$\frac{\dot{E}x_{total,21} - \dot{E}x_{total,20}}{\dot{E}x_{total,24} - \dot{E}x_{total,25}}$
HE ₃	$\dot{E}x_{total,23} - \dot{E}x_{total,24}$	$\dot{E}x_{total,1} - \dot{E}x_{total,21}$	$(\dot{E}x_{total,23} - \dot{E}x_{total,24}) - (\dot{E}x_{total,1} - \dot{E}x_{total,21})$	$\frac{\dot{E}x_{total,1} - \dot{E}x_{total,21}}{\dot{E}x_{total,23} - \dot{E}x_{total,24}}$
HE ₄	$\dot{E}x_{total,2} - \dot{E}x_{total,3}$	$\dot{E}x_{total,17} - \dot{E}x_{total,14}$	$(\dot{E}x_{total,2} - \dot{E}x_{total,3}) - (\dot{E}x_{total,17} - \dot{E}x_{total,14})$	$\frac{\dot{E}x_{total,17} - \dot{E}x_{total,14}}{\dot{E}x_{total,2} - \dot{E}x_{total,3}}$
HE ₅	$\dot{E}x_{total,8} - \dot{E}x_{total,9}$	$\dot{E}x_{total,12} - \dot{E}x_{total,11}$	$(\dot{E}x_{total,8} - \dot{E}x_{total,9}) - (\dot{E}x_{total,12} - \dot{E}x_{total,11})$	$\frac{\dot{E}x_{total,12} - \dot{E}x_{total,11}}{\dot{E}x_{total,8} - \dot{E}x_{total,9}}$
HE ₆	$\dot{E}x_{total,28} - \dot{E}x_{total,29}$	$\dot{E}x_{total,13} - \dot{E}x_{total,12}$	$(\dot{E}x_{total,28} - \dot{E}x_{total,29}) - (\dot{E}x_{total,13} - \dot{E}x_{total,12})$	$\frac{\dot{E}x_{total,13} - \dot{E}x_{total,12}}{\dot{E}x_{total,28} - \dot{E}x_{total,29}}$
HE ₇	$\dot{E}x_{total,26} - \dot{E}x_{total,27}$	$\dot{E}x_{total,16} - \dot{E}x_{total,15}$	$(\dot{E}x_{total,26} - \dot{E}x_{total,27}) - (\dot{E}x_{total,16} - \dot{E}x_{total,15})$	$\frac{\dot{E}x_{total,16} - \dot{E}x_{total,15}}{\dot{E}x_{total,26} - \dot{E}x_{total,27}}$
CND	$\dot{E}x_{total,9} - \dot{E}x_{total,10}$	$\dot{E}x_{total,Tc,out} - \dot{E}x_{total,Tc,in}$	$(\dot{E}x_{total,9} - \dot{E}x_{total,10}) - (\dot{E}x_{total,Tc,out} - \dot{E}x_{total,Tc,in})$	$\frac{\dot{E}x_{total,Tc,out} - \dot{E}x_{total,Tc,in}}{\dot{E}x_{total,9} - \dot{E}x_{total,10}}$
SEP	$\dot{E}x_{total,3}$	$\dot{E}x_{total,4} + \dot{E}x_{total,5}$	$\dot{E}x_{total,3} - (\dot{E}x_{total,4} + \dot{E}x_{total,5})$	$\frac{\dot{E}x_{total,4} - \dot{E}x_{total,5}}{\dot{E}x_{total,3}}$
M1	$\dot{E}x_{total,4} + \dot{E}x_{total,6}$	$\dot{E}x_{total,8}$	$(\dot{E}x_{total,4} + \dot{E}x_{total,6}) - \dot{E}x_{total,8}$	$\frac{\dot{E}x_{total,8}}{\dot{E}x_{total,4} + \dot{E}x_{total,6}}$
M2	$\dot{E}x_{total,16} + \dot{E}x_{total,17}$	$\dot{E}x_{total,18}$	$(\dot{E}x_{total,16} + \dot{E}x_{total,17}) - \dot{E}x_{total,18}$	$\frac{\dot{E}x_{total,18}}{\dot{E}x_{total,16} + \dot{E}x_{total,17}}$
M3	$\dot{E}x_{total,18} + \dot{E}x_{total,22}$	$\dot{E}x_{total,19}$	$(\dot{E}x_{total,18} + \dot{E}x_{total,22}) - \dot{E}x_{total,19}$	$\frac{\dot{E}x_{total,19}}{\dot{E}x_{total,18} + \dot{E}x_{total,22}}$
P1	W_{P1}	$(\dot{E}x_{total,11} - \dot{E}x_{total,10})$	$W_{P1} - (\dot{E}x_{total,11} - \dot{E}x_{total,10})$	$\frac{\dot{E}x_{total,11} - \dot{E}x_{total,10}}{W_{P1}}$
P2	W_{P2}	$(\dot{E}x_{total,22} - \dot{E}x_{total,7})$	$W_{P2} - (\dot{E}x_{total,22} - \dot{E}x_{total,7})$	$\frac{\dot{E}x_{total,22} - \dot{E}x_{total,7}}{W_{P2}}$

Table 3 Purchase equipment cost of the major components

Component	Investment cost rate (z)	Constants	CEPCI (Year & value)
TUR	$z_{\text{TUR}} = 4405 \times (W_{\text{TUR}})^{0.7}$		CEPCI ₂₀₀₀ = 394.1 CEPCI ₂₀₂₁ = 699.97
HE1, HE2, HE4, HE5, HE6, HE7	$z_{\text{(HE)}} = Z_{\text{R}} \left(\frac{A}{A_{\text{R}}} \right)^{0.6}$	Reference cost, $Z_{\text{R}} = 16,000$ \$ $A_{\text{R}} = 100$ m ²	
Vapour generator, HE3	$z_{\text{(HE)}} = Z_{\text{R}} \left(\frac{A}{A_{\text{R}}} \right)^{0.6}$	$Z_{\text{R}} = 17,500$ \$ $A_{\text{R}} = 100$ m ²	
CND	$z_{\text{(CND)}} = Z_{\text{R}} \left(\frac{A}{A_{\text{R}}} \right)^{0.6}$	$Z_{\text{R}} = 8000$ \$ $A_{\text{R}} = 100$ m ²	
Pump	$z_{\text{Pump}} = z_{\text{R, Pump}} \left(\frac{W_{\text{Pump}}}{W_{\text{R, Pump}}} \right)^{m_{\text{p}}} \left(\frac{1 - \eta_{\text{is, pump}}}{\eta_{\text{is, pump}}} \right)^{n_{\text{p}}}$	$Z_{\text{R, Pump}} = 2100$ \$ $\dot{W}_{\text{R, Pump}} = 10$ kW $m_{\text{p}} = 0.26$ $n_{\text{p}} = 0.5$	

Individual investment cost in the system's major components is provided in Table 3.

Advanced exergy analysis

An effectual tool in determining energy systems is the advanced exergy analysis. The amount of exergy destruction is investigated in detail in this approach. The destruction of actual exergy in an element is split into two parts: i) avoidable exergy destruction and ii) unavoidable exergy destruction. Further, the components of exergy destruction are split into endogenous and exogenous exergy destructions. The avoidable exergy destruction ($\dot{E}x_{\text{D},i}^{\text{AV}}$) is the segment of exergy destruction that can be diminished by developing the design of the component. The unavoidable exergy destruction ($\dot{E}x_{\text{D},i}^{\text{UN}}$) is the amount of exergy destruction that cannot be minimized due to the constraints in material attributes, cost in producing the component and construction methods. The endogenous exergy destruction in every component is associated with the irreversibility existing within that particular component, whereas the interaction of the other components with the *i*th component results in irreversibility and exogenous exergy destruction.

The following assumption are considered for real, ideal and unavoidable conditions [28].

Real condition: ΔT_{SHE} , ΔT_{CND} are 10 °C, η_{TUR} , η_{Pump} efficiencies are 75%.

Ideal condition: ΔT_{SHE} , ΔT_{CND} are 0 °C, η_{TUR} , η_{Pump} efficiencies are 100%.

