Energy, exergy, economic, and environmental (4E) analyses and optimization of a CCHP system with steam turbine

Mahmood Chahartaghi1 | Reza Namdarian1 | Seyed Majid Hashemian1 | Rahmat Malek1 | Seyedesmail Hashemi2

1Faculty of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran
2Faculty of Economics, Allameh Tabataba’i University, Tehran, Iran

Abstract
Due to finding solutions to reduce energy consumption and improve the electricity production efficiency in the power cycles, using the waste heat of power cycles in the combined generation systems can be a useful approach. Also, by using the wasted energy of the power generation cycles, the cooling and heating demands can be met. Therefore, this study presents energy, exergy, economic, and environmental evaluations of a new configuration of combined cooling, heating, and power (CCHP) or tri-generation system with a steam turbine. This CCHP system includes a steam boiler, a steam turbine, a heat exchanger, a single-effect absorption chiller, and pumps. Some important performance parameters such as electrical efficiency, combined electrical and cooling efficiency, combined electrical and heating efficiency, and tri-generation efficiency, as well as exergy efficiency, are considered. Also, various output and environmental performance parameters such as percentage of operational cost reduction, percentage of fuel consumption reduction, percentage of pollutant emission reduction, and economic and technical issues based on different inlet temperatures and pressures of the steam turbine are investigated. In addition, the performance of the absorption chiller at different operating conditions has been investigated. This study shows that the usage of the CCHP system leads to reduction of 24.91% in carbon dioxide emission, 15.83% in fuel consumption, and 35.34% in operating costs compared with conventional systems. Also, the results show that there is a good improvement in the overall performance of the system with the tri-generation efficiency of 82.46%.

KEYWORDS
carbon dioxide reduction, CCHP, exergy efficiency, fuel cost reduction, Rankine cycle, tri-generation efficiency
1 | INTRODUCTION

Recently, combined cooling heating and power (CCHP) or tri-generation plants have been attracting a lot of attention due to their higher thermal efficiency, lower operational costs, and lower pollutant emission. Due to greenhouse gas emissions and the issue of reduction in the amount of fossil fuels and global warming, the use of effective systems such as the tri-generation system becomes even more important. The power generated by the tri-generation system is achieved by one or more prime movers; for example, gas turbines,\textsuperscript{1,2} combustion engines,\textsuperscript{3,4} fuel cells,\textsuperscript{5} and Stirling engines.\textsuperscript{6,7} The steam turbine used in the Rankine cycle can be utilized in a tri-generation system. The Rankine cycle is similar to the organic Rankine cycle (ORC). The only difference is that in the Rankine cycle, water steam is utilized, and in the ORC, some types of organic fluids are used.

Al-Sulaiman et al\textsuperscript{5} illustrated that for a tri-generation system including an ORC and a solid oxide fuel cell (SOFC), the highest value of electrical efficiency could be 14\%, and by using the tri-generation system, the overall efficiency can increase up to 89\%. In another study, Al-Sulaiman et al\textsuperscript{3} showed that there had been many studies of tri-generation systems with internal combustion engines as prime movers, and few studies have been conducted on gas turbines and microturbines as the main prime movers. Also, most studies have been performed based on energy and economic analyses, and less attention was paid to exergy, environmental, and thermo-economic analyses of the tri-generation system compared with their energy and economic investigations. Tom\textsuperscript{8} showed that there are concerns about fossil fuel consumption and increase in the greenhouse gas emissions. So, developing the systems to achieve higher efficiency is needed to raise the proportion of energy output per unit of the fuel consumption. For a conventional power plant, thermal efficiency is almost lower than 40\%. Therefore, 60\% or more of the energy of a system is not used. Also, the overall thermal efficiency for a power plant that separately generates electricity and heat is about 60\%. Jradi and Riffat\textsuperscript{9} studied various prime movers and cooling systems, which were applicable for operation in the hybrid systems. Also, they discussed recent strategies for optimizing the performance of CCHP systems and increasing their efficiency. Ahmadi et al\textsuperscript{10} presented thermodynamic modeling of a combined cooling, heating, and power system. The prime movers in their tri-generation system were steam and gas turbines. They performed energy, environmental, and exergy analyses. The impacts of operating parameters on energy, exergy and energy, and exergy efficiencies were also investigated. Sanaye et al\textsuperscript{11} showed that selecting the type of prime mover could be a very important point for performance of tri-generation systems. However, according to various types of prime movers, some studies have been performed. Chahartaghi and Alizadeh\textsuperscript{12} presented PEM fuel cell as a prime mover of CCHP systems for residential applications. In their study, energy and exergy analyses have been performed for the system. Also, they reported a 45\% decline in the consumption of fuel in comparison with conventional systems for the same application. Wu and Wang\textsuperscript{13} proposed a CCHP system to supply energy, in which the electrical energy required on-site was generated by the prime mover, and the waste heat of the prime mover was recovered to provide heating and cooling demands. Through recovering the waste heat from the system, the CCHP efficiency can improve from 60\% to 90\%. Sheykhi et al\textsuperscript{14} illustrated that the use of hybrid prime mover in combined heat and power (CHP) or cogeneration systems led to a significant increase in the power generation, thermal efficiency, and initial energy savings. Also, by using the hybrid system, carbon dioxide emissions and payback periods have been significantly reduced.

