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Research Article

Energy and Economic Optimization of Regenerative Organic Rankine Cycle with in Energy Recovery System of a Steel Plant

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ABSTRACT

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Abstract:
This paper is to provide the design, analysis, and optimization of regenerative ORC for the waste heat recovery in a steel-works facility. A feedwater heater is installed in the system to further increase thermal efficiency. The system is examined by energy, exergy, and thermos-economic approaches. To achieve the highest performances, the selection of various parameters is carried out by using NSGA-II optimizing both exergy efficiency and total annual cost at the same time. The software MATLAB interface with REFPROP library is used for modeling and design variables include turbine inlet pressure, superheat temperature difference, condenser pressure, and the isentropic efficiencies of the rotating components. Thus, it has been shown that a proper tuning of some of these parameters may bring a satisfactory compromise between thermodynamic and economic performance. The optimum design gave a maximum exergy efficiency of 64.88%, an energy efficiency of 38.23%, a net power output of 1756.2 kW, and an estimated annual cost of $14.88 million. These results suggest that optimization of ORC systems could be a viable and practical solution for better energy utilization in heavy industries.

Keywords:
Energy recovery, Organic Rankine Cycle, Regenerative, Steel Plant, Optimization, NSGAII

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1. Introduction

Waste heat recovery in steel production via new thermodynamic cycles such as the Organic Rankine Cycle (ORC), Kalina Cycle (KC), and thermoelectric generators (TEG) has been of great interest in recent years. For the work done by Elahi et al., ORC performance for waste heat recovery was compared based on low Global Warming Potential (GWP) working fluids such as R1233zd(E). By a thermodynamic exergy-based approach, the authors demonstrated that the use of these environmentally friendly fluids would have a significant effect on exergy efficiency and reduce environmental harm (Elahi et al., 2022).

Lan et al. conducted comparative assessment of ORC, KC, and TEG technologies for steel industry waste heat recovery at temperatures from 50–200°C. They utilized energy, exergy, economic, and environmental assessment with the EES program and concluded that ORC and KC are significantly superior to TEG for temperatures above 100°C (Lan et al., 2022).

Atashbozorg et al. also analyzed the hot rolling and electric arc furnace parts of a steel plant in another study. They modeled ORC and KC systems by thermodynamic simulation and exergy-economic assessment. According to their findings, Kalina KCS34 cycle had a higher performance both in terms of exergy efficiency and cost-profit ratio (Atashbozorg et al., 2022).

Lan et al. also investigated the integration of TEG and ORC systems in a two-stage heat recovery system for industrial vehicles. Based on their studies, they were able to establish that the hybrid configuration improved fuel saving and efficiency in electricity generation, including low-temperature operating conditions (Lan et al., 2023).

Kaşka did a real-world exergy and energy analysis for an ORC system for power generation from flue gases within a Turkish steel factory. Using actual operating conditions, the study recognized major exergy loss areas, primarily in the evaporator and recommended improvement strategies (Kaşka, 2013).

Chen et al. conducted an extensive comparison of ORC and Kalina cycles in a waste heat recovery setting. They utilized MATLAB modeling for comparing energy, exergy, sustainability, and economical parameters. The results identified that combining the two cycles would enhance overall system efficiency (Chen et al., 2022).

Fergani and Morosuk applied an exergy-based analysis method to an ORC system for industrial waste heat recovery. They separated avoidable and unavoidable exergy losses through components and thereby identified potential areas of substantial thermodynamic improvement (Fergani & Morosuk, 2023).

Sohrabi et al. also compared Kalina cycle and ORC in a Combined Generation of Electricity, Heating and Cooling (CGAM) system. Thermodynamic modeling using MATLAB revealed that at some operating conditions, ORC was more efficient than the Kalina cycle (Sohrabi et al., 2023).

Behzadi and Behbahaninia developed a multi-objective optimization model for an ORC waste-to-energy facility in Tehran. Their work used exergy-economic analysis and illustrated the immense improvement both exergy and economic efficiency can attain with the proper selection of working fluid and optimization parameters (Behzadi & Behbahaninia, 2021).

Lastly, Nemati et al. also conducted a comparative exergy analysis of Kalina and ORC cycles with a CGAM configuration. Based on their simulations by employing Engineering Equation Solver (EES), ORC performed better under part load and normal industrial operating conditions (Nemati et al., 2017).

These researches in total illustrate the increasing importance of exergy analysis as a tool for optimizing waste heat recovery in the steel industry and call for the fact that recovery cycles should be chosen based on heat source properties, system complexity, and environmental objectives.

By examining the research background, it can be seen that in past research, various cycles such as Rankine Organic and Kalina types have been studied. Most of the research has examined the thermodynamic and economic or simultaneous aspects of these cycles. However, in the research background, the Rankine organic cycle with a turbine exhaust has not been subjected to dual-objective optimization, and thermo-economic and exergy analysis as two objective functions have not been studied in it.

2. Cycle description

Power generation and conversion of thermal energy into electrical energy were carried out in power generation cycles of power plants. In recent years, cycles have been introduced that can convert waste heat from sources such as furnaces into power. In an industry such as steel, these waste energy sources are high and for this reason they are classified as energy-intensive industries. The energy system used in the present study includes the organic Rankine and power generation cycles. Their operation is presented in order below. The organic Rankine cycle (ORC) is an energy system that is used to generate electricity from low-temperature thermal sources, making it particularly suitable for applications such as waste heat recovery, renewable energies such as geothermal energy and solar thermal energy. The organic Rankine cycle has the same function as the conventional Rankine cycle (steam power plant), except that it uses an organic working fluid instead of water [4]. The main components of a simple Rankine cycle include an evaporator, organic turbine, condenser and a pump. In addition, in the present work, a feed water heater has been added to increase the cycle efficiency. The organic Rankine cycle schematic of the present work is shown in Figure 1

