Novel integrated structure consisting of CO₂ capture cycle, heat pump unit, Kalina power, and ejector refrigeration systems for liquid CO₂ storage using renewable energies

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Abstract
Nowadays, the development of various technologies for improving the quality of life in human societies and, consequently, increased global warming have prioritized environmental factors to reduce major industrial pollutants including carbon dioxide (CO₂). Designing efficient integrated processes improves the performance of the whole system. In this study, a novel integrated structure is designed to capture CO₂ from power plants' flue gases and liquefy it. For this purpose, a monoethanolamine-based CO₂ capture cycle, an ejector refrigeration system, a Kalina power unit, and an organic Rankine power plant are utilized. High- and low-temperature heat of the system is provided by the heat pump cycle and geothermal energy, respectively. Then, 2.641 kg/s of liquid CO₂ is generated as the final product of the system. In the proposed system, 20,562 kW heat duty and 657.3 kW power are supplied geothermal energy and the photovoltaic (PV) system, respectively. The coefficient of performance of the heat pump cycle and thermal efficiency of the organic Rankine unit is calculated at 3.661% and 12.64%, respectively. Results of the exergy investigation indicate that the highest exergy destruction belonged to PV cells, which independently accounted for 39.81% of the total reversibility. The exergy efficiency and total reversibility of the structure are computed at 24.2% and 6555 kW. Sensitivity analysis was performed on several of the most important parameters of the combined structure. The outcomes indicate that the ratio of liquid CO₂ rate to total power consumption and net power consumption increase up to 4.096 kg/s LCO₂/MW and 1669 kW, respectively, when the CO₂ concentration in the flue gas increases from 1 to 9 mol%.

Keywords
CO₂ capture cycle, ejector refrigeration system, heat pump unit, liquid CO₂ storage, process integration, renewable energies
1 INTRODUCTION

Human activities, raw material processing, increased energy production and consumption, and consequently, a growing trend of pollution have caused temperature increases and global climate alteration. \(^1\) Carbon dioxide (CO\(_2\)) capture and storage (CCS) are among the important technologies for reducing greenhouse gas emissions in the environment. \(^2\) Agreements made at Paris Climate Change Conference to decrease greenhouse gas emissions and determine global warming by 2°C by 2035 were approved by the countries participating in the conference. Also, strict environmental policies were developed to achieve this goal. \(^3,4\) It has been nearly a century since the removal of CO\(_2\) from gas streams in the industrial sector to use pure CO\(_2\) for various purposes. Also, CCS was predicted to be effective in tackling global warming. \(^5\)

Precombustion, oxy-fuel combustion, and postcombustion captures are among the CCS methods, the most important of which is postcombustion capture because it can be easily added to operational units. \(^6\) Obviously, combustion gases have a high concentration of CO\(_2\). Therefore, cryogenic, absorption, and amine-based methods, as well as membrane processes, can be used for CO\(_2\) separation. \(^7\) Feron et al. \(^8\) investigated a postcombustion CO\(_2\) capture (PCC) system and developed a process model using amines. The technoeconomic assessment of the PCC procedure demonstrated that CO\(_2\) capture costs were reduced by 22% and 15% in coal-fired and natural gas power units, respectively, using 30 wt% monoethanolamines (MEAs). Li et al. \(^9\) presented an MEA-based proof-of-concept for energy harvesting from the CO\(_2\) capture system. They proposed and validated the CO\(_2\)-regenerative amine-based battery (CRAB) process. Results of the technoeconomic analysis showed that the CRAB energy harvesting unit enhanced the efficiency of power production by 1.75%. Jiang et al. \(^10\) proposed an advanced ammonia-based integrated NO\(_x\)/SO\(_x\)/CO\(_2\) emission control system focusing on a low-cost process. The results indicated this process reduced costs by 23.3% and 17.8% by removing CO\(_2\), NO\(_x\), and SO\(_x\) for saving capital and CO\(_2\)-avoided costs, respectively. Shirmohammadi et al. \(^11\) designed a hybrid structure for the CO\(_2\) capture and storage based on the amine-based CO\(_2\) capture unit by HYSYS software. Energy consumption and CO\(_2\) capture efficiency were reported at 4.78 MJ/kg CO\(_2\) and 81.2%, respectively. Shirmohammadi et al. \(^12\) used multiobjective optimization to evaluate the CO\(_2\) capture process integrated with the urea plant. They combined neural networks and genetic algorithms to optimize exergy efficiency and total cost rate. The height of the absorber and stripper towers, the ratio of CO\(_2\) to lean MEA flow rate, and lean MEA temperature as essential parameters for optimization were considered. Liu et al. \(^13\) molded a novel CCS process for exhaust gases from the coal chemical industry based on the CO\(_2\) purification and capture cycle, the absorption refrigeration (AR) cycle, and the organic Rankine cycle (ORC). The outcomes revealed that the exergy efficiency of the whole system from wasted heat was 42.88%. Wang et al. \(^14\) developed a novel CCS process using the CO\(_2\) purification and capture cycle, the AR unit, and the ORC plant. The results demonstrated that the exergy efficiency of the whole system and CO\(_2\) capture are obtained at 17.56% and 43.15%, respectively. A new tristructure for the CO\(_2\) capture unit optimization was designed by Oh et al. \(^15\) Energy consumption, flue gas temperature, and CO\(_2\) capture yield were obtained at 3.78 MJ/kg CO\(_2\), 40°C, and 86%, respectively. The mole fraction of flue gas included 76.65% N\(_2\), 12.91% O\(_2\), 6.71% H\(_2\)O, and 3.73% CO\(_2\). The CO\(_2\) capture unit based on the aqueous MEA was developed in Aspen Plus software by Li et al. \(^16\) The energy consumption, CO\(_2\) purity, and reboiler temperature were considered 3.1 MJ/kg CO\(_2\), 123.7°C, and 99.1 mas%, respectively. The cogeneration system of heat and power integrated with the PCC unit was examined based on the life cycle analysis by Morales-Mora et al. \(^17\) The CO\(_2\) capture cycle with the 1075 t/day capacity was designed by the HYSYS software. The energy efficiency, CO\(_2\) removal, and CO\(_2\) purity were calculated at 4.36 MJ/kg CO\(_2\), 95.4%, and 95%, respectively. A novel hybrid system for the cogeneration of biomethane and liquid CO\(_2\) based on a biogas upgrading system, a PCC unit, AR structure, and Kalina/ORC power plants developed by Ebrahimi et al. \(^18\) The exergy efficiency of the combined system and energy consumption of the PCC unit were achieved at 73.10% and 4.2 MJ/kg CO\(_2\), respectively. The new hybrid system based on cogeneration of heat and power units integrated with the PCC process was investigated by Wu et al. \(^19\) The results exhibited that the CO\(_2\) removal, efficiency penalty, and power output were obtained at 90%, 19.32%, and 525.01 MWe, respectively.

