Development of a new CO₂ liquefaction system using the Linde–Hampson process, Kalina power generation unit, and flat plate solar collectors with Al₂O₃/H₂O nanofluid

Bahram Ghorbani¹ | Alireza Khatami Jouybari²

¹Faculty of Engineering Modern Technologies, Amol University of Special Modern Technologies, Amol, Iran
²Faculty of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran

Correspondence
Bahram Ghorbani, Faculty of Engineering Modern Technologies, Amol University of Special Modern Technologies, Amol, Iran.
Email: b.ghorbani@ausmt.ac.ir

Abstract
Greenhouse gas emissions into the atmosphere have had devastating environmental effects, including ozone depletion and global warming. Carbon dioxide (CO₂) is widely used in oil and gas plants, the food industry, and as a working fluid in the power industry. Carbon dioxide is liquefied for long-term storage, to be transported to remote areas, and is used for peak shaving in the power plants. Solar flat plate collectors and wasted heat from the CO₂ liquefaction system can be used in power plant systems. Also, the use of nanoparticles in the collectors improves the thermal properties of the working fluid and increases the efficiency of solar collectors. This study has developed a new hybrid system for CO₂ liquefaction using Linde–Hampson system, Kalina power generation unit, and flat plate solar collectors. The Linde–Hampson system’s dissipated heat and solar collectors are used to supplying part of the power of the CO₂ liquefaction system. The combined system produces 9416 kmol/h of liquid CO₂ by absorbing 35.97 MW of power. The Kalina power generation unit provides 9.546 MW of power by absorbing 76.98 MW of the CO₂ liquefaction cycle’s dissipated heat and 91.18 MW from flat plate collectors. Based on the output of exergy assessment, exergy efficiency and exergy degradation of the developed integrated structure are 44.16% and 118.3 MW, respectively. Moreover, significant portions of exergy destruction in the combined process belong to solar collectors (74.68%), heat exchangers (12.47%), and compressors (7.157%), respectively. The use of Al₂O₃ nanoparticles in pure water has been investigated for heat transfer in flat panel solar collectors. According to the sensitivity analysis results, as the volume ratio of particles in nanofluid increases to 6%, the production capacity of the Kalina cycle and exergy efficiency improves to 9.56 MW and 9.522%, respectively. Also, as the pressure of the pumped fluid in the Kalina cycle increases from 800 to 1600 kPa, the exergy yield of the Kalina cycle and the exergy yield of the whole combined system increase to 36.34% and 44.26%, respectively.
INTRODUCTION

The utilization of fossil fuels releases large amounts of greenhouse gases (mainly CO₂) into the atmosphere. International regulations such as the Kyoto Protocol are enacted to control greenhouse gas emissions and their devastating environmental effects. On the other hand, CO₂ is considered a valuable substance widely used in various industries such as oil and gas for the injection in oil and gas extraction wells to enhance the extraction.¹,² Some of its most important applications include beverages, fast freezing of meat and fruits, sudden drying of food, disinfection of grains, welding, pharmaceutical, electricity, and oil and gas industries. However, the molecule of CO₂ is highly unstable and relatively unreactive thermodynamically.³,⁴ The liquefaction method is used for long-term CO₂ storage and transports it to distant areas. Aliyon et al.⁵ developed four integrated structures to liquefy CO₂ using absorption refrigeration cycles, compression refrigeration cycles, Linde–Hampson single-pressure, and dual-pressure Linde–Hampson (DPLH) liquefaction processes. According to the results, the refrigeration cycle had a coefficient of performance (COP) of 2.617 and the absorption refrigeration cycle had the lowest performance coefficient of 0.537 in their novel integrated structure. Also, the exergy efficiency of absorption and compression refrigeration cycles, Linde–Hampson single-pressure, DPLH system were 85.53%, 51.63%, 21.38%, and 28.33%, respectively. Aliyon et al.⁶ investigated a combined structure for the extraction and liquefaction of CO₂ from the exhaust fumes of a coal-fired power plant. The chemical adsorption unit was used by the post-combustion method to separate the carbon dioxide. They used different cycles, such as absorption refrigeration, compression, Linde–Hampson single-pressure, and double-pressure to liquefy carbon dioxide. Seo et al.⁷ used four cycles of Linde–Hampson single-pressure, double-pressure, Precooled Linde–Hampson liquefaction system, and closed-loop system to liquefy carbon dioxide. The required power of four cycles of Linde–Hampson single-pressure, double-pressure, precooled Linde–Hampson liquefaction system, and the closed-loop system was 485.9, 472.5, 381.5, and 376.2 kJ/kg, respectively.⁵

The multipurpose vessels (MPV) which can carry CO₂ and other energy carriers have attracted much attention from researchers. Some carriers transport CO₂ from energy consumers to storage facilities such as oil/gas wells, and other vessels transport energy sources from oil/gas wells to energy consumers. Therefore, it is possible to carry CO₂ in one direction and different loads in the other direction using multipurpose vessels (MPV).⁸ Ghorbani et al.⁹ investigated a combined process for the separation and liquefaction of CO₂ using post-combustion capture with chemical absorption and the DPLH system at non-peak hours. Organic Rankine power production systems and gas turbine combined plant were used in peak hours. Based on the output of exergy investigation, the highest share of exergy degradation in equipment occurs in distillation towers (0.4852), exchangers (0.4362), and compressors (0.0286). Byeong-Yong et al.¹⁰ used liquefied natural gas (LNG) refrigeration to liquefy carbon dioxide vapor in CO₂ transport tankers. The natural gas produced was used as the input fuel of combustion engines. Roussanaly et al.¹¹ studied the ship-based CO₂ transport at two pressures of 7 and 15 barg for an annual volume of 20 MtCO₂/year and transport distances up to 2000 km. The results showed that shipping with 7 barg pressure reduced shipping costs up to 30% compared with 15 barg. Seo et al.⁷ studied four CO₂ liquefaction units for ship-based CO₂ and storage using the life cycle cost (LCC) assessment. The results illustrated that the Linde–Hampson unit and the DPLH system have higher capital and operational costs than the other CO₂ liquefaction systems. Also, the closed unit depicts the minimum LCC while the Linde–Hampson unit with precooling had just slightly higher rates than the closed unit.

