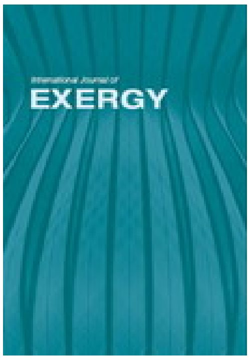

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Analysis of Kalina cycle for recovering waste heat from flue gas exhaust in pressurised pulverised combined cycle

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Abstract: A thermodynamic analysis is performed to investigate the performance of a Kalina cycle (KC) integrated with a standalone 400 MW pressurised pulverised combined cycle (PPCC). The KC extracts waste heat from the plant's flue gas exhaust. The thermodynamic analysis shows that the proposed integrated plant has an energy and exergy efficiencies of 44.56% and 40.88%, respectively. Moreover, KC generates an additional power of 8.89 MW with energy and exergy efficiencies of 12.25% and 33.81%, respectively. The economic study shows that the cost of electricity generation and payback period of KC are ₹2.24 per unit and 1.95 years, respectively.

Keywords: combined cycle; energy; exergy; economic; Kalina cycle; plant waste heat.

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1 Introduction

India is a vast country with enormous electricity demand, and waste heat from various power generation units can help to meet some of that demand. The total installed energy generation capacity by each sector from different resources in India as of April 2023, according to the Central Electricity Authority (CEA, 2023), was 416,591.38 MW. The primary source of energy generation in India is coal, where coal-based power plants dominate 50% of the total installed capacity. In power plants, a massive amount of waste heat is released at very low temperatures. This heat is difficult to convert efficiently into useful work from the conventional method, and because of that, it is mostly released into the atmosphere (Loni et al., 2021). Numerous studies concluded that low-grade power generation cycles could produce power using thermal waste energy because this cycle uses organic fluid as working fluid, and this fluid has a lower boiling point. These power cycles can be run using the waste heat available at different plant portions, such as the condenser, flue gas exhaust etc. Organic Rankine cycle (ORC) and Kalina cycle (KC) are the most efficient low-grade power conversion cycles in which a mixture of ammonia-water is used in KC, and organic fluid is used in ORC as a working fluid (Kalan et al., 2021; Gao et al., 2012). Utilising waste heat minimises the usage of fossil fuels and the damaging effects they have on the environment. According to Mittal et al. (2012) for one unit of electricity generation from a coal-based power plant, 0.91–0.95 kg/kWh of CO_2 is emitted, so utilising waste heat can avoid a tremendous amount of CO_2. The overall efficiency of ORC is lower (Hettiarachchi et al., 2007) for waste heat utilisation at moderate temperatures. In contrast, The KC is an efficient method of producing energy from low-grade waste heat (Kalina, 1983). The KC has the advantage of using a binary mixture as a working fluid with varying boiling temperatures; another notable advantage is that the heat transfer method has less irreversibility and also has a low ozone depletion potential and good thermo-physical characteristics. Extensive literature is available on the performance characteristics and thermodynamic analysis of KC. Koroneos et al. proposed a KC system to generate electricity using geothermal energy, incorporating a 70% mass fraction of ammonia (Koroneos and Rovas, 2013). Özahi and Tozlu (2020) have optimised the KC integrated with a solid waste-based power plant, in which the waste heat collected from the exhaust gas, indicating a 3.62% increase in efficiency. Pandey et al. (2023) investigated the feasibility of a solar power combined cycle involving the Brayton cycle (BC), ORC, and KC. Their results indicate that the BC and KC are suitable for a combined cycle, while the use of ORC is discouraged. Hossain et al. utilised low-grade heat by running the KC system and optimised the KC system, and their results show an increase in power output of 1,015 kW with a 0.8 mass fraction of ammonia (Hossain et al., 2021).

Different research articles indicate the widespread utilisation of KC in various contexts, especially for harnessing waste heat or low-quality thermal energy. However, there is a dearth of literature for waste heat utilisation using KC in power plants. The present study integrates the KC with a standalone 400MW pressurised pulverised combined cycle (PPCC) plant. The KC enhances the plant's overall efficiency by utilising the waste heat available at the flue gas exhaust stream of the PPCC plant and converts the low-grade thermal energy from the flue gas into useful work resulting in increase of the plant's net power output. The additional power generation also helps in reducing the exergy destruction hence, improving the exergy efficiency. This integration helps to optimise the utilisation of available energy resources and increase the plant's overall performance.

The objectives of the present study are:

- 3-E (energy, exergy, economic) analysis of KC system
- make a comparison by considering the same parameters of the standalone and proposed plants
- parametric analysis to investigate the changes in plant efficiencies.