The ejector refrigeration systems among the other refrigeration cycles have the lower maintenance, installation, and equipment costs. Moreover, the ejector refrigeration process allows the use of an extensive range of refrigerants. However, it has a lower coefficient of performance (COP) than other refrigeration cycles. \(^20\) A novel cogeneration structure of refrigeration and power based on the Kalina unit and ejector cooling system was developed by Kostamzadeh et al. \(^21\) Thermal and exergy efficiencies of the cogeneration unit were 17.6% and 10.78%, respectively. A new tri-generation system of refrigeration, heat, and power based on the Brayton unit,
a transcritical ejector cooling process, and a supercritical 
CO₂ cycle was designed by Xu et al.²² The outcomes 
showed that the exergy efficiency in the proposed system 
was more than the initial structure. Besides, the 
sensitivity analysis of the system revealed that a rise in 
the temperature of the turbine input stream improves the 
net output power and exergy efficiency. Tan et al.²³ 
utilized a boil-off gas (BOG) reliquefaction process with 
an ejector process and two compression refrigeration 
units to liquify natural gas. The COP, energy consump-
tion, and exergy efficiency were calculated at 0.24, 
0.59 kWh/kg BOG, and 39.7%, respectively. Ghorbani 
et al.²⁴ a continuous low-temperature cooling based on 
ejector refrigeration unit, Kalina power plant, phase 
change material, and photovoltaic (PV) system was 
designed. The COP of the refrigeration unit and exergy 
efficiency of the hybrid system were 0.8277% and 28.97%, 
respectively. The main problem with the PV systems is 
their high installation, start-up, and expansion costs. The 
evolution of science and technology has reduced PV cell 
manufacturing costs; however, it is still considered an 
important issue in these systems. The technology and 
raw materials used to manufacture PV panels can greatly 
influence the future of their manufacturing factories. The 
important criteria for selecting PV panels as well as 
economic and environmental conditions should be 
examined to determine the PV system efficiency.²⁵ The 
ORC is essentially similar to the steam Rankine cycle, 
except that it uses organic fluids with a lower boiling 
point to better match its operation with heat sources with 
lower temperatures.²⁶ Mechanical heat pumps use the 
compression cycle to increase the working fluid tem-
perature.²⁷ Two new heat pump cycles in high temperature 
with three fluids using vapor compression systems were 
developed and investigated by Singh et al.²⁸ The first and 
second systems included the working fluids composition 
of water/biphenyl and cyclohexane/biphenyl, respec-
tively. The energetic/exergetic COPs for the first and 
second systems were obtained at 2.3/1.1 and 3.8/1.9, 
respectively.

Several methods have been developed for CO₂ 
capture and storage from power plant exhaust gases. 
Absorption and compression refrigeration plants have 
been used to liquify CO₂. The use of ejector refrigeration 
cycles integrated with combined heat and power with 
renewable energy systems can be considered a novel 
method for storing and liquefying carbon dioxide. This 
study aims to liquify the CO₂ existing in power plants' 
flue gases based on the PCC plant, Kalina/ORC power 
units, medium-temperature heat pump system, and 
ejector refrigeration process. The required heat and 
power are supplied by geothermal energy and PV system, 
respectively. The geothermal energy and the PV system 

Based on the climatic conditions of Meshkin Shahr in 
Iran are designed.

2 SYSTEM DESCRIPTION

In this paper, a novel integrated system to remove CO₂ 
from power plants’ flue gases and liquefy it based on the 
PCC unit, Kalina/ORC power plant, medium-
temperature heat pump structure, and ejector refrigera-
tion process are developed. The geothermal energy and 
the PV panels to supply heat and power of a hybrid 
system based on the climatic conditions of Meshkin 
Shahr in Iran are considered. Figure 1 shows the block 
flow diagram of the integrated liquid CO₂ production 
structure using geothermal energy, PV system, heat 
pump, Kalina power generation cycle, and ejector 
refrigeration cycle. Figure 2 shows the process diagram 
of streams of the proposed integrated system. This 
integrated system capture 2.641 kg/s CO₂ from the plant’s 
exhaust and then liquefies it in the ejector refrigeration 
cycle, receiving 20,562 kW heat flow from the geothermal 
source and 657.3 kW power from the PV panels.

The flue gas of the power plant under stream A36 with 
318.1 K temperature and 100 kPa pressure enters the PCC 
cycle. The flue gas contain 76.45 mol% nitrogen, 13.58 mol% 
oxygen, 3.54 mol% carbon dioxide and 6.43 mol% water. The 
whole methodology for the CO₂ capture system by chemical 
absorption contains the CO₂ absorber tower and stripper 
tower. The absorption tower does not require external 
utilities. But the stripper tower needs the HE11 condenser 
and the HE12 reboiler to the proper performance of the 
capture process. The outlet stream from the end of the T100 
tower goes to the P2 pump under stream A40 and its 
pressure rise to 274 kPa. The stream enters the HE10 
exchanger and the outlet stream temperature from the 
exchanger increases to 98°C. The heat needed to raise the 
temperature of stream A40 provides by the return stream 
from the end of the T200 tower (stripper). In the T100 tower, 
stream A49 (amine solvent/water) from the top of the tower 
and the flue gas from the end of the column are entered, and 
the absorption procedure is achieved by an uneven 
connection between these streams. The rich amine is carried 
from the end of the T100 tower (absorber) to from the top of 
the T200 tower (stripper) and is retrieved to the CO₂ capture 
unit using the inlet heat to reboiler. The heat needed by the 
reboiler of the T100 tower is provided by geothermal energy. 
The gas exiting from the top of the stripper tower (stream 
A57) is composed of 0.06 mol% nitrogen, 0.02 mol% oxygen, 
93.17 mol% carbon dioxide, and 6.75 mol% water and then 
enters the C2 compressor with a temperature of 
324.1 K and a pressure of 195.0 kPa for compression. Then, it 
enters the HE13 heat exchanger (stream A58) with a
temperature of 437.0 K and a pressure of 553.0 kPa to be cooled. The output stream from HE13 contains CO$_2$ and water, which water is separated from the bottom of the D4 flash drum. The CO$_2$ stream enters the ejector refrigeration cycle after compression in the C3 compressor to 1600 kPa pressure and cooling in the HE14 exchanger to 309.3 K temperature, and becomes liquid during heat transfer with the HE7 exchanger. The cogeneration cycle of refrigeration and power includes a Kalina power unit and an ejector refrigeration system. The heat needed for the power unit is provided by the heat pump system. Stream A8 enters the HE2 exchanger at a temperature of 370.2 K and a pressure of 2000 kPa, and the temperature rises to 473.1 K. This two-phase stream contains water and ammonia and enters the D5 drum under stream A9. The output stream from the top of the flash drum enters the T1 turbine and its pressure is reduced to 1235 kPa and then it as the primary stream goes to the ejector. The output stream from the turbine enters the ejector together with a part of the return stream and exits it under stream A15 with a temperature of 386.5 K. The output stream from the ejector is cooled in the HE8 exchanger and then part of this stream after cooling in the HE6 exchanger and pressure drop in the V2 valve provides the refrigeration required for liquefaction of CO$_2$ in the HE7 exchanger. Then, it goes to the ejector as a secondary stream. Also, the output stream from the D1 drum, after reducing the temperature and pressure in the HE3 exchanger and the V2 valve, is mixed with the rest of the return stream and enters the HE5 exchanger under stream A23, and the temperature decreases to 294.9 K. Then the output stream pressure from the condenser increases in the P1 pump and after preheating it enters the HE2 exchanger and thus the cycle continues. The waste heat from the subsections under stream A34 enters the HE16 exchanger of the ORC unit. The temperature of stream
A69 reaches 393.1 K by receiving 1511 kW of heat in the HE16 exchanger. Stream A70 enters the T2 Turbine at 393.1 K temperature and 500 kPa pressure, and its pressure is reduced to 200 kPa. Part of the output stream from the T2 turbine enters the T3 turbine and its pressure is reduced by 80 kPa and then its temperature in the condenser is reduced to 301 K. The output stream from the condenser enters the P4 pump and its pressure increases up to 200 kPa. The output stream from the P4 pump is mixed with a part of the output stream from the T2 turbine and enters the P3 pump under stream A77 and its pressure rises up to 500 kPa. Table 1 presents the molar compounds of some streams used in the CO2 liquefaction structure. Table 2 lists the main specifications of some streams involved in the hybrid CO2 liquefaction system. Table 3 provides the main specifications of the equipment utilized in the hybrid CO2 liquefaction system.