The majority of the developed processes ignore the excess heat of the intercoolers used in the combined plant to liquefy CO₂. This dissipative heat can be recovered in power production cycles. Kalina power unit and organic Rankine system (ORC) are among the principal structure that widely are utilized to produce power from low-temperature sources or excess energy from heat systems. The Kalina systems work better than ORCs at low-temperature situations because the employed fluid is the water–ammonia compound; the compound receives thermal energy to produce power and the energy return is delivered at a greater performance. Therefore, they produce more power for a constant inlet heat compared with ORCs. Kalina power systems have lower prices of operating and maintenance contrasted to ORCs, but the primary prices of these cycles are higher. The output stream from the ORCs turbine is turned into a two-phase stream due to pressure decrease. To prevent corrosion in the turbine...
blades, the outlet pressure should occur at the output of the last blade of the turbine. Though, the output stream from the Kalina unit turbine is a saturated mixture and does not make corrosion.\textsuperscript{12,13} The main feature of the Kalina cycle is its higher efficiency than other power generation cycles due to the unique properties of the water–ammonia operating fluid. In cycles with water–ammonia fluid, temperature adaptation or the same pinch is better between the temperature profile of the heat source flow and the temperature change profile of water–ammonia fluid. As a result, the thermodynamic irreversibility of the evaporator decreases throughout the heat transfer process in the evaporator, and the heat transfer process takes place more efficiently. According to the results reported by Jonsson,\textsuperscript{14} in most cases of the Kalina cycle, the downstream cycle of gas diesel engines produces more power than the Rankine cycle. Vera et al.\textsuperscript{15} investigated a combined power production plant using the ocean thermal energy conversion (OTEC) unit and the ORC power generation cycle. For the thermodynamic evaluation of the cycle, different working fluids were investigated. According to the results, the highest thermodynamic (3.60\%) and electrical (2.57\%) efficiencies belong to the integrated structure based on the R1234y working fluids. Romero et al.\textsuperscript{16} used the difference between the cold and hot temperatures of the Pacific Coast of Mexico and the solar collectors in the Kalina power production unit. A nonlinear mathematical model was used to optimize the developed integrated structure. Based on the output, the energetic efficiency of the developed combined unit varies between 3.5 and 7.4\%. Khanmohammadi et al.\textsuperscript{17} proposed two cycles of hydrogen production using polymer electrolyte membrane (PEM) electrolyzer, OTEC system, and solar collectors. The ORC with ocean floor cooling source and flat plate collector heat source was applied in the first structure. The heat source of flat plate collectors and thermoelectric generator (TEG) was used in the second structure. The exergy efficiency of the hydrogen production cycle with collector and collector/TEG heat source were 48.69\% and 54.98\%, respectively.

Solar flat plate collectors (SFPCs) are considered a type of heat exchanger that heats the fluid inside its tubes by absorbing direct and scattered sun radiation by the absorber plate. These collectors have lower efficiency and fluid outlet temperature for applications with low temperatures compared with other types of collectors.\textsuperscript{18} The use of nanoparticles in energy-carrying fluids is considered as a solution to raise the efficiency of solar flat plate collectors.\textsuperscript{19} Boustani et al.\textsuperscript{20} used three nanoparticles of aluminum oxide (Al\textsubscript{2}O\textsubscript{3}), titanium dioxide (TiO\textsubscript{2}) and copper(II) oxide (CuO) to enhance the exergy efficiency of SFPCs. Three nanoparticles of Al\textsubscript{2}O\textsubscript{3}, TiO\textsubscript{2}, and CuO were used in this regard. According to the results, as solar radiation increases, exergy efficiency and the overall loss coefficient rise. Besides, as wind speed increases and air temperature decreases, the exergy efficiency improves. The use of nanofluids instead of water reduced the overall loss factor by 0.4\%. For radiation intensities of 200–600 W/m\textsuperscript{2}, the total dissipation coefficient of both fluids increased from 2.36 to 2.59 for pure water and from 2.35 to 2.58 for nanofluids. Veysi et al.\textsuperscript{21} examined the exergy analysis of the SFPCs and the effect of Al\textsubscript{2}O\textsubscript{3} nanoparticles on various output parameters. The genetic algorithm for optimizing the exergy efficiency of solar flat plate collectors was implemented using the variables of temperature, input temperature of the SFPCs, the volumetric concentration of nanofluids, and flow rate. According to the results, as the volumetric concentration of nanoparticles raises from 0 to 14.23\%, the exergy efficiency increases to 10.96\%. Alawi et al.\textsuperscript{22} examined the influence of metal oxides, non-metal, and solid oxides on energy-carrying fluids in flat plate collectors. The effect of different thermal parameters, such as nanoparticle type, concentration, size/shape, solar irradiation, and mass amount were examined. Based on the output, when the mass flow rate rises, the exergy efficiency drops, and the energy yield has a growing trend first and then a decreasing trend. Said et al.\textsuperscript{23} examined the impact of increasing Al\textsubscript{2}O\textsubscript{3} nanoparticles on different output parameters of solar flat panel collectors in a laboratory study. According to the results, energy efficiency with 13 nm nanoparticles increased to 73.7\%. Yousefi et al.\textsuperscript{24} through a laboratory study, examined the effect of Al\textsubscript{2}O\textsubscript{3} nanoparticles on the pure water working fluid in the SFPCs. Results signified that the efficiency of the SFPCs increased by 28.3\% at a volume concentration of nanoparticles of 0.2\%. Sint et al.\textsuperscript{25} studied the influence of CuO–water nanoparticles on the working fluid of pure water in the SFPCs. According to the results, when the volumetric concentration increases, respectively, the specific heat capacity of the nanofluid and the total heat dissipation coefficient decrease. However, nanofluid thermal conductivity, density, nanofluid viscosity, and collector energy efficiency increase. Loni et al.\textsuperscript{26} investigated the effects of the nanoparticles concentration (0–5 vol\%) toward the thermal and exergy efficiencies of the collector. The results showed that the thermal efficiency reduced and exergy efficiency rose with growing nanoparticle volume concentration. Mahian et al.\textsuperscript{27} implemented an analytical method to investigate the influences of tube roughness, nanoparticle dimensions, and various thermophysical patterns on entropy production in a solar collector that uses H\textsubscript{2}O/Al\textsubscript{2}O\textsubscript{3} nanofluid as the operating fluid. According to the results, as the volume percentage of nanoparticles increases in the base fluid, entropy production reduces, and the outlet temperature of the collector will increase. Moreover, the percentage of nanoparticles mixing with the base fluid and the size of nanoparticles will not have
a significant influence on entropy production at low mass flows. Ghasemi et al.28 studied the impact of H₂O/Al₂O₃ nanofluid on solar collector’s performance, and solar parabolic trough collector’s efficiency numerically. The temperature field, thermal efficiency, and the output average temperature were investigated. According to the results, nanofluid, as a working fluid, has a better efficiency than water.

Extensive studies have been conducted on CO₂ liquefaction with different long-term and portable storage methods. Most studies have focused on energy, exergy, economic and environmental optimization. In these studies, the CO₂ compression cycle’s wasted heat has not been recovered in a power generation unit such as the Kalina cycle. Also, the use of flat panel solar collectors and the effect of nanoparticles on heat transfer fluids in CO₂ liquefaction structures based on literature have not been performed. This study uses the heat loss of the carbon CO₂ liquefaction cycle along with SFPCs in the Kalina power unit. H₂O/Al₂O₃ nanofluid is employed to increase the efficiency of solar flat plate collectors. For the evaluation of the developed combined structure, energy, exergy, and sensitivity analyses are investigated.

2 | PROCESS DESCRIPTION

As CO₂ demand is less than its production, it is necessary to store it to be used at the time of consumption. CO₂ liquefaction is one of the methods of its storage and transportation to distant places. This paper develops a new integrated structure for liquefying CO₂ using the Linde–Hampson cycle, Kalina power unit with a cold source of the deep ocean, and solar flat plate collectors.