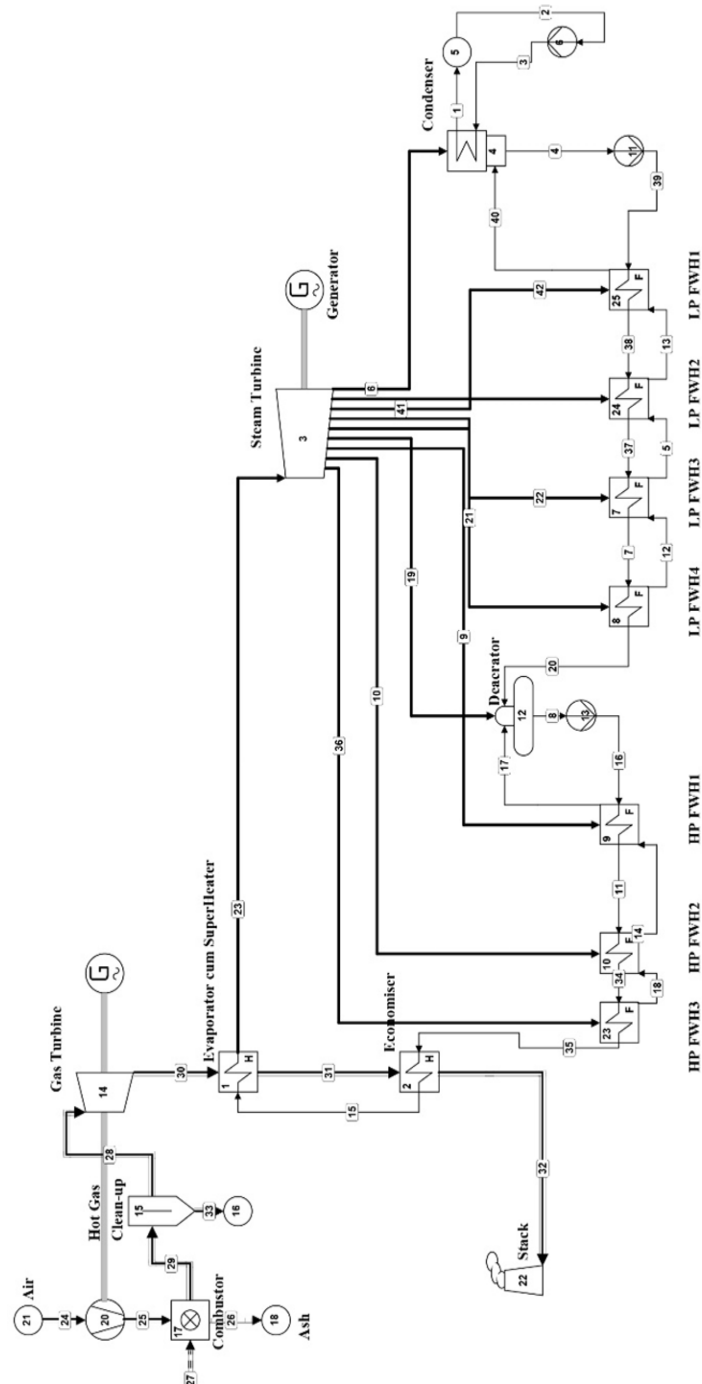
2 Methodology

The thermodynamic study is carried out using a commercially available simulation tool called 'CYCLE-TEMPO' (Delft University of Technology, 2007). Cycle-tempo serves as a valuable tool for the detailed thermodynamic analysis and optimisation of a wide range of energy conversion systems. It covers not only conventional power plants but also diverse applications such as solar ORC power plants, fuel cells, and unconventional systems like Kalina-cycle power plants. The software's ability to perform exergy analysis and its computational efficiency make it an essential resource for understanding and improving the performance of these systems (Delft University of Technology, 2007). The component modelling process begins with the power plant flow diagram. It then specifies various operational parameters for each component, such as pressure, temperature, flow rate at the inlet and exit, compressor, pump, and motor efficiency. It has many mechanical components, including a boiler, turbine, heat exchanger, compressor, pump, etc., as well as chemical components, including a combustor, gasifier, and fuel cell, and pipes for carrying various media, including water, steam, gas mix, ash, flue gases, etc. Equations for mass balance, energy balance, exergy balance, and chemical species balance primarily govern this software's mathematical model.

2.1 PPCC plant configuration

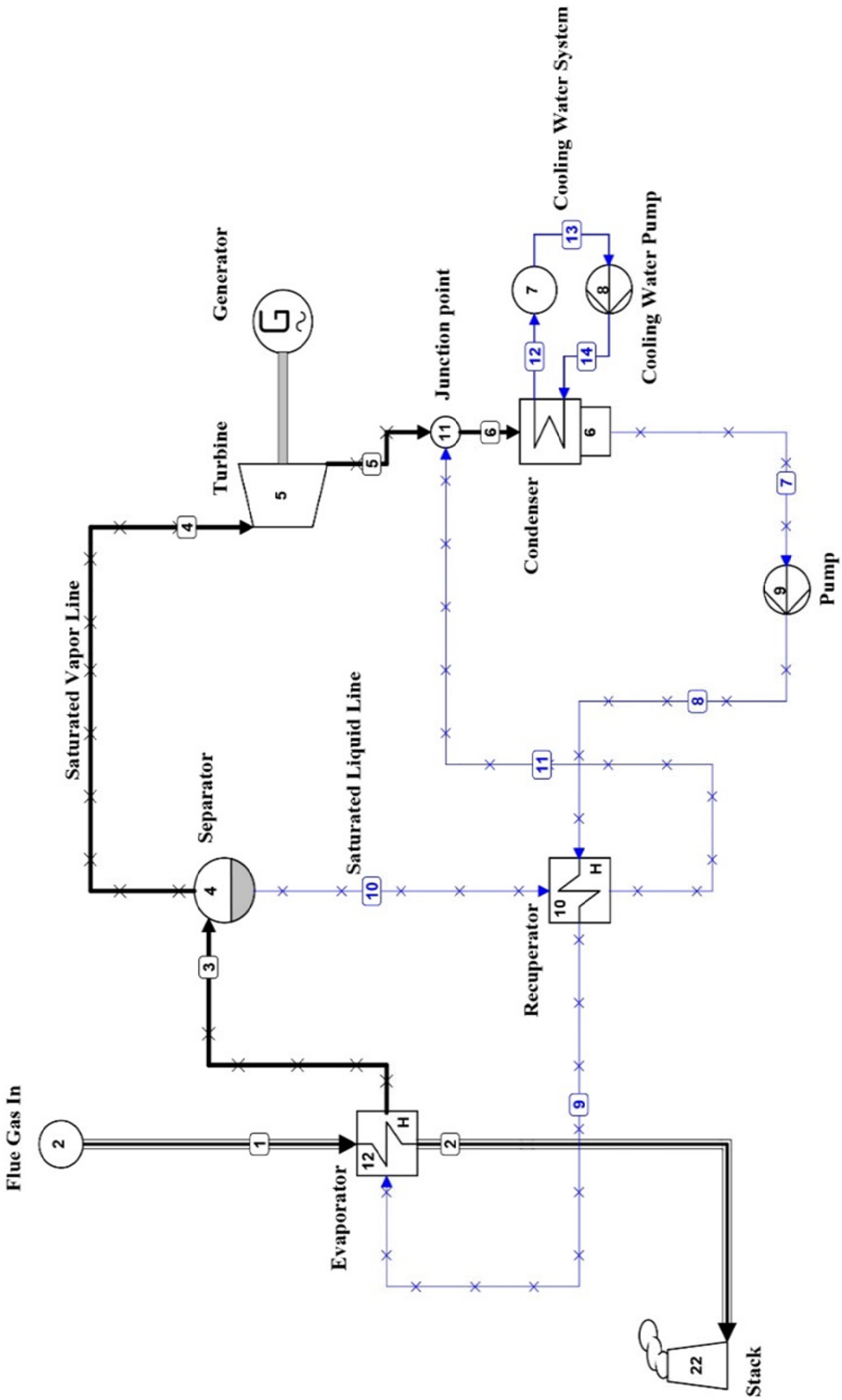
A 400MW supercritical PPCC plant employed in this study is treated as a standalone unit (Kalimuthu et al., 2017), shown in Figure 1. The plant consists of a steam turbine, a gas turbine, feed water heaters, etc. This system burns pulverised coal in a pressurised combustion chamber to generate high-temperature and high-pressure gases that drive a gas turbine. The plant has 250 bar/600°C supercritical steam characteristics for the steam cycle and gas pressure and temperature of 15.5 bar and 1593.33°C, respectively, for the gas turbines input (Kalimuthu et al., 2017). Technological improvements allow a gas turbine's input temperature to reach up to 1,600°C (Yuri et al., 2013). Following the expansion of the gas turbine, the exhaust gas passes through a heat exchanger; this residual energy is used to drive a steam turbine, which produces additional electricity.

