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RESEARCH ARTICLE

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Innovative thermodynamic integration: kalina, orc and rankine cycles to obtain sustainable energy from gas turbine waste heat

Ahmet Elbir*

**Suleyman Demirel University, YEKARUM, Isparta, Turkey, ORCID: 0000-0001-8934-7665*

Abstract

The research presents the thermodynamic performance analysis in which Kalina, Organic Rankine Cycle (ORC) and Rankine cycles are integrated to ensure sustainable energy production from the waste heat of the UGT-25000 gas turbine. In the comparisons, the highest performance level in terms of energy efficiency was given by the Gas Turbine + Kalina Cycle with 68.57%, whereas the others' energy efficiencies were determined as 68.13% (Gas Turbine + ORC), 68.05% (Gas Turbine + Rankine) and 65.72% (Gas Turbine only). According to exergy efficiency, the highest value was given by the Gas Turbine + Kalina Cycle with 23.71%. The exergy efficiencies of the remaining cycles were 17.71% (Gas Turbine + Rankine), 17.52% (Gas Turbine alone) and 13.28% (Gas Turbine + ORC). On cost of energy and carbon footprint basis, the best performance was also exhibited by the Gas Turbine + Kalina Cycle with figures of \$0.36/kWh and 3.66 kg CO_2/h, respectively. But the cost of energy per unit of the Gas Turbine alone is \$0.63/kWh and the carbon footprint is 20.46 kg CO_2/h. The results obtained show that the Kalina cycle plays a significant role in sustainable production of energy both cost saving and reducing the carbon footprint. Thermodynamic calculations were done using the Engineering Equation Solver (EES) software and detailed study of the energy and exergy losses in system components was conducted. The study provides a valuable guideline for effective utilization of waste heat and supply of sustainable solutions by integrated systems in the energy sector.

Keywords: Gas turbine; Rankine cycle; Kalina cycle; ORC; energy analysis; exergy analysis.

* Corresponding author. Tel.: 0506-711-8859.
E-mail address: ahmetelbir@sdu.edu.tr

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1. Introduction

Energy is a fundamental necessity of contemporary societies and the demand for clean resources is growing day by day. That's why efficiency in energy generation and utilization of alternative resources are being studied. Recent studies in the field of energy are evaluated in this article and in what ways novel strategies can affect major issues such as energy efficiency, variability in resources and environmental factors. In the meantime, there is an increasingly rapid demand for energy coupled with global concerns such as global warming which emphasize the need for revolution in the field of energy. Here, the use of renewable energy sources promises to reduce carbon emissions in energy production, enabling steps to be taken towards the future of sustainability. Evaluating the progress achieved in the energy sector, developing measures to increase efficiency in energy production, to restrict environmental impacts and to use energy resources in a sustainable manner. In this study, the thermodynamic investigation of energy conversion cycles combining (KC), (ORC) and Rankine cycles integration with a gas turbine has been carried out. Our aim is to increase system efficiency in electricity generation by using thermal energy more efficiently with the combination of these cycles. Some parallel literature studies explore the thermodynamic efficiency of energy conversion cycles and gas turbine integration; In the article, they conducted a comprehensive exploration of the thermodynamic properties and performance of different working fluids. They examined the effect of different working fluids of different compositions according to efficiency, energy production and cost. These issues had set the stage for the identification of the optimal compositions to achieve maximum thermodynamic efficiency and the best energy conversion performance [1]. In this paper, they have drawn a detailed comparison on Kalina and ORC cycles' working principle, thermodynamic efficiency and performance. Researchers have compared different cycles based on energy conversion efficiency, energy production and environmental impact. They showed that ORC gives maximum results to the Kalina cycle [2]. In their study, potential single, double, and triple system arrangements were examined using energy, exergy, and environmental impacts. The concept behind the study utilized a real gas turbine (GT) cycle as the topping cycle and Rankine cycle (RC) and (KC) as the bottom cycles. For each single, double, and triple cycle, parametric loop optimization was also performed besides determining the maximum possible total performances to determine the best working parameters [3]. S-CO_2 Brayton combined cycles with the inclusion of the (ORC) and Kalina cycle as sub-cycles have been suggested by this paper for enhanced cycle performance [4]. The paper addresses an early feasibility assessment of a low-temperature dual power plant considering working fluid choice, net power output calculation, working fluid performance analysis, and economic cost comparison between Organic Rankine Cycle and Kalina cycle [5]. The system exploits geothermal energy as the heat source and comprises a Kalina cycle, LiBr/H_2O heat transformer, and water treatment system. A parametric study analyzed the effect of turbine inlet pressure and evaporator outlet temperature on system performance [6]. Herein, the Kalina cycle for the heat recovery of geothermal energy is compared with the (ORC) [7]. This paper discusses a review of the Kalina Cycle, a simple Kalina Cycle, a Rankine versus Kalina Cycles comparison, an explanation of thermodynamic analysis of the Kalina Cycle, and a review of various Kalina systems and applications [8]. This work reports a double configuration of the Kalina cycle for boiler stack heat recovery in a steam power plant, involving two fundamental Kalina cycles [9]. The possibility of incorporating another multiphase extender into the low-concentration ammonia-water solution cycle of the Kalina cycle has scarcely been discussed in literature. This paper proposes two new Kalina cycles through the incorporation of a multiphase expander following the Kalina evaporator [10]. The integration of the (ORC), organic flash cycle (OFC), and Kalina cycle (KC) presented a system design to improve the electricity generation of a supercritical CO_2 recompression Brayton (SCRB) cycle. For the selection of the most suitable base cycle for waste heat recovery for the SCRB cycle, SCRB/ORC, SCRB/OFC, and SCRB/KC integrated plants were compared using thermodynamics, exergoeconomics, and sustainability [11]. A system was designed in this study through which the utilization of an ORC to harness the excess energy of Kalina cycle systems (KCS) driven by a geothermal unit is possible. The most striking feature of the Kalina cycle is the additional heat gained during heat addition to the evaporator due to its thermophysical effects. Detailed modeling of the system, along with energy, exergy, and economic analyses, were conducted [12]. They analyzed the relationship between heat transfer rate and entropy formation. With the EES program. They stated that the highest entropy production was in the evaporator [13]. They designed a Kalina cycle to utilize the waste heat energy of the exhaust gas. Energy and mass conservation expressions of all components in the cycle were derived and optimum analyzes were made using the Aspen HYSYS program developed by Aspentech. The system used the (ORC) to recycle energy from waste heat. However, they stated that Kalina cycles perform much better than the Organic Rankine cycle and their initial investment costs are less in terms of cost [14]. In the study, saturated and superheated ORC WHR systems with different working fluids were examined using exergy exergoeconomic, advanced exergy and advanced exergoeconomic analysis [15]. In their study, a thermodynamic theoretical performance analysis was performed. Performance evaluation of multi-purpose cooling used parameters such as exergetic performance and calculated system coefficient, exergy efficiency, performance coefficient, and exergy destruction rate as performance criteria [16]. In their study, they used the dip cycles Kalina, organic Rankine, Goswami and three-sided flash cycles to recover the low-grade thermal energy of the exhaust gases of the gas cycle. Taking into account energy and economic criteria, they modeled and optimized a non-dominant sequencing genetic algorithm in the MATLAB software. They further stated that the most preferred alternative is the Goswami cycle and the least preferred alternative is the Kalina cycle [17].