Also, some studies have been presented about energy, economic, exergy, and environmental (4E) analysis of the combined generation systems. Xu et al\textsuperscript{15} presented the performance of low-grade compression-absorption refrigeration cycles based on 4E analyses. They evaluated some main parameters of the system such as COP, exergy destruction, total cost, and carbon dioxide generation cost at different operating conditions. Cui et al\textsuperscript{16} presented the performance of cascade absorption refrigeration cycle for recovering low temperature waste heat according to energy, exergy, and economic analyses. Also, they utilized the algorithm genetic method to optimize the cost and exergy destruction of their system. Liu et al\textsuperscript{17} performed 4E analyses of a combined generation system including CO\textsubscript{2} capture system, organic Rankine cycle, and absorption refrigeration system. The ORC efficiency and exergy destructions of the ORC and absorption system were evaluated, and the life cycle assessment was utilized for environmental analysis of the system.

Ghaebi et al\textsuperscript{18} performed 4E analyses of two combined power and hydrogen production cycles. These cycles included a city gate station system, a Rankine cycle, a PEM electrolyzer, and an absorption power system. They estimated some performance parameters of the systems such as energy efficiency, exergy efficiency, and total cost of system, as well as carbon dioxide production.

Arabkoohsar and Nami\textsuperscript{19} performed thermodynamic and economic analyses of a CHP-ORC system with waste heat recovery. Carvalho et al\textsuperscript{20} studied the analysis of the life cycle for a tri-generation system in a hospital. The main aims of their research were minimizing the annual costs and evaluating CO\textsubscript{2} emissions. Al-Sulaiman et al\textsuperscript{21} performed energy and exergy evaluations of a tri-generation system based on SOFC and ORC. By using the tri-generation system, there was up to 25 percent profitability in the exergy efficiency compared with the electric power cycle. Pantaleo et al\textsuperscript{22} presented technical and economic
comparisons between steam and gas turbines as top cycles for the CHP system. To raise the efficiency, they integrated an ORC to these cycles and evaluated the system performance. Fang et al.\textsuperscript{23} presented a new configuration for the CCHP-ORC system that can adjust electricity to thermal energy by modifying the electric chiller and load of the ORC system. Kim and Perez-Blanco\textsuperscript{24} utilized an ORC and a compression refrigeration cycle for combined electricity and cooling generation. They also presented sensitivity analysis on some parameters, such as the inlet pressure and temperature of the steam turbine. Zhao et al.\textsuperscript{25} performed sensitivity analysis of the effective parameters of a CCHP system consisting of steam and gas turbines, a SOFC, and a LiBr-water absorption chiller to provide electricity, heating, and cooling demands. Javan et al.\textsuperscript{26} utilized an ORC, an ejector refrigeration system, and hot water steam as the energy sources of a CCHP system to recover the heat loss of an internal combustion engine. Also, they optimized the system to achieve the highest exergy efficiency and lowest total system cost. Zare\textsuperscript{27} compared the ORC and Kalina cycles to generate power by using the geothermal energy. Also, he connected a hot water system and an absorption refrigeration cycle to the mentioned cycles to produce hot and cold water as a tri-generation system. Then, the genetic algorithm was used for optimization of both cycles. He illustrated that the Kalina cycle had higher exergy efficiency than the ORC. Cho et al.\textsuperscript{28} investigated various energy and exergy analyses of CCHP systems for evaluating their optimum performance.

According to previous works, a comprehensive research for analysis of a CCHP system with steam turbine can be useful.

Due to the importance of energy consumption, especially fossil fuels, which are nonrenewable fuels, reductions in energy consumption and air pollution are important issues that have attracted the attention of researchers in these years. In addition, the CCHP systems can simultaneously meet the cooling and heating needs of different buildings from the wasted energy of the power plants.

Therefore, in this research, energy, exergy, economic, and environmental analyses of a new configuration of CCHP system with the steam turbine as prime mover have been conducted. Few studies have been performed on the prime mover of steam turbine compared with other prime movers in the tri-generation applications. In some of the previous works, the organic Rankine cycle was studied, but the Rankine cycle was not analyzed in the CCHP with absorption chiller. Also, the analyses in many of the previous works were performed based on one or two perspectives including energy, economics, and environment. But, in this paper, a comprehensive study by consideration of energy, exergy, economic, and environmental (4E) issues has been carried out and the performance parameters of the system such as tri-generation system efficiency, percentage of emission reduction, percentage of fuel consumption reduction, percentage of operational cost reduction, and economic evaluation under different conditions of inlet temperatures and pressures to the steam turbine have been investigated. Also, optimization of the performance of the CCHP system has been conducted. The objective function of this optimization is the percentage of fuel cost reduction (CR) of the CCHP system.

Consequently, this study is a comprehensive research and can be complement of the previous papers.

## 2 | SYSTEM DESCRIPTION

Different types of prime mover can be used in the CCHP plants. The proposed CCHP system includes a boiler that uses natural gas in the combustion chamber, a steam turbine to generate electricity, a heat exchanger to produce the required heat, and a single-effect LiBr-water absorption chiller for cooling requirements as shown in Figure 1. It can be noticed that in this system, there are two cycles including Rankine cycle (steam turbine cycle) as power generation unit and the absorption chiller. The released heat from the combustion of natural gas is used as the heat source of the Rankine cycle. The waste heat in the Rankine cycle is used to supply the cooling and heating demands, in which some part of the waste heat is utilized by heat exchanger for heating demand, and the other part of the waste heat is utilized in the absorption chiller for cooling purposes.

In the Rankine cycle, water as saturated liquid leaves the desorber at point 14 and enters the pump and its pressure rises. Then, water enters the boiler, and after absorbing the heat of combustion, the superheated vapor leaves the boiler. It enters the turbine at point 11, and after expansion, the output work is generated. The expanded fluid then leaves the turbine at point 12 and enters the heat exchanger to supply heating demands and then enters the desorber of absorption chiller at point 13 as the heat source of the chiller.