The block diagram of energy transfer and streams in the combined process of CO₂ liquefaction is shown in Figure 1. The wasted heat of the Linde–Hampson liquefaction cycle supplies part of the heat of the Kalina power generation unit. The process diagram of the integrated structure for CO₂ liquefaction is presented in Figure 2, consisting of the DPLH liquefaction process, the Kalina power production unit, and the SFPCs.

Table 1 presents the specification of the molar composition of the streams employed in the proposed structure. The water–ammonia mixture has been used in the Kalina power generation cycle. The HYSYS package with the Peng Robinson equation is employed to model the liquefaction cycle of the DPLH and Kalina power production unit. Also, Matlab programming has been used to simulate flat panel solar collectors and the effect of using nanoparticles in pure water. Table S1 lists the specification of the operating conditions of the streams employed in the developed structure in the Appendix S1.

The following hypotheses are intended to simulate an integrated structure5,9,20,21:

1. The effect of pressure decrease in exchangers and drums has been ignored.
2. Waste heat in various equipment has been ignored.
3. Adiabatic efficiency of compressors, turbines, and pumps are examined to be 75%, 90%, and 90%, respectively.

![Figure 1](image-url)
4. The outer diameter of the riser pipes is considered with 0.9 mm of pipe thickness.
5. The properties of the fluid in the collector are constant during the process.
6. The ambient temperature inside the collector glass cover is fixed and equal to 300 K.
7. Nanoparticles with an average diameter of 15 nanometers are considered.

More theory and background information on the Linde–Hampson system and Kalina power generation unit can be found in references. In the following, the
different sub-sections used in the integrated structure are examined.

### 2.1 Dual-pressure Linde–Hampson cycle

Stream B1, which contains 97 mol% of carbon dioxide, enters the compressors C1 and C4, respectively, and its pressure increases to 1970 kPa. HE1 and HE2 heat exchangers are used for the Intercooler. Water is used as the desired flow for the Intercooler. The stream containing CO2 enters the flash drum D1 after compression under the two-phase flow B5. Water current and part of the impurity from the bottom of the flash drum come out in liquid form. The gas flow B6 enters the mixer together with the return flow B22.

Mixer outlet flow (flow B8) enters the compressor C2 (at 24.87°C and 1970 kPa), and its pressure increases to 3900 kPa. Subsequently, the output flow is cooled in the HE3 exchanger. The two-phase flow B10 enters the flash drum D2 at 32°C temperature and 3900 kPa pressure. The outlet gas flow of the top of the flash drum, which contains richer CO2 than the inlet flow, enters the mixer under the B12 stream with the return flow of B24, and finally enters the second stage of CO2 liquefaction. The flow B13 enters the compressor C3 at 27.33°C temperature and 3900 kPa pressure. After its pressure increases to 10,000 kPa, the output flow is cooled to 35°C by heat exchange with the HE4 exchanger. The outlet flow from the intercooler enters the HE5 multipass heat exchanger, and the temperature decreases to 33°C. Next, the cooled outlet flow from the multiplexchanger goes to the V1 throttle valve, and the pressure is reduced to 3900 kPa. Reducing the pressure in the throttle valve decreases the outlet flow temperature to 3.338°C. Two-phase flow B17 enters the flash drum. The outlet gas stream of the top of the D3 drum is used to increase the efficiency of the CO2 liquefaction structure as a return stream. Also, the liquid outlet stream of the bottom of the drum enters the V2 throttle valve, and the pressure decreases to 1970 kPa.

This pressure drop leads to a decrease in the temperature of the two-phase outlet flow to −19.76°C. Flow B19 goes to the drum D4, and the final product of liquid CO2 exits the bottom of the drum (stream B20) at −19.76°C and 1970 kPa. The outlet gas flows from the top of the drum below is used as the return flow after heat transfer in the exchanger HE5.

### 2.2 Kalina power production unit

The Kalina cycle has a remarkable performance for the utilization of low-temperature to medium-temperature heat sources. Water and ammonia solution is also selected and used as a working fluid for several reasons. The use of this working fluid causes evaporation to start at low temperatures, resulting in more efficient use of heat from the heat source. Following the flexibility in changing the concentration of water and ammonia solution, the concentrated solution enters the turbine. The dilute solution enters the low-pressure condenser, which improves the temperature compliance in the evaporator and increases the cycle efficiency. Besides, given that the molecular masses of ammonia and water are very close, water vapor, and ammonia act almost like water vapor, making it possible to use a standard steam turbine.

On the other hand, ammonia is inexpensive, available, and harmless to the environment, and the use of water and ammonia solutions in industrial applications and power plants is highly safe. The wasted heat from the dual-pressure CO2 liquefaction cycle in heat exchangers HE1, HE2, HE3, and HE4 is transferred to the Kalina power generation cycle by water flow. These flows enter the mixer, then enter the HE6 evaporator under stream B33 at 99.95°C temperature and 101.3 kPa pressure and leave it at a temperature of 25°C. The heat loss from the CO2 liquefaction cycle provides only 91.18 MW of the heat inlet to the Kalina cycle. Flat panel solar collectors supply the rest of the heat inlet to the Kalina cycle. The pumped stream of water and ammonia (flow B36) at 6.992°C temperature and 1400 kPa pressure is divided into three parts and enters the evaporator HE6, HE7, and HE9 and their temperatures increase to 92.77°C, 70.88°C, and 79°C, respectively. The outlet flow of the evaporators goes to the mixer and then enters the D5 flash drum by the two-phase flow B43. The concentrated ammonia–water solution flow goes to the T1 turbine from the top of the flash drum to generate power, and the outlet liquid flow from the bottom of the flash drum enters the HE9 heat exchanger as a return flow. The current leaving the heat exchanger HE9 enters the throttle valve V3, and its pressure is reduced to 450 kPa, and after being mixed with the outlet stream of the turbine T1, enters the HE8 condenser (stream B50) at 35.38°C and 450 kPa. For cooling the HE8 condenser, the cold underwater layers of the oceans are used. The output current from the condenser enters the pump at a temperature of 6.8°C, and the cycle continues as the pressure increases.