The major objective of this research is to comprehensively explore the hermodynamic efficiencies of such systems by integrating Kalina, Organic Rankine Cycle (ORC) and Rankine cycles to maximize the energy conversion capability of waste heat from gas turbines. By comparing the energy and exergy efficiencies of such combined cycles, the research hopes to better exploit waste heat and contribute to sustainable energy production. In addition, it is designed to present novel solutions for the energy sector by evaluating the potential effects of these systems in terms of reducing energy costs and carbon emissions.

2. Material and Method

2.1. Thermodynamic equations

In thermodynamic analysis under steady state conditions, the fundamental mass balance equation can be expressed as follows: [18], [19], [20];

$$\sum \dot{m}_{in} = \sum \dot{m}_{ex} \tag{1}$$

Here, $\dot{m}$ denotes the mass flow rate, with the indices 'in' and 'ex' referring to the inlet and outlet conditions, respectively. The energy balance can be expressed as:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right) = \dot{Q}_{ex} + \dot{W}_{ex} + \sum_{ex} \dot{m}\left(h + \frac{V^2}{2} + gz\right) \tag{2}$$

In this context, $\dot{Q}$ represents the heat transfer rate, $\dot{W}$ denotes the power, h is the specific enthalpy, v is the velocity, z is the height, and g is the gravitational acceleration. The entropy balance equation for steady-state conditions can be formulated as:

$$\sum_{in} \dot{m}_{in} s_{in} + \sum_k \frac{\dot{Q}}{T_k} + \dot{S}_{gen} = \sum_{ex} \dot{m}_{ex} s_{ex} \tag{3}$$

In this equation, s represents the specific entropy, and $\dot{S}_{gen}$ is the rate of entropy generation. The exergy balance equation is given as:

$$\sum \dot{m}_{in}\, ex_{in} + \sum \dot{E}x_{Q,in} + \sum \dot{E}x_{W,in} = \sum \dot{m}_{ex} ex_{ex} + \sum \dot{E}x_{Q,ex} + \sum \dot{E}x_{W,ex} + \dot{E}x_D \tag{4}$$

The specific flow exergy is expressed as:

$$ex = ex_{ph} + ex_{ch} + ex_{pt} + ex_{kn} \quad (5)$$

The kinetic and potential components of the exergy are considered negligible, as is the chemical exergy. The physical or flow exergy (ex_{ph}) is defined as:

$$ex_{ph} = (h - h_o) - T_o(s - s_o) \quad (6)$$

where h and s denote the specific enthalpy and entropy in the actual state, respectively. . h_o and s_o represent the enthalpy and entropy at the reference state, respectively.

Exergy destruction is equal to the specific exergy multiplied by the mass flow rate;

$$\dot{E}x_D = ex * m \quad (7)$$

$\dot{E}x_D$, represents work-related exergy ratios and is given by:

$$\dot{E}x_D = T_0\dot{S}_{gen} \quad (8)$$

$\dot{E}x_W$, are work-related exergy ratios and are given as:

$$\dot{E}x_W = \dot{W} \quad (9)$$

$\dot{E}x_Q$, are the exergy rates related to heat transfer and are given as below.

$$\dot{E}x_Q = \left(1 - \frac{T_o}{T}\right)\dot{Q} \quad (10)$$

Exergy destruction within the system;

$$\dot{E}x_{D,syst.} = \dot{E}x_{in} - \dot{E}x_{aut} \quad (11)$$

What work comes out of the system;

$$\dot{W}net_{out} = \dot{Q}_{in} - \dot{Q}_{out} \quad (12)$$

System thermal efficiency (η);

$$\eta = \frac{energy\ in\ exit}{total\ energy\ inlets} \quad (13)$$

The exergy efficiency (ψ) can be defined as follows;

$$\psi = \frac{exergy\ in\ exit}{total\ exergy\ inlets} \quad (14)$$

To evaluate carbon emissions from electricity consumption, the direct energy consumed, denoted as "E," is multiplied by the carbon intensity, "eCO_2," as shown in the equation [22]. In this study, "E" represents the emissions calculated by subtracting the net power of the subcycle from the net power.

$$\text{Carbon Emissions} = E \times eCO_2 \tag{15}$$

In terms of the carbon intensity of electricity generation, countries can be divided into three main groups: group A, which has a carbon intensity of up to 0.29 kg.CO_2/kWh; group B 0.30–0.69 kg.CO_2/kWh; and group C above 0.70 kg.CO_2/kWh.[23].

When we subtract the net power obtained from waste heat from the net power obtained initially and divide this by the efficiency, and multiply the result by the electricity price determined for the cost, we find the decrease in the integrated system power production cost.

$$electricitycost = \frac{power\ gained}{cycle\ efficiency} * electricityprice \tag{16}$$

2.2 Thermodynamic Assumptions

Assumptions and Analysis Tools Used in Thermal Calculations

- The system performance is assumed to be stable and consistent.
- A pure substance is used within the system.
- Compression in the compressors is considered adiabatic.
- Pressure drops and heat transfer within system components and pipelines are neglected.
- Counterflow heat exchangers are used in the heat source exchangers, and heat losses are ignored.
- The dead state of the fluids (air, water, R600a) circulating in all cycles is taken as a temperature of 288 K and an atmospheric pressure of 1 bar.
- The system performance is assumed to be stable and consistent.
- Gravitational potential energy and kinetic energy are not considered.
- The superheat was increased by 120°C in the steam Rankine cycle.
- Heat transfers in the heat exchangers are assumed to be equal.
- Carbon intensity is taken as 0.50 kg CO_2/kWh [23].
- The unit electricity price is set at $0.14/kWh [24].
- Temperature values in the gas turbine are taken from UGT-25000 gas turbine specifications [25].