Unavoidable conditions, ΔT_{SHE} , ΔT_{CND} are 3 °C, η_{TUR} , η_{Pump} efficiencies are 95%.

Exergoenvironmental analysis

The exergoenvironmental analysis is investigated in the proposed power generation system. Both the technical and environmental parameters are assessed. LCA is used to estimate the impact of products on the environment. Eco-Indicator

99 is implemented in CML2001 and ReCiPe Endpoint. Exergoenvironmental analysis provides useful information for designing systems with the least amount of environmental impact by describing the evolution of the effects on the environment associated with energy transfer devices at components. Exergy-environmental analysis (EEA) combines energy analysis and environmental analysis, depending on the life cycle assessment (LCA). The analysis's impact on the environment's constituents will be revealed. LCA is viewed as an effective technique for analysing a thermodynamic system's environmental effects. The following techniques are used to investigate LCA: Eco-Indicator 99, ReCiPe Endpoint, and CMI 2001. The five stages of LCA are: (1) material extraction; (2) production of diverse manufacturing processes; (3) transportation of fuel, materials, and components; (4) use of energy and power; and (5) waste and material disposal. A higher value of Pts was shown in the components as a result of the higher environmental repercussions. According to the environmental analysis of the planned system, improvements should be concentrated on the parts that have the biggest effects. According to the environmental analysis of the planned system, improvements should be concentrated on the parts that have the biggest effects. In addition to the energy approach, the exergoenvironmental analysis identifies the components involved in the justification of a higher impact on society. The present work is used to identify the combined economic and environmental assessment of power generation systems suitable for renewable energy applications. Based on the investigation, the parameters suggested for improving performance are extended to practical applications. In applications like geothermal district heating systems, cogeneration plants, reformed methane steam processes for hydrogen production, and the combined thermodynamic cycle power plant based on chemical loop technology, a number of studies have been successfully conducted in various systems [36].

The greater value of Eco-Indicator 99 will lead to a higher amount of environmental impact. The mass function of the

Table 4 Component mass equation [28],

Components	Weight Function	Unit
TUR	$w = 4.90 \times (W_{Tur})^{0.73}$	$t, \text{ mW}$
HE ₁	$w = 2.7712(Q_{ECO})^{1.0362}$	$t, \text{ mW}$
HE ₂	$w = 13.911(Q_{EVA})^{0.6802}$	$t, \text{ mW}$
HE ₃	$w = 8.4235 \times (Q_{SH})^{0.8717}$	$t, \text{ mW}$
HE ₄ , HE ₅ , HE ₆ , HE ₇	$w = 2.14 \times (Q_{HTRGN})^{0.7}$	$t, \text{ mW}$
CND	$w = 0.073(Q)^{0.99}$	$t, \text{ mW}$
Pump ₁ , Pump ₂	$w = 0.0061(W_p)^{0.95}$	$t, \text{ kW}$

components is summarized in Table 4 [28]. Mass functions for the components in the system are summarized in Table 3.

\dot{Y} is the device-related environmental effects (mPts h⁻¹) provided in Eq. (16). Total mPts is the summation of the Eco 99 Indicator, process, and disposal.

$$\dot{Y} = \frac{\text{Total mPts}}{n \times N} \tag{16}$$

where number of years, $n = 30$, number of operating hours, $N = 7500 \text{ h/year}$.

Table 4 describes the cost balance equations and environmental impact balance equations for MTKCS components. As the energy transfer and material streams are greater in number than the overall components, auxiliary equations are sufficient to evaluate the unknown variables. On evaluating the equation of the components involved in the system, the decision variables needed for assessing the

exergoenvironmental analysis are calculated. Unit cost and environmental impact correlation of fuel and product for every components of system is summarized in Table 6.

Where number of years, $n = 30$, number of operating hours, $N = 7500 \text{ h/year}$.

Table 5 describes the cost balance equations and environmental impact balance equations for MTKCS components. As the energy transfer and material streams are greater in number than the overall components, auxiliary equations are sufficient to evaluate the unknown variables. On evaluating the equation of the components involved in the system, the decision variables needed for assessing the exergoenvironmental analysis are calculated. Unit cost and environmental impact correlation of fuel and product for every components of system is summarized in Table 5.

In Eq. 17, the exergoenvironmental impact rate (B) is the product of unit environmental impact (b) and the exergy rate of individual components (Table 6).

$$\dot{B}_i = b_i \times \dot{E}x_i \tag{17}$$

Equation 18 provides the environmental impact incurred on the system components due to irreversibility. The relative environmental impact difference ($r_{b,i}$) and exergoenvironmental factor ($f_{b,i}$) are considered as the two variables in the system analysis.

$$\dot{B}_{D,i} = b_{F,i} \times \dot{E}x_{D,i} \tag{18}$$

Table 5 Cost and environmental impact balance equation of MTKCS components

Components	Cost balance equations		Environmental impact balance equations	
	Main equations	Auxiliary equations	Main equations	Auxiliary equations
TUR	$\dot{C}_1 + \dot{Z}_{Tur} = \dot{C}_2 + \dot{C}_{w,Tur}$	$c_{W,Pump1} = c_{W,Pump2} = c_{W,Tur} = c_w$	$\dot{B}_1 + \dot{Y}_{Tur} = \dot{B}_2 + \dot{B}_{w,Tur}$	$b_1 = b_2 \quad b_{WPump1} = b_{WPump2} = b_{WTur} = b_w$
HE ₁	$\dot{C}_{25} + \dot{C}_{19} + \dot{Z}_{HE1} = \dot{C}_{20} + \dot{C}_{26}$	$c_{25} = c_{26}$	$\dot{B}_{25} + \dot{B}_{19} + \dot{Y}_{HE1} = \dot{B}_{20} + \dot{B}_{26}$	$b_{25} = b_{26}$
HE ₂	$\dot{C}_{24} + \dot{C}_{20} + \dot{Z}_{HE2} = \dot{C}_{21} + \dot{C}_{25}$	$c_{24} = c_{25}$	$\dot{B}_{24} + \dot{B}_{20} + \dot{Y}_{HE2} = \dot{B}_{21} + \dot{B}_{25}$	$b_{24} = b_{25}$
HE ₃	$\dot{C}_{23} + \dot{C}_{21} + \dot{Z}_{HE3} = \dot{C}_1 + \dot{C}_{24}$	$c_{23} = c_{24}$	$\dot{B}_{23} + \dot{B}_{21} + \dot{Y}_{HE3} = \dot{B}_1 + \dot{B}_{24}$	$b_{23} = b_{24}$
HE ₄	$\dot{C}_2 + \dot{C}_{14} + \dot{Z}_{HE4} = \dot{C}_3 + \dot{C}_{17}$	$c_2 = c_1$	$\dot{B}_2 + \dot{B}_{14} + \dot{Y}_{HE4} = \dot{B}_3 + \dot{B}_{17}$	$b_2 = b_1$
HE ₅	$\dot{C}_8 + \dot{C}_{11} + \dot{Z}_{HE5} = \dot{C}_9 + \dot{C}_{12}$	$c_8 = c_9$	$\dot{B}_8 + \dot{B}_{11} + \dot{Y}_{HE5} = \dot{B}_9 + \dot{B}_{12}$	$b_8 = b_9$
HE ₆	$\dot{C}_{28} + \dot{C}_{12} + \dot{Z}_{HE6} = \dot{C}_{29} + \dot{C}_{13}$	$c_{28} = c_{29}$	$\dot{B}_{28} + \dot{B}_{12} + \dot{Y}_{HE6} = \dot{B}_{29} + \dot{B}_{13}$	$b_{28} = b_{29}$
HE ₇	$\dot{C}_{26} + \dot{C}_{15} + \dot{Z}_{HE7} = \dot{C}_{27} + \dot{C}_{16}$	$c_{26} = c_{27}$	$\dot{B}_{26} + \dot{B}_{15} + \dot{Y}_{HE7} = \dot{B}_{27} + \dot{B}_{16}$	$b_{26} = b_{27}$
P1	$\dot{C}_{11} = \dot{C}_{10} + \dot{C}_{WPump1} + \dot{Z}_{Pump1}$	$c_{pump1} = c_w$	$\dot{B}_{11} = \dot{B}_{10} + \dot{B}_{WPump1} + \dot{Y}_{Pump1}$	$b_{WPump1} = b_w$
P2	$\dot{C}_{22} = \dot{C}_7 + \dot{C}_{WPump2} + \dot{Z}_{Pump2}$	$c_{pump2} = c_w$	$\dot{B}_{22} = \dot{B}_7 + \dot{B}_{WPump2} + \dot{Y}_{Pump2}$	$b_{WPump2} = b_w$
M1	$\dot{C}_4 + \dot{C}_6 + \dot{Z}_{M1} = \dot{C}_8$	None	$\dot{B}_4 + \dot{B}_5 + \dot{Y}_{M1} = \dot{B}_8$	None
M2	$\dot{C}_{16} + \dot{C}_{17} + \dot{Z}_{M2} = \dot{C}_{18}$	None	$\dot{B}_{16} + \dot{B}_{17} + \dot{Y}_{M2} = \dot{B}_{18}$	None
M3	$\dot{C}_{22} + \dot{C}_{18} + \dot{Z}_{M3} = \dot{C}_{19}$	None	$\dot{B}_{22} + \dot{B}_{18} + \dot{Y}_{M3} = \dot{B}_{19}$	None
SEP	$\dot{C}_3 + \dot{Z}_{SEP} = \dot{C}_4 + \dot{C}_5$	None	$\dot{B}_3 + \dot{Z}_{SEP} = \dot{B}_4 + \dot{B}_5$	None
CND	$\dot{C}_9 + \dot{C}_{cin} + \dot{Z}_{CND} = \dot{C}_1 + \dot{C}_{Cout}$	$c_{10} = c_9$	$\dot{B}_9 + \dot{B}_{cin} + \dot{Y}_{CND} = \dot{B}_1 + \dot{B}_{Cout}$	$b_{10} = b_9$
S1	$\dot{C}_5 = \dot{C}_6 + \dot{C}_7$	$c_4 = c_5$	$\dot{B}_5 = \dot{B}_6 + \dot{B}_7$	$b_4 = b_5$
S2	$\dot{C}_{13} = \dot{C}_{14} + \dot{C}_{15}$	$c_{14} = c_{15}$	$\dot{B}_{13} = \dot{B}_{14} + \dot{B}_{15}$	$b_{14} = b_{15}$