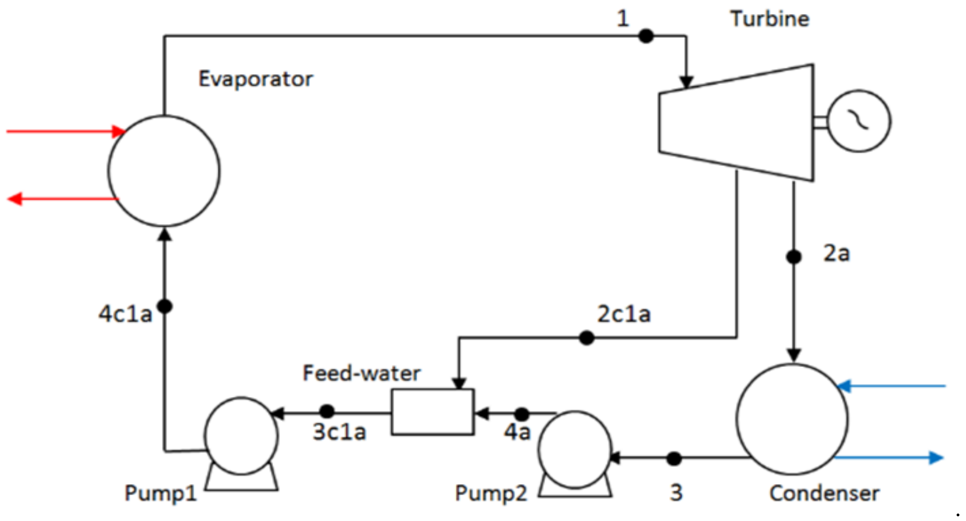


Figure 1. ORC cycle in study

First, the organic fluid, upon receiving heat in the evaporator, exits with the thermodynamic characteristics of flow 1 and enters the turbine to produce power. After its expansion, it leaves the turbine with the characteristics of flow 2. It should be noted that a part of the working fluid flow enters the feedwater heater as a sub cooler from the turbine. The working fluid appears in a condensed liquid state in flow 3 after passing through the condenser. In the next step, by pump 2, the working fluid pressure at point 4a is increased to the feedwater heater pressure. Then, its temperature is increased by the feedwater heater and it leaves it in flow conditions 3c1a until its pressure is increased by pump 1 to the working pressure of the cycle. This cycle is repeated to produce power.

3. Thermodynamic Modeling and Analysis

3-1. Mass and energy balance

The main energy and mass equations used in the analysis of the first law of thermodynamics for the control volume are given in equations (1) and (2):

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\sum \dot{Q} - \sum \dot{W} + \sum \dot{m}_i h_i - \sum \dot{m}_e h_e = 0 \tag{2}$$

ORC systems generally consist of five main components: evaporator, turbine, condenser, pump, and feed heater. In this section, we will describe and analyze the mass and energy equations for each component. By solving these equations, the first law of thermodynamics efficiency can be obtained.

Relations (3) to (5) are the turbine mass and energy equations:

$$\dot{m}_2 = \dot{m}_1 \tag{3}$$

$$\dot{W}_{\text{turbine}} = \dot{m}_1 h_1 - \dot{m}_2 h_2 \tag{4}$$

$$\mathrm{h}_2 = \mathrm{h}_1 + \frac{\mathrm{h}_2 - \mathrm{h}_1}{\eta_{\mathrm{is}}} \tag{5}$$

Equations (6) and (7) are the mass and energy equations for the condenser, respectively:

$$\dot{m}_1 = \dot{m}_2 \tag{6}$$

$$\dot{Q}_{\text{cond}} = \dot{m}_1 h_1 - \dot{m}_2 h_2 \tag{7}$$

Pump mass and energy equations:

$$\dot{m}_1 = \dot{m}_2 \tag{8}$$

$$\dot{W}_{\text{pump}} = \dot{m}_2 h_2 - \dot{m}_1 h_1 \tag{9}$$

$$\dot{W}_{\text{pump}} = \frac{\dot{m}_1 (P_1 - P_2)}{\rho_1 \eta_{\text{pump}}} \tag{10}$$

Mass and energy equations of the evaporator:

$$\dot{m}_1 = \dot{m}_2 \tag{11}$$

$$\dot{m}_{IEG} = \dot{m}_{OEG} \tag{12}$$

$$\dot{Q}_{\text{evap}} = \dot{m}_2 h_2 - \dot{m}_1 h_2 = \dot{m}_{IEG} h_{IEG} - \dot{m}_{OEG} h_{OEG} \tag{13}$$

Feed heater mass equation:

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \tag{14}$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \tag{15}$$

The mass fraction going to SRORC power supply can be expressed as follows:

$$\varkappa_{C1} = (h_{31} - h_4)/\,(h_{21} - h_4) \tag{16}$$

The thermodynamic efficiency of the first law is known as thermal efficiency. To calculate the thermal efficiency of the cycle, we must calculate the power output and the heat input to the system. The thermal efficiency equation of the system is calculated from equation:

$$\eta_t = \frac{W_{net}}{Q} \quad (17)$$

Where Wnet is obtained from equation 18:

$$W_{net} = W_{exp} - \sum W_p \quad (18)$$

3-2. Exergy balance

The exergy loss equations for each component of the system are written below:

$\dot{I}_{\text{evap}} = m_1e_1 - m_2e_2 + m_{ie}e_{ie} - m_{oe}e_{oe}$	evaporator	(19)
$\dot{I}_{\text{cond}} = m_1e_1 + m_3e_3 - (m_2e_2 + m_4e_4)$	Condenser	(20)
$\dot{I}_{\text{pump}} = m_1e_1 - m_2e_2 + \dot{W}_{pump}$	Pump	(21)
$\dot{I}_{turbine} = m_1e_1 - m_2e_2 - \dot{W}_{\text{turbine}}$	Turbine	(22)
$\dot{I}_{\text{fw}} = m_1e_1 + m_2e_2 - (m_3e_3)$	Feed heater	(23)
$\dot{I}_{\text{IHX}} = m_1e_1 + m_3e_3 - (m_2e_2 + m_4e_4)$	Internal HX	(24)
$\dot{I}_{\text{separator}} = m_1e_1 + m_2e_2 - (m_3e_3)$	Separator	(25)
$\dot{I}_{\text{valve}} = m_1e_1 - m_2e_2$	Expansion valve	(26)
$\dot{I}_{\text{mixer}} = m_1e_1 + m_2e_2 - (m_3e_3)$	mixer	(27)