### 2.3 Flat plate solar collectors

The SFPCs with pure water operating fluid are used to provide part of the heat input to the evaporators. Also, the effect of adding Al2O3 nanoparticles in pure water is investigated. The SFPCs consists of solar panel, glass cover, insulation, frame and header, and riser tubes. The SFPCs transfer heat as a heat exchanger to the working fluid inside the tubes by absorbing direct and scattered
solar radiation using absorber plates. Thermal and optical analysis of collectors is used for thermodynamic analysis of flat plate collectors. The following equation is applied to determine the useful energy absorbed in terms of fluid inlet and outlet temperatures:

$$Q_u = m C_p (T_o - T_i)$$  \hspace{1cm} (1)$$

where $m$ is the mass flow rate; $C_p$ denotes the specific heat capacity and $T_o$ and $T_i$ represent the input and output temperature, respectively. Equation (1) becomes the following equation by considering the useful heat absorbed by the collector in terms of the amount of solar radiation$^{20,21}$:

$$Q_u = A_p F_R (S - U_f (T_i - T_o))$$  \hspace{1cm} (2)$$

where $A_p$ is the area of the absorber plate; $F_R$ denotes the heat removal factor and $S$ and $U_f$ represent the radiation received and overall heat loss coefficient, respectively. In the above equation, the value of the heat recovery coefficient is defined as follows$^{20,21}$:

$$F_R = \frac{m C_p}{U_f A_p} \left[1 - \exp \left( - \frac{F' U_f A_p}{m \phi C_p} \right) \right]$$  \hspace{1cm} (3)$$

In this equation, $F'$ is the collector efficiency coefficient which is determined by the following equation$^{20,21}$:

$$F' = \left( \frac{w U_f}{\pi D h_f} + \frac{1}{C_p} + \frac{w}{D + (w - D) p} \right)$$  \hspace{1cm} (4)$$

where $w$ is the space between the two parallel tubes. $D$ refers to the tube outer diameter, $C_p$ and $h_f$ refer to bond conductance and convective heat transfer coefficient inside the absorber, respectively. Further explanations of the equations used to calculate the various parameters in the flat plate collectors are presented in the Appendix S1.$^{20,21}$

The thermophysical properties of nanofluids are assessed by the next equations. The nanofluid thermal conductivity is determined from the following equation.$^{21}$

$$k_{nf} = \frac{k_{np} + 2k_{bf} + 2\varphi(k_{np} - k_{bf})}{k_{np}/k_{bf} + 2 - \left( \frac{\varphi k_{np} - k_{bf}}{k_{nf}} \right)}$$  \hspace{1cm} (5)$$

in which, $k_{np}$ is the nanoparticles thermal conductivity, $k_{bf}$ resembles the base fluid thermal conductivity, and $\varphi$ represents the nanoparticles volume fraction.

The nanofluid density can also be determined from the following equation.$^{29}$

$$\rho_{nf} = \varphi \rho_{np} + (1 - \varphi) \rho_{bf}$$  \hspace{1cm} (6)$$

The nanofluid dynamic viscosity can be determined from the following equation.$^{30}$

$$\mu_{nf} = \mu_{bf} \left( 1 + 2.5 \varphi + 6.5 \varphi^2 \right)$$  \hspace{1cm} (7)$$

The nanofluid thermal capacity can be determined from the subsequent equation.$^{31}$

$$c_{p,nf} = \frac{(1 - \varphi) \rho_{bf} c_{p,bf} + \varphi \rho_n c_{p,n}}{(1 - \varphi) \rho_{bf} + \varphi \rho_n}$$  \hspace{1cm} (8)$$

The thermophysical properties of Al$_2$O$_3$ nanoparticles and pure water at temperature of 293 K are listed in Table 2. Also, Table 3 shows the characteristics of the flat plate environment and collectors used in the integrated structure.

### 3 | ENERGY AND EXERGY ANALYSES

Unlike energy, exergy cannot be conserved but is destroyed due to irreversibility. Internal irreversibilities include friction, infinite expansion, mixing, and chemical reactions. On the other hand, external irreversibility is more likely to occur due to heat transfer between finite temperature differences. In fact, exergy is lost when the energy of a flow is discharged into the surroundings. In the absence of nuclear impacts, magnetic, electrical, surface tension, kinetic and potential exergies, the exergy of the whole system can be considered as the sum of two distinct components of physical and chemical exergies. Physical exergy is proportional to the work done to transfer a system from its original state to a state of mechanical–thermal equilibrium with the environment.$^{32}$

Also, chemical exergy is determined as the maximum work that can be obtained to transfer a system in mechanical and thermal equilibrium with the environment. It has

| Fluid     | Heat capacity (J/kg K) | Density (kg/m$^3$) | Thermal conductivity (W/m K) | Viscosity (kg/ms) |
|-----------|------------------------|--------------------|------------------------------|------------------|
| Water     | 4182                   | 998                | 0.597                        | 998 × 10$^{-6}$  |
| Al$_2$O$_3$ | 773                   | 3880               | 36                           | –                |
the most stable structure in equilibrium with its surroundings. The equipment is examined as a control volume. In the thermodynamic analysis of cycles and equations, the steady state of mass and energy conservation is written for each control volume. Regardless of kinetic energy and potential changes,\(^{33}\) which are calculated as follows:

\[
\sum m_i = \sum m_e
\]  

(9)

### TABLE 3  The characteristics of the flat plate collectors used in the combined structure

| Parameters                      | Unit  | Value     |
|---------------------------------|-------|-----------|
| Absorption area                 | m\(^2\) | 1.51      |
| Collector dimensions            | cm\(^2\) | 200/94/9.5 |
| Tilt angle                      | degree | 45        |
| Sun temperature                 | K     | 4350      |
| Optical efficiency              |       | 0.84      |
| Emissivity of the absorber plate|       | 0.96      |
| Plate thickness                 | m     | 0.0005    |
| Thermal conductivity of the     | W/mK  | 383       |
| absorber plate                  |       |           |
| Emissivity of the covers        |       | 0.9       |
| Thermal conductivity of the     | W/mK  | 0.05      |
| insulation                      |       |           |
| Thickness of the back insulation| m     | 0.07      |
| Thickness of the sides          | m     | 0.04      |
| diameter of tube                | m     | 0.01      |
| Thickness of tube               | m     | 0.0009    |
| Number of riser tubes           |       | 7         |
| Length of riser tubes           | m     | 2         |
| Center to center distance of    | m     | 0.143     |
| tubes                           |       |           |

\[
Q_{in} + \sum m_i h_i = \sum m_e h_e + W_{ev}
\]  

(10)

The coefficient of performance is used to evaluate the refrigeration cycle of the CO\(_2\) liquefaction. The ratio of refrigeration produced to liquefy CO\(_2\) to the inlet energy required is considered as the coefficient of performance, which is calculated as follows:

\[
\text{COP} = \frac{\text{Refrigeration load}}{\text{Inlet energy required}}
\]  

(11)

The total exergy rate for each flow includes physical exergy and chemical exergy, which are calculated as follows:

\[
ex = ex^{ch} + ex^{ch}
\]  

(12)

\[
ex^{ch} = (h - h_0) - T_0 (s - s_0)
\]  

(13)

\[
ex^c = \sum (x_i ex^c_i) + \Delta G^{mix} = \sum (x_i ex^c_i) + (G - \sum x_i G_i)
\]  

(14)

where \(ex^c_i\) refers to the component chemical exergy in the standard condition, \(x_i\) denotes the component mole fraction, and the parameters \(G\) and \(G_i\) present the Gibbs free energy of the solution and component at the environment condition. The HYSYS package and Matlab programming language are employed to determine the chemical exergy for the non-ideal mixture of various composites. The exergy balance of each compound can be recorded as follows\(^{34}\):

\[
Ex_{in} + E_{Q_i} = E_{out} + E_{Q_{out}} + W_{shaft} + I
\]  