In thermodynamic analyses, Engineering Equation Solver (EES) software was used. This software was preferred to perform energy, exergy and entropy calculations of system components. EES stands out as an effective tool especially in solving complex thermodynamic equations and system optimizations. The performance parameters of the system, energy and exergy losses, thermodynamic efficiencies of the components were analyzed in detail with the help of this software.

2.3 Brayton Cycle

Figure 1. Gas turbine Brayton cycle represents the working principle of gas turbines used for power generation.

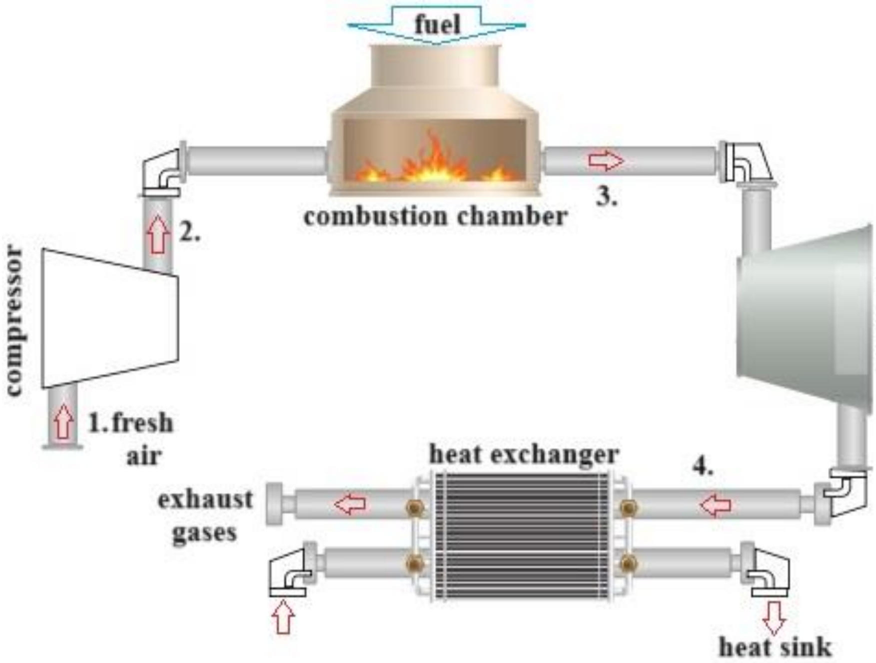

Fig. 1. Gas Turbine

The Brayton cycle that the operation of the gas turbine is dependent on is illustrated by Figure 1. The process is made up of four basic processes: heat addition, expansion, compression, and cooling, and each has to be effective in order to achieve the turbine's overall process:

1-2 Compression: In the first stage, the atmospheric gas is compressed to a high-pressure state, usually by means of a compressor. This causes the gas to be heated and its energy potential to be raised. 2-3 Heat addition: The compressed gas is then directed to a heat source (usually a combustion chamber). This heat source increases the gas temperature, hence increasing the energy content of the gas. In the combustion chamber, as the gas passes through, the fuel is burned and the gas temperature increased. 3-4 Expansion: After the heat addition step, the gas is diverted to a high speed turbine. The energy extracted from the gas is converted to mechanical energy in the turbine. When the pressure of the gas is reduced, the turbine work rotates the turbine shaft and generates mechanical energy.

Table 1 gives the thermodynamic values of the positions of the system in Figure 1.

Table 1. Thermodynamic values of the positions of the Brayton Cycle (Figure 1.)

Location	T [K]	s [kJ/kg.K]	P [bar]	h [kJ/kg]	ex [kj/kg]	m [kg/s]
T_0. Air	288	5.665	1	288.4	0	-------
1.	288	5.665	1	288.4	0	88
2.	813	5.865	21	836.6	490.5	88
3.	1493	6.568	21	1628	1079	89.8
4.	738	6.633	1	754.6	187.3	89.8

2.4 ORC and Rankine Cycle

Figure 2. The cycle used in ORC is shown.

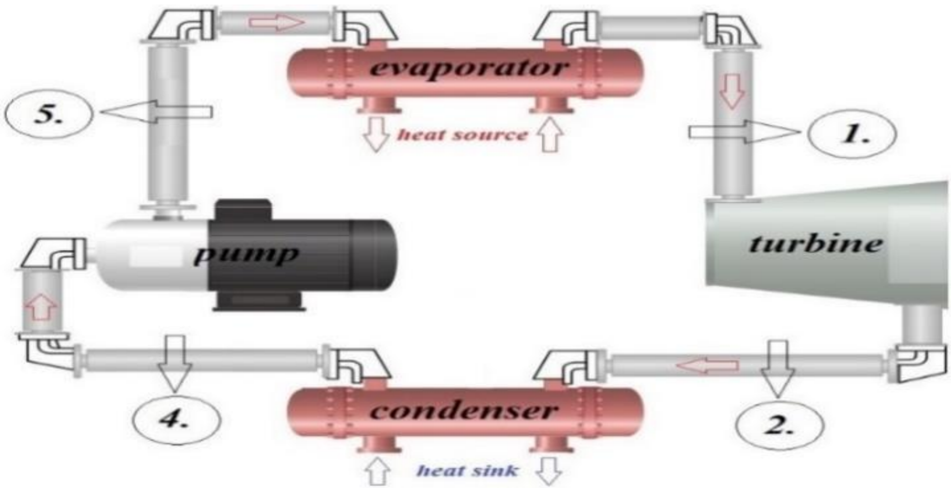

Fig. 2. Organic Rankine Cycle

Figure 2 illustrates the Organic Rankine Cycle (ORC), highlighting its key components and the thermodynamic processes involved in converting low-grade heat into mechanical energy.