By using the input heat of the desorber, water evaporates from the mixture of the LiBr-water and enters the condenser (point 7). In the condenser, the water vapor condenses and leaves the condenser as saturated liquid (point 8). After that, the water is throttled and enters the evaporator of chiller (point 9) at low temperature as liquid-vapor mixture. The evaporator supplies the cooling demands of the system. Then, water as vapor leaves the evaporator and enters the absorber (point 10) and is absorbed by the LiBr and changed into solution mixture of LiBr-water. The mixture leaves the absorber (point 1) and is pumped to the heat exchanger (point 2). Then, the mixture is preheated by the heat exchanger and leaves it and enters the desorber (point...
3) and the cycle is completed. In this study, natural gas is selected as fuel in the Rankine cycle, and its properties are listed in Table 1. Several assumptions have been used to perform system modeling and analysis. The system works at steady state, and the single-effect absorption chiller can operate at its full cooling capacity. Also, the pressure changes can be neglected except for pumps, turbines, and valves. Also, the combustion is assumed to be complete, and therefore, the combustion products have only CO₂ emission as a greenhouse gas. This model is developed using analysis, which is discussed below. To solve the operating equations, the Engineering Equation Solver (EES) is used. The input data used are listed in Table 1.

### TABLE 1 Input value for system

| Parameter                      | Value |
|-------------------------------|-------|
| Boiler efficiency             | 0.7   |
| Electrical generator efficiency| 0.97  |
| Turbine isentropic efficiency | 0.85  |
| Heat exchanger efficiency     | 0.8   |
| Isentropic efficiency of cycle pump | 0.8  |
| Ambient temperature (K)       | 298   |
| Ambient pressure (kPa)        | 101.3 |
| LHV of natural gas (kJ/kg)    | 46 250|
| Lifetime of equipment (year)  | 20    |

### 3 | MODELING

The system modeling has been considered based on energy, exergy, environmental, and economic issues.

#### 3.1 Energy and exergy analyses

In this section, energy and exergy analyses for the system have been presented. The conditions of each point have been illustrated in Figure 1. The power generated by the turbine depends on the mass flow rate in the steam turbine and the enthalpy difference in the turbine according to Equation (1).

\[
W_{st} = \dot{m}_s (h_{11} - h_{12}) \eta_{gen}
\]  

where \( h_{12} \) is the outlet enthalpy of the steam turbine, which is calculated in real terms from Equation (2).

\[
h_{12} = h_{11} - \eta_{st} (h_{11} - h_{12v})
\]  

The output work of the pump is obtained from Equation (3).

\[
W_p = \dot{m}_s v_{14} (P_{15} - P_{14})
\]  

\( P_{14} \) and \( P_{15} \) are the pressure of the water at the inlet and outlet sections of the pump.

![Schematic of the proposed CCHP system](image-url)
The net power of the system is calculated from Equation (4):
\[ W_{net} = (W_{n} - W_{p}) \]  

(4)

The overall rate of heat released by natural gas combustion is obtained by Equation (5):
\[ Q_i = m_F \cdot \text{LHV}_F \cdot \eta_b \]  

(5)

where \( m_F \) is the fuel mass rate, and \( \text{LHV}_F \) is the lower heating value of the fuel.

The electrical efficiency of the system is obtained from Equation (6):
\[ \eta_{El} = \frac{W_{net}}{Q_i} \]  

(6)

The combined electrical and heating (cogeneration of electrical and heating) efficiency is calculated according to Equation (7):
\[ \eta_{cog,h} = \frac{W_{net} + Q_h}{Q_i} \]  

(7)

The heating capacity is obtained from Equation (8):
\[ Q_h = m_s (h_{12} - h_{13}) \times \eta_{he} \]  

(8)

where \( \eta_{he} \) is the heat exchanger efficiency.

The combined electrical and cooling efficiency (\( \eta_{cog,c} \)) is defined by Equation (9):
\[ \eta_{cog,c} = \frac{W_{net} + Q_{ev}}{Q_i} \]  

(9)

where the subscripts of cog, c, and ev denote the combined electrical and cooling (cogeneration of power and cooling) and evaporator.

Also, the governing relations of desorber of absorption chiller, according to balances of mass and energy, can be presented by Equations (10)-(12),
\[ m_3 = m_4 + m_7 \]  

(10)
\[ m_3x_3 = m_4x_4 \]  

(11)
\[ m_3h_3 - m_4h_4 - m_7h_7 + Q_{Des} = 0 \]  

(12)

where \( x \) is the solution concentration, and \( Q_{Des} \) is the input heat to the desorber (generator) as waste heat of power cycle.

In addition, the governing relations of elements of absorption chiller, including the evaporator, the condenser, and the absorber, are presented in Equations (13)-(16), respectively:
\[ Q_{ev} = m_s (h_{10} - h_9) \]  

(13)
\[ Q_{con} = m_s (h_7 - h_8) \]  

(14)
\[ m_1 + h_6 - Q_{abs} - m_1h_1 = 0 \]  

(15)
\[ \text{COP} = \frac{Q_{ev}}{Q_{Des}} \]  

(16)

where \( Q_{ev}, Q_{con}, Q_{abs} \), and COP are the cooling capacity of the evaporator, heat output by the condenser, the heat output of the absorber, and the coefficient of performance of the absorption chiller, respectively.