(15)

### TABLE 4  The equations utilized to obtain the yield and exergy destruction of each of the equipment\(^{20,22,35,36}\)

| Equipment                   | Exergy destruction                              | Exergy efficiency                  |
|------------------------------|-----------------------------------------------|-----------------------------------|
| Heat exchangers              | \(I = \sum (\text{mex})_{in} - \sum (\text{mex})_{out}\) | \(\eta_{ex} = 1 - \left( \frac{\sum \text{mex}_{\text{max}}}{\sum \text{mex}_{\text{min}}} \right)_{\text{hot}} + \left( \frac{\sum \text{mex}_{\text{max}}}{\sum \text{mex}_{\text{med}}} \right)_{\text{cold}}\) |
| Pumps                        | \(I = W_{shaft} + \sum (\text{mex})_{in} - \sum (\text{mex})_{out}\) | \(\eta_{ex} = \frac{\sum (\text{mex})_{\text{min}}}{W_{shaft}}\) |
| Compressors                  | \(I = W_{shaft} + \sum (\text{mex})_{in} - \sum (\text{mex})_{out}\) | \(\eta_{ex} = \frac{\sum (\text{mex})_{\text{min}}}{W_{shaft}}\) |
| Turbines                     | \(I = \sum (\text{mex})_{in} - \sum (\text{mex})_{out} - W_{shaft}\) | \(\eta_{ex} = \frac{\sum (\text{mex})_{\text{min}}}{W_{shaft}}\) |
| Expansion valves             | \(I = \sum (\text{mex})_{in} - \sum (\text{mex})_{out}\) | \(\eta_{ex} = \frac{\sum (\text{mex})_{\text{min}}}{\sum (\text{mex})_{\text{out}}}\) |
| Flash drums                  | \(I = \sum (\text{mex})_{in} - \sum (\text{mex})_{out}\) | \(\eta_{ex} = \frac{\sum (\text{mex})_{\text{min}}}{\sum (\text{mex})_{\text{out}}}\) |
| Flat plate collectors        | \(\Delta P = \rho g (L_s\sin\beta + h_l)\) \(h_l = \frac{8\eta_{\text{gpr}}}{\rho^\text{gpr} g^2 A_{\text{in}}^2} \left( \frac{L_{\text{in}}}{A_{\text{in}}} + \sum m_i K_i \right)\) | \(\eta_{ex} = \frac{\left| \frac{1}{j_A} \left( \frac{1}{L_s} \left( \frac{L_{\text{in}}}{A_{\text{in}}} + \sum m_i K_i \right) + \frac{8\eta_{\text{gpr}}}{\rho^\text{gpr} g^2 A_{\text{in}}^2} \left( \frac{L_{\text{in}}}{A_{\text{in}}} + \sum m_i K_i \right) \right) \right|}{\frac{L_s\sin\beta + h_l}{j_A}}\) |
| Cycle                        | \(I = \sum (\text{mex})_{in} - \sum (\text{mex})_{out}\) | \(\eta_{ex} = \frac{\sum (\text{mex})_{\text{min}}}{\sum (\text{mex})_{\text{out}}}\) |
The mentioned equation is applied to assess the irreversibility or exergy destroyed, where \( E_{x_{\text{in}}} \) and \( E_{x_{\text{out}}} \) are the exergy of the inlet and outlet material flow, \( E_{x_{Q_{i}}} \) and \( E_{x_{Q_{\text{out}}}} \) are the exergy of the input and output energy flow, \( W_{\text{shaft}} \) is the work done on or by the plant and \( I \) is the irreversibility or exergy destroyed. The equations used to obtain each piece of equipment’s efficiency and exergy destruction are shown in Table 4.

4 | RESULTS AND DISCUSSION

This study has developed an integrated CO\(_2\) liquefaction structure using the DPLH system, Kalina power production unit, and the SFPCs. The lower layers of the ocean are used to provide cooling for the condenser of the Kalina power generation cycle. The HYSYS package and Matlab programming language were utilized to model the combined process. Energy analysis, exergy, and sensitivity are employed to assess the combined structure.

4.1 | Energy analysis results

The specification of the molar composition of the streams employed in the combined CO\(_2\) liquefaction structure is shown in Table 1. Linde–Hampson refrigeration process produces 9416 kmol/h of liquid CO\(_2\) by absorbing 35.97 MW of power. The inlet heat to the Kalina cycle evaporator includes 91.18 MW of waste heat from the CO\(_2\) liquefaction cycle and 76.98 MW of heat generated by the flat panel solar collectors. Based on the output of energy analysis, the thermal efficiency of the Kalina cycle in the base state, refrigeration cycle performance coefficient, and the amount of power produced by the Kalina unit are 5.676%, 1.816, and 9.546 MW, respectively. The operational specifications of the equipment applied in the combined process for liquefaction of CO\(_2\) are shown in Table 5. Matlab programming is used to analyze the numerical modeling of the flat panel collector. Collectors simulation information is extracted from references.\(^{20,21}\)

4.2 | Validation analysis results

The various sections of the proposed combined structure separately are verified with related articles and similar technical patents. Table 6 presents the validation results of the exergy efficiency of SFPCs under different conditions of solar radiation, mass flow rate, and inlet flow temperatures compared with reference.\(^{20}\) Pure water is chosen as the operating fluid for heat transfer in the collector tubes. According to the results, numerical modeling of solar flat collectors has been done with the least possible error compared with the reference.\(^{20}\) The characteristics of the different parameters of the dual-pressure CO\(_2\) liquefaction refrigeration cycle in the basic and modified state are listed in Table 7. The use of the intercooler, or in other words, multipass compression of carbon dioxide, is one of the reasons for reducing energy consumption in the modified cycle. The performance coefficient of the Linde–Hampson cycle in the reference\(^5\) and the present cycle is given as 1.829 and 1.816, respectively.

4.3 | Exergy analysis results

The two parameters of exergy yield and exergy destruction are considered to evaluate the exergy analysis of the integrated structure in all equipment utilized in the combined process. The amount of physical and chemical exergy of each flow utilized in the combined structure is obtained using the HYSYS package and Matlab programming and is presented in Table 8. The specifications of the inlet and outlet exergy, the exergy destruction, and the exergy yield of each of the equipment are shown in Table 9. The equations used in Table 4 are used to determine the exergy efficiency and its destruction. Exergy efficiency and exergy destruction of the total integrated structure are 44.16% and 118.3 MW, respectively. The exergy destruction share of each piece of equipment utilized in the combined process for CO\(_2\) liquefaction is shown in Figure 3. According to the output of the exergy study, the highest portion of exergy destruction belongs to solar collectors (74.68%), heat exchangers (12.47%), and compressors (7.157%). Based on the results, HE6 and HE7 with exergy destructions of 8.283 MW and 4.179 MW have the highest exergy destruction rate among heat exchangers. The exergy efficiency of different equipment used in the integrated structure is shown in Figure 4. Flat plate collectors and V1 and V2 throttle valves have lower exergy efficiencies of 9.47%, 53.98%, and 67.14%, respectively.