Figure 1 Layout of PPCC plant



Source: Kalimuthu et al. (2017)

Figure 2 Layout of KC (see online version for colours)



2.2 Proposed plant (PPCC integrated with KC) configuration

In the proposed plant configuration (PPCC-KC), the KC has been incorporated into the PPCC's exhaust flue gas stream to extract the waste heat. KC is a thermodynamic cycle that utilises a binary mixture of two fluids, typically ammonia and water. An evaporator, separator, turbine, condenser, and pump are the main components of the cycle, shown in Figure 2. The process begins in the evaporator, where the heat source transfers thermal energy to the working fluid mixture. As the mixture absorbs heat, the ammonia vaporises due to its lower boiling point, while the water remains liquid. The vapour and liquid mixture then enters the separator, where the ammonia vapour is separated from the remaining liquid. The rich ammonia vapour then enters the turbine, where it expands and drives the turbine to produce power. The rich ammonia vapour exiting the turbine enters the condenser, where it is cooled and condensed back into a liquid state; after that, it enters the pump, and a high-pressure liquid mixture is sent to the evaporator, and the cycle continues. Table 1 shows the parameter of the KC system.

Table 1 KC parameters

Flue gas temperature inlet to the evaporator (°C)	280
Flue gas temperature exit to the evaporator (°C)	140
$\dot{m}$ of ammonia-water to the evaporator (kg/s)	49.77
Ammonia mass fraction (AMF) (%)	70
Turbine inlet pressure (TIP) (bar)	35
Turbine outlet pressure (bar)	8
Cooling Water (CW) inlet temperature (°C)	28
Isentropic efficiencies of turbine and pump (%)	90 and 85
Generator efficiency (%)	98.7

2.3 Fuel characteristics

In evaluating low to medium-temperature waste heat, the selection of fluids played a crucial role. High enthalpy of evaporation, thermal conductivity, and low condensation pressure are the three most essential desirable characteristics in working fluids. Finding a working fluid with all these characteristics is very challenging. A high boiling point describes water. And ammonia is a fluid which can dissolve uniformly in water, so it is possible to alter the concentration of ammonia in the water. The ammonia-water mixture's boiling point decreases as the ammonia concentration rises. Ammonia and water have a higher heat-carrying capacity than ammonia, although ammonia has a lower enthalpy of evaporation than water. These are the key elements that set KC apart from other cycles. However, the ammonia-water mixture has some drawbacks, including high condensing pressure. The Ammonia exhibits specific characteristics, including a molecular weight of 17.03 grams/mole, a critical temperature of 132°C, a critical pressure of 113 bars, a boiling temperature of –33.33°C, and an ozone depletion potential of 0 (Soltani et al., 2020).

Indian coal is used as a fuel input for the thermodynamic analysis of the PPCC plant. The composition of this coal as per ultimate analysis includes 39.2% carbon, 2.7% hydrogen, 7.9% oxygen, 0.8% nitrogen, and 0.5% sulphur. Additionally, the ash content is 48.87%. The higher heating value (HHV) of this coal is 15.846 MJ/kg (Kalimuthu et al., 2017). This coal has a high ash percentage (48.87%), which makes it considered low-grade coal, while its low sulphur level makes it high-quality coal. Because of its higher ash content, which reduces its heating value and causes more emissions when burned. However, its lower sulphur content is beneficial for the environment, as it reduces sulphur dioxide emissions, a major contributor to acid rain.