Table 6 Unit cost and environmental impact correlation of MTKCS components

Components	$c_{f,i}, \$ GJ^{-1}$	$c_{p,i}, \$ GJ^{-1}$	$b_{f,i}, \$ GJ^{-1}$	$b_{p,i}, \$ GJ^{-1}$
TUR	$\frac{\dot{C}_1 - \dot{C}_2}{\dot{E}x_1 - \dot{E}x_2}$	$\frac{c_w \times W_T}{\dot{E}x_{P,Tur}}$	$\frac{B_1 - B_2}{\dot{E}x_1 - \dot{E}x_2}$	$\frac{b_w \times W_T}{\dot{E}x_{P1}}$
HE ₁	$\frac{\dot{C}_{25} - \dot{C}_{26}}{\dot{E}x_{25} - \dot{E}x_{26}}$	$\frac{\dot{C}_{20} - \dot{C}_{19}}{\dot{E}x_{20} - \dot{E}x_{19}}$	$\frac{\dot{B}_{25} - \dot{B}_{26}}{\dot{E}x_{25} - \dot{E}x_{26}}$	$\frac{\dot{B}_{20} - \dot{B}_{19}}{\dot{E}x_{20} - \dot{E}x_{19}}$
HE ₂	$\frac{\dot{C}_{24} - \dot{C}_{25}}{\dot{E}x_{24} - \dot{E}x_{25}}$	$\frac{\dot{C}_{21} - \dot{C}_{20}}{\dot{E}x_{21} - \dot{E}x_{20}}$	$\frac{\dot{B}_{24} - \dot{B}_{25}}{\dot{E}x_{24} - \dot{E}x_{25}}$	$\frac{\dot{B}_{21} - \dot{B}_{20}}{\dot{E}x_{21} - \dot{E}x_{20}}$
HE ₃	$\frac{\dot{C}_{23} - \dot{C}_{24}}{\dot{E}x_{23} - \dot{E}x_{24}}$	$\frac{\dot{C}_1 - \dot{C}_{21}}{\dot{E}x_1 - \dot{E}x_{21}}$	$\frac{\dot{B}_{23} - \dot{B}_{24}}{\dot{E}x_{23} - \dot{E}x_{24}}$	$\frac{B_1 - B_{21}}{\dot{E}x_1 - \dot{E}x_{21}}$
HE ₄	$\frac{\dot{C}_2 - \dot{C}_3}{\dot{E}x_2 - \dot{E}x_3}$	$\frac{\dot{C}_{17} - \dot{C}_{14}}{\dot{E}x_{17} - \dot{E}x_{14}}$	$\frac{\dot{B}_2 - \dot{B}_3}{\dot{E}x_2 - \dot{E}x_3}$	$\frac{\dot{B}_{17} - \dot{B}_{14}}{\dot{E}x_{17} - \dot{E}x_{14}}$
HE ₅	$\frac{\dot{C}_8 - \dot{C}_9}{\dot{E}x_8 - \dot{E}x_9}$	$\frac{\dot{C}_{12} - \dot{C}_{11}}{\dot{E}x_{12} - \dot{E}x_{11}}$	$\frac{\dot{B}_8 - \dot{B}_9}{\dot{E}x_8 - \dot{E}x_9}$	$\frac{B_7 - \dot{B}_6}{\dot{E}x_7 - \dot{E}x_6}$
HE ₆	$\frac{\dot{C}_{28} - \dot{C}_{29}}{\dot{E}x_{28} - \dot{E}x_{29}}$	$\frac{\dot{C}_{13} - \dot{C}_{12}}{\dot{E}x_{13} - \dot{E}x_{12}}$	$\frac{\dot{B}_{28} - \dot{B}_{29}}{\dot{E}x_{28} - \dot{E}x_{29}}$	$\frac{\dot{B}_{13} - \dot{B}_{12}}{\dot{E}x_{13} - \dot{E}x_{12}}$
HE ₇	$\frac{\dot{C}_{26} - \dot{C}_{27}}{\dot{E}x_{26} - \dot{E}x_{27}}$	$\frac{\dot{C}_{16} - \dot{C}_{15}}{\dot{E}x_{16} - \dot{E}x_{15}}$	$\frac{\dot{B}_{26} - \dot{B}_{27}}{\dot{E}x_{26} - \dot{E}x_{27}}$	$\frac{\dot{B}_{16} - \dot{B}_{15}}{\dot{E}x_{16} - \dot{E}x_{15}}$
P ₁	$\frac{c_w \times W_{P1}}{W_{P1}}$	$\frac{\dot{C}_{11} - \dot{C}_{12}}{\dot{E}x_{11} - \dot{E}x_{12}}$	$\frac{b_w \times W_{P1}}{W_{P1}}$	$\frac{\dot{B}_{11} - \dot{B}_{12}}{\dot{E}x_{11} - \dot{E}x_{12}}$
P ₂	$\frac{c_w \times W_{P2}}{W_{P2}}$	$\frac{\dot{C}_{22} - \dot{C}_7}{\dot{E}x_{22} - \dot{E}x_7}$	$\frac{b_w \times W_{P2}}{W_{P2}}$	$\frac{\dot{B}_{22} - \dot{B}_7}{\dot{E}x_{22} - \dot{E}x_7}$
M ₁	$\frac{\dot{C}_6 + \dot{C}_4}{\dot{E}x_6 + \dot{E}x_4}$	$\frac{\dot{C}_8}{\dot{E}x_8}$	$\frac{\dot{B}_6 + \dot{B}_4}{\dot{E}x_6 + \dot{E}x_4}$	$\frac{\dot{B}_8}{\dot{E}x_8}$
M ₂	$\frac{\dot{C}_{16} + \dot{C}_{17}}{\dot{E}x_{16} + \dot{E}x_{17}}$	$\frac{\dot{C}_{18}}{\dot{E}x_{18}}$	$\frac{\dot{B}_{16} + \dot{B}_{17}}{\dot{E}x_{16} + \dot{E}x_{17}}$	$\frac{\dot{B}_{18}}{\dot{E}x_{18}}$
M ₃	$\frac{\dot{C}_{18} + \dot{C}_{22}}{\dot{E}x_{18} + \dot{E}x_{22}}$	$\frac{\dot{C}_{19}}{\dot{E}x_{19}}$	$\frac{\dot{B}_{18} + \dot{B}_{22}}{\dot{E}x_{18} + \dot{E}x_{22}}$	$\frac{\dot{B}_{19}}{\dot{E}x_{19}}$
SEP	$\frac{\dot{C}_3}{\dot{E}x_3}$	$\frac{\dot{C}_4 + \dot{C}_5}{\dot{E}x_4 + \dot{E}x_5}$	$\frac{\dot{B}_3}{\dot{E}x_3}$	$\frac{\dot{B}_4 + \dot{B}_5}{\dot{E}x_4 + \dot{E}x_5}$
CND	$\frac{\dot{C}_9 - \dot{C}_{10}}{\dot{E}x_9 - \dot{E}x_{10}}$	$\frac{\dot{C}_{Tin} - \dot{C}_{Tout}}{\dot{E}x_{Tin} - \dot{E}x_{Tout}}$	$\frac{\dot{B}_9 - \dot{B}_{10}}{\dot{E}x_9 - \dot{E}x_{10}}$	$\frac{\dot{B}_{Tin} - \dot{B}_{Tout}}{\dot{E}x_{Tin} - \dot{E}x_{Tout}}$

$$r_{b,i} = \frac{b_{F,i} - b_{P,i}}{b_{F,i}} \tag{19}$$

$$f_{b,i} = \frac{\dot{Y}_i}{\dot{Y}_1 + \dot{B}_{D,i}} \tag{20}$$

In Table 7 and Table 8, the results of advanced destruction cost rates and the total cost rate of MTKCS are summarized. The exogenous exergy destruction cost rates of all the equipment's are lower than the endogenous exergy destruction cost rates. The irreversibility associated with the interaction of the total number of components with a particular component is smaller in amount than the irreversibility existing in the *i*th component. The unavoidable exergy destruction cost rates of overall components are greater than the avoidable exergy destruction cost rates.

Hence, the components in the proposed system are restricted to economic and technological restrictions and cannot be diminished in the exergy destruction. The components' HE2, HE3, HE5, HE7, turbine and separator avoidable exogenous exergy destruction are higher than

Table 7 Exergy destruction cost rates of the MTKCS system in advanced analysis

Components	$\dot{C}_{D,K}^{EN}, \$ h^{-1}$	$\dot{C}_{D,K}^{EX}, \$ h^{-1}$	$\dot{C}_{D,K}^{UN}, \$ h^{-1}$	$\dot{C}_{D,K}^{AV}, \$ h^{-1}$	$\dot{C}_{D,K}^{UN}, \$ h^{-1}$	$\dot{C}_{D,K}^{UN}, \$ h^{-1}$	$\dot{C}_{D,K}^{UN}, \$ h^{-1}$	$\dot{C}_{D,K}^{UN}, \$ h^{-1}$
	$\dot{C}_{D,K}^{EN} = c_{F,k} \dot{E}_{D,K}^{EN}$	$\dot{C}_{D,K}^{EX} = \dot{C}_{D,K} - \dot{C}_{D,K}^{EN}$	$\dot{C}_{D,K}^{UN} = c_{F,k} \dot{E}_{D,K}^{UN}$	$\dot{C}_{D,K}^{AV} = c_{F,k} \dot{E}_{D,K}^{AV}$	$\dot{C}_{D,K}^{UN} = c_{F,k} \dot{E}_{D,K}^{UN}$	$\dot{C}_{D,K}^{UN} = c_{F,k} \dot{E}_{D,K}^{UN}$	$\dot{C}_{D,K}^{UN} = c_{F,k} \dot{E}_{D,K}^{UN}$	$\dot{C}_{D,K}^{UN} = c_{F,k} \dot{E}_{D,K}^{UN}$
HE ₁	0.07161	0.03931	0.09483	0.01681	0.06242	0.00919	0.03241	0.0069
HE ₂	0.07415	0.03326	0.08044	0.02637	0.07197	0.00218	0.00847	0.02479
HE ₃	0.05982	0.04147	0.06339	0.03539	0.05946	0.00036	0.00393	0.03754
HE ₄	0.23596	0.18534	0.29005	0.12329	0.13574	0.10022	0.15431	0.03103
HE ₅	0.04655	0.03702	0.05011	0.03233	0.04542	0.00113	0.00469	0.03233
HE ₆	0.03472	0.00241	0.03435	0.00085	0.03218	0.00254	0.00217	0.00024
HE ₇	0.0521	0.03328	0.05138	0.03329	0.05017	0.00193	0.00121	0.03207
MXT	0.36789	0.1109	0.3638	0.11106	0.36118	0.00671	0.00262	0.10828
SEP	0.15858	0.01707	0.15858	0.01543	0.15628	0.0023	0.0023	0.01477
CND	0.00267	0.00116	0.00183	0.00133	0.00167	0.001	0.00016	0.001
P ₁	0.03587	0.01618	0.02843	0.01312	0.01268	0.02319	0.01575	0.00043
P ₂	0.00245	0.00105	0.00219	0.00087	0.00131	0.00114	0.00088	0.00017

Table 8 Advanced investment cost rates of the system of MTKCS

	$\dot{Z}_{D,K}^{EN}, \$ h^{-1}$	$\dot{Z}_{D,K}^{EX}, \$ h^{-1}$	$\dot{Z}_{D,K}^{AV}, \$ h^{-1}$	$\dot{Z}_{D,K}^{UN}, \$ h^{-1}$	$\dot{Z}_{D,K}^{EN-UN}, \$ h^{-1}$	$\dot{Z}_{D,K}^{AV-UN}, \$ h^{-1}$	$\dot{Z}_{D,K}^{EX-UN}, \$ h^{-1}$	$\dot{Z}_{D,K}^{EN}, \$ h^{-1}$	$\dot{Z}_{D,K}^{AV}, \$ h^{-1}$	$\dot{Z}_{D,K}^{EX}, \$ h^{-1}$	$\dot{Z}_{D,K}^{UN}, \$ h^{-1}$	$\dot{Z}_{D,K}^{EN-UN}, \$ h^{-1}$	$\dot{Z}_{D,K}^{AV-UN}, \$ h^{-1}$	$\dot{Z}_{D,K}^{EX-UN}, \$ h^{-1}$
	$\dot{Z}_{D,K}^{EN} = \dot{E}_{PK}^{EN} \left(\frac{\dot{z}}{\dot{E}_{PK}} \right)_k$	$\dot{Z}_{D,K}^{EX} = \dot{Z}_{D,K}^{real} - \dot{Z}_{D,K}^{EN}$	$\dot{Z}_{D,K}^{AV} = \dot{Z}_{D,K}^{real} - \dot{Z}_{D,K}^{EN}$	$\dot{Z}_{D,K}^{UN} = \dot{E}_{PK}^{UN} \left(\frac{\dot{z}}{\dot{E}_{PK}} \right)_k$	$\dot{Z}_{D,K}^{EN-UN} = \dot{Z}_{D,K}^{EN} - \dot{Z}_{D,K}^{UN}$	$\dot{Z}_{D,K}^{AV-UN} = \dot{Z}_{D,K}^{AV} - \dot{Z}_{D,K}^{UN}$	$\dot{Z}_{D,K}^{EX-UN} = \dot{Z}_{D,K}^{EX} - \dot{Z}_{D,K}^{UN}$	$\dot{Z}_{D,K}^{EN} = \dot{E}_{PK}^{EN} \left(\frac{\dot{z}}{\dot{E}_{PK}} \right)_k$	$\dot{Z}_{D,K}^{AV} = \dot{Z}_{D,K}^{EN} + \dot{E}_{PK}^{AV} \left(\frac{\dot{z}}{\dot{E}_{PK}} \right)_k$	$\dot{Z}_{D,K}^{EX} = \dot{Z}_{D,K}^{EN} + \dot{E}_{PK}^{EX} \left(\frac{\dot{z}}{\dot{E}_{PK}} \right)_k$	$\dot{Z}_{D,K}^{UN} = \dot{E}_{PK}^{UN} \left(\frac{\dot{z}}{\dot{E}_{PK}} \right)_k$	$\dot{Z}_{D,K}^{EN-UN} = \dot{Z}_{D,K}^{EN} - \dot{Z}_{D,K}^{UN}$	$\dot{Z}_{D,K}^{AV-UN} = \dot{Z}_{D,K}^{AV} - \dot{Z}_{D,K}^{UN}$	$\dot{Z}_{D,K}^{EX-UN} = \dot{Z}_{D,K}^{EX} - \dot{Z}_{D,K}^{UN}$
HE ₁	0.089194643	0.010805357	0.005778756	0.094221244	0.005154341	0.005154341	0.084040302	0.084040302	0.000624415	0.000624415	0.010180942	0.010180942	0.000624415	0.010180942
HE ₂	0.199207954	0.010792046	0.006290221	0.203709779	0.005966962	0.005966962	0.193240992	0.193240992	0.000323259	0.000323259	0.010468787	0.010468787	0.000323259	0.010468787
HE ₃	0.053071325	0.006928675	0.001426492	0.058573508	0.001261764	0.001261764	0.051809561	0.051809561	0.000164728	0.000164728	0.006763947	0.006763947	0.000164728	0.006763947
HE ₄	0.529606148	0.020393852	0.018069164	0.531930836	0.017399165	0.017399165	0.512206983	0.512206983	0.00067	0.00067	0.019723852	0.019723852	0.00067	0.019723852
HE ₅	0.037686747	0.002313253	0.001349398	0.038650602	0.00127136	0.00127136	0.036415387	0.036415387	7.80375E-05	7.80375E-05	0.002235216	0.002235216	7.80375E-05	0.002235216
HE ₆	0.067173751	0.012826249	0.00316182	0.07683818	0.002654891	0.002654891	0.06451886	0.06451886	0.00027181	0.00027181	0.012319321	0.012319321	0.00027181	0.012319321
HE ₇	0.026777108	0.003222892	0.00253012	0.02746988	0.00225831	0.00225831	0.024518798	0.024518798	0.002287974	0.002287974	0.002951081	0.002951081	0.002287974	0.002951081
MXT	3.886350039	0.313649961	0.030637628	4.169362372	0.028349654	0.028349654	3.858000385	3.858000385	0	0	0.311361987	0.311361987	0	0.311361987
SEP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CND	0.121788079	0.028211921	0.011125828	0.138874172	0.009033288	0.009033288	0.112754791	0.112754791	0.00209254	0.00209254	0.026119381	0.026119381	0.00209254	0.026119381
P ₁	0.01560166	0.00439834	0.002904564	0.017095436	0.002265801	0.002265801	0.013335859	0.013335859	0.000638763	0.000638763	0.003759577	0.003759577	0.000638763	0.003759577
P ₂	0.007608696	0.002391304	0.000652174	0.009347826	0.000496219	0.000496219	0.007112476	0.007112476	0.000155955	0.000155955	0.002235535	0.002235535	0.000155955	0.002235535

Table 9 Model validation between present work with Refs

Literature results				Present work				
Reference	Pressure, bar	Temperature/ °C	Parameter	Result	Pressure, bar	Temperature/ °C	Parameter	Result
[29]	10	160	Exergetic Efficiency, %	69.83	45	180	Exergetic Efficiency, %	82.35
[31]	60	280	Exergetic Efficiency, %	41.9	45	180	Exergetic Efficiency, %	34.5
[30]	86	380	\dot{Z}_{Turbine} , \$ h ⁻¹	7.012	45	180	\dot{Z}_{Turbine} , \$/hr	4.2
[32]	32	182.77	Thermal efficiency, %	17.24	32	182.77	Thermal efficiency, %	17.64
[32]	32	182.77	Second law efficiency, %	58.43	32	182.77	Second law efficiency, %	66

the avoidable endogenous exergy destruction rate. Hence, lowering the exergy elimination rate of the remaining components will result in a reduction in the avoidable exergy destruction rate. The endogenous investment cost rate for all the components of the proposed system is higher than the exogenous investment cost. The irreversibility related to an individual component is sufficient to examine the improvement in the design cost. Due to design and metallurgical limitations, there may not be a compromise in the total cost rate of the components, ensuring the higher unavoidable investment cost rate. The endogenous available investment cost for the components of the novel system proposed is very minimal, hence investigating the components with technological improvement will not produce a favourable reduction in exergy destruction.

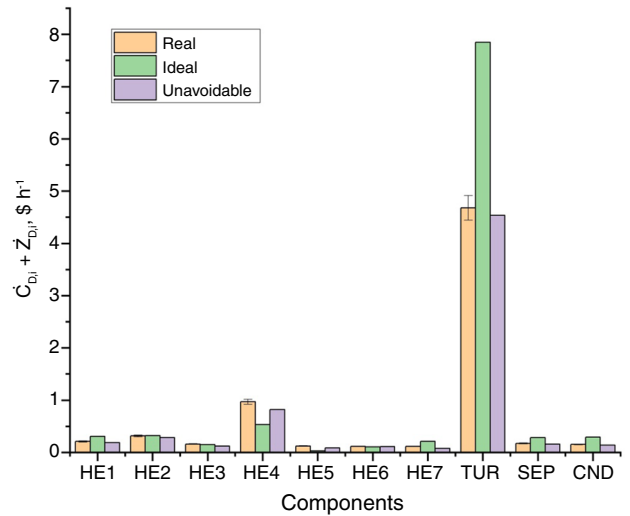


Fig. 3 $\dot{C}_{D,i} + \dot{Z}_{D,i}$ \$ h⁻¹ of MTKCS at Real, Ideal and Unavoidable conditions

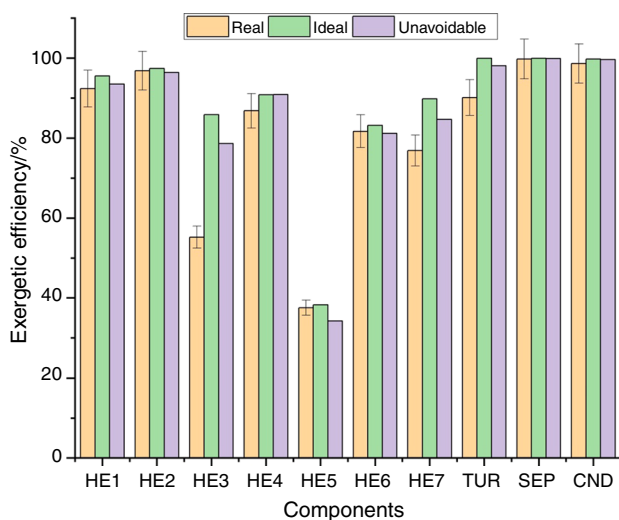


Fig. 2 Exergetic Efficiency, % of MTKCS at Real, Ideal and Unavoidable conditions

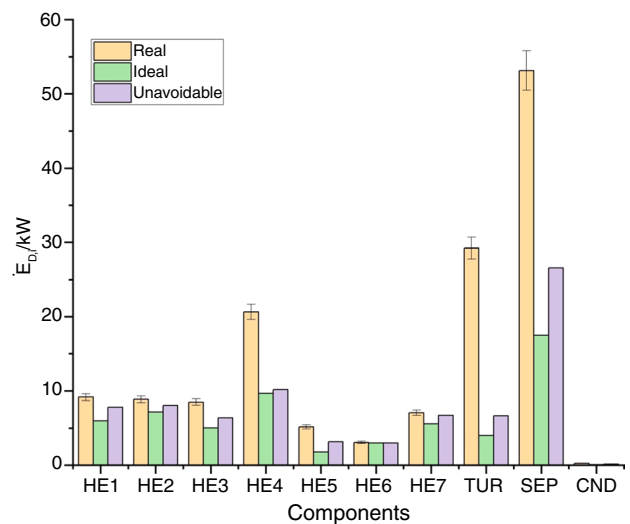


Fig. 4 $\dot{E}_{D,i}$ kW of MTKCS at Real, Ideal and Unavoidable conditions

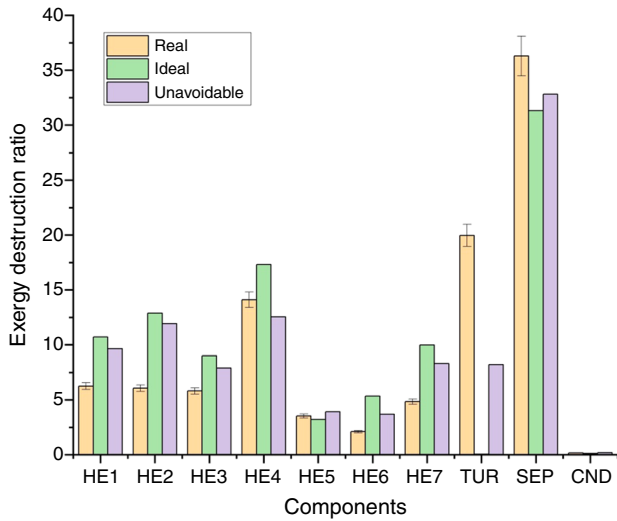


Fig. 5 Exergy Destruction Ratio of MTKCS at Real, Ideal and Unavoidable conditions

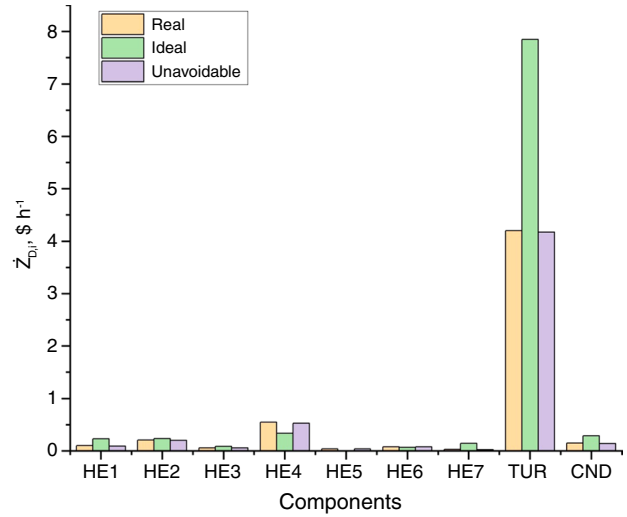


Fig. 7 Investment cost rate (\dot{Z}_D) $\$ h^{-1}$ of MTKCS at Real, Ideal and Unavoidable conditions

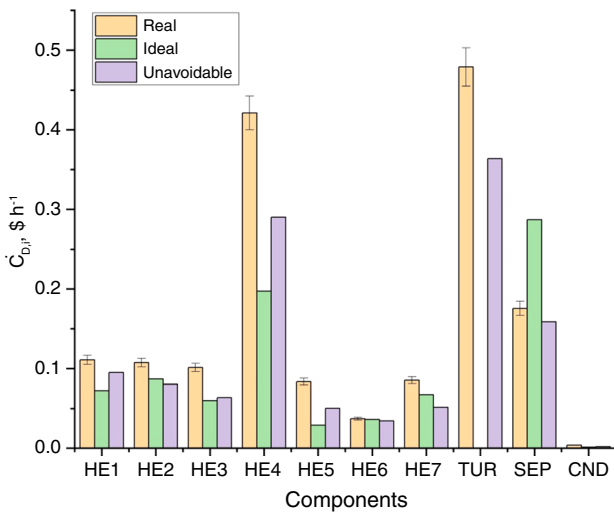


Fig. 6 Exergy destruction cost rate (\dot{C}_D), $\$ h^{-1}$ of MTKCS at Real, Ideal and Unavoidable conditions

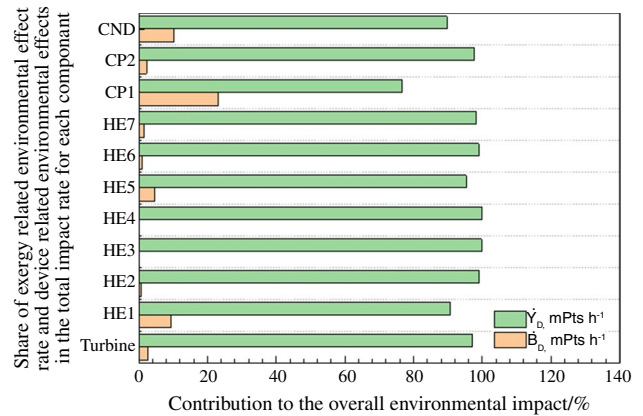


Fig. 8 Share of various environmental blow in overall impact rate for MTKCS components

Validation of the present results with the references

The proposed cycle is validated by the literature results, as shown in Table 9.

Results and discussions

In this work, exergoenvironmental assessment in addition to the conventional and advanced exergy analysis has been made.

Exergy investigation in the novel power generation system

In improving the operation of the proposed system, additional recommendation will be provided by the advanced exergy analysis. The exergetic efficiency of the major components in the system assessed under real, ideal and unavoidable conditions is shown in Fig. 2. The exergetic efficiency

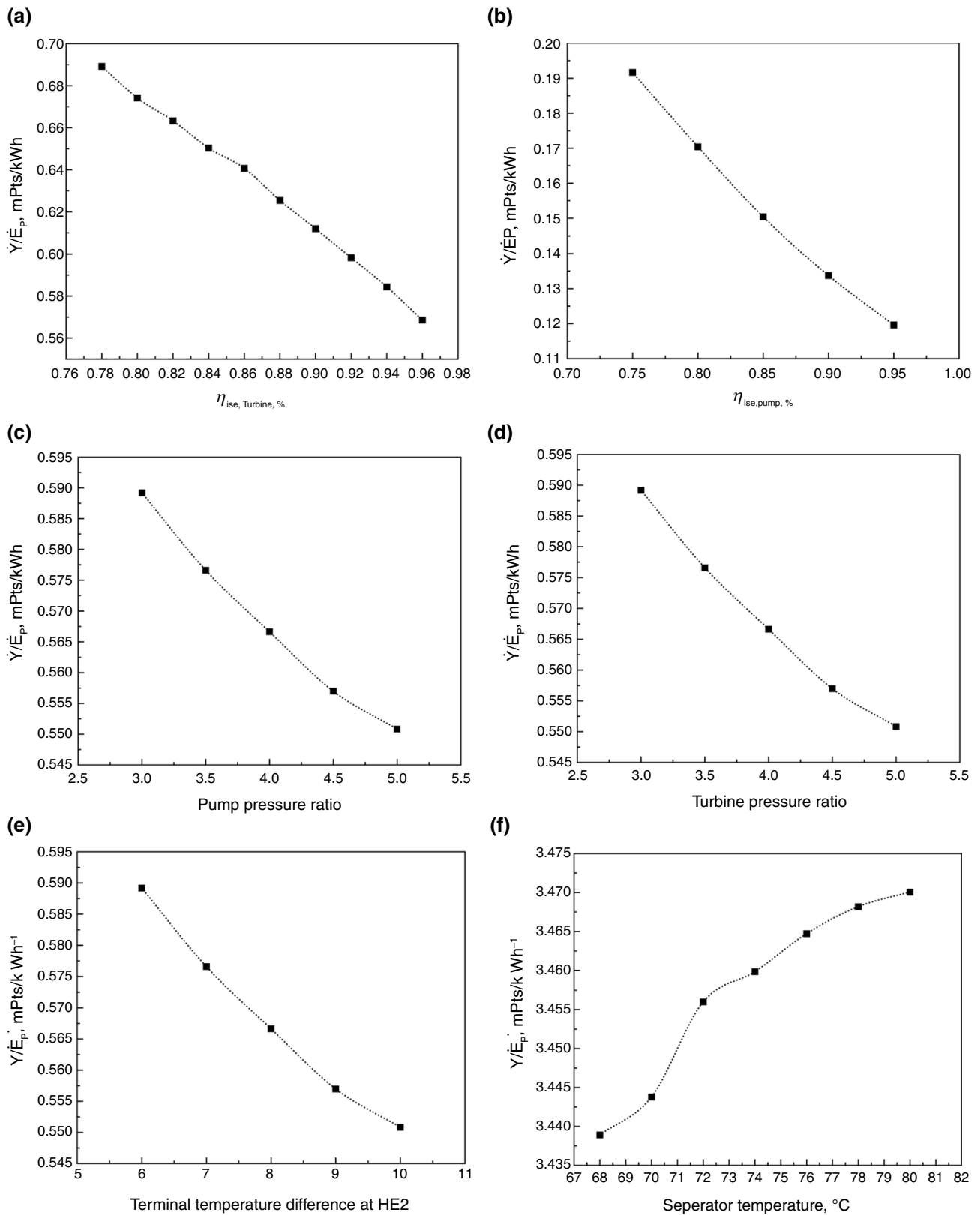


Fig. 9 The outcomes of \dot{Y}/\dot{E}_p with a range of parametric values in MTKCS **a** $\eta_{ise, turbine}$ %, **b** $\eta_{ise, pump}$ %, **c** pump pressure ratio, **d** turbine pressure ratio, **e** TTD at HE2 and **f** Separator temperature °C

of the real cycle for the components has resulted the lowest value. This is because the plant working under real conditions will be examined with the irreversibility associated with it. The advanced exergy analysis provides the details about the interaction of the components with the technical restrictions for the benefit of the system. The values of the exergetic efficiency of the components for the three conditions reveal that under ideal condition, without irreversibility the system will result with higher performance followed by unavoidable and real conditions.

The decision variable $\dot{C}_{D,i} + \dot{Z}_i$ of MTKCS is investigated and presented in Fig. 3. Among the components examined, the maximum cost rated is resulted in the component turbine. Hence, with reducing the cost rate of the components with higher cost rate, the overall cost rate is minimized. With the technical improvement, the cost rate will be minimized (Figs. 4, 5). The present graph is concerned with Figs. 6–7. In Fig. 6, the other components which require higher investment are examined and resulted as HE4 and separator. As the focus is on the major equipment, hence no much improvement is required in the minor components. The result from Fig. 6 reveals than the component seeking higher exergy destruction cost rate is seeking revision. The investment cost rate as shown in Fig. 7 is similar to the combined cost rates. Hence, only the component turbine is exhibited with higher investment. The result of the total cost rate suggests that the requirement for the component need to revise in

technical, design and metallurgical aspects. Kalina cycle system at turbine inlet temperature of 150 °C results an overall exergy destruction value of 51.8 kW at real conditions and 61.26 kW at unavoidable conditions [35]. The present system results an overall exergy destruction value of 59.82 kW at real conditions and 79.37 kW at unavoidable conditions at a turbine inlet temperature of 190 °C.

Figure 4 shows the exergy destruction for the components under real, ideal, and unavoidable conditions. Among the major components investigated for more destruction, the component turbine needs revision. Among the heat exchangers in the system, the component HE4 has more destruction than the other components under real conditions. These two components are associated with the other components flow rate, hence associated with higher irreversibility. By reducing the overall components destruction value, the two components will result in lower exergy destruction.

The exergy destruction ratio is a key factor in identifying the losses as shown in Fig. 5. The components with higher input temperature will result in a higher destruction ratio. Hence, components turbine and separator result with a higher destruction ratio. The network and the exergy efficiency at 26 bar turbine inlet pressure resulted in 1672 kW and 63.66% at unavoidable condition [28]. The proposed system results in 1702 kW network and 65% exergy efficiency at the same conditions.

Table 10 Cycle data on energy and exergy account

State	<i>P</i> /bar	<i>T</i> /°C	<i>X</i>	<i>m</i> /kg s ⁻¹	<i>h</i> /kJ kg ⁻¹	<i>S</i> /kJ ⁻¹ kg ⁻¹ K	Exergy/kW
1	45	0.8	190	1.27	1825.3	5.053	20,786.23
2	12.06	0.8	80	1.27	1615.6	5.113	20,490.68
3	12.06	0.8	80	1.27	1048.9	3.625	20,207
4	12.06	0.98	80	0.851	1443.3	4.745	15,609.2
5	12.06	0.44	80	0.425	124.1	0.99	3659.08
6	12.06	0.44	80	0.148	124.1	0.99	1274.23
7	12.06	0.44	80	0.277	124.1	0.99	2411.16
8	12.06	0.85	80	1	1247.8	4.34	16,863.85
9	12.06	0.85	69.03	1	1194.3	4.19	16,855.57
10	12.06	0.85	35	1	92.6	0.55	16,838.64
11	45	0.85	36.1	1	98.9	0.554	16,843.75
12	45	0.85	47.06	1	152.4	0.723	16,846.86
13	45	0.85	72.65	1	281.8	1.111	16,860.58
14	45	0.85	72.65	0.851	281.8	1.111	14,347.9
15	45	0.85	72.65	0.148	281.8	1.111	2495.32
16	45	0.85	109.2	0.148	1132.3	3.429	2518.91
17	45	0.85	109.2	0.851	1132.3	3.429	14,483.53
18	45	0.85	109.2	1	1132.3	3.429	17,001.47
19	45	0.8	109.2	1.28	799.82	2.629	20,395.44
20	45	0.8	129.78	1.28	1141.3	3.484	20,505.85
21	45	0.8	177.81	1.28	1787	4.969	20,775.75
22	45	0.44	79.8	0.277	127.7	0.981	2412.7

Table 11 Summarization of MTKCS component-related environmental impact

Components	Mass Function (w)/MW	Material	Eco 99 Indicator/mPts/kg		Process/mPts/kg	Disposal/mPts/kg	Total/mPts	$\dot{Y}/\text{mPts s}^{-1}$
Turbine	$4.90(W_{\text{Tur}})^{0.73}$	Steel 25%	86	21.5	12.1	-70	943,848.64	0.0011
		Steel High Alloy 75%	910	682.5				
HE1	$2.7712(Q_{\text{HE1}})^{1.0362}$, MW	Steel 100%	86		12.1	-70	15,624.688	0.000019
HE2	$13.911(Q_{\text{HE2}})^{0.6802}$, MW	Steel 100%	86		12.1	-70	322,204.14	0.00039
HE3	$8.4235(Q_{\text{HE3}})^{0.8717}$, MW	Steel 100%	86		12.1	-70	474,254.03	0.00058
HE4	$2.14(Q_{\text{HE4}})^{0.7}$, MW	Steel 100%	86		12.1	-70	6,417,853.24	0.0079
HE5	$2.14(Q_{\text{HE5}})^{0.7}$, MW	Steel 100%	86		12.1	-70	152,208.13	0.00018
HE6	$2.14(Q_{\text{HE6}})^{0.7}$, MW	Steel 100%	86		12.1	-70	192,076.65	0.00023
HE7	$2.14(Q_{\text{HE7}})^{0.7}$, MW	Steel 100%	86		12.1	-70	99,743.17	0.000123
Condenser	$0.073(Q)^{0.99}$, MW	Steel 100%	86		12.1	-70	58,222.46	0.000071
Pump1	$0.0061(W_{\text{P1}})^{0.95}$, kW	Cast Iron 65%	286	156	16.9	-70	5710.46	0.0000070
		Steel 35%	40	30.1				
Pump2	$0.0061(W_{\text{P2}})^{0.95}$, kW	Cast Iron 65%	286	156	16.9	-70	747.966	0.0000009
		Steel 35%	40	30.1				

Environmental analysis

Figure 8 provides the result of the overall impact caused by the individual contributions. The device-related environmental effects (\dot{Y}_D) are larger for the entire components of the novel system proposed than the exergy-related environmental effect rate (\dot{B}_D). The total mPts value of every component is associated with the environmental effects on the device. Exergy-related environmental effect rate is dependent on the exergoenvironmental impact rate and total exergy of the state points. The pump has resulted in a lower device environmental impact, whereas HE4 has resulted in a lower environmental effect rate. The device with the higher environmental impact rate requires attention to minimize the overall impact. Similar to the exergy results, the component turbine and HE4 resulted in higher total exergy-related environmental effects and device-related environmental effects. Minimizing the impact of these two components will pay off in an overall reduction in environmental blow.

Figure 9 shows the results relative environmental impact (\dot{Y}/\dot{E}_p) with a range of isentropic efficiency of turbine, isentropic efficiency of pump, pump pressure ratio, turbine pressure ratio, terminal temperature difference at HE2 and separator temperature. The variable (\dot{Y}/\dot{E}_p) decreases with an increase in the parameters $\eta_{\text{ise,turbine}}$, $\eta_{\text{ise,pump}}$, PPR, TPR and TTD at HE2. Whereas it increases with the parameter separator temperature.

The exergy destruction value is reduced by a larger amount, whereas product exergy is lowered by a smaller amount by increasing the isentropic pump efficiency as in Fig. 9 a, which together results in declination in relative

environmental impact. The higher the ratio, the more attention should be applied to the component being investigated. The environmental impact rate increased by 3% and 4%, respectively, on account of the turbine's isentropic efficiency as in Fig. 9 b. The lowest value of relative environmental impact results in a pump pressure ratio of 5 as in Fig. 9 c. The highest value of relative environmental impact register at a lower pressure ratio. In Fig. 9 d, with an increase in turbine pressure ratio and increased product exergy, energy destruction increases by 10–60%. The environmental effect rate increases very minimally, less than 7%. For these reasons, the decision variables (\dot{Y}/\dot{E}_p) result in an increased amount. TTD is considered as one of the parameters that influence the first law and second law performances of the system as in Fig. 9 e. An increase in the TTD value means the relative exergy destruction increases and descends. With a fixed product exergy value at an increment in TTD, the destruction increases up to a TTD value of 8 K and then lowers. Both the energy and exergy performances have been changed on increasing the separator temperature in Fig. 9 f. The product exergy value changes with increase in separator temperature. Relative exergy destruction decreases at high separator temperature whereas increments for relative environmental impact. The product exergy descends with exergy destruction, cost rate, and environmental effect favouring decrement in the decision variables at higher separator temperatures.

The cycle data and environmental impact for the proposed system are resulted in Table 10 and Table 11. Table 12 summarizes data on thermodynamic properties, environmental impact amount (\dot{B} , mPts h⁻¹), and environmental strike per

Table 12 Exergoenvironmental analysis results for the MTKCS

State Points	m/ kg s ⁻¹	T/ °C	P/ bar	\dot{B} / mPt h ⁻¹	b/ mPT/ GJ
1	45.00	0.80	195.00	314,468.48	4676
2	11.97	0.80	122.00	310,226.41	4676
3	11.97	0.80	75.00	307,381.53	4676
4	11.97	0.98	75.00	506,445.71	9676
5	11.97	0.47	75.00	128,201.58	9676
6	11.97	0.47	75.00	81,757.94	9676
7	11.31	0.47	75.00	48,077.33	9676
8	11.97	0.85	75.00	587,538.33	9676
9	11.97	0.85	66.50	586,806.82	9676
10	11.97	0.85	37.00	585,761.81	9676
11	45.00	0.85	38.40	585,935.98	9676
12	45.00	0.85	54.31	586,668.906	9685.8
13	45.00	0.85	73.77	589,255.91	9721
14	45.00	0.85	73.77	535,015.90	9390
15	45.00	0.85	73.77	34,152.18	9390
16	45.00	0.85	117.00	35,114.64	9560
17	45.00	0.85	117.00	538,160.39	9353
18	45.00	0.85	117.00	559,009.90	9132
19	45.00	0.80	117.00	607,091.78	9181
20	45.00	0.80	129.16	614,513.70	9266
21	45.00	0.80	177.81	625,542.912	9312
22	45.00	0.47	76.00	48,093.76	9673
23	5.00	0.00	200.00	614,394.40	247,040
24	5.00	0.00	195.38	593,494.82	247,040
25	5.00	0.00	139.16	374,502.75	247,040
26	5.00	0.00	123.30	321,666.83	247,040
27	5.00	0.00	119.41	308,397.81	247,040
28	5.00	0.00	88.77	78,031.04	247,040
29	5.00	0.00	57.31	60,768.87	247,040

unit energy (b, mPts GJ⁻¹) at system state points. The environmental impact rates are estimated from the indices matrix consisting of [9, 9] rows and columns. Increased environmental impact rate value is the result of higher total exergy and unit environmental impact of exergy flow (Fig. 10).

The changes in the results of r_b and f_b are shown in Fig. 5. Whenever a component gets an excessive amount of heat or fuel, its environmental impact rate rises. Due to the high exergy destruction rate and environmental impact per exergy unit, the component HE5 has a high environmental impact rate. The findings show that high-pressure components have a significant negative impact on the environment, which must be reduced for the process to be more effective. The exergoenvironmental factor relies on the component's impact on the environment and is indirectly related to the exergoenvironmental impact rate. HE1, one of the primary elements, has a lower value as an exergoenvironmental factor yet has to be improved.

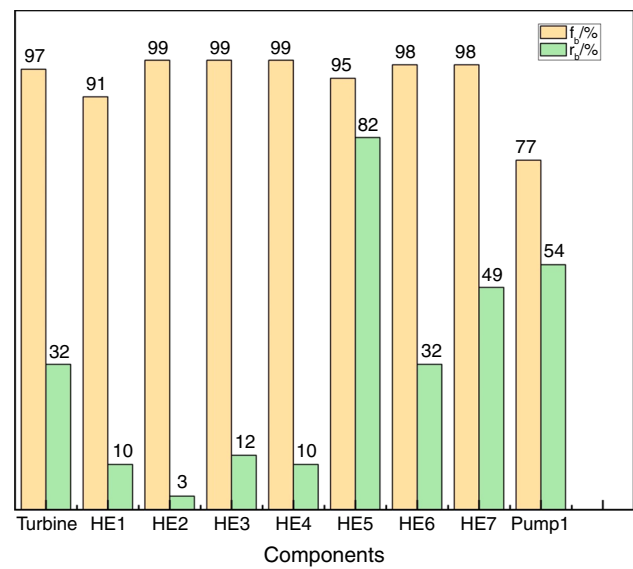


Fig. 10 The outcomes of exergoenvironmental relative environmental impact difference ($r_{b,i}$) and exergoenvironmental factor ($f_{b,i}$) of the proposed system

Conclusions

In an energy and exergoenvironmental scenario, a novel solar energy-driven Kalina power production system is examined. The present work evaluates thermoeconomic analyses, exergoenvironmental analyses, and traditional and advanced exergy analyses. Advanced exergy analysis is taken into account in order to disclose the losses caused by irreversibility in the components, and the components require modification. To determine the effect caused by components' irreversibility, the exergoenvironmental analysis is enhanced. With 30 kW and 20 kW, respectively, the turbine and HE4 possess more exergy destruction at real conditions. According to the advanced exergy perspective, the HE5 and HE3 require development because its exergetic efficiency is only 38% and 57% under real conditions, respectively. The component turbine and HE4's exergy destruction cost rate and investment cost rate are high at 47\$ h⁻¹, 40\$ h⁻¹ and 4\$ h⁻¹ and 0.5\$ h⁻¹, respectively.

The LTRGN has a rate of 54.83 mPts h⁻¹ for environmental effects and a rate of 45.16 mPts h⁻¹ for device-related environmental effects. At 75% pump efficiency, the ($\dot{Y}/\dot{E}P$) values yield 0.19 mPts kWh⁻¹. The turbine and heat exchangers are the components that have a significant environmental impact. Due to the combined effects of a high energy destruction rate and environmental impact per energy unit, the component turbine has a high environmental impact rate value of 3.59 mPts h⁻¹. The HE1's exergoenvironmental factor is substantially lower on comparing with other heat exchangers; hence, it needs to be improved. As a result of this study, the key factors contributing to greater energy loss

and the environmental effect are discovered, and it is advised that they be improved for better performance.

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