3 | SYSTEM SIMULATION

The PCC unit, ejector refrigeration system, Kalina and ORC power plants, heat pump cycle, PV panels, and geothermal energy as subsections are utilized in the hybrid structure. HYSYS software and m-file code in MATLAB programming are employed to simulate the hybrid structure. The Peng–Robinson equation of state is employed to simulate the ejector refrigeration system, Kalina and ORC power plants, and heat pump cycle in the HYSYS software. The amine package and Eisenberg model to simulate the PCC system in HYSYS software are used. Background Information on the streams/components and more theory on the ORC, heat pump system, and Kalina/ejector refrigeration system can be extracted from references.21,28,29

3.1 | Geothermal energy

The background information on geothermal energy, including the temperature of 438 K and the pressure of 7 bar, is extracted from the geographical location of Meshkin Shahr in Iran.30

3.2 | Energy analysis

The energy balance equations can be obtained using the specific enthalpy and considering the control volume for each of the equipment applied in the developed hybrid system.31

\[ \sum_{i} m_{in,i} h_{in,i} - \sum_{j} m_{out,j} h_{out,j} - W + Q = 0. \]  

(1)

In heat exchangers, the energy balance is calculated by Equation (2) as follows:

\[ m_{in,i}(h_{in1,i} - h_{in2,i}) = m_{out,i}(h_{out1,i} - h_{out2,i}), \]

\[ T_{in1,i} = T_{out1,i} + \Delta T_{in,HXi}. \]  

(2)
The isentropic efficiency is employed to receive the equilibrium energy equation for pumps, compressors, and turbines, as defined by the following:\(^3\):

\[
\eta_h = \frac{h_{\text{out}} - h_{\text{in}}}{h_{\text{in}}}, \quad (3)
\]

\[
h_{\text{out}} = \left( h_{\text{out}}^S - h_{\text{in}} \right) \eta_h + h_{\text{in}}, \quad (4)
\]

The conservation equations of energy and mass for mixers are presented as follows:\(^3\):

\[
m_{\text{in}} h_{\text{in},1} + m_{\text{in},2} h_{\text{in},2} = m_{\text{out}} h_{\text{out}}, \quad (5)
\]

\[
m_{\text{in}} + m_{\text{in},2} = m_{\text{out}}. \quad (6)
\]

The conservation equations of energy and mass for separators are shown as follows:\(^3\):

\[
m_{\text{in}} h_{\text{in}} = m_{\text{out},1} h_{\text{out},1} + m_{\text{out},2} h_{\text{out},2}. \quad (7)
\]

\[
m_{\text{in}} = m_{\text{out},1} + m_{\text{out},2}. \quad (8)
\]

The expansion process under a steady enthalpy procedure is based on the thermodynamics first law as described below:\(^3\):

\[
h_{\text{in}} = h_{\text{out}}. \quad (9)
\]

The mass balance, equilibrium, summation, and heat balance equations are used to determine the operational conditions of towers.\(^3\)

### 3.3 Exergy analysis

Exergy analysis is used to calculate the exergy flow in the system and determine its nonoptimal components by the first law of thermodynamics. The exergy rate of the whole system is calculated by\(^3\):
### TABLE 2  Operating conditions of some flows used in the proposed structure

| Stream | Temperature (K) | Pressure (kPa) | Molar flow (kgmol/h) | Mass flow (kg/h) | Temperature (K) | Pressure (kPa) | Molar flow (kgmol/h) | Mass flow (kg/h) | Temperature (K) | Pressure (kPa) | Molar Flow (kgmol/h) | Mass Flow (kg/h) |
|--------|----------------|----------------|----------------------|-----------------|----------------|----------------|----------------------|-----------------|----------------|----------------|-----------------------|-----------------|
| A1     | 353.5          | 100.0          | 74.86                | 6300            | A29            | 383.1          | 100.0                | 78.89           | A57            | 324.1          | 195.0                 | 231.1           |
| A2     | 433.1          | 100.0          | 74.86                | 6300            | A30            | 298.1          | 100.0                | 16.94           | A58            | 437.0          | 553.0                 | 232.5           |
| A3     | 546.3          | 3020           | 74.86                | 6300            | A31            | 393.1          | 100.0                | 16.94           | A59            | 300.1          | 553.0                 | 232.5           |
| A4     | 374.2          | 3020           | 74.86                | 6300            | A32            | 298.1          | 100.0                | 305.2           | A60            | 300.1          | 553.0                 | 15.53           |
| A5     | 353.1          | 3020           | 74.86                | 6300            | A33            | 433.1          | 100.0                | 39.85           | A61            | 300.1          | 553.0                 | 217.0           |
| A6     | 298.1          | 100.0          | 64.16                | 1156            | A34            | 399.1          | 100.0                | 135.7           | A62            | 399.7          | 1600                  | 217.0           |
| A7     | 353.1          | 100.0          | 64.16                | 1156            | A35            | 372.7          | 100.0                | 135.7           | A63            | 309.3          | 1600                  | 217.0           |
| A8     | 370.1          | 2000           | 155.2                | 2772            | A36            | 316.1          | 100.0                | 6200            | A64            | 245.9          | 1600                  | 217.0           |
| A9     | 430.7          | 1235           | 83.36                | 1481            | A39            | 320.4          | 100.0                | 20,777          | A67            | 397.5          | 700.0                 | 10,204          |
| A10    | 473.1          | 2000           | 71.85                | 1291            | A40            | 320.4          | 274.0                | 476,033         | A68            | 395.7          | 700.0                 | 10,684          |
| A11    | 315.2          | 2000           | 71.85                | 1291            | A41            | 438.1          | 700.0                | 479.9           | A69            | 341.5          | 500.0                 | 170.0           |
| A12    | 315.6          | 33.70          | 71.85                | 1291            | A42            | 371.1          | 204.0                | 476,033         | A70            | 393.1          | 500.0                 | 170.0           |
| A13    | 305.1          | 33.70          | 14.47                | 257.1           | A45            | 394.1          | 205.0                | 16.29           | A73            | 354.0          | 80.00                 | 137.7           |
| A14    | 305.1          | 33.70          | 14.47                | 257.1           | A46            | 394.1          | 205.0                | 20,544          | A74            | 301.1          | 80.00                 | 137.7           |
| A15    | 287.1          | 33.70          | 14.47                | 257.1           | A47            | 389.0          | 170.0                | 20,544          | A75            | 301.2          | 200.0                 | 137.7           |
| A16    | 244.5          | 1.100          | 14.47                | 257.1           | A48            | 344.6          | 100.0                | 20,544          | A76            | 372.3          | 200.0                 | 32.30           |
| A17    | 305.1          | 33.70          | 14.47                | 257.1           | A50            | 298.1          | 200.0                | 159,199         | A78            | 298.1          | 100.0                 | 6116            |
| A18    | 311.8          | 33.70          | 155.2                | 2772            | A51            | 303.1          | 200.0                | 159,199         | A79            | 308.1          | 100.0                 | 6116            |
| A19    | 294.9          | 33.70          | 155.2                | 2772            | A52            | 373.6          | 195.0                | 464.5           | A80            | 293.1          | 100.0                 | 834.4           |
| A20    | 294.9          | 2000           | 155.2                | 2772            | A53            | 353.1          | 100.0                | 2504            | A81            | 303.1          | 100.0                 | 834.4           |
| A21    | 286.1          | 100.0          | 14.47                | 257.1           | A54            | 298.1          | 100.0                | 2504            | A82            | 353.1          | 100.0                 | 2569            |
| A22    | 301.1          | 100.0          | 56.28                | 1014            | A55            | 324.1          | 195.0                | 464.5           | A83            | 381.1          | 700.0                 | 479.9           |