4.4 | Sensitivity analysis results

Sensitivity investigation is used as a tool to recognize the most influential parameters as well as sensitive elements of an integrated structure. This method shows the sensitivity and variation in yield parameters and important processes or cycles modeled against changes in operating conditions. The performance of the cycle in various operating states can be examined by this tool.
### TABLE 5  The operational specifications of the equipment applied in the hybrid process for liquefaction of CO₂

| Pump | Parameter | Adiabatic efficiency | Power | P ratio | Outlet temperature | Capacity |
|---|---|---|---|---|---|---|
| Unit | % | kW | – | °C | m³/h |
| P1 | 90.00 | 251.7 | 3.182 | 143.9 | 849.7 |
| P2 | 90.00 | 6337 | 48.42 | 6.947 | 4651 |
| P3 | 90.00 | 80.35 | 1.627 | 60.00 | 4102 |

| Compressor | Parameter | Adiabatic Efficiency | Power | ΔP | P ratio | Polytrophic Efficiency | Outlet temperature |
|---|---|---|---|---|---|---|---|
| Unit | % | kW | kPa | – | % | % | °C |
| C1 | 75.00 | 11,672 | 429.0 | 3.043 | 77.60 | 152.3 |
| C2 | 75.00 | 7046 | 1930 | 1.980 | 76.89 | 88.00 |
| C3 | 75.00 | 14,466 | 6100 | 2.564 | 77.54 | 118.3 |
| C4 | 75.00 | 12,252 | 1331 | 3.083 | 77.66 | 176.1 |

| Turbine | Parameter | Adiabatic Efficiency | Power | ΔP | Polytrophic Efficiency | Outlet temperature |
|---|---|---|---|---|---|---|
| Unit | % | kW | kPa | % | % | °C |
| T1 | 90.00 | 16,134 | 930.0 | 89.14 | 28.21 |

| Heat Exchanger | Parameter | Min. approach | LMTD | Heat duty | Cold Pinch Temp. |
|---|---|---|---|---|---|
| Unit | °C | °C | kW | °C |
| HE1 | 2.253 | 11.98 | 10,269 | 150.0 |
| HE2 | 6.073 | 7.874 | 19,354 | 170.0 |
| HE3 | 7.000 | 7.490 | 9310 | 25.00 |
| HE4 | 8.330 | 9.140 | 52,327 | 110.0 |
| HE5 | 15.00 | 22.23 | 2216 | 20.00 |
| HE6 | 8.191 | 12.56 | 91,183 | 91.77 |
| HE7 | 5.000 | 20.38 | 91,183 | 70.88 |
| HE8 | 1.081 | 1.187 | 152,314 | 34.00 |
| HE9 | 1.162 | 8.746 | 10,052 | 79.00 |

### TABLE 6  The validation of the exergy yield of flat panel solar collectors under different conditions compared to reference

| Solar radiation on solar collector (W/m²) | Mass flow rate (kg/s) | Inlet fluid temperature of solar collector (K) | Exergy efficiency of FPC (In this paper) | Exergy efficiency of FPC (Reference) |
|---|---|---|---|---|
| 200 | 0.006 | 329.28 | 4.548 | 4.54 |
| 300 | 0.008 | 342.24 | 6.324 | 6.32 |
| 400 | 0.009 | 354.48 | 7.918 | 7.92 |
| 500 | 0.011 | 366.18 | 9.412 | 9.39 |
| 600 | 0.012 | 377.41 | 10.78 | 10.75 |
4.4.1 | The effect of the main parameters on the collectors of the flat plate

The influence of increased solar radiation on the exergy yield of the SFPCs and the outlet temperature of pure water from the collector is shown in Figure 5. As the solar radiation rises, according to equation (S2), the temperature of the outlet fluid the collector increases. Based on the exergy equation for flat plate collectors in Table 4, there is a direct relation between the temperature of the fluid exiting the collector and an indirect relation between the exergy efficiency and the intensity of solar radiation. Therefore, with increasing the intensity of solar radiation, the increased temperature ratio of the output fluid from the collector is more than increasing the intensity of solar radiation in the denominator. Figure 6 shows the effect of increasing solar radiation on the heat efficiency of the SFPCs and the overall heat transfer coefficient of the collector. According to the results, as the solar radiation increases from 500 to 1100 W/m², the collector’s thermal efficiency and total heat transfer coefficient increase to 74.6% and 2.4188 W/m² K, respectively.

4.4.2 | The effect of nanoparticles on flat plate collectors

In addition to the common methods, adding particles with high conductivity to the base fluid is examined as one of the newest methods to raise the efficiency of the SFPCs. The effect of the volume concentration of Al₂O₃ nanoparticles on thermal conductivity and specific heat capacity of nanofluid is shown in Figure 9. The results show that as the volume concentration of Al₂O₃ nanoparticles increases in pure water, the nanofluid thermal conductivity enhances, and the nanofluid’s specific heat capacity decreases. The specific heat of metals is lower than that of liquids, so it can be expected that the nanofluid’s specific heat will decrease compared with the base fluids due to the presence of nanoparticles in the base fluid. Also, given that the thermal conductivity of nanoparticles is high and the thermal conductivity of base fluids is low, the presence of nanoparticles in the base fluids can improve the nanofluids’ thermal conductivity.

4.4.2 | The effect of nanoparticles on flat plate collectors

TABLE 7 The validation of the different parameters of the dual-pressure CO₂ liquefaction refrigeration cycle in the basic and modified state compared to reference

| Parameter                          | In this paper (Modified) | In this paper (Base) | Aliyon et al. (2020) |
|-----------------------------------|--------------------------|----------------------|----------------------|
| Refrigeration energy (kW)        | 39,087                   | 39,113               | 39,783               |
| Total energy (kW)                | 45,437                   | 48,003               | 48,239               |
| Refrigeration energy (kW)        | 21,513                   | 21,513               | 21,750               |
| Compression energy (kW)          | 18,718                   | 26,489               | 26,488               |
| Total cooling energy (kW)        | 79,009                   | 93,827               | 94,083               |
| Refrigeration cooling energy (kW)| 61,637                   | 61,638               | 61,898               |
| Compression cooling energy (kW)  | 17,371                   | 32,188               | 32,184               |
| Coefficient of performance (–)   | 1.816                    | 1.818                | 1.829                |
interactions. The density of nanoparticles is higher than that of liquids, so the density of nanofluids increases by adding nanoparticles to the base fluid. The effect of the volumetric concentration of Al$_2$O$_3$ nanoparticles on the temperature of the outlet fluid from the flat plate collector and the exergy efficiency is shown in Figure 11. As the volumetric concentration of Al$_2$O$_3$ nanoparticles increases from 0 to 8%, the exergy efficiency and temperature of the outlet fluid from the flat plate collector increase to 9.541% and 76.53°C, respectively. Figure 12 shows the effect of the volumetric concentration of Al$_2$O$_3$ nanoparticles on the Nusselt number (Nu) of nanofluids and the net power of the Kalina cycle. According to the results, with increasing the volumetric concentration of Al$_2$O$_3$ nanoparticles from 0 to 6%, the Nusselt number of nanofluids and the net power of the Kalina cycle increase to 3445 and 9.560 MW, respectively.