2.4 Assumptions

Based on the listed assumptions, the thermodynamic analysis has been done

- The plant that is being studied has a 400MW capacity (net) (Kalimuthu et al., 2017).
- The ambient pressure and temperature based on Indian climatic conditions are 1.013 bar and 28°C.
- The combustor pressure is 16 bar, surplus air is 90% and bottom ash temperature is 1050°C (Kalimuthu et al., 2017).
- The operating fluid of KC is ammonia water.
- The working fluid's condenser inlet temperature is higher than the cooling water's exit temperature.
- Saturated liquid condition at condenser outlet.
- Turbines and pumps are considered to have isentropic efficiency of 90% and 85%, respectively (Kalimuthu et al., 2017).

2.5 Performance parameters

The proposed plant's performance can be measured in terms of energy and exergy efficiencies (Kalimuthu et al., 2017)

$$Energy\ efficiency(\eta) = \frac{\dot{W}_{net}}{\dot{m}_{coal} \times HHV\ of\ coal} \tag{1}$$

$$Exergy\ efficiency(\varepsilon) = \frac{\dot{W}_{net}}{\Psi_{coal} \times \dot{m}_{coal}} \tag{2}$$

where $\dot{W}_{net}$ is the net power output (MW) of the proposed plant, which is the net power output from the gas turbine, steam turbine and KC, $\dot{m}$ is the mass flow rate (kg/sec) and Ψ is the specific exergy (kJ/kg).

2.6 Mathematical modelling of KC

The first and second laws of thermodynamics are used to analyse the performance of the KC. The following equations are used for system analysis (Yang et al., 2022).

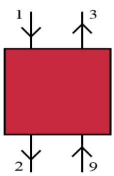
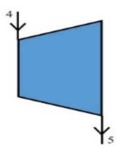
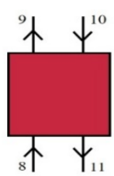
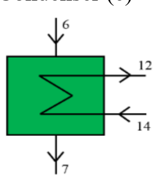
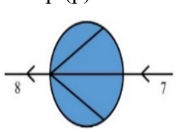
$$Energy\ balance\ equation: \sum\nolimits_i \dot{m}_i h_i + \dot{Q} = \sum\nolimits_o \dot{m}_o h_o + \dot{W} \tag{3}$$

Here, h is the specific enthalpy (kJ/kg), $\dot{Q}$ is the heat flow (kW), i represents inlet and o represents outlet

$$\text{Exergy balance equation}: \dot{E}_i = \dot{E}_o + \dot{E}_{dest} \tag{4}$$

Here, $\dot{E}_i$ is the inlet exergy flow, $\dot{E}_o$ is outlet exergy flow and $\dot{E}_{dest}$ is exergy destruction.

Table 2 Thermodynamic equations of different components used in KC

Components	*Energy equations*	*Exergy equations*
Evaporator (e) 	$\dot{m}_1 = \dot{m}_2 = \dot{m}_{EFG}$ $\dot{m}_9 = \dot{m}_3 = \dot{m}_{KC}$ $\dot{Q}_e = \dot{m}_{KC}(h_3 - h_9) = \dot{m}_{EFG}(h_1 - h_2)$	$\dot{E}_{e,dest} = \dot{m}_{EFG}(\Psi_1 - \Psi_2) - \dot{m}_{KC}(\Psi_3 - \Psi_9)$ $\varepsilon_e = \frac{\dot{m}_{KC}(\Psi_3 - \Psi_9)}{\dot{m}_{EFG}(\Psi_1 - \Psi_2)}$
Turbine (t) 	$\dot{m}_4 = \dot{m}_5 = \dot{m}_{KC} - \dot{m}_{10}$ $\dot{W}_t = \dot{m}_4(h_4 - h_5)$ $\eta_t = \frac{\dot{W}_t}{\dot{W}_{t,s}}$	$\dot{W}_{t,rev} = \dot{m}_4(\Psi_4 - \Psi_5)$ $\dot{E}_{t,dest} = \dot{W}_{t,rev} - \dot{W}_t$ $\varepsilon_t = \frac{\dot{W}_t}{\dot{W}_{t,rev}}$
Recuperator (r) 	$\dot{m}_8 = \dot{m}_9 = \dot{m}_{KC}$ $\dot{m}_{10} = \dot{m}_{11} = \dot{m}_{KC} - \dot{m}_4$ $\dot{Q}_r = \dot{m}_{KC}(h_9 - h_8) = \dot{m}_{KC} - \dot{m}_4(h_{10} - h_{11})$	$\dot{E}_{r,dest} = \dot{m}_{10}(\Psi_{10} - \Psi_{11}) - \dot{m}_{KC}(\Psi_9 - \Psi_8)$ $\varepsilon_r = \frac{\dot{m}_{KC}(\Psi_9 - \Psi_8)}{\dot{m}_{10}(\Psi_{10} - \Psi_{11})}$
Condenser (c) 	$\dot{m}_6 = \dot{m}_7 = \dot{m}_{KC}$ $\dot{m}_{14} = \dot{m}_{12} = \dot{m}_{CW}$ $Q_c = \dot{m}_{KC}(h_6 - h_7) = \dot{m}_{CW}(h_{12} - h_{14})$	$\dot{E}_{c,dest} = \dot{m}_{KC}(\Psi_6 - \Psi_7) - \dot{m}_{CW}(\Psi_{12} - \Psi_{14})$ $\varepsilon_e = \frac{\dot{m}_{CW}(\Psi_{12} - \Psi_{14})}{\dot{m}_{KC}(\Psi_6 - \Psi_7)}$
Pump (p) 	$\dot{m}_7 = \dot{m}_8 = \dot{m}_{KC}$ $\dot{W}_p = \dot{m}_{KC}(h_8 - h_7)$ $\eta_p = \frac{\dot{W}_{p,s}}{\dot{W}_p}$	$\dot{W}_{p,rev} = \dot{m}_{KC}(\Psi_8 - \Psi_7)$ $\dot{E}_{p,dest} = \dot{W}_p - \dot{W}_{p,rev}$ $\varepsilon_p = \frac{\dot{W}_{p,rev}}{\dot{W}_p}$

Now, the energy and exergy efficiency of the KC is obtained using equation (5) and equation (6),

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_i} \tag{5}$$

$$\varepsilon = \frac{\dot{W}_{net}}{\dot{E}_i} \tag{6}$$

Here, $\dot{W}_{net}$ is the net power generated through the KC, $\dot{Q}_i$ is the heat input through the exhaust flue gas (EFG) and $\dot{E}_i$ is the exergy input.