The efficiency of the tri-generation system is calculated according to Equation (17):
\[ \eta_{tri} = \frac{W_{net} + Q_h + Q_{ev}}{Q_i} \]  

(17)

The electrical exergy efficiency of the proposed system is calculated according to Equation (18):
\[ \eta_{ex,el} = \frac{W_{net}}{E_{sj}} \]  

(18)

where \( E_{sj} \) is the rate of exergy of fuel obtained from Equation (19):
\[ E_{sj} = m_f \cdot e_{sf} \]  

(19)

where \( e_{sf} \) is the chemical exergy of fuel, and it is obtained from Equation (20):
\[ e_{sf} = \varphi \cdot \text{LHV}_F \]  

(20)

where \( \varphi \) is the ratio of fuel chemical exergy to the heating value. For natural gas, the value of \( \varphi \) is considered to be 1.04. The combined exergy efficiency of electricity and cooling (\( \eta_{ex,cog,c} \)) is obtained from Equation (21):
\[ \eta_{ex,cog,c} = \frac{W_{net} + \left( \frac{T_0 - T_w}{T_{ev}} \right) Q_{ev}}{E_{sj}} \]  

(21)

where \( T_0 \) is the ambient temperature.

The combined exergy efficiency of electricity and heating is obtained from Equation (22):
\[ \eta_{ex,cog,h} = \frac{W_{net} + \left( 1 - \frac{T_0}{T_w} \right) Q_h}{E_{sj}} \]  

(22)
The exergy efficiency for the tri-generation system is obtained according to Equation (23).

$$\eta_{ex,tri} = \frac{\dot{W}_{net} + \left( \frac{T_h - T_c}{T_c} \right) \dot{Q}_{ev} + \left( 1 - \frac{T_h}{T_c} \right) \dot{Q}_h}{F_{x,y}}$$  \hspace{1cm} (23)$$

The electric-to-heating ratio and the electric-to-cooling ratio are defined and calculated from Equations (24) and (25), respectively.31

$$r_{el,h} = \frac{\dot{W}_{net}}{\dot{Q}_h}$$  \hspace{1cm} (24)$$

$$r_{el,c} = \frac{\dot{W}_{net}}{\dot{Q}_c}$$  \hspace{1cm} (25)$$

Also, the following equations are used to evaluate the CCHP system from the issues of consumption of fuel and TPES (primary energy saving), compared with the conventional systems.34

$$F_\text{CCHP} = \dot{Q}_i$$  \hspace{1cm} (26)$$

$$F^{SP} = \frac{\dot{W}_{net}}{\eta_{i,e}^{SP}} + \frac{\dot{Q}_{efficiency}}{\eta_{i,e}^{SP}} + \frac{\dot{Q}_{ev}}{\eta_{e,COP_{El}}^{SP}}$$  \hspace{1cm} (27)$$

where \( F_\text{CCHP} \) and \( F^{SP} \) are the amounts of fuel consumed for the CCHP (tri-generation) system and the amount of fuel consumed for the conventional system, respectively. The primary energy saving (TPES) is calculated from Equation (28).26,34

$$\text{TPES} = 100 \left( \frac{F^{SP} - F_\text{CCHP}}{F^{SP}} \right)$$  \hspace{1cm} (28)$$

### 3.2 Environmental analysis

The carbon dioxide reduction index (TCO2ER) is used to evaluate the reduction of CO2 emissions in the tri-generation system compared with a conventional system. To determine TCO2ER, the mass of CO2 produced by the CCHP system \( m\text{CO}_2^{CCHP} \) and that for the conventional system \( m\text{CO}_2^{SP} \) are used. Therefore, Equations (29) and (30) can be presented.34

$$m\text{CO}_2^{CCHP} = \mu\text{CO}_2^{F} F_\text{CCHP}$$  \hspace{1cm} (29)$$

$$m\text{CO}_2^{SP} = \mu\text{CO}_2^{W} \left( \dot{W}_{net} \right) + \frac{\mu\text{CO}_2^{F} \left( \dot{Q}_h \right)}{\eta_{i,e}^{SP}} + \frac{\mu\text{CO}_2^{W} \left( \dot{Q}_{ev} \right)}{\eta_{e,COP_{El}}^{SP}}$$  \hspace{1cm} (30)$$

where \( \mu\text{CO}_2^{F} \) and \( \mu\text{CO}_2^{W} \) are the carbon dioxide emission factors for fuel and network electricity, respectively.

| Equipment          | Initial investment cost ($/kW) | Operating and maintenance cost ($/kW) |
|--------------------|--------------------------------|-------------------------------------|
| Steam turbine      | 6000 \( \left( W_{net}^{0.7} \right) \) | 0.008                               |
| Heat exchanger     | 30                             | 0.003                               |
| Absorption chiller | 160                            | 0.001                               |
| Pump               | 3540 \( \left( W_{P} \right)^{0.71} \) | 0.01                                |
| Boiler             | 50                             | 0.0027                              |

According to Equation (31), TCO2ER is calculated as follows.

$$\text{TCO}_2\text{ER} = 100 \left( \frac{m\text{CO}_2^{SP} - m\text{CO}_2^{CCHP}}{m\text{CO}_2^{SP}} \right)$$  \hspace{1cm} (31)$$

### 3.3 Economic analysis

In this section, the economic analysis covers all initial investment costs, operating costs, and maintenance costs, which for the CCHP system equipment are presented in Table 2.

#### 3.3.1 Net present value (NPV)

Investment costs are incurred at the start of the installation of the CCHP system, and its operating costs are incurred when using the equipment. Also, the equipment salvage costs will be returned at the end of the equipment life cycle operation. So, in order to compare them better, all these costs must match with the scenarios under consideration. The present net worth approach solves this by matching all costs at present.34,35 The net present value of the investment cost (NPWC) is defined by Equation (32).36

$$\text{NPWC} = \sum_{j=1}^{N} (C \times NC)_j$$  \hspace{1cm} (32)$$

where \( C \) represents the cost of investment by the capacity for each element, and \( NC \) denotes the nominal element capacity.