3-3. Exergy efficiency

Based on the second law of thermodynamics, the exergy efficiency of systems can be calculated using the following equation:

$$\eta_e = W_{net}/[Q\left(1 - \frac{T_0}{T_m}\right)] \quad (28)$$

T0 is the ambient temperature and Tm is the average temperature of the heat source, which can be calculated as follows:

$$T_m = (T_{in} - T_{out})/\ln(T_{in}/T_{out}) \quad (29)$$

Analyzing different systems from a thermodynamic perspective does not necessarily imply that a system with higher efficiency is the best system in terms of cost. In order to examine systems with thermodynamic and economic factors simultaneously, the concept of thermo-economics has been defined. Thermo-economics combines empirical principles and economic analysis at the level of system components. Various methods for thermo-economic analysis have been proposed, including exergy cost theory, average cost approach, and specific exergy cost (SPECO). For the analysis of energy conversion systems, the SPECO method provides a simple scheme and increases the calculation time by using a matrix formula. Therefore, the specific exergy cost (SPECO) method was used in this study.

3-4. Cost equation

Thermo-economics relies on the concept that exergy is the only rational basis for allocating costs to the interactions that a thermal system exchanges with its surroundings and is a source of inefficiency within it. Thus, for the input and output material flows with exergy transfer rates (exergy flows) and the power and the exergy transfer rate associated with heat transfer, we write:

$$\dot{C}_i = c_i\dot{E}_i \quad (30)$$

$$\dot{C}_e = c_e\dot{E}_e \quad (31)$$

$$\dot{C}_w = c_w \dot{E}_w \quad (32)$$

$$\dot{C}_q = c_q \dot{E}_q \quad (33)$$

Here, ci, ce, cw, and cq denote the average unit costs of each component, and $\dot{C}_I$, $\dot{C}_e$, $\dot{C}_w$, and $\dot{C}_q$ are the cost streams associated with the waste streams. Exergy costing involves cost balances formulated separately for each component of the system. The cost balance applied to the component shows that the sum of the cost rates associated with all available exergy streams is equal to the sum of the input cost rates to all exergy streams plus the appropriate costs (cost rates) resulting from investment and operation and maintenance costs. The sum of the last two terms is denoted by $\dot{Z}$. Accordingly, for an example of a reversible component that receives a heat transfer and produces power, we write:

$$c_{w,k}\,\dot{w}_k + \sum \dot{C}_{out,k} = c_{q,k}\,\dot{E}_{q,k} + \sum \dot{C}_{in,k} + \dot{Z}_k \quad (34)$$

In this equation, $\dot{Z}k$ is the sum of operating, maintenance, and investment costs.

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \quad (35)$$

$\dot{Z}_k$represents the total cost rate related to the investment cost. $\dot{Z}_k^{CI}$is the operation and maintenance cost ($\dot{Z}_k^{OM}$calculated with the help of the capital recovery factor (CRF). (τ) It is the maintenance factor. To calculate $\dot{Z}_k^{CI}$ we have:

$$\dot{Z}_k^{CI} = \left(\frac{CRF}{\tau}\right) Z_k \quad (36)$$

In this equation, Zk is the cost of purchasing equipment K in US dollars and the capital recovery factor (CRF) is calculated from the following equation:

$$CRF = \frac{i_r(1+i_r)^n}{(1+i_r)^n - 1} \quad (37)$$

In equation (37), the discount rate is 12%, which is considered in this study, and n represents the total operating period of the system for 20 years.

3-5. Equipment Purchase Cost

For the economic studies related to the cycle studied in the present research, we need a series of relations to calculate the purchase cost of the components used in the system. These costs are determined based on the operating conditions of the system and the thermodynamic parameters.

The costs of the internal heat exchanger and evaporator strongly depend on the heat transfer area. In this regard, to determine the heat transfer area, the overall heat transfer coefficient between the hot and cold fluids must be calculated. In this research, we select the overall heat transfer coefficient according to the operating conditions and the working fluid of the system. the capital cost of the system components can be expressed as follows:

$$\dot{Z}_{Evaporator}^{CI} = 130\left(\frac{A_{Evaporator}}{0/093}\right)^{0/78} \quad (38)$$

$$Q_e = U_{coefficient}\, A_{evaporator}\, \Delta T_{LMTD} \quad (39)$$

$$\dot{Z}_{Pump}^{CI} = 3450\,(\dot{W}_{Pump})^{0/71} \quad (40)$$

$$\dot{Z}_{Condensor}^{CI} = 1773\, m_f \quad (41)$$

$$Log_{10}(\dot{Z}_{Turbine}^{CI}) = 2/629 + 1/4398 log_{10}(\dot{W}_{Turbine}) - 0/1776(log_{10}(\dot{W}_{Turbine})^2) \quad (42)$$

$$\dot{Z}_{Feed-water}^{CI} = C_{fw}\left(\frac{527.7}{397}\right)^{1/7} \quad (43)$$

$$log_{10}(C_{fw}) = 4/20 - 0/204\, log_{10}(\dot{V}_{fw}) + 0/1245(\, log_{10}(\dot{V}_{fw}))^2 \quad (44)$$

In order to solve the cost equations for each component, the exergy loss cost in each component of the cycle must first be calculated. There are more than one input and output streams in the cost balance for some components. It should be noted that in this case, the unknown cost parameters exceed the cost balances for that particular component. In this section, the exergy or auxiliary SPECO equations for the three organic Rankine cycles are given in Table (1).