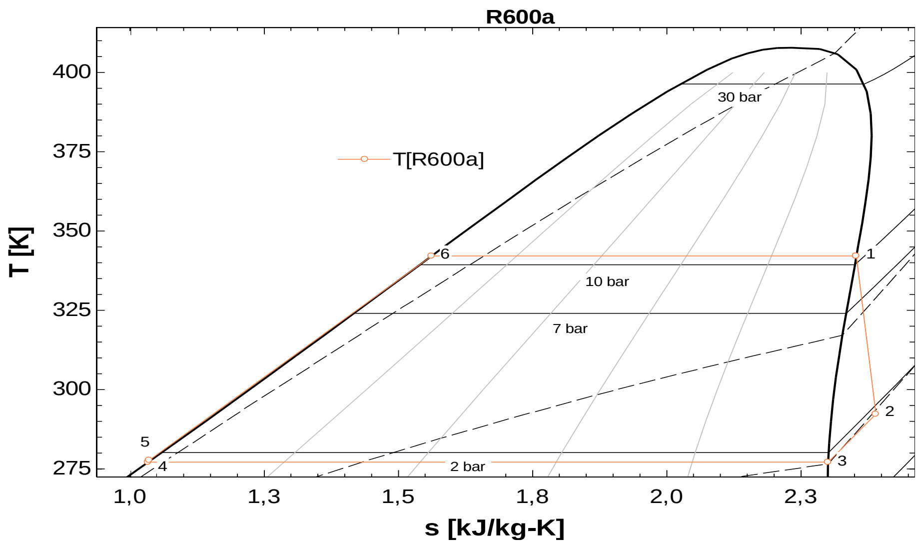

Fig. 3. Organic Rankine Cycle temperature-entropy diagram

Figure 3 presents the temperature-entropy (T-s) diagram of the Organic Rankine Cycle (ORC), showcasing the various phases of the cycle, including heat absorption, expansion, condensation, and compression:

5-1 Heat source: A heat source is required for the Rankine cycle and ORC. This source is usually provided through a boiler and may include high-temperature gases or liquids from a variety of sources such as fossil fuels, nuclear energy or solar energy. The thermal energy from the heat source heats the water in the boiler and provides steam formation. The steam happens in a high-pressure and high-temperature state. 1-2 Turbines: The high-pressure steam generated rotates the turbine blades as it expands in a turbine. This mechanical energy is taken as it passes through the turbine shaft and converted into electrical energy by a generator combined with the turbine. 2-4 Cooling: After the energy of the steam passing through the turbine is taken, it is turned into liquid again through a cooling system. 4-5 Pump: The liquefied steam is brought back to a high pressure state with the help of a pump and returns to the starting point of the cycle.

Table 2. Thermodynamic results of the Organic Rankine Cycle (Figure 3.)

Location	T [K]	s [kJ/kg.K]	P [bar]	h [kJ/kg]	ex [kj/kg]	m [kg/s]
T_0.R600a	288	2.458	1	582.2	0	-------
1.	378	2,381	21.76	681.5	100.4	65.89
2.	326.67	2.407	5.309	635.1	53.61	65.89
3.	313	2.323	5.309	608.4	28.21	65.89
4.	313	1.329	5.309	297	-268.3	65.89
5.	314.4	1.332	21.76	301.2	-264.2	65.89
6.	378	1.856	21.76	483	-90.19	65.89

Figure 4. The cycle used in Rankine cycles is shown.

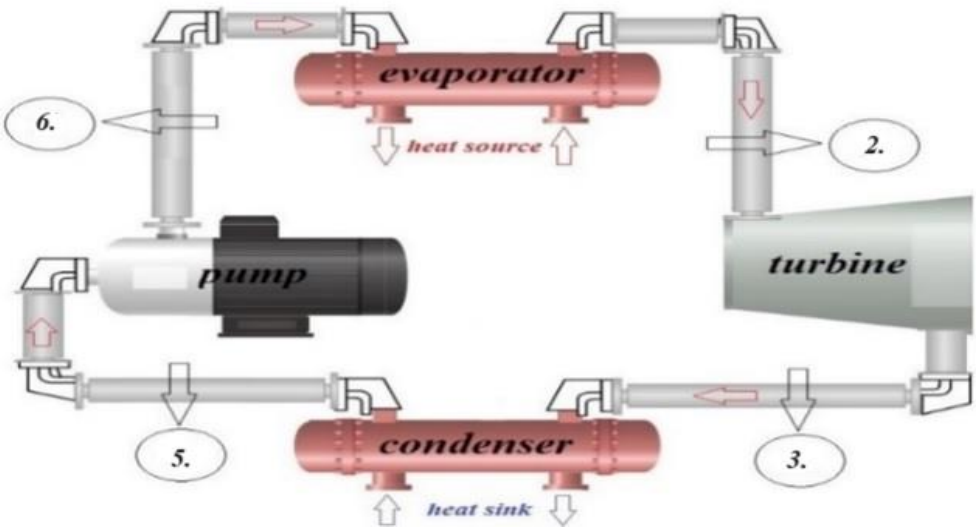

Fig. 4. Rankine Cycle

Figure 4 depicts the Rankine Cycle, outlining the essential processes of heat addition, expansion, condensation, and compression that are fundamental to the cycle's operation.