The net present worth benefit (NPWB) and the revenue of element salvage (SV) and annual system revenue \( (A) \) can be estimated by Equations (33)-(35).33,34

$$\text{NPWB} = A \times \left[ \frac{1 + i)^n - 1}{i(1 + i)^n} \right] + SV \times \left[ \frac{1}{(1 + i)^n} \right]$$  \hspace{1cm} (33)$$

$$SV = 0.2 \times \text{NPWC}$$  \hspace{1cm} (34)$$

$$A = \left( \text{Cost}^{SP} - \text{Cost}^{CCHP} \right) - \text{Cost}^{Service, CCHP}$$  \hspace{1cm} (35)$$
3.3.2 | Fuel costs

The fuel costs include purchasing natural gas and electricity from the grid for both of conventional system and of CCHP. It is assumed that, at nominal capacity, the CCHP system can meet the electrical, heating, and cooling demands without purchasing additional gas or electricity from the grid. In the CCHP system, to estimate the CR (fuel cost reduction), the fuel cost of the system to meet the energy requirements is illustrated in Equation (36). Then, for the conventional system, the fuel cost to provide the same energy amount is calculated from Equation (37).

\[
\text{Cost}^{\text{CCHP}} = \text{Cost}_F^{\text{CCHP}} \quad (36)
\]

\[
\text{Cost}^{sp} = \text{cost}_W (\dot{W}_{net}) + \left( \frac{\text{Cost}_F (\dot{Q}_h)}{\eta_{SP}^{EI}} \right) + \left( \frac{\text{Cost}_W (\dot{Q}_{ev})}{\text{COP}_{SP}^{EI}} \right) \quad (37)
\]

In these equations, \(\text{Cost}_W\) and \(\text{Cost}_F\) illustrate world-wide tariffs for electricity and fuel, respectively. The percentage of reduction in costs of the CCHP system in comparison with a conventional system is calculated from Equation (38).

\[
\text{CR} = 100 \left( \frac{\text{Cost}^{sp} - \text{Cost}^{\text{CCHP}}}{\text{Cost}^{sp}} \right) \quad (38)
\]

3.3.3 | Payback period

Calculation of the payback period (PB) traditionally is a quick and approximate way of comparing the projects economically and determining the time required for an initial investment with annual revenue and is obtained by Equation (39).

\[
-p + \sum_{y=1}^{PB} CF_y = 0 \quad (39)
\]

In another method, the payback period of the system with regard to the lifetime of the equipment and the interest rate can be evaluated. According to Equation (40), since the net present worth benefit (NPWB) is the same as the net present value of worth cost (NPWC), the PB is equal with \(y\).

\[
\text{NPWB} (y) - \text{NPWC} (y) = 0
\]

4 | VALIDATION

4.1 | Validation of the thermodynamic simulation of the absorption chiller

The results of Kaushik and Arora have been used to validate the thermodynamic simulation of the single-effect absorption chiller. Table 4 compares the results of the present study and the study of Kaushik and Arora. In this table, the input data are used as follows.

\[T_{gen} = 87.8^\circ \text{C}, \quad T_{eva} = 7.2^\circ \text{C}, \quad T_{cond} = T_{abs} = 37.8^\circ \text{C}, \quad E_L = 0.7\]

4.2 | Validation of the steam turbine

The results of Shabbir et al. have been used to validate the thermodynamic simulation of the steam turbine. Table 5 compares the results of the present study and the Ref.. In this table, the input data are used as follows.

\[T_11 = 300^\circ \text{C}, \quad P_{11} = 3300 \text{ kPa}, \quad P_{12} = 1000 \text{ kPa}\]

5 | RESULTS AND DISCUSSION

The CCHP system performance is evaluated through various parameters such as exergy and energy efficiencies, power, and the ratio of electrical power to heating and cooling capacity, as well as economic analysis and the percentage of carbon dioxide emissions. These parameters are investigated in the basic state with the steam turbine inlet temperature of 300°C and the inlet pressure of 3300 kPa and outlet pressure

| TABLE 3 | The input conditions for analyses of TCO2ER, TPES, and CR
| Parameter | Unit | Value \\
| COP\(_{EI}^{SP}\) | (-) | 3 \\
| \(\eta_{EL}^{sp}\) | (-) | 0.3 \\
| \(\eta_{SP}^{eli}\) | (-) | 0.8 \\
| \(\mu CO_2^F\) | (gr/kWh) | 170.65 \\
| \(\mu CO_2^W\) | (gr/kWh) | 705.55 \\
| Cost\(_F\) | ($/kWh) | 0.1 \\
| Cost\(_W\) | ($/kWh) | 0.02 |

| TABLE 4 | Validation of the thermodynamic simulation of the absorption chiller
| Parameter | Energy (kW) | Present work | Ref42 | Difference (%) \\
| \(Q_{gen}\) | 3095 | 3095.70 | 0.02 \\
| \(Q_{ev}\) | 2974.539 | 2945.27 | 0.99 \\
| \(Q_{cond}\) | 2537.521 | 2505.91 | 1.29 \\
| \(Q_{eva}\) | 2417.032 | 2355.45 | 2.6 \\
| COP | 0.781 | 0.7609 | 2.6 |
of 1000 kPa. Then, by change in the inlet temperature and pressure of the turbine, the system performance is estimated. The thermodynamic properties of different points in the CCHP system are presented in Table 6. The cooling capacity is assumed to be constant at maximum value for the single-effect absorption chiller.