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\[ \dot{E}_x = \dot{E}_{x_{ph}} + \dot{E}_{x_{ch}}, \]  
\[ \text{(10)} \]

where \( \dot{E}_x \), \( \dot{E}_{x_{ph}} \), and \( \dot{E}_{x_{ch}} \) represent the exergy flow rate of a fluid and the sum of physical and chemical exergy rates, respectively.

The physical exergy rate is calculated as follows\(^{32}\):

\[ \dot{E}_{x_{ph}} = \sum_i \dot{n}_i ((\tilde{h}_i - \bar{h}_0) - T_0 (\tilde{s}_i - \bar{s}_0)). \]  
\[ \text{(11)} \]

The chemical exergy is calculated as follows\(^{32}\):

\[ \dot{E}_{x_{ch}} = \dot{n} \left( \sum_i x_i \dot{E}_{x_{ch}}^{0} + R T_0 \sum_i x_i \ln(x_i \gamma_i) \right), \]  
\[ \text{(12)} \]

where \( \tilde{h}_0 \) and \( \bar{s}_0 \) are the enthalpy and entropy of the flow at ambient temperature and pressure, respectively, and \( \gamma_i \) is considered the activity coefficient of the \( i \)th component. Exergy efficiency, which is defined as the ratio of
useful exergy output to total exergy input, is calculated as follows\textsuperscript{32}:

$$\eta_{\text{ex}} = \frac{E_{\text{exout}}}{E_{\text{exin}}},$$

(13)

where $\eta_{\text{ex}}$, $E_{\text{exout}}$, and $E_{\text{exin}}$ are the exergy efficiency, exergy output, and exergy input, respectively. Exergy analysis mainly aims to determine the degree of irreversibility of different processes in a thermodynamic system and identify their locations. Accordingly, it specifies how the system performance improves. Equation (9) presents the exergy balance for the control volume under steady-state\textsuperscript{34}:

$$\dot{E}_{\text{in}} = \sum_{j} \left(1 - \frac{T_{0}}{T_{j}}\right) \cdot Q_{j} - W_{\text{cv}} + \sum_{i} \dot{E}_{X_{i}} - \varpi \dot{E}_{X_{e}}.$$  

(14)

### 3.4 Photovoltaic panels

In this study, the relevant parameters were used to evaluate the performance of the grid-connected PV system. The maximum power in PV cells is calculated as follows\textsuperscript{35}:

$$P_{\text{max}} = V_{\text{max}} I_{\text{max}},$$

(15)

in which $V_{\text{max}}$ and $I_{\text{max}}$ define the voltage and current of the PV cells at the maximum power state, respectively. The maximum efficiency in PV cell defines the ratio of the maximum net power and the solar radiation, which is computed as\textsuperscript{35}:

$$\eta = \frac{V_{\text{mp}} I_{\text{mp}}}{A G_{\text{a}}}. $$

(16)

The fill factor is a measure of the $I - V$ characteristic and is defined as follows\textsuperscript{35}:

$$FF = \frac{V_{\text{mp}} I_{\text{mp}}}{V_{\text{OC}} I_{\text{OC}}},$$

(17)

in which $V_{\text{OC}}$ stands for the voltage of the open circuit and $I_{\text{OC}}$ represents the current of the open circuit.

Besides, the equations to calculate cell voltage, current voltage, current, and temperature of the nominal operational cell are presented as follows\textsuperscript{35}:

$$I_{\text{M}} = N_{\text{PM}} I_{\text{C}},$$

(18)

$$V_{\text{M}} = N_{\text{SM}} V_{\text{C}},$$

(19)

$$R_{\text{SM}} = \frac{N_{\text{SM}}}{N_{\text{PM}}} R_{\text{SC}},$$

(20)

$$T_{\text{C}} = T_{a} + \frac{G}{800} (NOCT - 20^\circ \text{C}).$$

(21)

The PV system efficiency can be calculated by multiplying the inverter efficiency by the PV module efficiency by the following equation\textsuperscript{36}:

$$\eta_{\text{system}} = \eta_{\text{PV}} \times \eta_{\text{inv}}.$$  

(22)

### 3.5 Ejector

The mass balance of all the streams of the system is calculated as follows\textsuperscript{23,37}:

$$\sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{out}} = 0.$$  

(23)

The entrainment ratio is calculated by the following equation:

$$\sigma = \frac{\dot{m}_{\text{s}}}{\dot{m}_{\text{in}}},$$

(24)

in which $\dot{m}_{\text{s}}$ and $\dot{m}_{\text{in}}$ stand mass flow rates of the secondary and initial streams, respectively.

#### 3.5.1 Nozzle

As shown in Figure 3, point $H$ at the nozzle was the starting point of the expansion of the high-pressure fluid flow in the expander, which was simulated using HYSYS. The nozzle isentropic efficiency is defined as the difference between the specific enthalpies of the nozzle outlet ($h_{\text{H}}'$) and inlet ($h_{\text{H}}$) to the difference between the specific enthalpies of the ideal isentropic nozzle outlet ($h_{\text{H}}^{S}$) and inlet, calculated as follows:

$$\eta = \frac{h_{\text{H}}' - h_{\text{H}}}{h_{\text{H}}^{S} - h_{\text{H}}}. $$

(25)