### 4.4.3 Investigation of different parameters of the Kalina power generation cycle

The effect of pumped water–ammonia fluid pressure in the Kalina cycle by changes in the thermal efficiency of the Kalina power production process and the exergy efficiency of the combined process is shown in Figure 13. As the pumped pressure of the water–ammonia fluid increases from 800 to 1600 kPa, the thermal efficiency of the Kalina power production process and the exergy efficiency of the combined process rise to 5.918% and 44.26%, respectively.

#### Table 8 The amount of physical and chemical exergy of each of the streams applied in the combined process

| Stream | Physical exergy (kW) | Chemical exergy (kW) | Total exergy (kW) | Stream | Physical exergy (kW) | Chemical exergy (kW) | Total exergy (kW) |
|--------|---------------------|---------------------|------------------|--------|---------------------|---------------------|------------------|
| B1     | 4864.3              | 52867.1             | 57731.3          | B28    | 0.0                 | 3457.7              | 3457.7           |
| B2     | 14427.2             | 52867.1             | 67294.2          | B29    | 1966.1              | 659.3               | 2625.4           |
| B3     | 12261.4             | 52867.1             | 65128.4          | B30    | 3551.2              | 1225.0              | 4776.2           |
| B4     | 22420.6             | 52867.1             | 75287.7          | B31    | 766.8               | 6775.2              | 7542.0           |
| B5     | 18730.4             | 52867.1             | 71597.4          | B32    | 4956.5              | 3457.7              | 8414.2           |
| B6     | 18596.9             | 52774.3             | 71371.2          | B33    | 16222.6             | 12117.3             | 28339.9          |
| B7     | 5.8                 | 220.4               | 226.2            | B34    | 0.0                 | 12117.3             | 12117.3          |
| B8     | 23347.9             | 66034.3             | 89382.2          | B35    | 708.8               | 228648.7           | 229357.6         |
| B9     | 28916.9             | 66034.3             | 94951.2          | B36    | 29317.6             | 2620752.7          | 2650070.2        |
| B10    | 27979.0             | 66034.3             | 94013.3          | B37    | 13611.7             | 1216778.0          | 1230389.8        |
| B11    | 0.4                 | 7.8                 | 8.2              | B38    | 21551.2             | 1216778.0          | 1238329.3        |
| B12    | 27965.0             | 66040.2             | 94005.1          | B39    | 14030.6             | 1254217.3          | 1268247.9        |
| B13    | 45586.7             | 106427.5            | 152014.1         | B40    | 19529.8             | 1254217.3          | 1273747.1        |
| B14    | 57259.4             | 106427.5            | 163686.9         | B41    | 1675.3              | 149757.3           | 151432.6         |
| B15    | 51407.1             | 106427.5            | 157834.6         | B42    | 2449.3              | 149757.3           | 152206.6         |
| B16    | 51341.9             | 106427.5            | 157769.4         | B43    | 43219.8             | 2620752.7          | 2663972.5        |
| B17    | 48286.2             | 106427.5            | 154713.6         | B44    | 40688.2             | 2143063.0          | 2183751.2        |
| B18    | 30466.8             | 66025.4             | 96492.2          | B45    | 3573.2              | 228648.7           | 232221.9         |
| B19    | 29677.6             | 66025.4             | 95703.0          | B46    | 22768.7             | 2143063.0          | 2165831.8        |
| B20    | 24758.3             | 52761.4             | 77519.6          | B47    | 2419.8              | 477695.3           | 480115.1         |
| B21    | 4887.9              | 13295.5             | 18183.4          | B48    | 1422.9              | 477695.3           | 479118.1         |
| B22    | 4875.3              | 13295.5             | 18170.8          | B49    | 1358.6              | 477695.3           | 479053.9         |
| B23    | 17749.5             | 40472.0             | 58221.4          | B50    | 24087.9             | 2620752.7          | 2644840.6        |
| B24    | 17646.3             | 40472.0             | 58118.3          | B51    | 29075.2             | 2620752.7          | 2649827.8        |
| B25    | 0.0                 | 659.3               | 659.3            | B52    | 18876.6             | 193482.4           | 212359.0         |
| B26    | 0.0                 | 1225.0              | 1225.0           | B53    | 9198.3              | 193482.4           | 202680.7         |
| B27    | 0.0                 | 6775.2              | 6775.2           |        |                     |                     |                  |
of the Kalina power production process and the irreversibility of the combined process are shown in Figure 14. As the results show, when the pumped water–ammonia fluid pressure increases from 800 to 1600 kPa, the exergy yield of the Kalina power production process rises to 36.34%, and the irreversibility of the integrated

| Components | Inlet exergy (kW) | Outlet exergy (kW) | Exergy destruction (kW) | Exergy efficiency |
|------------|-------------------|-------------------|-------------------------|------------------|
| HE1        | 67953.6           | 67753.9           | 199.7                   | 0.9806           |
| HE2        | 76512.6           | 76373.6           | 139.0                   | 0.9928           |
| HE3        | 101726.5          | 101555.3          | 171.1                   | 0.9816           |
| HE4        | 167144.6          | 166248.8          | 895.9                   | 0.9829           |
| HE5        | 234239.4          | 234058.5          | 180.9                   | 0.9184           |
| HE6        | 1258729.7         | 1250446.6         | 8283.1                  | 0.9092           |
| HE7        | 1480606.9         | 1476427.9         | 4179.0                  | 0.9457           |
| HE8        | 2879683.2         | 2879185.4         | 497.9                   | 0.9967           |
| HE9        | 631547.7          | 631324.7          | 223.0                   | 0.9778           |
| T1         | 2183751.2         | 2181966.4         | 1784.8                  | 0.9004           |
| C1         | 69403.6           | 67294.2           | 2109.3                  | 0.8193           |
| C2         | 96428.4           | 94951.2           | 1477.2                  | 0.7904           |
| C3         | 166481.0          | 163686.9          | 2794.1                  | 0.8069           |
| C4         | 77380.8           | 75287.7           | 2093.2                  | 0.8292           |
| P1         | 2650079.6         | 2650070.2         | 9.4                     | 0.9628           |
| P2         | 238559.3          | 237988.1          | 571.2                   | 0.9099           |
| V1         | 157769.4          | 154713.6          | 3055.8                  | 0.5398           |
| V2         | 96492.2           | 95703.0           | 789.2                   | 0.6714           |
| V3         | 71597.4           | 71371.2           | 226.2                   | 0.6819           |
| D1         | 71597.4           | 71597.4           | 0.0                     | 1.0000           |
| D2         | 94013.3           | 94013.3           | 0.0                     | 1.0000           |
| D3         | 154713.6          | 154713.6          | 0.0                     | 1.0000           |
| D4         | 95703.0           | 95703.0           | 0.0                     | 1.0000           |
| D5         | 2663972.5         | 2663866.3         | 106.1                   | 1.0000           |
| Collectors | 97666.6           | 9252.6            | 88414.1                 | 0.0947           |
| Cycle      | 211854.4          | 93654.3           | 118200.1                | 0.4421           |

FIGURE 3 The share of exergy destruction of each of the equipment used in the integrated structure for CO₂ liquefaction
structure decreases to 118.1 MW. Figure 15 illustrates the effect of ammonia concentration of the operating fluid in the Kalina cycle on changes in the thermal yield of the Kalina power production process and its exergy efficiency.