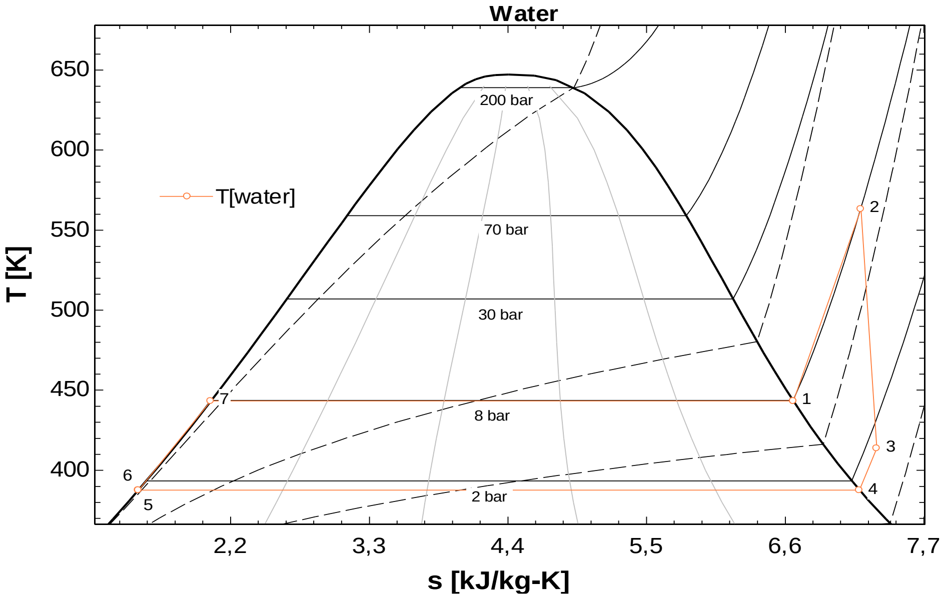

Fig. 5. Rankine Cycle temperature-entropy diagram

Figure 5 illustrates the temperature-entropy (T-s) diagram of the Rankine Cycle, depicting the key stages of the cycle such as heat addition, expansion, condensation, and compression. 6-1 Heat source: Liquid water at high pressure and high temperature is heated by the heat received from the heat source and turns into steam. The temperature of this vapor is generally above the saturated vapor temperature of water vapor at this stage. 1-2 Superheat: Steam from the steam generator is directed to the superheat section to add more heat. In the superheat section, the steam receives extra heat and its temperature increases. This process ensures that the vapor remains in the gas phase and keeps it at higher temperature and pressure. 2-3 Turbine: Super-superheated steam is directed from high pressure to low pressure into a turbine. Mechanical work is done during the expansion of steam in the turbine. This work causes the turbine to spin and drives a generator to produce electricity. Superheating allows the steam to carry more energy during this process. 3-5 Condenser: The steam coming out of the turbine is cooled in a condenser. This cooling process causes the vapor to return to its liquid phase and be returned to the steam generator for reuse. 5-6 Pump: The liquefied steam is brought back to a high pressure state with the help of a pump and returns to the starting point of the cycle.

In Table 3, the thermodynamic values of the positions of the system in figure 5 are given.

Table 3. Thermodynamic values of the positions of the Rankine Cycle (Figure 5.)

Location	T [K]	s [kJ/kg.K]	P [bar]	h [kJ/kg]	ex [kj/kg]	**m** [kg/s]
T_0.water	288	0.2244	1	63.08	0	-------
1.	443	6.665	7.922	2768	2608	9.809
2.	563	7.202	7.922	3036	2868	9.809
3.	413.7	7.327	1.659	2753	2583	9.809
4.	387.4	7.189	1.659	2698	2530	9.809
5.	387.4	1.467	1.659	480	398.3	9.809
6.	387.5	1.467	7.922	480.8	399.1	9.809
7.	443	2.042	7.922	719.1	628.7	9.809

2.5 Kalina Cycle

Figure 6 shows the Kalina cycle.

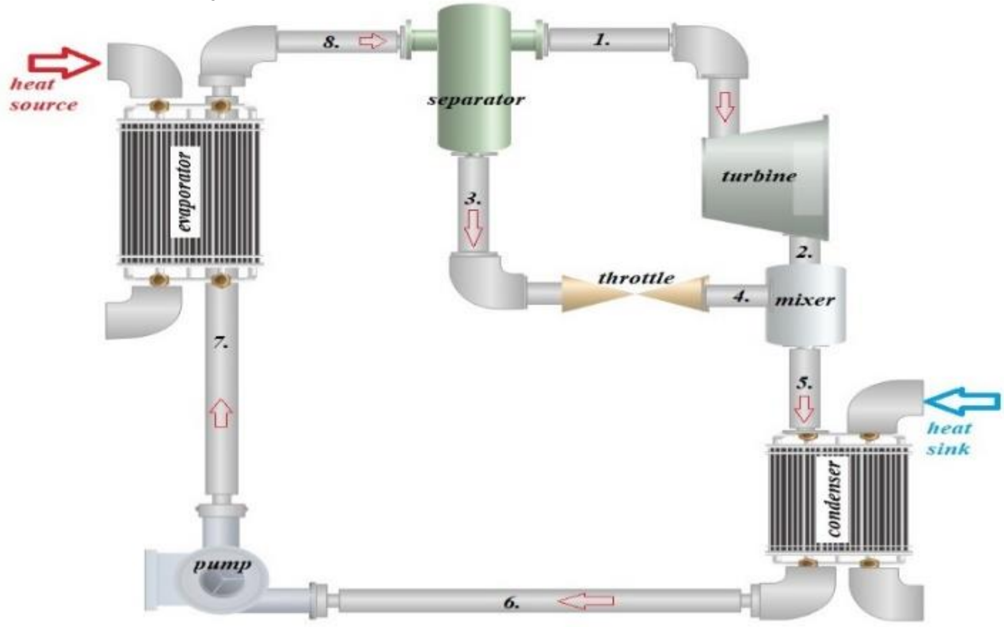

Fig. 6. Kalina cycle

Figure 6 presents a diagram detailing the thermodynamic performance of the Kalina cycle and the energy flow between its components. 7-8 Thermal Energy Intake from the Heat Source: The Kalina cycle uses thermal energy, usually from low and medium temperature sources. Thermal energy is used to heat the "Kalina mix", a special organic fluid used in the Kalina cycle. Kalina mixture consists of organic components mixed in a certain ratio. This mixture has the ability to work more efficiently at low temperatures. 1-2 Steam Formation and Expansion: When the Kalina mixture is heated, it evaporates and is directed to a high pressure turbine. As the steam rotates the turbine blades, it expands and generates mechanical energy. This mechanical energy is converted into electrical energy by means of a generator. 3-4 pressure reduction at the turbine outlet: The hot saturated liquid is sent to the mixer at low pressure with a throttling valve, where it is mixed with the saturated mixture and reduced to the turbine outlet pressure. 5-6 Cooling and Condensation of Steam: The steam coming out of the turbine is cooled and condensed by a cooler (condenser). This process allows the vapor to become liquid again. 6-7 Recovering the Fluid and Directing it to the Heater: The condensed fluid is pumped back to the heater (steam generator) with the help of a pump. In this step, the pressure of the fluid is increased and it is made ready to receive thermal energy in the heater again. Separation of fluid in 8-3 separator: Ammonia, which does not evaporate in the evaporator and is weaker than saturated steam, exits as a saturated liquid in the case of mixture 3.

In Table 4, the thermodynamic values of the positions of the system in figure 6 are given.

Table 4. Thermodynamic values of the positions of the Kalina cycle (Figure 6.)