Figure 2 shows the effect of increasing the steam turbine inlet temperature on the electrical power and heating capacity. Since the inlet temperature of the turbine increases, the electric power and heating capacity will increase due to the increase in the enthalpy difference between the outlet and inlet of the turbine and the heat exchanger. In fact, by increasing the inlet temperature to the steam turbine, the inlet energy to the cycle rises due to increase in the fuel consumption.

Figure 3 shows the effect of the inlet pressure changes in the turbine on the electrical power and the heating capacity at inlet temperature of the turbine equal with 300°C. It can be concluded that, due to the increase in the enthalpy difference in the inlet and outlet of the turbine, the electrical power increases and the heating capacity decreases due to decrease in the enthalpy difference in the inlet and outlet of the heat exchanger.

Figure 4 illustrates the influence of the inlet temperature of the steam turbine on the ratio of electrical power to heating and cooling capacities. With rising the inlet temperature of the steam turbine, the electrical power and heating capacity increase. However, due to the greater variation rate of the electrical power than heating capacity, the ratio of electrical power to heating capacity increases. The cooling capacity is assumed to be constant (at maximum chiller capacity), so the

| TABLE 5 | Validation of thermodynamic simulation of steam turbine |
|---------|-------------------------------------------------------|
| Parameter | Symbol | Present work | Ref29 | Difference (%) |
| Output temperature (°C) | $T_{12}$ | 179.92 | 180 | 0.04 |
| Output enthalpy (kJ/kg) | $h_{12}$ | 2767.90 | 2769.87 | 0.035 |
| Output power (kW) | $w_n$ | 1801 | 1800.02 | 0.054 |
| Output isentropic enthalpy (kJ/kg) | $h_{12s}$ | 2730 | 2731.94 | 0.0710 |

| TABLE 6 | Thermodynamic properties of different points in the CCHP system |
|---------|---------------------------------------------------------------|
| State | $P$ (kPa) | $m$ (kg/s) | $T$ (°C) | $h$ (kJ kg) |
| 1 | 1.016 | 8.0330 | 23.14 | 41.69 |
| 2 | 6.550 | 8.0330 | 23.14 | 41.70 |
| 3 | 6.550 | 8.0330 | 51.06 | 104.73 |
| 4 | 6.550 | 5.9276 | 90 | 228.60 |
| 5 | 6.550 | 5.9276 | 43.20 | 143.18 |
| 6 | 1.016 | 5.9276 | 52.64 | 143.18 |
| 7 | 6.550 | 2.1054 | 56.67 | 2605.22 |
| 8 | 6.550 | 2.1054 | 37.78 | 158.20 |
| 9 | 1.016 | 2.1054 | 7.20 | 158.20 |
| 10 | 1.016 | 2.1054 | 7.20 | 2513.75 |
| 11 | 3300 | 8.63 | 300 | 2983.01 |
| 12 | 1000 | 8.63 | 179.92 | 2767.90 |
| 13 | 1000 | 8.63 | 179.92 | 1458 |
| 14 | 1000 | 8.63 | 179.92 | 762.88 |
| 15 | 3300 | 8.63 | 180.31 | 765.75 |
The ratio of electrical power to the cooling capacity will increase due to rise in the electrical power.

Figure 5 illustrates the influence of the inlet pressure of steam turbine on the ratio of electrical power to the heating and cooling capacities. As the inlet pressure to the steam turbine increases, the electric power increases and the heating capacity decreases. Therefore, the ratio of electric power to the heating capacity will increase. Also, by increment of the inlet pressure to the steam turbine, the cooling capacity is assumed to be constant according to the assumption. Therefore, the ratio of electric power to the cooling capacity will also increase.

In Figure 6, the effects of steam turbine inlet temperature at inlet pressure of 3300 kPa on the electrical efficiency, combined power and cooling efficiency (cogeneration of power and cooling), combined power and heating efficiency (cogeneration of power and heating), and tri-generation efficiency are illustrated. By increasing the inlet temperature, the electrical power rises, and consequently, the electrical efficiency increases slightly. With increase in the inlet temperature to the steam turbine, the electrical power and heating capacity increase. Thus, the combined electrical and heating efficiency rises from 56.54% to 59.19%. With increment in the inlet temperature of the steam turbine, the fuel consumption and the heat input to the system increase. In addition, the cooling capacity is constant. Therefore, the combined electrical and cooling efficiency decreases because of rising
fuel consumption. At this range, the combined electrical and cooling efficiency decreases (from 35.2% to 33.66%). The tri-generation efficiency of system will also increase slightly due to the increase in the electric power and heating capacity from 82.46% to 82.56%.

Figure 7 shows the influence of steam turbine inlet pressure on the electrical efficiency, combined electrical and cooling efficiency, combined electrical and heating efficiency, and tri-generation efficiency at inlet temperature of 300°C. According to Figure 7, with increment in the inlet pressure of the turbine, the enthalpy difference in the steam turbine increases, and consequently, the electrical power rises. Therefore, the electrical efficiency increases from 8.64% to 13.15%.

With rise in inlet pressure of the steam turbine, the combined electrical and heating efficiency has a slight decrease due to the rise in the electrical power and decrease in the heating capacity and reaches from 56.54% to 56.04%. Also,
with increment in the inlet pressure of the steam turbine, the electrical power rises. In addition, the cooling capacity is constant. Therefore, the combined electrical and cooling efficiency increases by rise of the inlet pressure of the steam turbine. This efficiency will increase from 34.45% to 40.29%. The tri-generation efficiency of the system will also increase (from 82.35% to 83.18%) due to the increase in the electrical power and decrease in heat input to the system. Also, the fuel consumption will decrease.