The pressure of the output stream from the nozzle is equal to that of the secondary stream (point $S$ in Figure 3). The specific entropy of the ideal isentropic nozzle outlet ($S_{\text{H}}^{S}$) is equal to the entropy at point $H$. Using these data, ($h_{\text{H}}^{S}$) can be obtained. Thus, the nozzle isentropic efficiency is calculated by Equation (25). The initial stream velocity at the nozzle outlet ($U_{\text{H}}'$) is obtained by Equation (26) by excluding ($u_{\text{H}}$)\textsuperscript{23,37}:

$$R_{\text{SM}} = \frac{N_{\text{SM}}}{N_{\text{PM}}} R_{\text{SC}},$$

(20)

$$T_{\text{C}} = T_{a} + \frac{G}{800} (NOCT - 20^\circ \text{C}).$$

(21)
Mixers and tubes were used in HYSYS to simulate the mixing unit. The specific enthalpy of the output mixture from this unit ($h_O$) is calculated as follows:

$$h_O = \frac{1}{1 + \sigma} \cdot h_H + \frac{\sigma}{\sigma + 1} \cdot h_S - \frac{u_o^2}{2000},$$

(27)

where $u_o$ denotes the output mixture velocity from the mixing unit, obtained as follows:

$$u_o = u_{O,i} \sqrt{\eta_o} = \frac{u_{H'}}{1 + \sigma} \cdot \sqrt{\eta_o},$$

(28)

where $\eta_o$ is the mixture efficiency and $u_{O,i}$ represents the ideal output mixture velocity from this unit, calculated as follows:

$$u_{O,i} = \frac{1}{1 + \sigma} \cdot u_{H'}.$$

(29)

3.5.3 | Diffuser

Due to the identical flow equations, a compressor was used to simulate the diffuser in HYSYS. A low-pressure two-phase stream entered the diffuser and a high-pressure stream exited from it. The ideal specific enthalpy of the stream exiting from the diffuser ($h_C$) is calculated as follows:

$$h_C = \frac{1}{1 + \sigma} \cdot h_H + \frac{\sigma}{\sigma + 1} \cdot h_S,$$

(30)

$$h_{C,i} = h_O + \eta_d (h_C - h_O).$$

(31)

Then, the outlet pressure of the diffuser and the quality can obtain by the state equation.

$$p_C = f (h_{C,i}, x_C),$$

(32)

$$x_C = f (h_C, p_C).$$

(33)

The equation between the entrainment ratio and the quality of the outlet stream is described as

$$x_C = \frac{1}{1 + \sigma}.$$

(34)

The entrainment ratio can be selected to equal the quality of the output stream from Equations (33) and (34). The output stream from the ejector is gaseous and one of the analysis loops is reduced by the above solution method. The two-loop solution method is used if the output stream from the ejector is in two phases in the sensitivity analysis.

4 | SYSTEM VALIDATION

The integrated system developed in the present study consists of different sections in which the validation model is discussed separately. One of the major parts of the system is the combined power and ejector refrigeration cycle. The validation of hybrid power and ejector cooling cycle with research\textsuperscript{21} is presented in Figure 4. According to this figure, the performed simulation is in proper agreement with the results of the mentioned reference, so that the parameters of secondary to primary flow ratio, produced cooling, and power to cooling ratio in the present work are 17.36%, 156.3 kW, and 20.64%, respectively, and in the reference, are 16.28%, 160.6 kW, and 20.95%, respectively. The heat required for the combined power and ejector refrigeration cycle is supplied by the heat pump. In Figure 5, the main parameters of this section are compared with the works of Singh et al.\textsuperscript{28} According to this figure, energetic COP and exergetic COP in the present work are 3.661 and 1.680, respectively, while in reference to these parameters, 3.8 and 1.9 are calculated, respectively. These results indicate the appropriate accuracy of the two studies.
RESULTS AND DISCUSSION

In this section, the simulation and analyses result of the integrated system are presented. Tables 1 and 2 indicate the composition and operating condition of the system streams, respectively. In this structure, the hybrid system to capture CO₂ from flue gases of the power plants and liquefy it based on the CO₂ capture cycle, heat pump unit, ejector refrigeration system, and the Kalina/organic Rankine power plants was developed. The required heat was supplied by geothermal energy, so that 49.05 kg/s of flue gas entered the capture cycle and, then, 2.641 kg/s of CO₂ was generated with a purity of more than 99%. In total, 19,701 kW of heat flow was consumed by the distillation tower in the amine regeneration process, which was supplied by geothermal energy. After receiving 156.3 kW of cooling energy with a temperature of 245.9 K, the generated pure CO₂ was converted into a liquid. This cooling energy was supplied by the integrated cycle consisting of an ejector refrigeration system and a Kalina power cycle. The generated net power of this section was 32.27 kW. The required heat of the cycle was 1108 kW, which was supplied by the heat pump cycle. The heat and power consumption of the heat pump cycle were obtained as 860.9 and 323.5 kW, respectively. Thus, COP was calculated as 3.661. The low-temperature waste heat of the whole system was used in ORC to generate 191 kW of power. The ORC efficiency was obtained as 12.64% due to its low-quality heat source with a temperature of 399.1 K.

In general, 20,562 kW of heat, supplied by geothermal energy, as well as 657.3 kW of power was consumed in the proposed integrated system, which was generated by the PV system. The results of the simulation of the PV system in the present study to produce a power of 657.3 kW are shown in Figures 6 and 7. As shown in Figure 6, by increasing the voltage to the range of 40.6 V, the current remains almost constant, but at higher voltages, the current drops sharply. In Figure 7, the process of power generation compared with voltage changes is displayed. On the basis of the figure, by increasing the voltage to 40 V, the power output of the PV system enhances so that the required power of the system is supplied at 40.6 V. However, as the voltage increases further, the output power decreases significantly.

In the following, the results of exergy and sensitivity analyses are presented.

5 | RESULTS AND DISCUSSION

In this section, the simulation and analyses result of the integrated system are presented. Tables 1 and 2 indicate the composition and operating condition of the system streams, respectively. In this structure, the hybrid system to capture CO₂ from flue gases of the power plants and liquefy it based on the CO₂ capture cycle, heat pump unit, ejector refrigeration system, and the Kalina/organic Rankine power plants was developed. The required heat was supplied by geothermal energy, so that 49.05 kg/s of flue gas entered the capture cycle and, then, 2.641 kg/s of CO₂ was generated with a purity of more than 99%. In total, 19,701 kW of heat flow was consumed by the distillation tower in the amine regeneration process, which was supplied by geothermal energy. After receiving 156.3 kW of cooling energy with a temperature of 245.9 K, the generated pure CO₂ was converted into a liquid. This cooling energy was supplied by the integrated cycle consisting of an ejector refrigeration system and a Kalina power cycle. The generated net power of this section was 32.27 kW. The required heat of the cycle was 1108 kW, which was supplied by the heat pump cycle. The heat and power consumption of the heat pump cycle were obtained as 860.9 and 323.5 kW, respectively. Thus, COP was calculated as 3.661. The low-temperature waste heat of the whole system was used in ORC to generate 191 kW of power. The ORC efficiency was obtained as 12.64% due to its low-quality heat source with a temperature of 399.1 K.

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In the following, the results of exergy and sensitivity analyses are presented.