Location	T[K]	h [kJ/kg]	s [kJ/kg.K]	P [bar]	ex [kj/kg]	Qu [quality]	m [kg/s]	X [%NH3]	Fluid
1.	378	1392	4.097	40	252.3	1	19.825	0.9894	NH_3H_2O
2.	296.2	1216	4.202	8	46.08	0.9365	19.825	0.9894	NH_3H_2O
3.	378	288.4	1.372	40	-66.48	0	5.152	0.6531	NH_3H_2O
4.	320.6	288.4	1.47	8	-94.7	0.2231	5.152	0.6531	NH_3H_2O
5.	309.2	1025	3.647	8	14.92	0.7756	24.977	0.920	NH_3H_2O
6.	318	155.4	0.7153	8	-10.35	0	24.977	0.920	NH_3H_2O
7.	318.9	160.6	0.7196	40	-6.386	-0.001	24.977	0.920	NH_3H_2O
8.	378	1164	3.535	40	186.2	0.7937	24.977	0.920	NH_3H_2O
T[0].	288	-207.5	-0.5807	1	0	0	--------	0.92	NH_3H_2O

3. Results

The thermodynamic results of the Brayton cycle in Figure 1 are given in Table 5.

Table 5. Brayton cycle thermodynamic results

Component	Wpower [kW]		$\mathbf{Ex_{D.}}$ [kW]	$\boldsymbol{\varphi}$[%]	Qheat [kW]		$\boldsymbol{\delta_{is.}}$[%]
	(+) in	(-) out			(+) in	(-) out	
Compressor (1-2)	+48241		5079	89.47	--------		72.85
HX (2-3)	--------		4486	92.18	+71044		--------
Turbine (3-4)		-78404	1676	97.91	--------		94.95

In Table 5, it is seen that the compressor works to increase the pressure of the gas with a power input of 48241 kW and during this process, 74044 kW heat energy input is provided in the combustion chamber. As a result of this process, the system produces 78404 kW of energy by the turbine. Additionally, the exergy destruction ($Ex_{D.}$ kW), isentropic efficiency ($\delta_{is.}$ %) and exergy efficiencies (φ %) of the components in this system are given in Table 5. The highest exergy destruction occurred in the compressor.

The thermodynamic results of the ORC cycle in Figure 2 are given in Table 6.

Table 6. ORC thermodynamic results

Component	Wpower [kW]		$\mathbf{Ex_{D.}}$ [kW]	$\boldsymbol{\varphi}$[%]	Qheat [kW]		$\boldsymbol{\delta_{is.}}$[%]
	(+) in	(-) out			(+) in	(-) out	
Turbine (1-2)		-3059	24.94	99.19	--------		85
Condenser (2-4)	--------		12.24	99.94		-22275	--------
Pump (4-5)	+271.9		3.244	98.81	--------		75
Evaporator (5-1)	--------		407.5	98.33	+25062		--------

In Table 6, it is seen that the pump works to increase the pressure of the gas with a power input of 271.9 kW, and during this process, 25062 kW heat energy input taken from the waste exhaust pipes is provided. As a result of this process, the system produces 3059 kW of energy by the turbine. Additionally, the exergy destructions and exergy efficiencies of the components in this system are given in Table 6. The highest exergy destruction occurred in the evaporator that provides heat input.

The thermodynamic results of the Rankine cycle in Figure 4 are given in Table 7.

Table 7. Rankine cycle thermodynamic results

Component	Wpower [kW] (+) in (-) out	$\mathbf{Ex_{D.}}$ [kW]	$\boldsymbol{\varphi}$[%]	Qheat [kW] (+) in	$\boldsymbol{\delta_{is.}}$ [%] (+) in
Turbine (1-2)	-2779	18.32	99.35	--------	85
Condenser (2-4)	--------	169.1	99.21	-22291	------
Pump (4-5)	+7.626	0.04427	99.42	--------	75
Evaporator (5-1)	--------	214.2	99.12	+25062	------

In Table 7, it is seen that the pump works to increase the pressure of the gas with a power input of 7.6269 kW and during this process, 25062 kW heat energy input taken from the waste exhaust pipes is provided. As a result of this process, the system produces 2779 kW of energy by the turbine. Additionally, the exergy destructions and exergy efficiencies of the components in this system are given in Table 7. The highest exergy destruction occurred in the evaporator that provides heat input.

The thermodynamic results of the Kalina cycle in Figure 6 are given in Table 8.

Table 8. Thermodynamic results of the Kalina cycle in Figure 6

Component	Wpower [kW] (+) in (-) out	$\mathbf{Ex_{D.}}$ [kW]	$\boldsymbol{\varphi}$[%]	Qheat [kW] (+) in (-) out	$\boldsymbol{\delta_{is.}}$[%]
Turbine (1-2)	-3489	599.11	85.34	--------	85
Condenser (2-4)	--------	444.07	58.7	-21720	--------
Pump (4-5)	+130	30.87	76.23	--------	75
Evaporator (5-1)	--------	1649.04	74.47	+25062	--------

In Table 8, it is seen that the pump works to increase the pressure of the gas with a power input of 130 kW, and during this process, 25062 kW heat energy input from the waste exhaust pipes is provided. As a result of this process, the system produces 3489 kW of energy by the turbine. Additionally, the exergy destructions and exergy efficiencies of the components in this system are given in Table 8. The highest exergy destruction occurred in the evaporator that provides heat input

In Table 9, the yield percentage results of the energy and exergy analyzes in all systems are given.

Table 9. Energy efficiency and exergy efficiency of system components

Gas turbine [%]		Gas turbine+ ORC [%]	
Energy efficiency	Exergy efficiency	Energy efficiency	Exergy efficiency
65.72	17.52	68.13	13.28
Gas turbine + Rankine [%]		**Gas turbine+ Kalina [%]**	
Energy efficiency	Exergy efficiency	Energy efficiency	Exergy efficiency
68.05	17.71	68.57	23.71

The information given in Table 9 includes the energy and exergy efficiencies of the gas turbine and different cycles. Here is the analysis of this data:

Gas turbine: When the gas turbine is running alone, the energy efficiency is 65.72%, and the exergy efficiency is 17.52%. This is the state showing the amount of energy that the gas turbine can efficiently use when running alone and the system losses. Gas turbine + ORC: When the gas turbine is combined with the (ORC) system, the energy efficiency increases to 68.13%, but the exergy efficiency decreases to 13.28%. While the ORC system improves energy efficiency by recovering part of the waste heat generated at the exhaust of the gas turbine, it is observed that such recovery also creates exergy losses. Gas turbine + Rankine: When the gas turbine is combined with the Rankine cycle, the energy efficiency becomes 68.05% and the exergy efficiency is 17.71%. The Rankine cycle is another system to recover the heat at the exit of the gas turbine and thereby improve energy efficiency. It can be seen that there are also losses of exergy. Gas turbine + Kalina cycle: When gas turbine and Kalina cycle are employed in combination, the energy efficiency rises to 68.57% and exergy efficiency rises to 23.71%. The Kalina cycle focuses on more efficiently recovering the waste heat of the gas turbine and, therefore, raises the energy and exergy efficiencies by a significant margin.