In Figure 8, the impact of rising the steam turbine inlet temperature on the electrical exergy efficiency, combined electrical and heating exergy efficiency, combined electrical and cooling exergy efficiency, and tri-generation exergy efficiency is shown at inlet pressure of 3300 kPa. Since the
inlet temperature of the turbine increases, as mentioned, the electric power increases. Therefore, more useful exergy is achieved, and consequently, the electric exergy efficiency will increase. The combined electrical and cooling (cogeneration of electrical and cooling) exergy efficiency also increases with rising the electrical power. The combined electrical and heating (cogeneration of electrical and heating) exergy efficiency will also increase with increasing the electrical power and heating capacity. Also, the tri-generation exergy efficiency increases due to rise in the electrical power and heating capacity.

Figure 9 shows the effect of increasing the inlet pressure of the steam turbine on the electrical exergy efficiency, the combined electrical and heating exergy efficiency, the combined electrical and cooling exergy efficiency, and tri-generation exergy efficiency at inlet temperature of 300°C. All

FIGURE 9 Influence of the inlet pressure of turbine on the exergy efficiencies at inlet temperature of 300°C

FIGURE 10 Influence of the inlet temperature of the steam turbine on fuel consumption rate at inlet pressure of 3300 kPa
exergy efficiencies will increase due to increment in the electrical power and decline in the input exergy of the fuel. In fact, with increase in the inlet pressure to the steam turbine, the fuel consumption decreases, and consequently, the input exergy of fuel decreases, resulting in rise in the exergy efficiencies of the system in all cases of Figure 9.

Figure 10 illustrates the influence of increasing the steam inlet temperature on the mass flow rate of fuel. Due to the increment in the inlet temperature of the steam turbine, the fuel consumption will increase because of raising the heat input to the CCHP system.

Figure 11 shows the influence of increasing the steam inlet pressure on fuel consumption rate. By increment in the inlet pressure of the steam turbine, the inlet enthalpy of turbine increases, and therefore, the less value of fuel is consumed. Therefore, fuel consumption decreases with rise in the steam inlet pressure.

Figure 12 illustrates the effects of low pressure of chiller on the cooling capacity. With increment in the low pressure of the chiller, the enthalpy difference between outlet and inlet of the evaporator rises. Therefore, the cooling capacity increases at this condition.
In Figure 13, influence of the low pressure of chiller on coefficient of performance (COP) can be seen. As the low pressure increases, the enthalpy difference between the outlet and inlet of the evaporator rises, which leads to rise in the cooling capacity, and therefore, the COP of the chiller increases.

Figure 14 shows the influence of the heat exchanger efficiency on the COP of the chiller. By increasing the efficiency of the heat exchanger, the cooling capacity increases which this increment rate is more than the rate of heat input rising in the desorber. Consequently, the COP increases with the rise in the heat exchanger efficiency.

Figure 15 illustrates the influence of increasing the inlet temperature of the turbine on TCO2ER, CR, and TPES. By increment in the inlet temperature of the steam turbine, as mentioned, the fuel consumption increases, and therefore, the CO2 emission and operating costs increase in the CCHP system. Also, the rising rates of the fuel consumption, the emission production, and the operating cost in the conventional system are more than those for the CCHP system.

Also, with increment in the inlet temperature of the turbine, the electrical power and heating capacity increase. Therefore, the CCHP system operates more efficient than
conventional system, and therefore, with increasing the temperatures, $TCO_2ER$, CR, and TPES increase.

Figure 16 illustrates the influence of increasing the inlet pressure of the steam turbine on $TCO_2ER$, CR, and TPES at 300°C. With raising the inlet pressure of the steam turbine, fuel consumption decreases, and consequently, the emissions production and operating costs are reduced. According to Figures 15 and 16, the effect of the rise in the inlet pressure on the increase in $TCO_2ER$, CR, as well as TPES, will be greater than that by increase in the inlet temperature.

Figure 17 illustrates the influence of increasing the inlet temperature of the steam turbine on the payback period at interest rates of 15% and 20%. The increment in the inlet temperature of the steam turbine shows a decrease in payback period due to increase in the electrical power and heating capacity.
With increase in the inlet temperature of the steam turbine, the fuel consumption and its related costs increase, but the rising rates of the electric power and heating capacity are more than those of the fuel consumption, and consequently, the payback period decreases.

Figure 18 illustrates the influence of the inlet pressure of the steam turbine on the payback period at two interest rates of 15% and 20% and at inlet temperature of 300°C. Increasing the inlet pressure of the steam turbine increases the electrical power and decreases the fuel consumption and operating costs. However, at this condition, the heating capacity decreases, but the rates of decrease in fuel consumption and increase in electrical power are more than those for the heating capacity. Therefore, the payback period is reduced.
In this section, optimization of the performance of the CCHP system has been conducted. The objective function of this optimization is the percentage of fuel cost reduction (CR) of the CCHP system. The system is considered at constant cooling capacity. The inlet temperature and pressure to the steam turbine, the isentropic efficiency of the steam turbine, and the heat exchanger efficiency have been considered as decision variables. The variation bounds of the decision variables are presented below.\textsuperscript{29,31}

Using the genetic algorithm method, the system optimization is performed by changing the decision variables in the mentioned ranges. The optimization results of the CCHP system are listed in Table 7.

### 6 | OPTIMIZATION

The energy efficiency of tri-generation (CCHP) system has been evaluated more than efficiency of conventional system. The energy efficiency of the CCHP system for the inlet temperature of 300°C and the inlet pressure of 3300 kPa can be 82.46\%.