The performance analysis of the KC system's components is calculated using the energy and exergy equation of thermodynamics, shown in Table 2.

2.7 Economic assessment

For manufacturers and investors, comparing only the thermodynamics of the proposed systems is an inadequate metric. Therefore, it is essential to check the performance of the proposed system in terms of thermodynamics and economics for more realistic results. The purchased equipment cost (PEC) equation of each component of the KC system is shown in Table 3. Due to the separators and the mixing chambers incredibly low cost, their equipment purchase costs are not considered in this case. After calculating each component cost, the total PEC is calculated by adding all equipment costs. The heat transfer coefficient (kW/m^{2}K) of evaporator, condenser and recuperator used in the KC system are 0.125, 0.5, and 0.6 respectively (Mosaffa et al., 2017). This economic study considered some economic limitation such as yearly operational time (n) of 8,000 hours, interest (i) of 0.2, maintenance factor (Φ) of 1.06 and lifespan (N) of 20 years (Mosaffa et al., 2017).

$$PEC_{KC} = Z_t + Z_c + Z_p + Z_r + Z_e \tag{7}$$

Here, Z is the cost of component in Rupees (₹).

Table 3 Cost equations of various equipment of KC

KC components	*PEC*
Evaporator (e)	$Z = 1{,}397\ (A_e)^{0.89}$
Turbine (t)	$Z = 4{,}405\ \left(\dot{W}_t\right)^{0.7}$
Condenser (c)	$Z = 1{,}397\ (A_c)^{0.89}$
Pump (p)	$Z = 1{,}120\ \left(\dot{W}_p\right)^{0.8}$
Recuperator (r)	$Z = 2{,}681\ (A_r)^{0.59}$

Source: Mosaffa et al. (2017)

After calculating the PEC, the capital recovery factor (CRF) can be determined by (Mosaffa et al., 2017):

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{8}$$

The unit cost of the electricity (C_{elec}) generated from the KC system is determined by (Köse et al., 2022):

$$C_{elec} = \frac{CRF * PEC + \Phi}{\dot{W}_{net} * n} \tag{9}$$

Lastly, the payback period (PB) of system is calculated using (Köse et al., 2022):

$$PB = \frac{\log \dfrac{\left(\dot{W}_{net} * n * C_{pric}\right) - \Phi}{\left(\dot{W}_{net} * n * C_{pric}\right) - \Phi - (i * PEC)}}{\log(1+i)} \tag{10}$$

where C_{pric} is the regional cost of electricity in West Bengal, India (West Bengal Electricity Regulatory Commission, 2023) and the value is ₹ 7.32 which is equal to 0.08865 USD (1 USD = ₹ 82.57 as on 18th May 2023).

2.8 KC model validation

This study employs the same parameters as the literature (Li et al., 2013) to validate the mathematical model and calculation outcome of the KC model obtained using the Cycle Tempo software. Table 4 compares the results of the calculations based on thermal efficiency and demonstrates that the results of the model developed in this study are in good concordance with the calculation results in the literature, indicating that the KC mathematical model has good accuracy.

Table 4 Model validation of KC

	Literature (Li et al., 2013)	*Present study*
Evaporator outlet temperature (°C)	105	105
Evaporator inlet temperature (°C)	65.98	66.73
Ammonia mass fraction (%)	0.606	0.606
Expander inlet pressure (bar)	15.5	15.5
Expander outlet temperature (°C)	71.20	70.86
Condenser pressure (bar)	6.90	6.90
Condenser outlet temperature (°C)	35	35.30
Energy efficiency (%)	7.78	7.90

3 Results and discussion

The thermodynamic analysis of the PPCC-KC plant has been conducted using the same parameters as the standalone. The thermodynamic analysis reveals that the standalone plant has energy and exergy efficiencies of 43.46 % and 39.87% respectively and the proposed plant has an energy and exergy efficiencies of 44.56% and 40.88% respectively. It shows an improvement in efficiencies of about 2.53% in the proposed plant. This increment in efficiency (2.53%) is due to the utilisation of waste with the use of the KC.

3.1 Energetic and Exergetic balance of the proposed plant

Energetic and exergetic comparisons of a plant provide different types of information about the plant's performance. Energy analysis is based on the 1st law of thermodynamics, and it looks at how much energy goes into a plant and how much energy comes out of it. The energy efficiency of a plant is the ratio of how much work it does to how much energy it takes in. Energy analysis is helpful for assessing the plant's overall energy performance and identifying opportunities for energy savings. In contrast, Exergy analysis focuses on the quality of the energy input and the quality of the energy output from the plant. It is based on the 1st and 2nd laws of thermodynamics. The plant's exergetic efficiency is calculated as the ratio of useful exergy output to total exergy input. Exergy analysis is helpful for assessing the thermodynamic quality of the energy used in the plant as well as identifying opportunities to improve the efficiency of energy conversion processes.

3.1.1 Energy balance

Table 5 displays the proposed plant's energetic balance. The energetic balance allows for a comprehensive evaluation of the plant's energy efficiency. The heat energy that the coal releases serves as the plant's energy input, and the electrical energy that the plant typically produces serves as its energy output. Analysing the energetic balance makes it possible to identify areas where energy losses occur, such as the condenser, stack, and other place. This information can be used to identify opportunities for energy savings and optimise the plant's operation to improve overall energy efficiency. The table shows that the cooling water required in the condenser experiences high energy loss (24.27%).

Table 5 Energy balance

Components	*Energy balance (%)*	
	Standalone plant (Kalimuthu et al., 2017)	*Proposed plant*
Efficiency	43.46	44.56
Heat Rejected in cooling water	24.27	24.27
Heat Rejected through stack	22.67	13.36
Heat rejected through bottom ash	4.20	4.20
Heat rejected through cooling water of Kalina cycle	-	8.18
Other Losses (by difference)	5.40	5.43

3.1.2 Exergy balance

Table 6 shows the exergy balance of the standalone and the proposed plants. It provides a detailed analysis of the thermodynamic quality of the energy used and produced in the plant. Exergy is a measure of the available work that can be obtained from a given amount of energy. By analysing the exergetic balance, it is possible to identify areas where exergy losses occur due to irreversibilities in the plant, such as heat transfer losses, friction losses, etc. According to the table, the combustor has the highest exergy losses (32.32%).

Table 6 Exergy balance

Component	*Exergy balance (%)*	
	Standalone plant (Kalimuthu et al., 2017)	*Proposed plant*
Efficiency	39.87	40.88
Loss in combustor	32.32	32.32
Loss in steam generator (excluding combustor)	3.48	3.48
Loss in stack	6.78	3.68
Loss in gas turbine	2.56	2.56
Loss in steam turbine	2.15	2.15
Loss in compressor	1.57	1.57
Loss in condenser and cooling water	0.98	1.61
Loss in bottom ash	2.33	2.33
Loss in evaporator of Kalina cycle	-	1.21
Other losses (by difference)	7.96	8.21

3.2 Thermodynamic and economic results of KC

This study analyses the thermodynamics and economics of the KC, as shown in Table 7. The thermodynamic analysis reveals that the KC has an energy and exergy efficiency of 12.25% and 33.81%, respectively. The table shows that the pump work required for the process is 228.90 kW, and the cycle produces a net power of 8898 kW. The economic analysis reveals that the total PEC of the KC equipment is 775,991,433.1 rupees, with a unit cost of electricity of 2.24₹/kWh and a payback period of 1.95 years.

Table 7 Thermodynamic and economic parameters of the KC

Parameters	*Value*
$P_{t,i}$ (bar)	35
$T_{t,i}$ (°C)	167.72
$h_{t,i}$ (kJ/kg)	1,782.09
$P_{t,o}$ (bar)	8
$T_{t,o}$ (°C)	107.89
$h_{t,o}$ (kJ/kg)	1,551.85
$\dot{m}_t$ (kg / s)	39.641
$\dot{W}_p$ (kW)	228.90
$\dot{W}_{net}$ (kW)	8,898
η (%)	12.25
ε (%)	33.81
PEC (₹)	775,991,433.1
C_{elec} (₹/kWh)	2.24
PB (year)	1.95

The exergy efficiency and exergy destruction of each component used in the KC is depicted in Figure 3. The figure reveals that the evaporator exhibits the highest exergy destruction, followed by the condenser, recuperator, turbine, and pump. Additionally, the turbine demonstrates high exergy efficiency, followed by the pump, evaporator, recuperator, and condenser.

Figure 3 Exergy efficiency of KC components (see online version for colours)

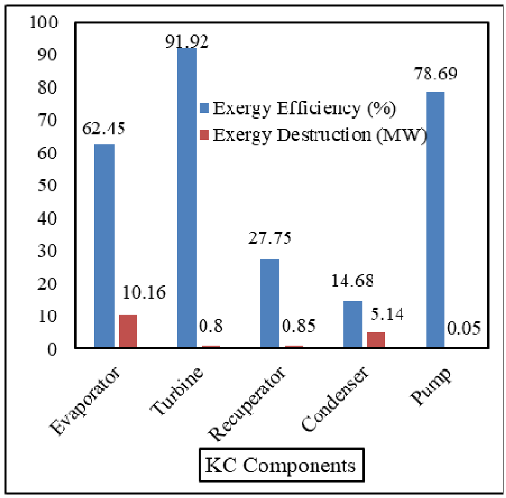
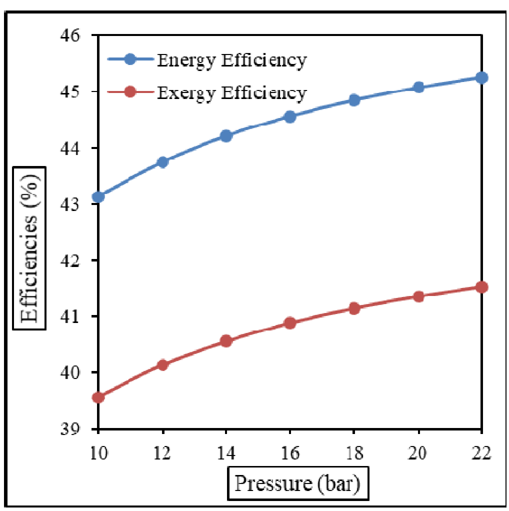


Figure 4 Effect of combustor operating pressure on efficiencies (see online version for colours)



3.3 *Environment analysis*

In India, most power plants are coal-based, and the release of greenhouse gases from these industries is a serious environmental problem. CO_2 is the most significant contributor to global warming. Other greenhouse emissions, such as SO_x and NO_x are also related to the coal-based industry, despite using low-sulphur HA coal. CO_2 is thus our primary issue for analysis. Literature tells that for one unit of electricity generation from a coal-based power plant, 0.91–0.95 kg/kWh of CO_2 is emitted, so utilising waste heat can avoid a tremendous amount of CO_2 (Mittal et al., 2012). The present study utilised the waste heat and generated 8898 kW of net additional power; that much power can avoid around 194 tonnes of CO_2 per day when compared with the coal-based power plant for the production of the same.