The results of the analysis show that different cycles play a crucial role in the energy and exergy efficiencies of gas turbine systems. Each cycle is related to its pros and cons, and the cycle to be selected must be identified in relation to the specific requirements of the system.

Table 10 shows the comparative results of different energy production cycles in terms of energy costs and carbon emissions.

Table 10. Energy cost and emissions per of system components

Gas turbine [energy]		Gas turbine + ORC [energy]	
Cost $/kWh	Emissons Kg.CO_2/h	Cost $/kWh	Emissons Kg.CO_2/h
160.2	20.46	78.12	19.04
Gas turbine + Rankine [energy]		Gas turbine + Kalina [energy]	
Cost $/kWh	Emissons Kg.CO_2/h	Cost $/kWh	Emissons Kg.CO_2/h
78.12	19.05	76.32	18.75

Analysis results in Table 10, Gas Turbine: When the gas turbine operates alone, the energy cost is calculated as 160.2 $/kWh and the amount of carbon emissions gained is 20.46 Kg.CO_2/h. Gas Turbine + ORC (Organic Rankine Cycle): When the gas turbine and ORC system are combined, the energy cost decreases significantly and drops to 78.12 $/kWh, while carbon emissions also decrease and are measured as 19.05 Kg.CO_2/h. Gas Turbine + Rankine Cycle: When the gas turbine and the Rankine cycle are combined, the energy cost is again at the level of 78.12 $ / kWh, while carbon emissions are measured as 19.06 Kg.CO_2 / h. Gas Turbine + Kalina Cycle: When the gas turbine and Kalina cycle are combined, the energy cost is at the lowest level, i.e. 76.32 $/kWh, and carbon emissions are measured as 18.75 Kg.CO_2/h. Table 11 shows the comparative results of different energy production cycles in terms of exergy cost and exergy emissions.

Table 11. Exergy cost and exergy emissions per of system components

Gas turbine [exergy]		Gas turbine + ORC [exergy]	
Cost $/kWh	Emissons Kg.CO_2/h	Cost $/kWh	Emissons Kg.CO_2/h
63	3.94	63	3.94
Gas turbine + Rankine [exergy]		Gas turbine + Kalina [exergy]	
Cost $/kWh	Emissons Kg.CO_2/h	Cost $/kWh	Emissons Kg.CO_2/h

62.28	3.93	62.28	3.93

Analysis results in Table 11, Gas Turbine: When the gas turbine operates alone, the exergy cost is calculated as 63 $/kWh and the amount of exergy emissions gained is 3.94 Kg.CO_2/h. Gas Turbine + ORC (Organic Rankine Cycle): When the gas turbine and ORC system are combined, the exergy cost increases and becomes 82.8 $/kWh, while exergy emissions are measured with a slight decrease as 3.93 Kg.CO_2/h. Gas Turbine + Rankine Cycle: When the gas turbine and the Rankine cycle are combined, the exergy cost is 62.28 $/kWh and exergy emissions are 3.93 Kg.CO_2/h. 00Gas Turbine + Kalina Cycle: When the gas turbine and Kalina cycle are combined, the exergy cost drops significantly and reaches only 0.36 $/kWh, while exergy emissions are measured as 3.66Kg.CO_2/h.

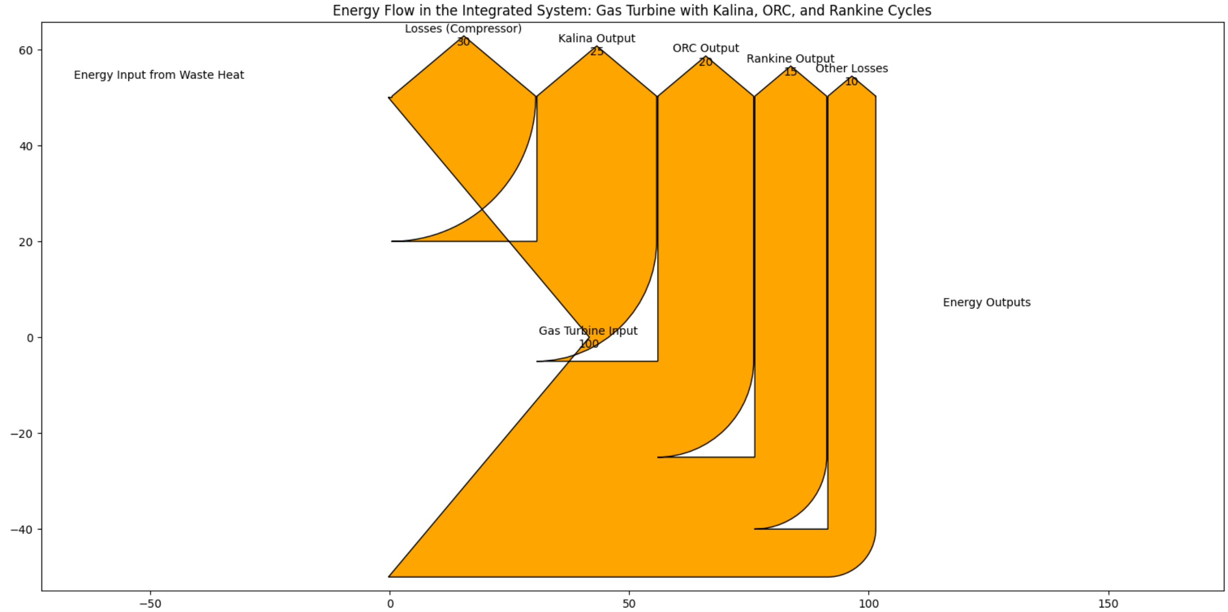

Fig. 7. Sankey diagram represents the energy flow in Kalina, ORC and Rankine cycles integrated with gas turbine