The values of electrical power, heating capacity, and cooling capacity of the CCHP system for the inlet temperature of 300°C and the inlet pressure of 3300 kPa of the turbine are 1776 kW, 9044 kW, and 4959.489 kW, respectively.

With increase in the inlet temperature of steam turbine, the electric power and heating capacity increase, and the cooling capacity is constant. Also, with increment in the inlet pressure of steam turbine, the electrical power increases and the heating capacity decreases.

The values of CO\textsubscript{2} emission reduction in the CCHP system, CR, and TPES are 24.91\%, 35.34\%, and 15.83\%, respectively, compared with conventional systems for the inlet temperature of 300°C and inlet pressure of 3300 kPa of the turbine. By increment in the inlet temperature and pressure of the steam turbine, these values increase.

The payback period values for the inlet temperature of 300°C and the inlet pressure of 3300 kPa of the steam turbine with two interest rates of 20\% and 15\% are 10.61 and 6.721 years, respectively.

### 7 | CONCLUSION

In this study, energy, exergy, environmental, and economic analyses of a new configuration of a CCHP system using a steam turbine as prime mover have been performed. This system includes boiler, steam turbine, heat exchanger, single-effect absorption chiller, and pump. The performance of the system has been investigated with changes in the inlet temperature and pressure of the steam turbine, as well as the heat exchanger efficiency. The following results can be summarized.

- The energy efficiency of tri-generation (CCHP) system has been evaluated more than efficiency of conventional system. The energy efficiency of the CCHP system for the inlet temperature of 300°C and the inlet pressure of 3300 kPa can be 82.46\%.
- The values of electrical power, heating capacity, and cooling capacity of the CCHP system for the inlet temperature of 300°C and the inlet pressure of 3300 kPa of the turbine are 1776 kW, 9044 kW, and 4959.5 kW, respectively.
- With increase in the inlet temperature of steam turbine, the electric power and heating capacity increase, and the cooling capacity is constant. Also, with increment in the inlet pressure of steam turbine, the electrical power increases and the heating capacity decreases.
- The values of CO\textsubscript{2} emission reduction in the CCHP system, CR, and TPES are 24.91\%, 35.34\%, and 15.83\%, respectively, compared with conventional systems for the inlet temperature of 300°C and inlet pressure of 3300 kPa of the turbine. By increment in the inlet temperature and pressure of the steam turbine, these values increase.
- The payback period values for the inlet temperature of 300°C and the inlet pressure of 3300 kPa of the steam turbine with two interest rates of 20\% and 15\% are 10.61 and 6.721 years, respectively.
Nomenclature

Symbols

| Symbol | Description |
|--------|-------------|
| \( \eta_{gen} \) | Electrical efficiency of the generator |
| CCHP | Combined cooling, heating, and power |
| CHP | Combined heating and power |
| ORC | Organic Rankine cycle |
| NPV | Net present value |
| NPWB | Net present worth benefit |
| NPWC | Net present worth cost |
| SV | Salvage value |
| \( T \) | Temperature |
| \( W \) | Power |
| \( \text{Cost}^{_{\text{CCHP}}} \) | Fuel costs of the CCHP system |
| \( \text{Cost}^{_{SP}} \) | Fuel costs of the conventional system |
| \( \text{Cost}_{F} \) | Natural gas purchase |
| \( \text{Cost}_{el} \) | Electricity purchase |
| CR | Fuel cost reduction |
| \( F_{\text{CCHP}} \) | Consumption fuel for CCHP system |
| \( F_{\text{SP}} \) | Consumption fuel for conventional system |
| \( \text{TCO}_{2}\text{ER} \) | Tri-generation CO\(_2\) emission reduction |
| COP | Coefficient of performance |
| NC | Capacity of each component |
| \( h \) | Enthalpy |
| \( \eta_{st} \) | Steam turbine efficiency |
| \( v \) | Specific volume |
| \( \eta_{b} \) | Boiler efficiency |
| LHV\(_{F} \) | Fuel lower heating value |
| \( \dot{m}_{F} \) | Fuel mass flow rate |
| \( \dot{Q}_{h} \) | Heating capacity |
| \( \dot{m}_{s} \) | Steam mass flow rate |
| \( \eta_{he} \) | Heat exchanger efficiency |
| \( \eta \) | Efficiency |
| \( \dot{Q}_{ev} \) | Cooling capacity |
| \( \eta_{\text{ex,el}} \) | Electrical exergy efficiency |
| \( r_{el,h} \) | Electrical-to-heating energy ratio |
| \( r_{el,ev} \) | Electrical-to-cooling energy ratio |
| \( \eta_{SP}^{_{\text{el}}} \) | Boiler efficiency |
| \( \eta_{SP}^{_{\text{el}}} \) | Thermal power plant efficiency |
| COP\(_{SP}^{_{\text{el}}} \) | Coefficient of performance of electric chiller |
| \( \mu_{\text{CO}_{2}}^{_{F}} \) | Carbon dioxide emission factor for fuel |
| \( \mu_{\text{CO}_{2}}^{_{W}} \) | Carbon dioxide emission factor for electricity grid |
| \( p \) | Initial cost of the system |
| CF\(_{y} \) | Financial process revenue |
| PB | Payback period |

Subscripts

| Subscript | Description |
|-----------|-------------|
| cog, c | Cooling cogeneration |
| cog, h | Heating cogeneration |
| ev | Evaporator |
| ex | Exergy |
| SP | Separate production |
| y | Year |
| el | Electrical |

Greek symbols

| Symbol | Description |
|--------|-------------|
| \( h_e \) | Heat exchanger |
| \( F \) | Fuel |
| \( s \) | Steam |
| \( h \) | Heat |

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