Table 1. Cost rate equations and SRORC auxiliary equations

Evaporator	$\dot{C}_{41} + \dot{C}_{q\ eva} + \dot{Z}_{Evaporator} = \dot{C}_1$, $\dot{c}_{q=0/001}$	(45)
Turbine	$\dot{C}_1 + \dot{Z}_{Turbine} = \dot{C}_{w\ tur} + \dot{C}_2 + \dot{C}_{21}$, $\dot{c}_1 = \dot{c}_2$, $\dot{c}_1 = \dot{c}_{21}$	(46)
Condenser	$\dot{C}_2 + \dot{Z}_{condenser} = \dot{C}_{q\ con} + \dot{C}_3$, $\dot{c}_2 = \dot{c}_3$, $\dot{c}_{q\ eva} = \dot{c}_{q\ con}$	(47)
Pump 1 Pump 2	$\dot{C}_{31} + \dot{C}_{w\ pump1} + \dot{Z}_{pump1} = \dot{C}_{41}$ $\dot{C}_3 + \dot{C}_{w\ pump2} + \dot{Z}_{pump2} = \dot{C}_4$ $\dot{c}_3 = \dot{c}_4$, $\dot{c}_{31} = \dot{c}_{41}$, $\dot{c}_{w\ pump1} = \dot{c}_{w\ pump2} = \dot{c}_{w\ tur}$	(48)
Feed-water	$\dot{C}_4 + \dot{C}_{21} + \dot{Z}_{feed\text{-}water} = \dot{C}_{31}$	(49)

4. Optimization

Design and optimization are the application of the latest methods and techniques of the world's science to achieve the most economical and safest possible design for systems. Today, increasing energy efficiency in various industries has become a priority goal for researchers. Also, past experiences and research have shown that in terms of energy saving, measures such as timely repairs and maintenance save energy (Lawan et al.). But this also involves costs. So, these questions arise:

- ✓ How and where does energy quality decrease in industries?
- ✓ How can energy quality decrease be prevented and costs reduced?

The answers to these questions are only possible by developing and optimizing process industries, improving their performance, and creating combined cycles. Therefore, engineers improve the initial design of equipment through optimization and enhance their performance during installation and commissioning. These measures lead to achieve the highest production with the lowest cost and minimum energy consumption, which ultimately leads to maximum profitability and other benefits (Sivanandam et. al.). In this research, a multi-objective genetic algorithm (based on non-dominated ranking) is used to optimize the system, and a brief description of its operation is presented below.

4-1. Non-Dominate Sorting Multi-Objective Genetic Algorithm (NSGA-II)

Genetic algorithm is one of the heuristic algorithms for solving problems that is inspired by biological modeling of animal populations. In this algorithm, the characteristics of generations of organisms are likened to the values of objective functions, and improvements in these characteristics occur over time. The emergence of new generations leads to improvements in the values of the objective functions from the mixing of previous generations. In other words, this algorithm uses the principles of Darwinian natural selection to find the optimal formula or solution for predicting or matching the pattern. In this algorithm, the solutions obtained do not dominate each other. With two objective functions, for example, efficiency and cost, improving one may lead to weakening the other. The sum of these solutions forms a front called Pareto (Hajabdollahi et. al.)
figure 2 represents the flowchart of the multi-objective optimization algorithm (NSGA-II).

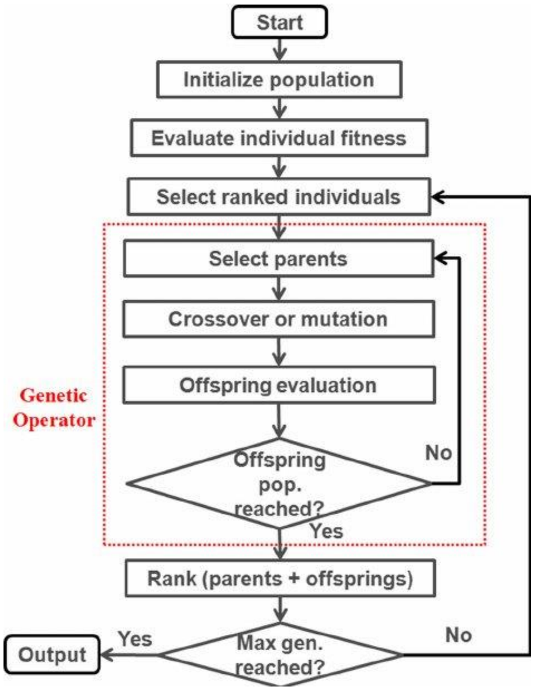


Figure 2. Flowchart of the multi-objective optimization algorithm (NSGA-II).

4-2. Objective functions, constraints and design parameters

In the analysis of energy systems (especially cogeneration systems), the efficiency and costs of the system are of great importance. Therefore, the current research has focused on the energy, exergy and exergo- economic analysis of a power generation system using an organic Rankine cycle and driven by waste energy from the gases of a steel plant. The optimization of the system is carried out by a two-objective genetic algorithm and the objective functions lead to the maximum exergy efficiency and the minimum annual cost rate of the system. These objective functions are expressed as follows, respectively:

$$\eta_{ex}=\frac{\dot{W}_{Net}}{\dot{E}x_{1g}-\dot{E}x_{2g}} \tag{50}$$

$$TAC=CRF\times\sum_{i=1}^{k}C_{inv,\,k}\times\phi \tag{51}$$

The maintenance factor for organic Rankine cycle equipment is given in Table 2.

Table 2. Repair and maintenance factor of organic Rankine cycle equipment.

equipment	1/25
Organic Turbine	1/15
condenser	1/15
evaporator	1/15
pump	1/25
feed water heater	1/15

In this study, the algorithm constants include 100 chromosomes, 85% probability of merger, 3% probability of mutation, 35% probability of selection towards the parents with a larger crowding distance, and the number of generations is 500. In addition, the design parameters considered for optimizing the organic Rankine cycle and Kalina cycle are presented in Table 3.

Table 3. design parameters

parameter	dimension	range	step
turbine inlet pressure	kPa	2000-3500	1
superheat temperature difference	C	40-80	1
condenser pressure	kPa	80-100	1
turbine isentropic efficiency	%	70-90	1
Pump 1 isentropic efficiency	%	70-90	1
Pump 2 isentropic efficiency	%	70-90	1

The constraints imposed on the system in terms of structural and environmental conditions are as follows:

•The exergy efficiency of the equipment must be less than 92%.

•The output quality of the organic turbine must not be less than 95%.