Figure 7 shows the energy flow in Kalina, ORC and Rankine cycles integrated with gas turbine. The total energy input received from the gas turbine is stated as 100 units. This energy is subject to various losses before being distributed to the system components. When the energy losses are examined, it is seen that the losses originating from the compressor are 30%. This draws attention as the largest loss in the system. In addition, the energy loss stated as "Other Losses" is 10% and these losses are caused by factors such as pressure drops and heat transfer losses. Energy recovery is provided by distributing the energy coming from the gas turbine to different cycles. Kalina cycle shows the highest performance with 25% energy output. This reveals that the Kalina cycle efficiently utilizes waste heat. The ORC system provided 20% energy output and contributed to energy conversion by taking advantage of the thermodynamic properties of organic fluids. The Rankine cycle provided 15% energy output and supported energy recovery using water vapor. Finally, Figure 7 visually explains how the gas turbine waste heat is distributed within the integrated systems and the energy recovery processes. This analysis shows that energy losses in the system should be reduced and the Kalina cycle should be optimized more effectively.

Table 12. Integrated with the GT, Kalina compares the energy and exergy efficiencies of the ORC and RC.

System	Energy Efficiency (%)	Exergy Efficiency (%)
Gas Turbine	65,72	17,52
Gas Turbine + ORC	68,13	13,28
Gas Turbine + Rankine	68,05	17,71
Gas Turbine + Kalina	68,57	23,71

Reasons for the performance differences of different systems according to Table 12 Kalina Cycle, Optimizing heat recovery at low and medium temperatures using the ammonia-water mixture, the Kalina cycle offered the highest performance with an energy efficiency of 68.57% and an exergy efficiency of 23.71%. This success is due to the low energy losses in the system and the thermodynamic properties of the working fluid increase the cycle performance. ORC (Organic Rankine Cycle), Although ORC works effectively at low temperature differences, it has a high performance with an energy efficiency of 68.13%, but it has a lower result than the Kalina cycle with an exergy efficiency of 13.28%. This is due to the fact that the heat transfer properties of organic fluids are limited. The Rankine Cycle (RC) has demonstrated a moderate performance with an energy efficiency of 68.05% and an exergy efficiency of 17.71%. Although it is an advantage due to its simpler cycle and low cost structure, it has a more limited impact on waste heat recovery compared to the Kalina cycle. Gas Turbine, The standalone gas turbine showed the worst performance with an energy efficiency of 65.72% and an exergy efficiency of 17.52%. The most significant reason for this is that waste heat cannot be utilized efficiently. Therefore, the Kalina cycle shows the best performance for combined systems, minimizing energy and exergy loss. Although there are a few good things about ORC and Rankine cycles, they are less efficient than the Kalina cycle. The least efficient is gas turbine, as it is not able to recycle waste heat.

The findings from this study were compared with similar studies done in the literature. Energy efficiency of the system where the Kalina cycle was implemented (68.57%) performed optimally compared to ORC (68.13%) and Rankine cycles (68.05%). For example, in a study by Gholamian and Zare (2016), the Kalina cycle and ORC's thermodynamic efficiencies were compared and it was stated that the Kalina cycle is more energy-efficient in certain situations. The outcome of this study verifies this study and illustrates the Kalina cycle's high ability to recover energy.

Regarding exergy efficiency, the Kalina cycle (23.71%) was determined to be greater than in previous literature. For example, as stated by Köse et al. (2021), it is reported that the Kalina cycle possesses greater exergy efficiency in energy generation from waste heat of gas turbines. The results in this study confirm the earlier work since the Kalina cycle was demonstrated to be an optimized solution for energy conversion from waste heat.

In addition, in energy consumption and carbon emissions, findings in this study are more eco-friendly than previous research. For example, in research by Wakana et al. (2013), the ORC and the Kalina cycles were compared and stated that the Kalina cycle was better when there was a low-temperature source. The energy cost $0.36/kWh and 3.66 kg CO_2/h of carbon emissions achieved in this study confirm the economic and environmental benefits of this system.

Thus, this paper demonstrated the superiority of the performance of the Kalina cycle in integrated energy conversion systems over previous studies presented in the literature and indicated the importance of the Kalina cycle in sustainable power generation.

4. Conclusions

In the analysis of the given data, there are two main factors to consider to determine which cycle is the best: energy efficiency and exergy efficiency. Generally, the best cycle will be the one with both energy and exergy efficiency. Health, we can find the best cycle based on the data:

If we examine the results in terms of energy efficiency, Gas turbine + Kalina cycle (Energy efficiency 68.57%) is the cycle with the highest energy efficiency. The energy efficiencies of other cycles are listed as 68.13% (Gas turbine + ORC), 68.05% (Gas turbine + Rankine) and 65.72% (Gas turbine only).

If we examine the results in terms of exergy efficiency, Gas turbine + Kalina cycle (Exergy efficiency 23.71%) is again the cycle with the highest exergy efficiency. The exergy efficiencies of other cycles are listed as 13.28% (Gas turbine + ORC), 17.71% (Gas turbine + Rankine) and 17.52% (Gas turbine only).

Gas Turbine + Kalina Cycle stands out as the best performing cycle in terms of both energy cost and carbon emissions. This cycle appears to be the best option for sustainable energy production, minimizing energy costs and reducing carbon emissions.

In terms of energy cost and carbon emissions, the Gas Turbine + Kalina Cycle ($0.36/kWh and 3.66Kg.$CO_2$/h) is by far the best performing cycle. This cycle contributes to sustainable energy production by both minimizing energy costs and reducing exergy emissions. Other cycles have higher exergy costs and emissions. Therefore, according to these figures, Gas Turbine + Kalina Cycle is the best cycle.

These findings are considerable additions to practical waste heat energy applications. Specifically, this research, motivated by the imperative for developing low-cost and sustainable technology for energy production, offers a template for producing renewable energy through reducing the price of energy production and carbon footprint.

In the future, the findings of this research can be used as a basis for more effective integration of renewable energy sources and optimization of energy conversion systems. In addition, implementation of new technologies such as the Kalina cycle in different areas of application can contribute to the solution of environmental and economic problems in the energy sector.

Therefore, the present study has been a valuable contribution toward the development of energy conversion systems and renewable energy solutions' generation. Further work should be carried out to investigate the scale-up applications of these systems and consider their performance under different operating conditions.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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