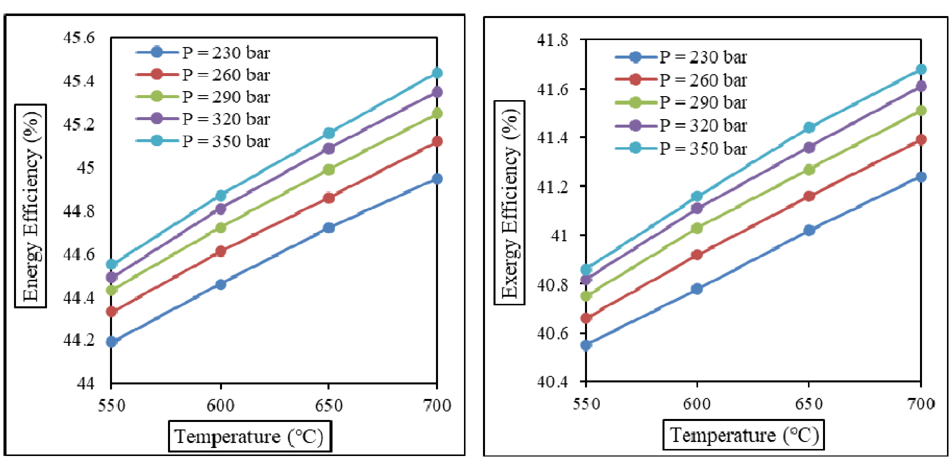
3.4 Parametric analysis

The parametric analysis measures the plant's performance by changing the variables that significantly impact its efficiency. Combustor operating pressure, Evaporator pressure, and steam parameters are the factors that the study took into account because they have an impact on efficiency. While keeping the other values fixed, specific parameters were changed.

3.4.1 Effect of combustor operating pressure on proposed plant efficiencies

Figure 4 depicts how the proposed plant's efficiencies are affected by varying combustor pressure. The figure shows that when combustor pressure increases, efficiency increases dramatically. The pressure in a combustor can significantly affect the efficiency of a thermal power plant. In general, higher combustor pressures can lead to increased thermal efficiency and reduced emissions, while lower combustor pressures can result in decreased thermal efficiency and increased emissions. Higher combustor pressure can increase the efficiency of the energy conversion process by increasing the temperature and pressure of the combustion gases. This can result in a higher temperature and pressure difference between the combustion gases and the environment, leading to more efficient conversion of energy into useful work and reducing exergy loss in the combustor.

Figure 5 Effect of steam parameters on proposed plant, (a) energy efficiency (b) exergy efficiency (see online version for colours)



(a) (b)

3.4.2 Effect of Steam parameters on efficiencies of the proposed plant

Figure 5(a) and Figure 5(b), respectively, illustrate how the steam pressure and temperature affect the efficiencies of the plant. The primary steam temperature ranges from 550°C to 700°C. Each temperature requires a different adjustment of the incoming steam pressure, which ranges from 230 to 350 bars. Both of the figures demonstrate that increasing steam pressure and temperature leads to an improvement in both energy and exergy efficiency. But metallurgical restrictions set the maximum pressure and temperature for main steam.

Figure 6 Effect of evaporator pressure on proposed plant efficiencies (see online version for colours)

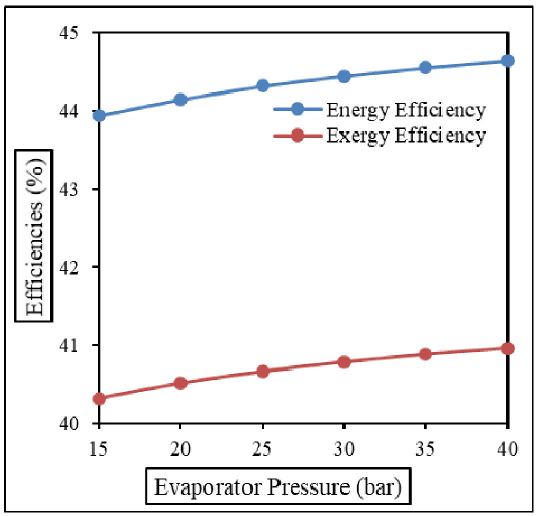
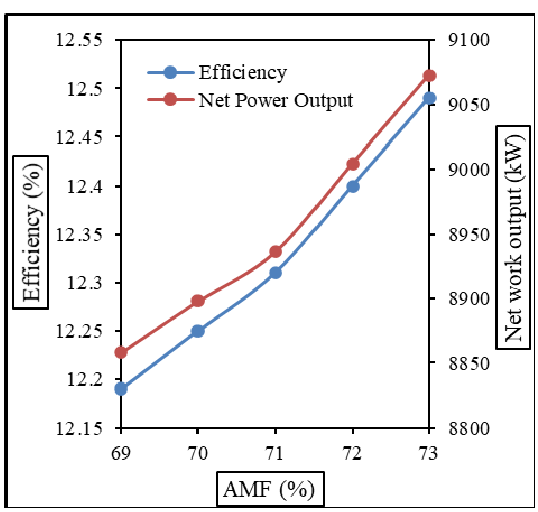


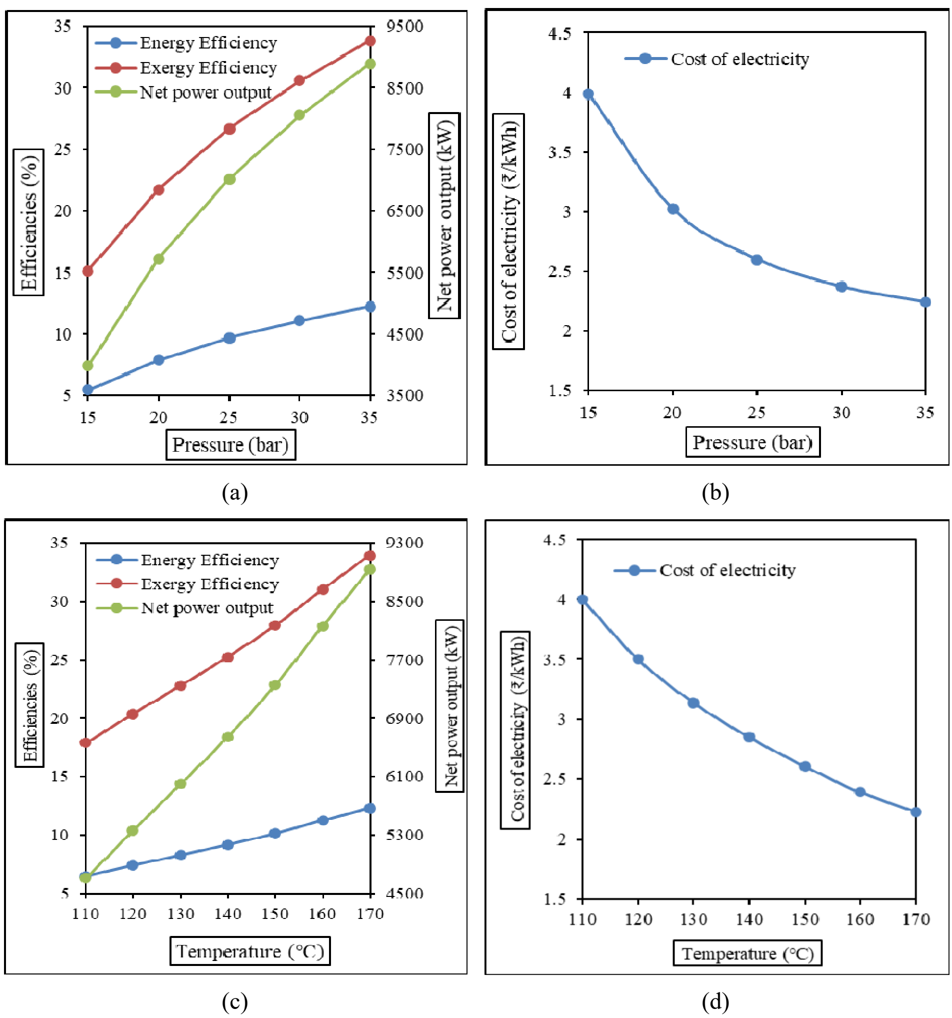
Figure 7 Effect of AMF on KC performance (see online version for colours)



3.4.3 Effect of Evaporator pressure on proposed plant efficiencies

The evaporator pressure has a direct impact on the cycle's efficiency, as shown in Figure 6. Generally, a higher evaporator pressure leads to higher thermal efficiency. This is because a higher pressure allows for a larger temperature difference between the heat source and the working fluid mixture, resulting in improved heat transfer. The high pressure increases the enthalpy of the working fluid mixture entering the turbine. This results in higher turbine work output, which increases the plant's overall efficiency.

Figure 8 (a) Effect of TIP on KC performance (b) Effect of TIP on cost of electricity of KC (c) Effect of TIT on KC performance (d) Effect of TIT on cost of electricity of KC (see online version for colours)



3.4.4 Effect of AMF on KC performance

Figure 7 illustrates how the mass fraction of ammonia affects the efficiency and power output of the KC. The KC production of power and thermal efficiency can be increased by increasing the mass percentage of ammonia in the working fluid. This is because ammonia has a lower boiling point than water, which allows for better utilisation of the heat source, due to which it can operate at higher temperatures and pressures before boiling and also because ammonia has a higher heat capacity than water, which allows for more heat to be absorbed and transferred in the system. As a result, increasing the AMF can increase the enthalpy of vaporisation, leading to higher thermal efficiency.

3.4.5 Effects of TIP and TIT on KC performance and cost of electricity

Figure 8(a) to Figure 8(d) illustrate the influence of turbine inlet pressure (TIP) and turbine inlet temperature (TIT) on KC performance and the cost of electricity. Figure 8(a) and Figure 8(c) show that when the TIP and TIT increase, the efficiencies and work output of the KC increase. This is because the increase in pressure allows more energy to be extracted from the working fluid as it expands through the turbine. This, in turn, increases the amount of work that the turbine can produce and thus improves the overall efficiency of the system. Figure 8(b) and Figure 8(d) illustrate the relationship between the turbine inlet pressure and temperature, respectively, of the KC and the cost of electricity. The figures show that increase in pressure and temperature lead to a decrease in the costs of electricity, attributed to generating higher amount of work output at elevated pressure and temperature at turbine inlet.

4 Conclusions

The followings are the major findings obtained from the present study:

- The KC produces additionally a net power output of 8.89 MW with energy and exergy efficiencies of 12.25% & 33.81%, respectively. This additional power generation helps in avoiding around 194 tonnes of CO_2 per day if equal amount of power is being produced from a conventional coal-based thermal power plant
- The payback period and unit cost of electricity for the KC system are 1.95 years and ₹ 2.24/kWh, respectively.
- The KC performance increases with increasing ammonia mass fraction, turbine inlet temperature and pressure, and the cost of electricity reduces with increasing turbine inlet temperature and pressure.
- The integrated PPCC-KC plant has an energy and exergy efficiencies of 44.56% and 40.88%, respectively. Furthermore, its energy balance shows that maximum loss takes place in the condenser; in contrast, exergy balance shows maximum loss in the combustor.

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