5. Optimization Results

The present work investigates the organic Rankine cycle for waste heat recovery in combination with the waste energy of a steelmaking process unit for power generation from energy, exergy, economic and exergo- economic perspectives. In this section, the optimization results are presented. The ambient temperature and pressure are considered to be 298.15 Kelvin and 101.325 kPa, respectively. The computational code of the system is implemented in the MATLAB2018b programming environment and is linked to the REFPROP9 extension to obtain the working fluid properties. The genetic algorithm based on non-dominated ranking is used to optimize the system. The system used for optimization is a Dell precision m4600 laptop with 8 GB RAM, 4 GB graphics, and i7-2760QM CPU, and the optimization time is about 55 minutes.

The system performance is evaluated by using sensitivity analysis based on the design parameters. This analysis is performed with respect to the optimum point, where one parameter is changed, while the other parameters remain constant. In the present work, the linear programming technique for multidimensional analysis of priorities (LINMAP) is used to determine the final optimal solution on the Pareto optimal front. Figure 4 shows the Pareto optimal front for Organic Rankine cycle. It should be noted that the number of solutions on this front is 1003 and the least crowded distance between them is 0.017312.

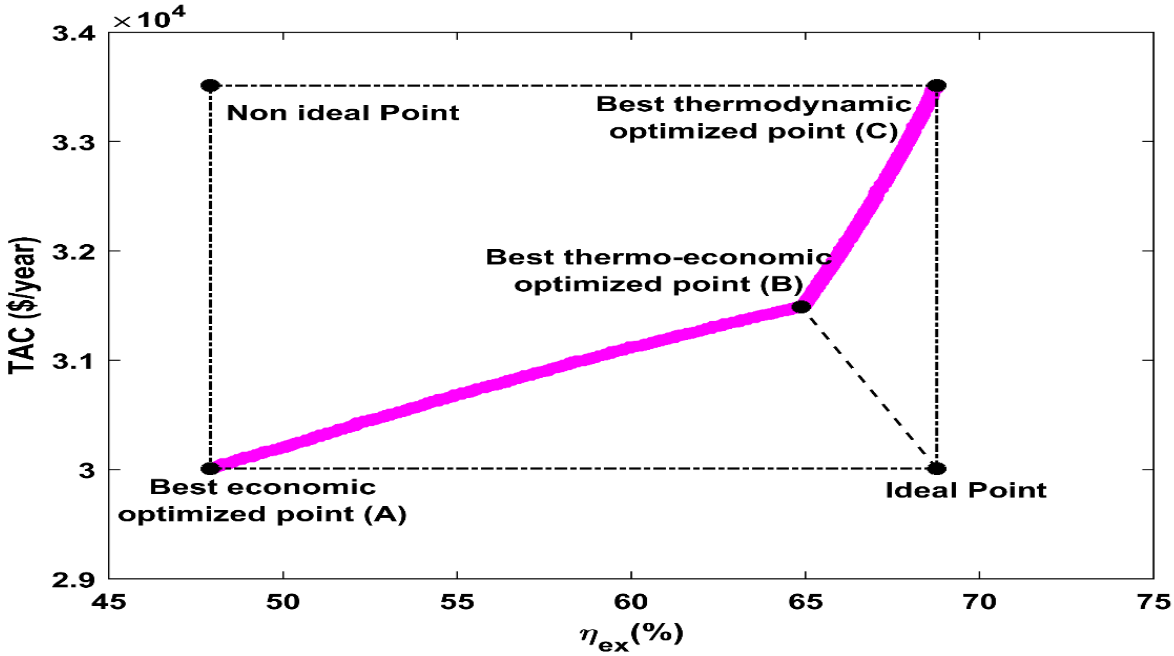


Figure 3. Pareto optimal front for the ORC cycle.

The ideal point, the best economically optimized point (A), the best optimized point (B), the best thermodynamically optimized point (C) and the non-ideal point are marked in Figure 4. The ideal point consists of the lowest total annual cost and the highest exergy efficiency, respectively. Selecting the final design from the Pareto-optimal front on the diagram requires a decision-making process. This process often relies heavily on engineering experience and the relative importance of each objective to the decision-maker. LINMAP is a common decision-making tool and can be used to identify the closest point to the ideal point on the Pareto front, which represents the best solution based on ideal conditions. Design point A represents the cost-optimal conditions. In contrast, design point C reflects the optimal scenario for exergy efficiency.

The optimal design and performance parameters of the organic Rankine cycle are listed in Table 3. According to this table, the lowest and highest energy and exergy efficiencies occur at design points A and C, respectively. While, the optimal design point has energy and exergy efficiencies of 23.38% and 64.88%, respectively. In addition, it can be stated that with the improvement of energy and exergy efficiencies, the annual cost of the system increases. On the other hand, the power output of the cycle with respect to design points A, B, and C is 1295.4, 1756.2, and 2100.1 kW, respectively. The annual cost of the cycle with respect to the optimal point (B) was estimated to be 1488.3×104 USD/year.

Table 4. Optimal results of the organic Rankine cycle.

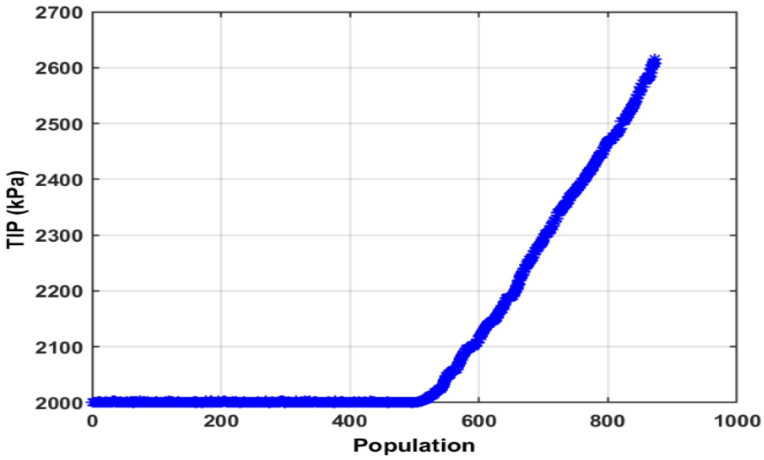
	parameters	**Dim.**	**A**	**B**	**C**
Design Parameters	turbine inlet pressure	kPa	2000	2000	26.16
	superheat temperature difference	C	4.4	40	4.3
	condenser pressure	kPa	98.8	83	82
	turbine isentropic efficiency	%	70	90	90
	Pump 1 isentropic efficiency	%	85	85	85

	parameters	Dim.	A	B	C
	Pump 2 isentropic efficiency	%	85	85	85
operational parameters	energy efficiency	%	17.24	23.38	28.2
	exergy efficiency	%	47.86	64.88	77.58
	Total annual cost	year/$	3.0001×10^4	3.1488×10^4	3.3969×10^4
	power generation	kW	1295.4	1756.2	21.1