5 | CONCLUSION

Researchers are looking for a way to improve flat panel solar collectors’ yield, which indirectly reduces greenhouse gas emissions. One of the suitable ways to increase
The efficiency of solar collectors is to use nanofluids to improve the thermal properties of the working fluid. This study analyzes the energy, exergy, and sensitivity of a new combined CO₂ liquefaction structure using the DPLH process, Kalina power generation cycle, and the SFPCs. The present study investigates the impact of Al₂O₃ particles in pure water for heat transfer in flat panel solar collectors under different conditions. The results of the analysis of energy, exergy, and sensitivity of the combined process are as follows.

1. The DPLH process produces 9416 kmol/h liquid CO₂ by absorbing 35.97 MW power. The 91.18 MW wasted heat from the CO₂ liquefaction cycle along with 76.98 MW of heat produced by the flat panel solar collectors are considered as the heat input of the Kalina power generation cycle. The amount of power generated and the thermal efficiency of the Kalina unit in the base state are 9.546 MW and 5.676%, respectively.

2. The exergy efficiency of the SFPCs, the Kalina cycle, and the hybrid process developed are 9.475%, 36.85%, and 9.475%, respectively.

The influence of increased solar radiation on the thermal yield of the SFPCs and the overall heat transfer coefficient of the collector.

The effect of increasing the inlet flow temperature to flat plate collectors on the exergy efficiency under different radiation conditions.
and 44.16%, respectively. Based on the output of exergy analysis, solar collectors, heat exchangers, and compressors contribute to maximum shares of exergy destruction, respectively. Besides, solar collectors, throttle valves, and compressors have the lowest exergy efficiencies, respectively. The results display that the performance of exergy evaluation should be considered together for exergy efficiencies and irreversibilities. The output investigation demonstrates that the exergy efficiency in valves is lower than other components (except collectors), while valves have fewer irreversibilities. Also, heat exchangers with high exergy degradation share have higher exergy efficiency than other equipment. In addition to the above principles, exergy analysis requires equipment that is directly related to power, such as turbines, compressors, and pumps to have low exergy degradation.

3. According to the results, as the solar radiation intensity increases from 500 to 1100 W/m², the amount of thermal and exergy yields of the SFPCs increases to 74.6% and 9.74%, respectively. Also, as the ammonia content in the Kalina power production unit operating fluid increases from 60% to 82.5%, the energy and exergy efficiencies of the Kalina cycle increase to 5.710% and 37.20%, respectively. As the water and ammonia flow pressure increases from 800 to 1600 kPa, the exergy yield of the whole hybrid system, the thermal
yield of the Kalina cycle and the exergy efficiency of the Kalina cycle increase to 44.26%, 5.918%, and 36.34%, respectively.

4. As Al$_2$O$_3$ nanoparticles in pure water rise from 0 to 6% of volume ratio, the temperature of the collector outlet fluid, the exergy yield of the solar collectors, and the cycle power of Kalina increase to 76.53 °C, 9.54%, and 9.560 MW, respectively. As the volume ratio of nanoparticles increases from 0 to 6% of the volume ratio, the nanofluid’s heat capacity decreases to 4.0136 kJ/kg.K and its density increases to 1228 kg/m$^3$.

5. Exergoeconomic assessments and optimization of the developed CO$_2$ liquefaction system are proposed for further research. The use of different nanoparticles in the fluid used in the collectors as well as the employing of different fluids in the Kalina power system can be suggested for future research.

**NOMENCLATURE**

**Acronyms**

| Acronym | Description                  |
|---------|------------------------------|
| CO$_2$  | Carbon dioxide               |
| Al$_2$O$_3$ | Aluminum oxide            |
| H$_2$O  | Water                        |
| DPLH    | Dual-pressure Linde–Hampson |
| COP     | Coefficient of performance   |
| MPV     | Multipurpose vessels         |
| LCC     | Life cycle cost              |
| OTEC    | Ocean thermal energy conversion |

**FIGURE 10** The influence of volumetric concentration of Al$_2$O$_3$ nanoparticles on the density and viscosity of nanofluids

**FIGURE 11** The effect of volumetric concentration of Al$_2$O$_3$ nanoparticles on the temperature of the outlet fluid from the flat plate collector and the exergy efficiency
**FIGURE 12** The influence of volumetric concentration of Al$_2$O$_3$ nanoparticles on the Nusselt number (Nu) of nanofluids and the net power output of the Kalina unit.

**FIGURE 13** The impact of pumped water–ammonia fluid pressure in the Kalina cycle on changes in the thermal yield of the Kalina unit and the exergy efficiency of the combined process.

---

**Variables/Letters**

- $P_{E}$: Area of the absorber plate
- $P_{i}$: Pump
- $F_{R}$: Heat removal factor
- $C_{i}$: Compressor
- $S$: Total radiation received
- $U_{l}$: Overall heat loss coefficient
- $e$: Specific flow exergy (kJ/kmol)
- $Ex$: Exergy (kJ)
- $D_{i}$: Flash drum
- $G$: Gibbs free energy
- $h$: Specific enthalpy (kJ/kmol)
- $HE_{i}$: Heat exchanger
- $C_{p}^{'}$: Specific heat capacity
- $F'$: Collector efficiency coefficient
- $m$: Mass flow rate (kg/s)
- $h_{f}$: Convective heat transfer coefficient inside the absorber
- $C_{b}$: Bond conductance
- $P$: Pressure (kPa)
FIGURE 14  The effect of pumped water–ammonia fluid pressure in the Kalina cycle on changes in the exergy yield of the Kalina unit and the irreversibility of the combined process.

FIGURE 15  The impact of ammonia concentration of the operating fluid in the Kalina cycle on changes in the thermal yield of the Kalina unit and its exergy efficiency.

\[ \dot{Q} \] Rate of heat transfer (kW)  
\[ k_{np} \] Nanoparticles thermal conductivity  
\[ k_{bf} \] Base fluid thermal conductivity  
\[ s \] Specific entropy (kJ/kmole.°C)  
\[ T \] Temperature (°C)  
\[ T_i \] Turbine  
\[ w \] Space between the two parallel tubes  
\[ W \] Work (kW)  
\[ D \] Tube outer diameter  
\[ V_i \] Valve  
\[ \eta \] Efficiency  
\[ \rho \] