

Sustainability Analysis of Low Temperature Solar-Driven Kalina Power Plant Using Emergy Concept

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Abstract

Selection, design, and optimization of the energy system with the efficient method is one the major problem in recent years. The combined Emergy-Exergy-Economic-Environmental analysis is one of these new methods selected for the analysis and optimization of energy systems. In this paper, the low temperature small solar-driven Kalina power plant is selected for distributed power generation in Qom city. The analysis procedure based on Emergy, Exergy, Economic and Environmental concepts is performed in two general steps. In the first step, the thermodynamic and exergy analysis is performed and the required thermodynamic and exergetic parameters are determined. For the calculation of emergy for different component and mass flow, in the second step, the weight and price of all equipment are evaluated and the emergy analysis is performed. Based on this analysis the emergy evaluation parameters such as monetary and ecological performance are presented and based on these parameters, the most destructive equipment is selected and a suitable procedure for improvement in the considered system is presented. In the final step, the exergy and emergy parameters in the proposed solar Kalina cycle are compared with some renewable and fossil power plant and this comparison show that the proposed cycle has suitable characteristics.

Keywords: Kalina; solar; power; exergy; emergy; monetary; ecological.

1. Introduction

With overgrowing concern over the impact of fossil fuels on the environment, finding the available alternative to these sources of energy is one of the main goals of humanity in recent decades. Within all different sources of energy, solar energy, in terms of economic and availability, seems to be the best possible choice. Over the past decade, the technologies related to using low-temperature heat sources for generating electricity have widely increased and improved. One of the thermodynamic cycles used to generate electricity from low-temperature sources is the Kalina cycle. This cycle is firstly proposed in 1982 by Kalina [1] which uses a mixture of ammonia and water as the working fluid which has lower boiling temperature compared to other conventional working fluids like water so this cycle can be used to generate electricity from low-temperature heat sources.

Rogdakis and Antonopoulos [2] showed that for the same working condition, Kalina cycle performs 20% better in term of efficiency compared to the conventional Rankin cycle. Hettiarachchi et al. [3] have compared the performance of the Kalina cycle with an organic Rankin cycle for a low-temperature geothermal heat source and examined the impact of the ammonia-water concentration and inlet pressure of turbine on the efficiency. Murugan and Subbarao [4] proposed a combination of Rankin and Kalina cycle to reduce energy loss and improve the efficiency of the cycle and also performed energy and exergy analysis on the proposed cycle. Various researches have been directed on integrating solar energy with the Kalina cycle. Lolos and Rogdakis [5] investigated a Kalina cycle in which the main heat source is maintained using flat solar collectors. The

effects of ammonia mass fraction at the turbine inlet on the performance of the cycle is examined. Sun et al. [6] investigated a solar assisted Kalina cycle with an auxiliary superheater and discussed the effect of system parameters for high-performance power generation. Ganesh and Srinivas [7] studied a low temperature solar parabolic trough collector Kalina cycle and performed energy analysis and investigated effects of different thermodynamic parameters in order to optimize the heat recovery from collectors and maximize the generated power and efficiency as well. Wang et al. [8] considered a solar-driven Kalina cycle with thermal storage and studied the effects of pressure and temperature in the inlet of the turbine of the performance of cycle over a period of time. Peng et al. [9] examined a novel solar-driven triple cycle including a gas turbine Bryton, steam Rankin and Kalina cycle to make the possibility of generating power during low insolation periods. the efficiency of the recommended cycle calculated to be 22.7%. Modi and Haglind [10] investigated a Kalina cycle with a central solar receiver and direct steam generator and compared the performance of the cycle in terms of exergy efficiency with Rankine cycle. Sun et al. [11] performed energy and exergy analysis on Kalina cycle system 11 with a flat collector solar system and an auxiliary superheater. An optimization is performed using the monthly solar radiation in Kumejima Island of Japan. Zare et al. [12] applied exergoeconomic analysis to a combination of Kalina cycle and Gas Turbine-Modular Helium Reactor where the waste heat from the top cycle is recovered by Kalina cycle. The results show the efficiency is 8.2% higher and the cost is 8.8% lower compared to the situation without waste heat recovery by the Kalina cycle. Rodríguez et al [13] performed thermo-

economic analysis on an organic Rankin cycle and a Kalina cycle to generate power from the geothermal heat source. Fifteen different working fluid for ORC and three ammonia-water compositions have been evaluated for the Kalina cycle. It was shown that the Kalina cycle has a leveled cost of electricity of 0.18 €/kW and also produced 18% more electricity. Boyaghchi and Sabaghian [14] performed exergoeconomic analysis on a solar driven Kalina cycle and studied the effect of different parameters on the exergetic efficiency and unit cost of the electricity of the plant.

Evaluating the economic and environmental performance of energy systems is one of the challenges in improving and optimizing the performance of these systems. Two powerful and common tools to cope with this problem are Exergoeconomic and exergoenvironmental analyses. In these analyses, monetary and ecological values (generally in the unit of USD and millipoints) are assigned to streams in the exergy balance of each component. However, the results of these analyses have different scale and dimensions as they are generally given in units of \$/GJ and mPts/Gj which makes it complex to evaluate the results and to determine the optimum point of the system. One alternative to address this issue is using emergy as an input value instead of exergy based values.

In the presented study, we carried out a thermodynamic model of a solar driven Kalina cycle at first, then performed an exergy analysis on the proposed cycle. The emergy analysis has been performed in order to find the performance of the cycle in terms of Transformity and sustainability index. In the end, the EMergoeconomic and EMergoenvironmental analysis have been done to find prior nominees for optimization of the ecological and economic performance of the cycle. The emergy concept is firstly presented by H.T. Odum in the early 1980s [15]. All of the energy used, directly or indirectly through conversion processes, to make a product or service can be evaluated using emergy method. In this method, all of the system's inputs (energy, mass, service, etc.) are transformed to an equivalent unit called solar energy joule. Brown and Ulgiati [16] used this method to evaluate the environmental performance of six different power plant which showed the renewable technology has better performance in term of sustainability compared to fossil fuel power plants. Furthermore, other works have been done by integrating the emergy concept with Life Cycle Assessment and evaluated the performance of different power plants [17-19]. Aghbashlo and Rosen [20] integrated emergy concept with conventional exergoeconomic and exergoenvironmental analysis by transforming input values in these analyses to emergy unit to improve the results and as a case study investigated a combined heat and power cogeneration system using this method and compared the results with conventional exergoeconomic and exergoenvironmental analysis. For the sake of simplicity, we will refer to these analyses as EMergoeconomic and EMergoenvironemntal analysis.

In this paper, the determination of a destructive and improper component in a small solar-driven Kalina cycle are considered, and the combined emergy, exergy, economic and environmental analysis is used for this purpose. The selection of mail destructive component in this paper is performed based on the flowing procedure: in the first step, the thermodynamic analysis of the cycle is performed, and the thermodynamic parameters of the cycle and thermal efficiency are determined. In the next step, the exergy

analysis is performed, and exergetic parameters are evaluated. In the third step, the mass and purchase cost of each component are calculated. In the fourth step the emergy balance is performed, the emergy values for all equipment and flows are calculated and the emergy evaluation parameters are examined. In the final step, the analysis of emergy parameters for the different component are performed and suitable approach for reduction of improper effects are proposed.

2. Modeling

2.1 Description of Proposed Cycle

The flow diagram of the solar driven Kalina cycle is illustrated in Figure 1. The heated fluid coming from solar collectors (14) exchanges its heat to the working fluid, mixture of ammonia and water, in superheater and evaporator. The superheated ammonia-water mixture (1) with an ammonia concentration of 0.95 become expanded in the mixture turbine to generate power (2). The exiting flow will be mixed with the weak ammonia mixture coming from the separator (13). The mixture loses its heat in a low-temperature regenerator and becomes condensed in the condenser (3-4-5). It is considered that the outlet flow of condenser is saturated liquid. Then the working fluid will be pumped to gain heat in low and high-temperature regenerators (6-7-8). The liquid becomes evaporated in the evaporator and then goes to the separator to make a rich ammonia-water vapor which goes to superheater to be superheated (9-10). To present a thermodynamic model of the proposed cycle the following assumptions are made:

- The ambient temperature and pressure are 25°C and 100 kPa.
- Pinch point (PP) and approach point (AP) of the boiler are 5°C and 10°C respectively.
- The isentropic efficiency of pump and turbine is 0.75%.
- The mechanical efficiency of the pump and the turbine is 96%.
- The leaving working fluid in the condenser is assumed to be saturated liquid.
- Calculations are performed in steady state conditions.

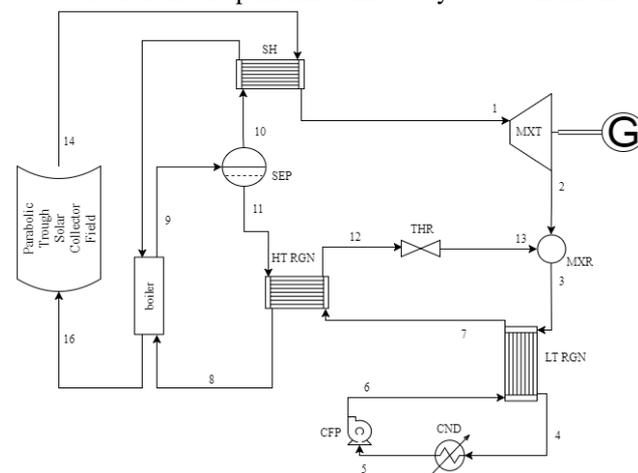


Figure 1. Schematic view of the solar-driven Kalina cycle.

2.2 Thermodynamic Modeling

2.2.1 Energy Balance Equation

In order thermodynamic modelling of the proposed cycle, a steady state model of the plant has been created in MATLAB software and REFPROP code has been used to find the enthalpy and the entropy of different streams. The following equations are used to model different components of the plant.

Mixture Turbine:

$$W_t = m_1(h_1 - h_2)\eta_{m,t}\eta_{ge} \quad (1)$$

Condensate Feed Pump:

$$W_p = \frac{m_5(h_6 - h_5)}{\eta_{m,p}} \quad (2)$$

Separator:

$$m_9h_9 = m_{10}h_{10} + (1 - m_{10})h_{11} \quad (3)$$

Condenser:

$$Q_{CND} = m_5(h_5 - h_4) \quad (4)$$

Superheater:

$$Q_{SH} = m_1(h_1 - h_{10}) \quad (5)$$

Low-Temperature Regenerator:

$$m_3h_3 + m_6h_6 = m_4h_4 + m_7h_7 \quad (6)$$

High-Temperature Regenerator:

$$m_7h_7 + m_{11}h_{11} = m_8h_8 + m_{12}h_{12} \quad (7)$$

Boiler:

$$Q_{boiler} = m_9(h_9 - h_8) \quad (8)$$

The outlet temperature of the solar collector and the input temperature of the boiler can be calculated as below:

$$T_{14} = T_1 + TTD_{SH} \quad (9)$$

$$T_8 = T_{bp} - AP \quad (10)$$

Where TTD_SH is the terminal temperature difference at super heater and T_bp is the bubble point temperature at boiler pressure. The outlet temperature at the hot side of the boiler can be calculated as below:

$$T_{16} = T_{bp} + PP \quad (11)$$

Net output power and cycle efficiency of the proposed system can be determined from the following equations:

$$W_{net} = (W_t - W_p) \quad (12)$$

$$\eta_{KC} = \frac{W_{net}}{Q_{boiler} + Q_{SH}} \times 100 \quad (13)$$

In order to calculate the length and number of parabolic trough collectors, the following concepts can be used. The relation between width and rim angle of the collector to its focal length can be written as Eq. (14):

$$f = \frac{W}{4 \times \tan(0.5 \phi_{rim})} \quad (14)$$

In the above equation, width (W) and rim angle (ϕ_{rim}) of the collector assumed to be 3 m and 80° respectively. The arc length of the collector's reflector is calculated from the Eq. (15):

$$L_{arc} = 2f \left[\sec\left(\frac{\phi}{2}\right) \tan\left(\frac{\phi}{2}\right) + \ln\left(\sec\left(\frac{\phi}{2}\right) + \tan\left(\frac{\phi}{2}\right)\right) \right] \quad (15)$$

The mass flow rate of the heat transfer fluid used as a working fluid in the solar collectors is determined with Eq. (16):

$$m_h = m_{14} = \frac{m_8(h_9 - h_8) + m_{10}(h_1 - h_{10})}{C_{ph}(T_{14} - T_{16})} \quad (16)$$

In the proposed solar system, there are parallel sections of collectors, thus the mass flow in each parallel section can be calculated by dividing the total mass flow (m_h) to the number of parallel sections (n_{ps}):

$$m_{h,ps} = \frac{m_h}{n_{ps}} \quad (17)$$

By the above variables, the length of each collector can be expressed with Eq. (18):

$$L = \frac{m_{14}C_{ph}(T_{14} - T_{16})}{\eta_c I_b W n_{ps}} \quad (18)$$

In which η_c is the efficiency of the parabolic trough collector and is determined from the following correlation:

$$\eta_c = 0.642 - 0.441 \left(\frac{T_{fi} - T_a}{I_b} \right) \quad (19)$$

Based on the above-calculated parameter, the total collector's area is calculated as below:

$$A_{c\ tot} = n_{ps} WL \quad (20)$$

2.2.2 Exergy Balance Equation

The exergy of a system is the maximum useful work possible during a process. The exergy is consisting of four different forms including potential, kinetic, physical, and chemical. In this work, the potential and kinetic exergy are neglected due to their deniable values compared to the other two forms. The physical and chemical exergy of each stream is calculated from the following equations:

$$\dot{E}_i^{PH} = \dot{M}(h_i - h_0 - T_0(s_i - s_0)) \quad (21)$$

$$E_i^{CH} = \dot{M}(\sum x_k \bar{e}_k^{CH} + \bar{R}T_0 \sum x_k \ln x_k) \quad (22)$$

Where T_0 is the reference temperature, x_k is the mole fraction gas and \bar{e}_k^{CH} represents standard molar chemical exergy of gas. Total exergy of a stream is the summation of physical and chemical exergy of that stream:

$$\dot{E} = \dot{E}^{PH} + \dot{E}^{CH} \quad (23)$$

The thermal exergy of heat flows can be calculated as below where T_s is the thermodynamic average temperature.

$$\dot{E}^Q = \dot{Q} \left(1 - \frac{T_0}{T_s} \right) \quad (24)$$

Based on the SPECO methodology, exergy destruction of each component is the difference between exergy of fuel and product of the component.

$$\dot{E}_D = \dot{E}_P - \dot{E}_F \quad (25)$$

Based on the above definitions, the exergy balance of each component is presented in Table 1.

Table 1. Exergy Analysis of the Solar Driven Kalina Cycle.

Components	Exergy Rate Balance	Exergy Efficiency
Boiler	$E_9 + E_{16} + E_D$ $= E_8 + E_{15}$	$\frac{E_9 - E_8}{E_{15} - E_{16}}$
Separator	$E_{10} + E_{11} + E_D = E_9$	$\frac{E_{10} + E_{11}}{E_9}$
Super heater	$E_1 + E_{15} + E_D$ $= E_{10} + E_{14}$	$\frac{E_1 - E_{10}}{E_{13} - E_{15}}$
Turbine	$E_2 + W_t + E_D = E_1$	$\frac{W_t}{E_1 - E_2}$
Mixer	$E_3 + E_D = E_2 + E_{13}$	$\frac{E_3}{E_{13} + E_2}$
LTRGN	$E_4 + E_7 + E_D = E_3 + E_6$	$\frac{E_7 - E_6}{E_3 - E_4}$
Condenser	$E_5 + E_{18} + E_D$ $= E_{17} + E_4$	$\frac{E_{18} - E_{17}}{E_4 - E_5}$
HTRGN	$E_8 + E_{12} + E_D$ $= E_7 + E_{11}$	$\frac{E_8 - E_7}{E_{11} - E_{12}}$
Collector	$E_{14} + E_D = E_{16} + E_{sun}$	$\frac{E_{14} - E_{16}}{E_{solar}}$
Pump	$E_6 + E_D = E_5 + W_p$	$\frac{E_6 - E_5}{W_p}$

2.3 Emery Analysis Equation

In order to perform the emery analysis on the proposed cycle, all input variables should be transformed into equivalent 'solar energy joules' (SEJ). This transformation can be done by multiplying the input variable to its relevant unit emery value (UEV) (or transformity). The amount of emery used to produce a given amount of mass, energy and etc. is called unit emery value or specifically transformity (when we are talking about energy). Unit emery values of a vast majority of materials and different kinds of energies are published in different articles, but transformity values are usually presented in the quantity of energy-based emery. As we are evaluating the system using exergy, we need to multiply these transformity values by a scale factor (β) to produce exergy-based values [21]. This scale factor can be described as follows

$$\beta = 1 + \frac{1}{3} \left(\frac{T_0}{T_S} \right)^4 - \frac{4}{3} \left(\frac{T_0}{T_S} \right) \quad (26)$$

where T_S is the temperature of the sun and T_0 is the reference point temperature.

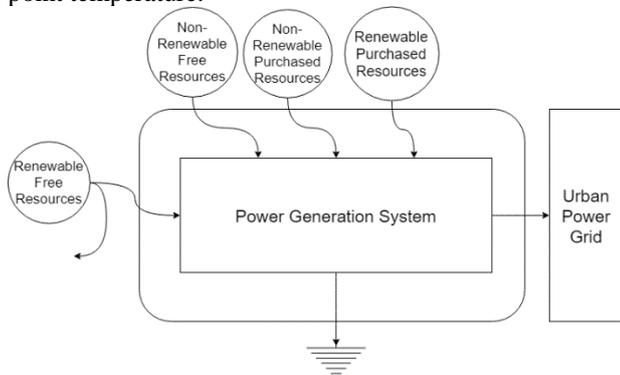


Figure 2. Boundary of the system.

Figure 2 shows the schematic of the boundary of the power generating cycle and input/output emery flows of the system. Inputs of the system are divided into four categories: renewable purchased sources (RP), non-renewable purchased sources (NP), free renewable sources (R1), free non-renewable sources (NR). Based on the emery inputs, five indices are defined to evaluate the performance of the cycle. The sum of all emery inputs is called yield (Y) and can be calculated with Eq. (27):

$$Y = RP + NP + R1 + NR \quad (27)$$

The emery yield ratio (EYR) is defined as below:

$$EYR = \frac{Y}{RP + NP} \quad (28)$$

This parameter presents the ability of the cycle to exploit local resources [22]. The larger EIR means that the higher emery (versus the invested emery) is returned to the system. Environmental load ratio (ELR) is the ratio between non-renewable and renewable resources used in the system and can be calculated from the following equation:

$$ELR = \frac{NR + NP}{R1 + RP} \quad (29)$$

Emery Sustainability Index (ESI) is the ratio of emery yield ratio and environmental loading. This parameter can measure the ecological sustainability, impact on the local environment, and the society's profit [23, 24]. A system with ESI higher than 5 is called a sustainable system and if this index is lower than 1, the system is not sustainable [25, 26].

$$ESI = \frac{EYR}{ELR} \quad (30)$$

Finally, the Transformity of the cycle is defined as the amount of emery used to produce the required electricity.

$$Transformity = \frac{Y}{W_{net}} \quad (31)$$

The purchased equipment cost and mass of components are estimated based on their operational parameters. The correlations from other researches ([17, 27-30]) are used to estimate the cost, mass, and composition of components (the required values for input emery of the system are listed in Table 2). These input variables should be in the form of unit per time that can be used in EMergoeconomic and EMergoenvironmental analysis. The following equation is used for this manner:

$$\dot{U}_k = \frac{PEC \times CRF \times \phi}{N \times 3600} \quad (32)$$

Where ϕ is the maintenance factor and assumed to be 1.06, N presents the working hours of the plant in a year which is 7446 in this study. CRF is the capital recovery factor related to the system lifetime and interest year and can be calculated from the following equation:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (33)$$

The Lifetime of the system (n) assumed to be 20 years and interest rate (i) is 10%.

Table 2. Input Variables of the System.

Item	material	data	unit	transformity	emery
NP					
MXT	Steel ^a	1.94E+05	g	3.79E+09	7.37E+14
	steel high alloy ^b	5.83E+05	g	4.87E+10	2.84E+16
CFP	Steel ^a	1.04E+04	g	3.79E+09	3.95E+13
	cast iron ^a	1.93E+04	g	2.42E+09	4.68E+13
boiler	Steel ^a	1.07E+07	g	3.79E+09	4.04E+16
SEP	Steel ^a	5.50E+04	g	3.79E+09	2.08E+14
SH	Steel ^a	1.01E+05	g	3.79E+09	3.85E+14
	steel low alloy ^b	3.04E+05	g	5.87E+09	1.79E+15
LTRGN	Steel ^a	3.04E+05	g	3.79E+09	1.15E+15
HTRGN	Steel ^a	1.06E+06	g	3.79E+09	4.02E+15
CND	Steel ^a	1.74E+06	g	3.79E+09	6.59E+15
	steel low alloy ^b	5.22E+06	g	5.87E+09	3.06E+16
COLL	Steel ^a	1.70E+08	g	3.79E+09	6.46E+17
R1					
Q_Sun		1.0722E+15	J	1	1.07E+15
RP					
Water		2.1444E+12	g	295000	6.33E+17
Production					
Electricity		4.0236e+13	J	3.46E+04	
Purchased Equipment Cost					
MXT		11952000	\$	9.95E+11 ^c	1.19E+19
CFP		1068300	\$	9.95E+11 ^c	1.06E+18
LTRGN		51391	\$	9.95E+11 ^c	5.11E+16
HTRGN		93327	\$	9.95E+11 ^c	9.29E+16
Boiler		159430	\$	9.95E+11 ^c	1.59E+17
SEP		8000	\$	9.95E+11 ^c	7.96E+15
SH		28869	\$	9.95E+11 ^c	2.87E+16
CND		95272	\$	9.95E+11 ^c	9.48E+16
COLL		724910	\$	9.95E+11 ^c	7.21E+17

2.3.1 EMergoeconomic Analysis

The principles of EMergoeconomic analysis is similar to conventional exergoeconomic analysis. The Specific Exergy Costing (SPECO) [31] method is used to evaluate the monetary energy values of all exergy flows. First, a monetary energy rate \dot{M}_i is defined as below:

$$\dot{M}_i = m_i \dot{E}_i \quad (34)$$

In which, the monetary energy per unit exergy is represented by m_i and monetary energy rate (\dot{M}_i) is represented in the quantity of sej per unit time. The monetary balance of each component can be written as follows:

$$\dot{M}_{P,k} = \dot{M}_{F,k} + \dot{U}_k \quad (35)$$

In Eq. (35), monetary-based energy rate of product and fuel streams are represented by $\dot{M}_{P,k}$ and $\dot{M}_{F,k}$ and \dot{U}_k is the monetary energy rate of component k:

$$\dot{U}_k = \dot{U}_k^{CI} + \dot{U}_k^{OM} \quad (36)$$

In Eq. (36), \dot{U}_k^{CI} and \dot{U}_k^{OM} are the capital investment and operation-maintenance cost of plant in the form of monetary energy rate, respectively. To calculate fuel and product's specific monetary value, the following equations can be used:

$$m_{P,k} = \frac{\dot{M}_{P,k}}{\dot{E}_{P,k}} \quad (37)$$

$$m_{F,k} = \frac{\dot{M}_{F,k}}{\dot{E}_{F,k}} \quad (38)$$

and the destruction rate of monetary energy is calculated from the following equation:

$$\dot{M}_{D,k} = m_{F,k} \dot{E}_{D,k} \quad (39)$$

Total energy rate of a component can be calculated by the sum of its energy destruction rate and monetary as below:

$$\dot{M}_{TOT,k} = \dot{U}_k + \dot{M}_{D,k} \quad (40)$$

The EMergoeconomic factor of each component can be calculated as follows:

$$f_{m,k} = \frac{\dot{U}_k}{\dot{U}_k + \dot{M}_{D,k}} \times 100 = \frac{\dot{U}_k}{\dot{M}_{TOT,k}} \times 100 \quad (41)$$

Based on the above definitions, the EMergoeconomic balance of each component is presented in Table 3.

Table 3. EMergoeconomic Balance.

Component	EMergoeconomic balance	Auxiliary equation
Boiler	$m_9 E_9 + m_{16} E_{16} = m_8 E_8 + m_{15} E_{15} + \dot{U}_{boiler}$	$m_{16} = m_{15}$
Separator	$m_{10} E_{10} + m_{11} E_{11} = m_9 E_9 + \dot{U}_{sep}$	$\frac{m_{10} - m_9}{m_{11} - m_9} = \frac{E_{10} - E_9}{E_{11} - E_9}$
Superheater	$m_1 E_1 + m_{15} E_{15} = m_{10} E_{10} + m_{14} E_{14} + \dot{U}_{sh}$	$m_{15} = m_{14}$
Turbine	$m_2 E_2 + m_{W_t} W_t = m_1 E_1 + \dot{U}_t$	$m_2 = m_1$
Mixer	$m_3 E_3 = m_2 E_2 + m_{13} E_{13} + \dot{U}_{mixr}$	
LTRGN	$m_4 E_4 + m_7 E_7 = m_3 E_3 + m_6 E_6 + \dot{U}_{ltrgn}$	$m_3 = m_4$
Condenser	$m_5 E_5 + m_{18} E_{18} = m_4 E_4 + m_{17} E_{17} + \dot{U}_{cnd}$	$m_{18} = m_{17} = 0$
HTRGN	$m_8 E_8 + m_{12} E_{12} = m_7 E_7 + m_{11} E_{11} + \dot{U}_{htrgn}$	$m_{12} = m_{11}$
Collector	$m_{14} E_{14} = m_{16} E_{16} + m_{sun} E_{sun} + \dot{U}_{coll}$	$m_{sun} = 0$
Pump	$m_6 E_6 = m_5 E_5 + m_{W_p} W_p + \dot{U}_p$	$m_{W_p} = m_{W_t}$

2.3.2 EMergoenvironmental Analysis

Similar to exergoenvironmental analysis, the EMergoenvironmental analysis is performed by applying the ecological energy values to exergy flows. Ecological energy rate can be expressed by multiplying the specific ecological energy of a stream (n_i) to exergy rate of this stream:

$$\dot{N}_i = n_i \dot{E}_i \quad (42)$$

The ecological energy balance of each component can be presented as follows:

$$\dot{N}_{P,k} = \dot{N}_{F,k} + \dot{V}_k \quad (43)$$

Where \dot{V}_k is the sum of energy rate in the construction phase (\dot{V}_k^{CO}), operation-maintenance (\dot{V}_k^{OM}), and disposal of the component (\dot{V}_k^{DI}).

$$\dot{V}_k = \dot{V}_k^{CO} + \dot{V}_k^{OM} + \dot{V}_k^{DI} \quad (44)$$

By EMergoenvironmental balance equations, the specific energy of product and fuel in the ecological analysis can be described as follows:

$$n_{P,k} = \frac{\dot{N}_{P,k}}{\dot{E}_{P,k}} \quad (45)$$

$$n_{F,k} = \frac{\dot{N}_{F,k}}{\dot{E}_{F,k}} \quad (46)$$

And the destruction rate of ecological energy is calculated from the following equation:

$$\dot{N}_{D,k} = n_{F,k} \dot{E}_{D,k} \quad (47)$$

Total energy rate of a component in the ecological analysis can be calculated by the sum of its destruction rate and it's component related monetary energy as below:

$$\dot{N}_{TOT,k} = \dot{V}_k + \dot{N}_{D,k} \quad (48)$$

The EMergoenvironmental factor for each component is calculated from the following equation:

$$f_{m,k} = \frac{\dot{V}_k}{\dot{V}_k + \dot{N}_{D,k}} \times 100 = \frac{\dot{V}_k}{\dot{N}_{TOT,k}} \times 100 \quad (49)$$

The EMergoeconomic balance of each component is presented in Table 4.

Table 4. EMergoenvironmental Balance.

Component	EMergoenvironmental balance	Auxiliary equation
Boiler	$n_9 E_9 + n_{16} E_{16} = n_8 E_8 + n_{15} E_{15} + \dot{V}_{boiler}$	$n_{16} = n_{15}$
Separator	$n_{10} E_{10} + n_{11} E_{11} = n_9 E_9 + \dot{V}_{sep}$	$\frac{n_{10} - n_9}{E_{10} - E_9} = \frac{n_{11} - n_9}{E_{11} - E_9}$
Super heater	$n_1 E_1 + n_{15} E_{15} = n_{10} E_{10} + n_{14} E_{14} + \dot{V}_{sh}$	$n_{15} = n_{14}$
Turbine	$n_2 E_2 + n_{W_t} W_t = n_1 E_1 + \dot{V}_t$	$n_2 = n_1$
Mixer	$n_3 E_3 = n_2 E_2 + n_{13} E_{13} + \dot{V}_{mixr}$	
LTRGN	$n_4 E_4 + n_7 E_7 = n_3 E_3 + n_6 E_6 + \dot{V}_{ltrgn}$	$n_3 = n_4$
Condenser	$n_5 E_5 + n_{18} E_{18} = n_4 E_4 + n_{17} E_{17} + \dot{V}_{cnd}$	$n_{18} = n_{17} = 6.86 \times 10^3$ a
HTRGN	$n_8 E_8 + n_{12} E_{12} = n_7 E_7 + n_{11} E_{11} + \dot{V}_{htrgn}$	$n_{12} = n_{11}$
Collector	$n_{14} E_{14} = n_{16} E_{16} + n_{sun} E_{sun} + \dot{V}_{coll}$	$m_{sun} = 1$
Pump	$n_6 E_6 = n_5 E_5 + n_{W_p} W_p + \dot{V}_p$	$n_{W_p} = n_{W_t}$

a: obtained from [33]

Based on the above definitions, the overall performance of the power plant in EMergoeconomic and EMergoenvironmental analysis can be described as follows:

$$\psi_{M.TOT} = \frac{\text{Outlet Monetary Energy}}{\text{Inlet Monetary Energy}} \quad (50)$$

$$\psi_{N.TOT} = \frac{\text{Outlet Ecological Energy}}{\text{Inlet Ecological Energy}} \quad (51)$$

3. Results and Discussion

Results of thermodynamic analysis and properties of each stream are shown in Table 5. The results show that the plant generates 75.05 kW output power with the thermal efficiency of 10.62 %.

Table 5. Thermodynamic Properties of Streams in the Solar Driven Kalina Cycle.

stream	ammonia concentration	pressure (kPa)	temperature(C)	mass flow (kg/s)	Total exergy (kW)
1	0.95	3560	135.00	0.47	391.45
2	0.95	750	68.75	0.47	306.04
3	0.7	750	47.84	1.00	538.61
4	0.7	750	44.45	1.00	534.33
5	0.7	750	29.24	1.00	517.91
6	0.7	3560	29.89	1.00	521.75
7	0.7	3560	42.68	1.00	523.98
8	0.7	3560	82.23	1.00	545.72
9	0.7	3560	125.00	1.00	688.22
10	0.95	3560	125.00	0.47	365.92
11	0.47	3560	125.00	0.53	305.71
12	0.47	3560	49.60	0.53	272.21
13	0.47	750	50.05	0.53	270.51
14	-	-	145.00	3.53	4019.36
15	-	-	139.25	3.53	3955.20
16	-	-	97.23	3.53	3475.99

Exergetic efficiency and exergy destruction of each component are presented in Figure 3 and Figure 4. Results show that the boiler and superheater have the most exergy destruction (68.8 % and 7.9 % of the total exergy destruction, respectively) and the lowest exergetic efficiency (29.7% and 39.8 %, respectively). The lowest exergetic efficiency in boiler shows that the boiler is the most prior component in order to improve the performance of the cycle from exergy analysis.

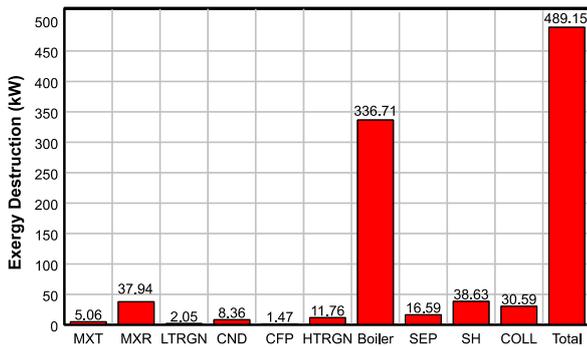


Figure 3. Exergy destruction of cycle's components.

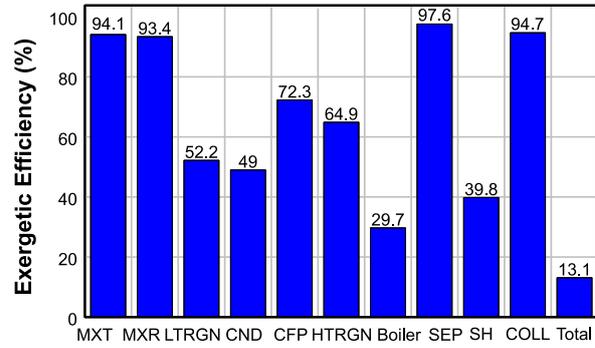


Figure 4. Exergy efficiency of cycle's components.

Results of EMergoeconomic analysis are summarized in Table 6. Results show that the turbine has the highest total monetary energy rate. This component has low monetary energy, but the energy destruction in this component is high and thus the turbine has the highest total monetary energy rate. Therefore, improving this component can improve the monetary performance of the cycle.

Table 6. Results of Monetary Analysis of the Proposed Cycle.

component	\dot{U}_k (sej/h)	\dot{M}_D (sej/h)	$\dot{U} + \dot{M}_D$	m_F (sej/GJ)	m_P (sej/GJ)	f_m (%)
MXT	1.99E+14	3.11E+12	2.02E+14	1.71E+14	8.69E+14	98.46
MXR	0.00E+00	2.41E+13	2.41E+13	1.76E+14	1.89E+14	0.00
LTRGN	8.55E+11	1.39E+12	2.24E+12	1.89E+14	4.68E+14	38.09
CND	1.59E+12	5.68E+12	7.26E+12	1.89E+14	-	21.82
CFP	1.78E+13	4.59E+12	2.24E+13	8.69E+14	3.41E+15	79.47
HTRGN	1.55E+12	7.71E+12	9.26E+12	1.82E+14	3.01E+14	16.76
Boiler	2.65E+12	7.47E+12	1.01E+13	6.17E+12	2.59E+13	26.19
SEP	1.33E+11	1.06E+13	1.07E+13	1.77E+14	1.82E+14	1.24
SH	4.80E+11	8.58E+11	1.34E+12	6.17E+12	2.07E+13	35.90
COLL	1.21E+13	0.00E+00	1.21E+13	0.00E+00	4.56E+13	100.00

Table 7 shows the results of EMergoenvironmental analysis. Table 7 shows that the mixer and separator have the highest energy destruction and total ecological energy rate. Thus, for improving the ecological performance of the cycle these components should be improved.

Table 7. Results of Ecological Analysis of the Proposed Cycle.

component	\dot{V}_k (sej/h)	\dot{N}_D (sej/h)	$\dot{V} + \dot{N}_D$	n_F (sej/GJ)	n_P (sej/GJ)	f_m (%)
MXT	2.44E+10	4.51E+12	4.53E+12	2.48E+14	2.63E+14	0.54
MXR	0.00E+00	3.50E+13	3.50E+13	2.56E+14	2.74E+14	0.00
LTRGN	9.62E+08	2.02E+12	2.02E+12	2.74E+14	5.26E+14	0.05
CND	3.11E+10	8.26E+12	8.29E+12	2.74E+14	0.00E+00	0.38
CFP	7.21E+07	1.39E+12	1.39E+12	2.63E+14	6.77E+15	0.01
HTRGN	3.36E+09	1.13E+13	1.13E+13	2.66E+14	4.10E+14	0.03
Boiler	3.38E+10	3.36E+11	3.70E+11	2.77E+11	9.98E+11	9.14
SEP	1.74E+08	1.55E+13	1.55E+13	2.59E+14	2.66E+14	0.00
SH	1.82E+09	3.85E+10	4.04E+10	2.77E+11	7.16E+11	4.50
COLL	5.40E+11	1.10E+08	5.40E+11	1.00E+09	2.04E+12	99.98

Figure 5 and Figure 6 illustrate monetary and ecological energy values of streams of the cycle. Results show that the ecological energy of streams is higher than their monetary energy because of higher ecological energy of input streams.

Based on the governed results, in all components (Except turbine) the monetary and ecological energy rate is avoidable compared to different streams. Also, the streams that enter from collector to considered cycle has a greater impact on the monetary performance of the cycle (compared to ecological impact).

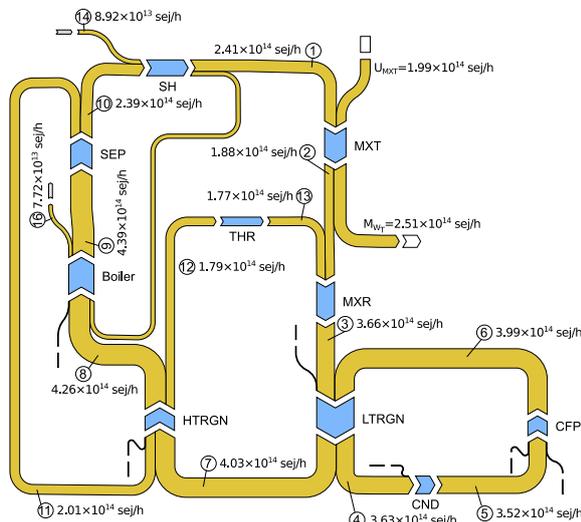


Figure 5. Sankey diagram of the EMergoeconomic analysis.

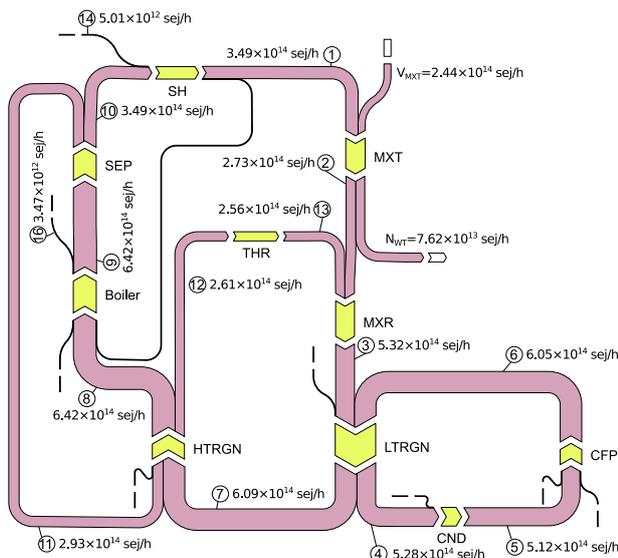


Figure 6. Sankey diagram of EMergoenvironmental analysis.

Table 8 shows the comparison between the energy indicators in the current study and other referenced power plants. Results show that the transformity (amount of energy needed for producing 1 joule of electricity) in the current system ($3.46E+04$) is lower than other considered renewable power plants. In the considered solar-powered Kalina cycle a large percentage of inputs energies have been purchased and the invested energy has a greater portion of input energy flows (compared to free resources energy), thus the EYR index is equal to 1.00. Environmental loading ratio (the ratio between non-renewable inputs to renewable ones) and of the proposed cycle energy sustainability index are 1.2 and 0.83, respectively. Results show that the ESI in the consider

power plant is lower than other renewable power plant and is higher than the fossil power plant.

Table 8. Solar Driven Kalina and Eight Other Power Plants Energy Indicators.

	Transformity	EYR	ELR	ESI	Reference
Solar-driven Kalina	$3.46E+04$	1.00	1.20	0.83	current study
Wind	$5.89E+04$	7.47	0.15	48.30	[16]
Geothermal	$1.42E+05$	4.81	0.44	11.05	[16]
Hydro	$5.87E+04$	7.65	0.45	16.90	[16]
Methane	$1.60E+04$	6.60	11.78	0.56	[16]
Oil	$1.87E+05$	4.21	14.24	0.30	[16]
Coal	$1.62E+05$	5.48	10.37	0.53	[16]
PV	$1.45E+05$	2.20	-	-	[34]
CSP	$6.59E+04$	5.06	0.39	13.10	[18]

The comparison of solar transformities in the proposed solar-driven Kalina cycle and other power plants are shown in Figure 7. Although the exergetic efficiency of the Kalina cycle is lower than a concentrated solar powered steam power plant; but because of lower input energies (related to different component) compared to a steam cycle, the calculated transformity of the current cycle is lower than the steam power plant.

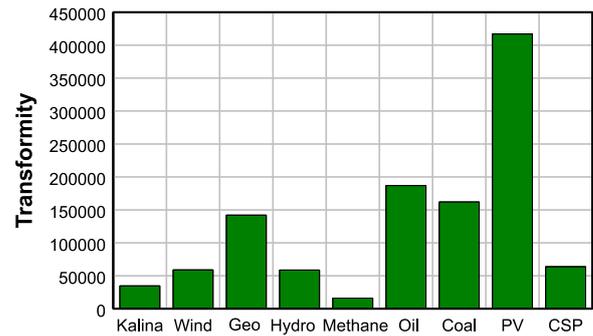


Figure 7. Transformities of a solar-driven kalina cycle compared to different power plants.

4. Conclusions

In this paper, the small solar-driven Kalina distributed power system is analyzed based on Energy, Exergy, Economic and Environmental principles. The analysis process consists of thermodynamic analysis, exergy analysis, weight estimation, purchase cost estimation, energy calculation and energy balances. In the final step, the suitable exergy and energy evaluation parameters are calculated for the evaluation process. The results of exergy analysis show that the boiler and super heater have the main role in the irreversibility of the current system and these should be improved. The results of EMergoeconomic show that for improvement in performance of the cycle the turbine and mixture should be modified. Comparison of the proposed solar-driven Kalina cycle with other referenced renewable and fossil power plant show that the current system operates in a suitable zone and has suitable characteristics and the transformity factor in the considered system is lower than the steam power plant.

Nomenclature

\dot{E}	Exergy flow rate
f_m	EMergoeconomic factor
f_n	EMergoenvironmental factor
Y	Total emergy of outputs
RP	Renewable purchased emergy
NP	Non-renewable purchased emergy
R1	Free renewable emergy
NR	Free non-renewable emergy
m	Specific monetary emergy
\dot{M}	Monetary emergy rate
n	Specific ecological emergy
\dot{N}	Ecological emergy rate
r_m	Relative monetary emergy difference
r_n	Relative ecological emergy difference
\dot{U}	Component monetary emergy rate
\dot{V}	Component ecological emergy rate
PEC	Process equipment cost
i	interest rate
Sej	Solar energy joules
β	Scale factor
h	Specific enthalpy
s	Specific entropy
MXT	Mixture turbine
MXR	Mixer
RGN	Regenerator
CND	Condenser
THR	Throttle
SEP	Separator
SH	Superheater
CFP	Condensate pump

Subscripts and superscripts

F	Fuel
P	Product
D	Destruction
PH	Physical
CH	Chemical

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