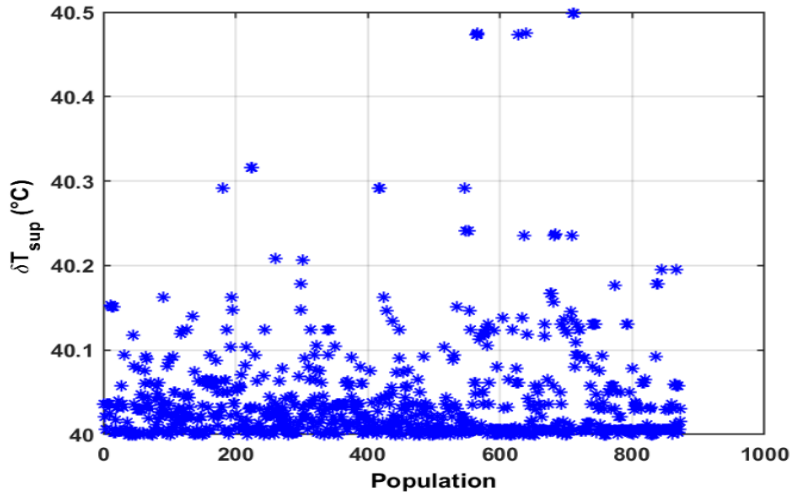
The distribution of design parameters in the Pareto optimal front based on the optimal point (B) is shown in Figure 2. This figure shows that all design parameters fall within the defined upper and lower limits. It is noteworthy that the optimal values for these parameters are scattered within their allowable ranges. This indicates that each parameter plays an important role in the trade-off between achieving high exergy efficiency and minimizing the total annual cost.

- ✓ Some parameters have a relatively good distribution within their allowable ranges.
- ✓ Certain parameters are at their respective maximum and minimum limits.

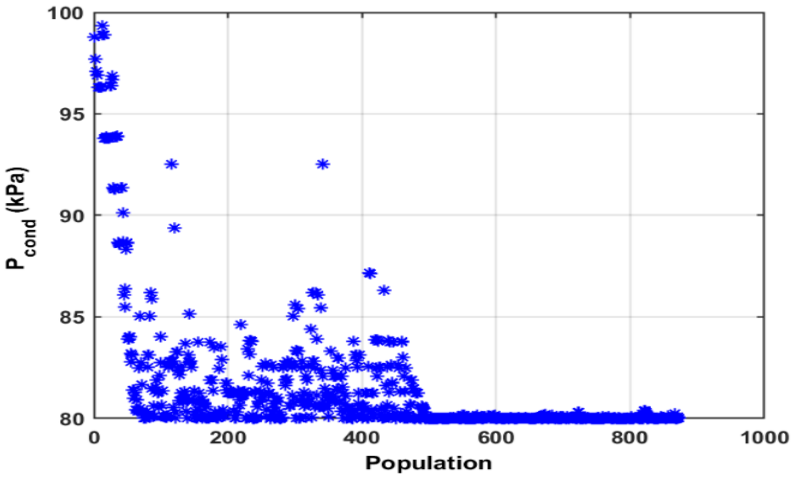
Figure 5 shows the variations of the optimal values of the objective functions for different optimal design parameters at points A, B and C. It is obvious that the variations of the objective functions at other design points in the Pareto optimal front follow a similar path to the three design points (A-C).



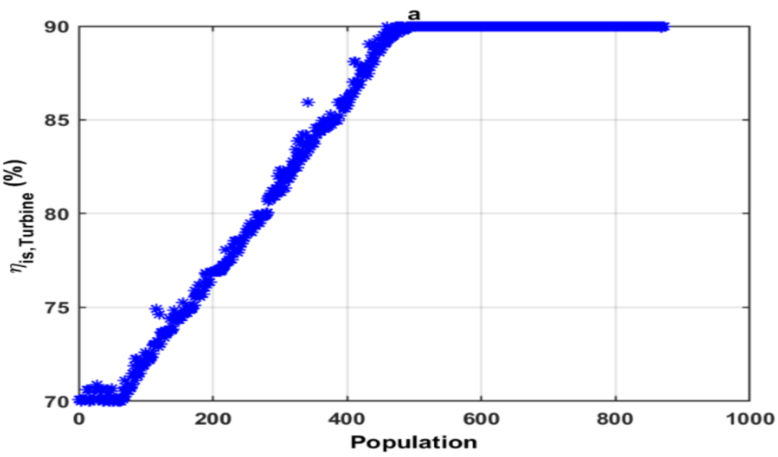
(a)


δT_sup (°C)
Population

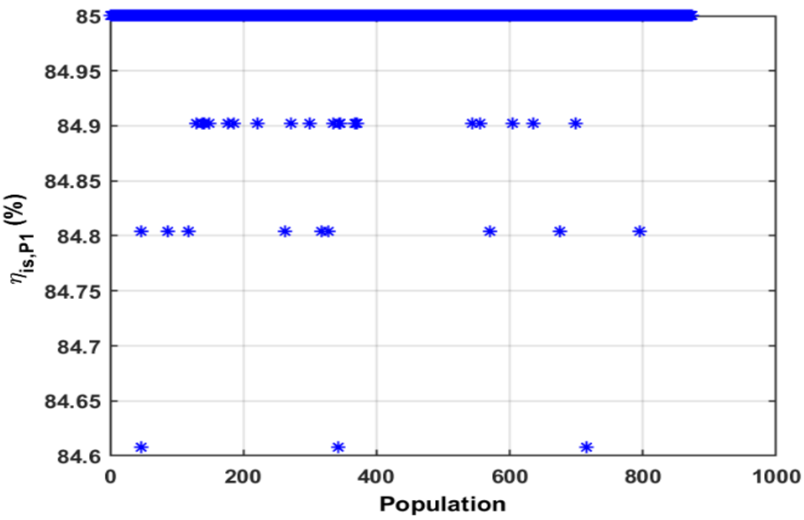
(b)