5.1 | Exergy assessment results

The exergy flow rates of the system streams are listed in Table 4. From the connection of HYSYS software to MATLAB programming, the physical, chemical, and total exergy of each stream are calculated. Thermodynamic data of streams are extracted from HYSYS software and calculations related to exergy assessments are performed in m-file code. According to the obtained data and equations listed in Table 5, the exergy efficiency, as well as exergy destruction of the system equipment, was calculated (Table 6). The results demonstrate that heat exchangers and distillation towers, despite the high exergy degradation compared with other equipment, have high exergy efficiency. Valves and pumps have low exergy efficiency among other equipment and also the exergy destruction rates of these devices are low and their effects on the whole system are ignored. Figure 8 illustrates the contribution of each system component to the total destruction. The PV panels, heat exchangers, and columns accounted for the highest rate of exergy destruction with 39.81%, 30.97%, and 23.22%, respectively. Figure 9 shows the exergy destruction of the system heat exchangers separately. The outcomes indicate that the highest contribution of exergy destruction in exchangers belongs to the HE10 (32.8%),...
HE9 (30.68%), and HE12 (22.38%). The exergy destruction share of each section is shown in Figure 10. According to the obtained result, the most destruction rate belongs to the CO2 capture cycle with 52.68% of the total rate. Exergy destruction and exergy efficiency of the whole integrated system were calculated as 6555 kW and 24.20%, respectively. Figure 11 shows the exergy flow diagram of the integrated system. Exergy due to flue gas flow of power plants, solar radiation entering the solar panels, and geothermal heat input to the system as input exergy streams are considered.

5.2 | Sensitivity investigation results

Parametric examination of the system is a proper tool that aims to determine the optimum states of the system by studying the system performance in various operating states. In the current study, some of the most essential structure parameters were nominated for sensitivity investigation and changed at specific intervals, the effects of which on structure performance were reported.

5.2.1 | Inlet flue gas CO2 content effect

The composition of the flue gas entering the system (stream A36) completely affected the performance of the CO2 capture cycle and, consequently, the whole system. Accordingly, the CO2 content in stream A36 was increased from 1 to 9 mol%, the results of which are shown in Figures 12–15. In the basic cycle, the CO2 content in stream A36 was considered to be 3.54 mol%. In stream A36 composition, only CO2 and N2 levels changed. The higher the molar percentage of CO2, the lower the molar percentage of N2 would be, and vice
| Stream | Molar Enthalpy (kJ/kmol) | Molar Entropy (kJ/kmol °C) | Exergy (kW) | Stream | Molar Enthalpy (kJ/kmol) | Molar Entropy (kJ/kmol °C) | Exergy (kW) |
|--------|--------------------------|---------------------------|------------|--------|--------------------------|---------------------------|------------|
| A1     | −146489                  | −157.7                    | 82080      | A43    | −20245                   | 97.38                     | 1013146    |
| A2     | −105085                  | −44.06                    | 82964      | A44    | −18713                   | 101.8                     | 1014403    |
| A3     | −89527                   | −36.84                    | 83243      | A45    | 13808                    | 218.3                     | 13608      |
| A4     | −142815                  | −148.5                    | 82828      | A46    | −21292                   | 92.59                     | 1000789    |
| A5     | −146489                  | −158.6                    | 82814      | A47    | −21292                   | 94.33                     | 1000730    |
| A6     | −286220                  | 53.7                      | 208.6      | A48    | −25789                   | 88.14                     | 985595     |
| A7     | −281933                  | 3099                      | 214.9      | A49    | −28679                   | 84.49                     | 975313     |
| A8     | −247574                  | 167.5                     | 2481       | A50    | −34106                   | 74.32                     | 137973     |
| A9     | −187742                  | 12150                     | 219.2      | A51    | −33733                   | 74.84                     | 147632     |
| A10    | −189207                  | 168                       | 2443       | A52    | −281933                  | 66.9                      | 8391       |
| A11    | −261460                  | 618.2                     | 286220     | A53    | −286220                  | 53.7                      | 8146       |
| A12    | −274401                  | 557.1                     | 2728       | A54    | −32110                   | 59.38                     | 621.4      |
| A13    | −274401                  | 556.3                     | 2728       | A55    | −10962                   | 134.7                     | 1920       |
| A14    | −274401                  | 560.3                     | 2728       | A56    | −32110                   | 59.38                     | 621.4      |
| A15    | −189857                  | 2626                      | 10396      | A57    | 210.8                    | 1299         |
| A16    | −227936                  | 2530                      | 14944      | A58    | 214.2                    | 1577         |
| A17    | −227936                  | 373                       | 6554       | A59    | 189.2                    | 1470         |
| A18    | −227965                  | 372.9                     | 7100       | A60    | 74.42                    | 14.73        |
| A19    | −227965                  | 372.9                     | 7100       | A61    | 197.4                    | 1455         |
| A20    | −227965                  | 372.9                     | 7100       | A62    | 199.9                    | 1648         |
| A21    | −227965                  | 372.9                     | 7100       | A63    | 189.2                    | 1616         |
| A22    | −227965                  | 372.9                     | 7100       | A64    | 1622                     | 1622         |
| A23    | −227965                  | 372.9                     | 7100       | A65    | 80.49                    | 597          |
| A24    | −227965                  | 372.9                     | 7100       | A66    | 59.38                    | 597          |
| A25    | −227965                  | 372.9                     | 7100       | A67    | 6291                     | 597          |
| A26    | −227965                  | 372.9                     | 7100       | A68    | 6291                     | 597          |
| A27    | −227965                  | 372.9                     | 7100       | A69    | 6291                     | 597          |
| A28    | −227965                  | 372.9                     | 7100       | A70    | 6291                     | 597          |
| A29    | −227965                  | 372.9                     | 7100       | A71    | 6291                     | 597          |
| A30    | −227965                  | 372.9                     | 7100       | A72    | 6291                     | 597          |
| A31    | −227965                  | 372.9                     | 7100       | A73    | 6291                     | 597          |
| A32    | −227965                  | 372.9                     | 7100       | A74    | 6291                     | 597          |
| A33    | −227965                  | 372.9                     | 7100       | A75    | 6291                     | 597          |
| A34    | −227965                  | 372.9                     | 7100       | A76    | 6291                     | 597          |
| A35    | −227965                  | 372.9                     | 7100       | A77    | 6291                     | 597          |
| A36    | −227965                  | 372.9                     | 7100       | A78    | 6291                     | 597          |
| A37    | −227965                  | 372.9                     | 7100       | A79    | 6291                     | 597          |
| A38    | −227965                  | 372.9                     | 7100       | A80    | 6291                     | 597          |
versa (Figure 12). As shown in Figure 12, the CO₂ level increased with decreasing the N₂ level, and consequently, the generated CO₂ purity and liquid CO₂, as the final product of the system, increased. Therefore, the produced cooling energy by the ejector refrigeration cycle increased, which was accompanied by an increase in streams A9 and A18 rates. The ratio of the thermal energy consumption of the CO₂ capture cycle to the generated pure CO₂ decreased by increasing the CO₂ rate in the flue gas. Accordingly, the thermodynamic justification of the cycle could be explained better, so that this ratio decreased from 16.79 to 4.28 MJ/kg CO₂ by increasing the CO₂ concentration in the flue gas from 1% to 9 mol%. Figure 13 shows the effect of flue gas composition on the amount of cooling energy produced by the ejector cycle as well as ORC parameters. The cooling energy produced by the ejector cycle increased from 52.61 to 412.1 kW by increasing the CO₂ rate. Also, the excess heat of the whole system, which was the ORC input, as well as the output power of this cycle increased.