P_cond (kPa)
Population

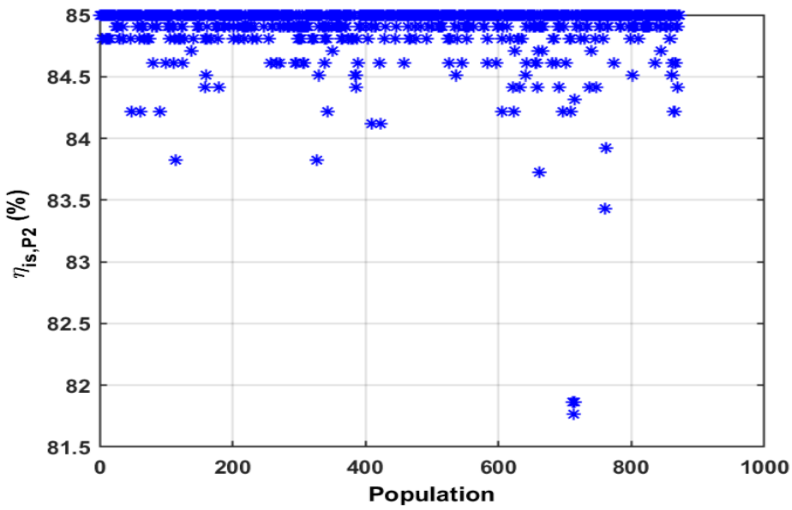
(c)


a
η_is, Turbine (%)
Population

(d)



(e)



(f)

Figure 4. Distribution of design parameters

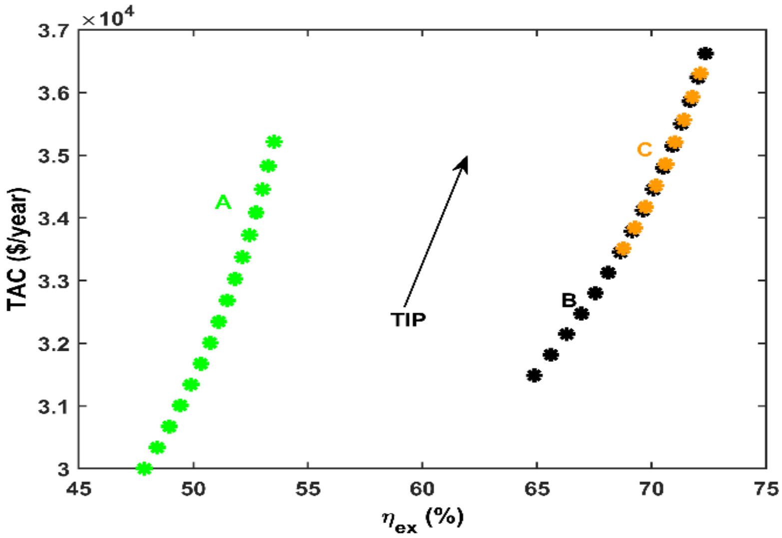
Based on the data in Figure 4(a), it is found that with increasing the inlet pressure of the organic turbine, the exergy efficiency of the cycle increases and the total annual cost increases accordingly. This is mainly because the input energy (enthalpy) of the flow to the turbine increases, while slightly reducing the mass flow rate of the organic fluid.

According to Figure 4(b), the sensitivity analysis shows that with increasing the superheat temperature difference, the exergy efficiency of the total annual cost of the cycle decreases and increases respectively. Due to the increase in this parameter, the mass flow rate of the recovered organic fluid decreases and at the same time the energy of the turbine inlet flow increases slightly. This results in a decrease in the overall power output of the cycle.

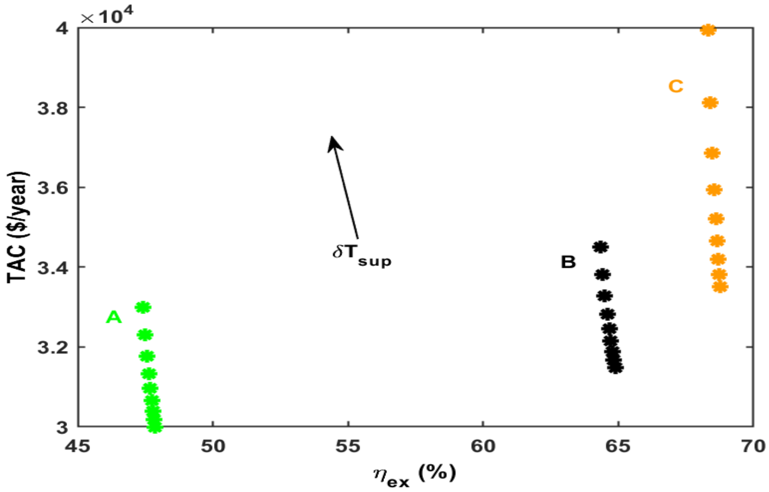
In Figure 4(c), it is observed that with increasing the condenser pressure, the exergy efficiency decreases and the total annual cost improves. The reason is that by increasing this parameter, the power produced in the organic turbine decreases and, given that the cycle input energy is constant, the exergy efficiency of the system decreases.

It is noteworthy that the trend expressed for the condenser pressure is expressed in reverse when examining the isentropic efficiency of the organic turbine. According to Figure 4 (d), by increasing this variable, the turbine performance improves and subsequently an increase in the power produced and cycle efficiency is seen. Due to this, the exergy efficiency improves, but the total annual cost increases.