Table 5

| Equipment | Exergy destruction | Exergy efficiency |
|-----------|-------------------|-------------------|
| Heat exchangers | I = ∑(m·ex)ₘin - ∑(m·ex)ₘout | \( \eta_{ex} = 1 - \left( \frac{\sum m \cdot \Delta h}{\sum m \cdot \Delta h_{cold}} \right) + \left( \frac{\sum m \cdot \Delta h}{\sum m \cdot \Delta h_{cold}} \right) \) |
| Compressors and pumps | I = \( ω + \sum (m·ex)ₘin - \sum (m·ex)ₘout \) | \( \eta_{ex} = \frac{\sum (m·ex)ₘin - \sum (m·ex)ₘout}{\sum (m·ex)ₘin - \sum (m·ex)ₘout} \) |
| Turbines | I = \( -ω + \sum (m·ex)ₘin - \sum (m·ex)ₘout \) | \( \eta_{ex} = \frac{\sum (m·ex)ₘin - \sum (m·ex)ₘout}{\sum (m·ex)ₘin - \sum (m·ex)ₘout} \) |
| Ejector | I = \( \sum (m·ex)ₘin - \sum (m·ex)ₘout \) | \( \eta_{ex} = \frac{\sum (m·ex)ₘin - \sum (m·ex)ₘout}{\sum (m·ex)ₘin - \sum (m·ex)ₘout} \) |
| Flash drums | I = \( \sum (m·ex)ₘin - \sum (m·ex)ₘout \) | \( \eta_{ex} = \frac{\sum (m·ex)ₘin - \sum (m·ex)ₘout}{\sum (m·ex)ₘin - \sum (m·ex)ₘout} \) |
| Expansion valve | I = \( \sum (m·ex)ₘin - \sum (m·ex)ₘout \) | \( \eta_{ex} = \frac{\sum (m·ex)ₘin - \sum (m·ex)ₘout}{\sum (m·ex)ₘin - \sum (m·ex)ₘout} \) |
| Photovoltaic panels | \( h_{conv} = 2.8 + 3V_n, \) \( h_{rad} = e_σ(T_{sky} + T_{cell})(T_{sky}^2 + T_{cell}^2), T_{sky} = T_{amb} - 6, \) \( U = h_{conv} + h_{rad}, \) \( Q = UA_{mod}(T_{mod} - T_{amb}), E_{ex} = Q(1 - \frac{T_{amb}}{T_{mod}}), \) \( E_{ex} = V_{oc}I_{sc}FF, \) \( E_{ex} = G_{mod}(1 - \frac{1}{2}(\frac{T_{amb}}{T_{mod}}) + \frac{1}{2}(\frac{T_{amb}}{T_{mod}})^2), \) \( I = E_{ex} - (E_{ex} - E_{th}) \) | \( \eta_{ex} = \frac{(E_{ex} - E_{th})}{E_{th}} \) |
| Column | I = \( \sum (m·ex)ₘin - \sum (m·ex)ₘout \) | W_{min} = \( \sum_{Out of stream} nb - \sum_{into stream} nb, \) \( b = h - T_{ex}, LW = T_{0} ΔS_{irr} \) |
| Cycle | I = \( \sum (m·ex)ₘin + Ex_{Solar} - \sum (m·ex)ₘout \) | \( \eta_{ex} = \frac{\sum (m·ex)ₘout + Ex_{Solar}}{\sum (m·ex)ₘin + Ex_{Solar}} \) |
TABLE 6 Exergy efficiency as well as exergy destruction of the system equipment

| Equipment | Inlet exergy | Outlet exergy | Exergy destruction | Exergy efficiency |
|-----------|--------------|---------------|--------------------|-------------------|
| HE1       | 84,637       | 84,583        | 54.13              | 0.937             |
| HE2       | 85,972       | 85,927        | 44.60              | 0.959             |
| HE3       | 83,037       | 83,029        | 7.470              | 0.902             |
| HE4       | 3320         | 3286          | 34.49              | 0.866             |
| HE5       | 5419         | 5415          | 3.140              | 0.982             |
| HE6       | 556.2        | 556.1         | 0.160              | 0.991             |
| HE7       | 1985         | 1974          | 10.31              | 0.934             |
| HE8       | 2883         | 2865          | 18.09              | 0.982             |
| HE9       | 1,123,568    | 1,122,946     | 622.8              | 0.962             |
| HE10      | 1,975,735    | 1,975,067     | 667.6              | 0.974             |
| HE11      | 10,353       | 10,312        | 40.59              | 0.986             |
| HE12      | 38,973       | 38,518        | 454.2              | 0.988             |
| HE13      | 1707         | 1703          | 3.600              | 0.993             |
| HE14      | 1703         | 1697          | 6.220              | 0.972             |
| HE15      | 26,087       | 26,036        | 50.59              | 0.961             |
| HE16      | 8380         | 8368          | 11.92              | 0.992             |
| T1        | 2481         | 2477          | 3.350              | 0.910             |
| T2        | 7889         | 7874          | 15.23              | 0.875             |
| T3        | 6291         | 6278          | 12.90              | 0.870             |
| C1        | 83,288       | 83,243        | 44.75              | 0.861             |
| C2        | 1592         | 1577          | 15.34              | 0.947             |
| C3        | 1694         | 1648          | 45.92              | 0.807             |
| P1        | 2702         | 2702          | 0.540              | 0.677             |
| P2        | 975,014      | 975,004       | 9.320              | 0.621             |
| P3        | 7581         | 7581          | 0.370              | 0.826             |
| P4        | 6120         | 6120          | 0.130              | 0.803             |
| Ejector   | 2796         | 2626          | 170.1              | 0.939             |
| D1        | 3099         | 3099          | 0.000              | 1.000             |
| D2        | 1,014,403    | 1,014,398     | 5.360              | 1.000             |
| D3        | 1920         | 1920          | 0.000              | 1.000             |
| D4        | 1470         | 1470          | 0.000              | 1.000             |
| V1        | 557.1        | 556.3         | 0.810              | 0.861             |
| V2        | 373.0        | 368.7         | 4.360              | 0.881             |
| V3        | 82,814       | 82,808        | 5.680              | 0.685             |
| V4        | 1,000,789    | 1,000,730     | 59.32              | 0.698             |
| T100      | 975,843      | 975,324       | 519.1              | 0.999             |
| T200      | 1,009,173    | 1,002,089     | 1003               | 0.640             |
| Photovoltaic | 3160    | 551.2         | 2609               | 0.174             |
| Cycle     | 8652         | 2096          | 6555               | 0.242             |
increase in the required heat of CO₂ capture and ejector refrigeration cycles. Consequently, the geothermal energy, which was the heat source of these cycles, increased. The rate of consumed power by the heat pump cycle also increased. This figure shows the ratio of liquid CO₂ to total power consumption. This ratio increased from 3.735 kg/s liquid CO₂ per MW at 1 mol% CO₂ to 4.096 kg/s liquid CO₂ per MW at 9 mol% CO₂. The generated CO₂ purity was among the important parameter that was considered in these changes. This parameter increased from 99.03% to 99.28% when the CO₂ concentration increased in the flue gas from 1% to 9 mol% (Figure 15). This figure indicates the total generated power, consumed power, and net consumed power of the whole integrated system. The net consumed power of the whole system increased from 238.0 to 1669 kW by increasing the CO₂ level from 1% to 9 mol%, the main reason for which could be attributed to the increased CO₂ generation.