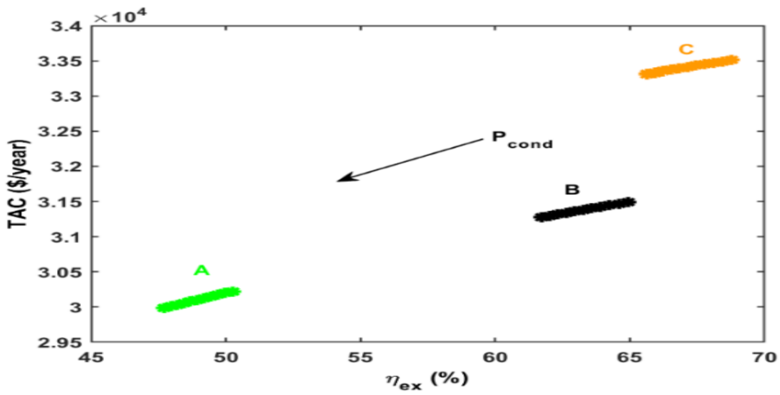
According to Figures 4 (e) and (f), increasing the isentropic efficiency of pumps 1 and 2 leads to improved performance and reduced work consumption. As a result, the exergy efficiency increases and the total annual cost of the cycle decreases.



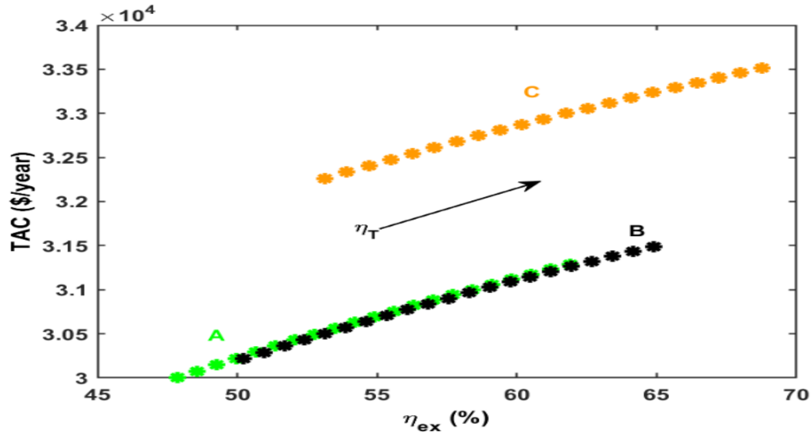
(a)



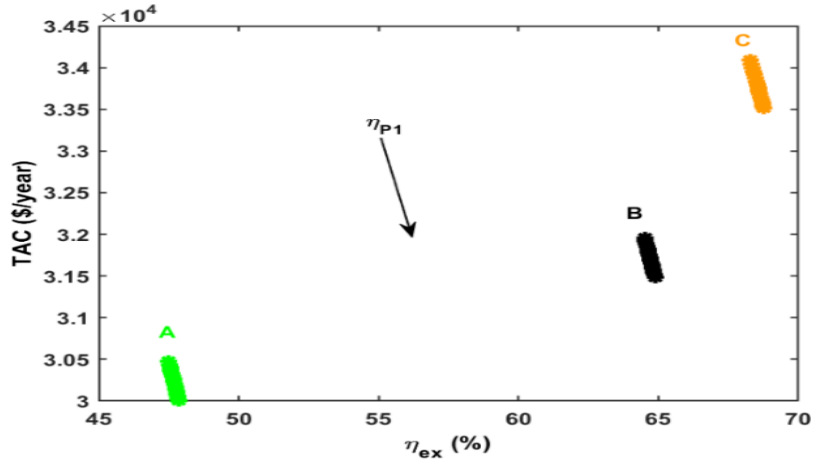
(b)



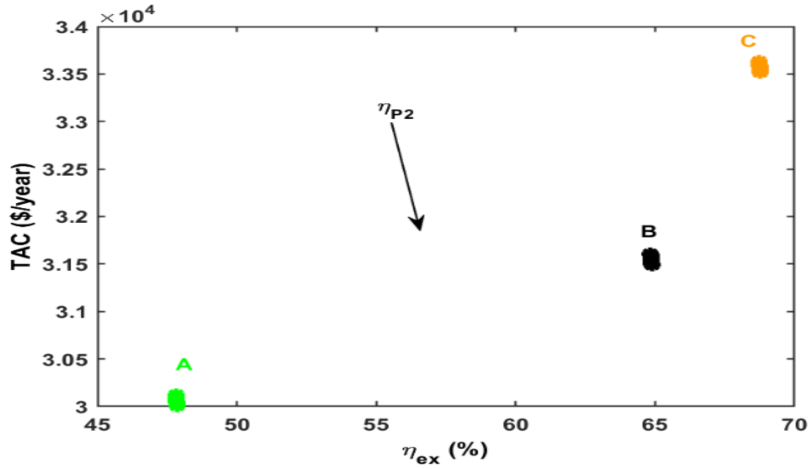
(c)



(d)



(e)



(f)

Figure 5. Effect of design parameters on the performance of the organic Rankine cycle

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Figure 5 shows the effect of various operating parameters on cycle performance . 6 operating parameters as variables and the effect of each of them on the decreasing or increasing trend of total cost or thermodynamic efficiency are shown in Figures 5-a to 5-f.

6. Conclusion

Waste heat recovery in the steel industry was subjected in this study to a detailed analysis, ORC being coupled with a feedwater heater. Energy, exergy, and Thermo- economics analyses are performed simultaneously with a multi-objective genetic algorithm (NSGA-II) to derive an optimal tradeoff between its thermodynamic performance and annual cost. From the results, turbine inlet pressure, the difference of superheat temperature, and the isentropic efficiencies of rotating machineries such as turbine and pumps greatly increased the exergy efficiency; however, any improved thermodynamic performance is always accompanied by increased annual cost, pointing out the conflict between technical and economic considerations. At the optimal design point obtained using the LINMAP approach, exergy efficiency is 64.88%, energy efficiency is 38.23%, power output is 1756.2 kW, and the annual cost is around $14.88 million. Such a sensitivity analysis reflects how a change in any of the design parameters like condenser pressure or pump efficiencies immediately affects the system output. Overall, using these multi-objective optimization algorithms would bring about the best system design and hence stable operation of energy recovery. This approach can play a crucial role in reducing fuel consumption and operational costs in energy-intensive industries such as steel production and can also be extended to other sectors with high waste heat potential.

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Declaration of Competing Interest

The author has no conflicts of interest to declare that are relevant to the content of this article.

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