**FIGURE 8** Exergy destruction contribution of each system component compared with the total destruction. PV, photovoltaic.

**FIGURE 9** Exergy destruction portion of the exchangers involved in the hybrid cycle.

**FIGURE 10** Exergy destruction contribution of the subsections compared with the total destruction. ORC, organic Rankine cycle; PV, photovoltaic.
5.2.2 Heat pump cycle pressure effect

The heat pump cycle pressure level is among the important parameters affecting the performance of the cycle. Figure 16 shows the effect of this pressure, that is, stream A3 pressure, on the major parameters of this cycle. Stream A3 temperature increased from 503.5 to 577.8K with an increase in the pressure from 10 to 50 bar. In other words, the quality of the produced heat or its temperature level was improved. The amount of heat
produced and power consumed by the heat pump cycle increased with rising pressure. However, the increased rate of the consumed power was higher than that of the produced heat. The produced heat and consumed power increased by 10.72% and 53.26% of their initial values, respectively, with increasing the pressure from 10 to 50 bar. Therefore, it could be concluded that the COP of this cycle decreased by increasing the pressure level.

5.2.3 | ORC pressure level effect

The ORC pressure level is among the parameters affecting the performance of the integrated system. The temperature level of the heat source of this cycle increases by increasing the operating pressure. Given that this heat is supplied by the excess heat of other parts, it may not be possible to supply it. In this
section, this variable is examined to determine its impact on ORC performance. As shown in Figure 17, stream A70 temperature, reflecting the required temperature level of the heat source, increased from 380.7 to 436.2 K with increasing stream A6 pressure from 3 to 12 bar. As the pressure increased, the heat consumption of the cycle increased from 1451 to 1732 kW. Accordingly, the net produced power of this cycle significantly increased from 132.7 to 300.7 kW. The overall performance of this cycle could be better explained by its efficiency. The efficiency of this cycle increased by 89.81% of its initial value and reached 17.36% with increasing the pressure from 3 to 12 bar. The main reason for the low efficiency of this part of the system could be attributed to the low-temperature level of its heat source, which is supplied by the excess heat of other parts of the system.
Carbon dioxide capture and storage from the flue gases of the power plant can help reduce environmental pollution. Liquidation of CO₂ can be utilized for peak shaving in the electricity industry and also facilitates its transport to remote areas. In this study, an integrated system to capture CO₂ from flue gases of the power plants and liquefy it based on a CO₂ capture cycle, heat pump unit, and the ejector refrigeration system integrated with the Kalina and organic Rankine power plants was introduced. The required heat and power of the hybrid system by geothermal energy and PV cells were supplied. The analysis results of thermodynamics, exergy, and sensitivity can be provided as the follows:

1. The proposed integrated system produced 2.641 kg/s of liquid CO₂ as the main product. The total power consumption of the whole system was 657.3 kW, which was supplied by the PV system. The total heat required by the system was 20,562 kW, which was supplied by geothermal energy. The ejector refrigeration cycle was applied to supply the required cooling energy for liquefying the separated CO₂ in the CO₂ capture cycle. This required cooling load was 156.3 kW at 244.6 K. The heat supplied by the heat pump cycle was 1108 kW at 546.4 K. The COP of this cycle was obtained as 3.661.

2. For exergy analysis, the irreversibility and exergy efficiency of equipment must be investigated. The exergy investigation results showed the highest exergy destruction of the whole system belonged to the PV system (39.81%), heat exchangers (30.96%), and columns (23.22%). The results showed that they have a lower exergy efficiency compared with other equipment, and also pumps and valves have the least contribution to exergy degradation. The exergy efficiency of the integrated system was obtained as 24.20%.

3. The performance of the integrated system was examined under different conditions by performing a parametric study and changing the important parameters of the system, such as inlet flue gas composition and heat pump and ORC pressure levels. The ratio of liquid CO₂ to total power consumption, power production, and total power consumption increased up to 4.096 kg/s liquid CO₂/MW, 597 kW, and 2264 kW, respectively, with the increase in the CO₂ concentration in the flue gas from 1 to 9 mol%. The sensitivity study indicated that the COP of the heat pump cycle increased up to 4.78 when the pressure level of this cycle was reduced from 50 to 10 bar. Besides, the COP of the ORC efficiency increased up to 17.36% when the pressure of this cycle increases from 3 to 12 bar.

4. It is recommended to perform economic and environmental analyses with multiobjective optimization on
the proposed system in future studies to evaluate the efficiency of this integrated system in terms of these aspects in addition to thermodynamic analysis.

**NOMENCLATURE**

| Symbol | Description |
|--------|-------------|
| \( \dot{E}_x \) | exergy rate |
| \( \dot{E}_{x,ch} \) | chemical exergy |
| \( E_{x,in} \) | input exergy |
| \( E_{x,out} \) | output exergy |
| \( \dot{E}_{x,ph} \) | physical exergy |
| \( H \) | starting point of the expansion of the high-pressure fluid flow in the expander |
| \( h_C \) | ideal specific enthalpy of the stream exiting |
| \( h_H \) | specific enthalpies of the nozzle inlet |
| \( h_{H'} \) | specific enthalpies of the nozzle outlet |
| \( h_{H''} \) | specific enthalpies of ideal isentropic nozzle outlet |
| \( h_O \) | specific enthalpy of the output mixture |
| \( \dot{h}_0 \) | enthalpy of the flow at ambient temperature and pressure |
| \( I_{OC} \) | represents the current of the open circuit |
| \( \dot{m}_{in} \) | mass flow rate initial |
| \( \dot{m}_s \) | mass flow rate secondary |
| \( S_{H''}^{\dot{S}} \) | specific entropy of the ideal isentropic nozzle outlet |
| \( S_0 \) | entropy of the flow at ambient temperature and pressure |
| \( U_{H'} \) | initial stream velocity at the nozzle outlet |
| \( u_o \) | output mixture velocity |
| \( u_{O,i} \) | ideal output mixture velocity |
| \( V_{OC} \) | voltage of the open circuit |

**GREEK LETTERS**

| Symbol | Description |
|--------|-------------|
| \( \eta \) | efficiency |
| \( \eta_{ex} \) | exergy efficiency |
| \( \eta_{inv} \) | inverter efficiency |
| \( \eta_{O} \) | mixture efficiency |
| \( \eta_{PV} \) | photovoltaic efficiency |
| \( \eta_{system} \) | system efficiency |
| \( \gamma_i \) | activity coefficient of the \( i \)th component |
| \( \sigma \) | entrainment ratio |
| \( \Sigma \) | sum |

**SUBSCRIPTS AND SUPERSCRIPTS**

| Subscript | Description |
|-----------|-------------|
| ch | chemical |
| i | \( i \)th component |
| in | inlet |
| out | outlet |
| ph | physical |

**COMPONENT NAMES**

| Component | Description |
|-----------|-------------|
| C | compressor |
| D | flash drum |
| HE | heat exchanger |

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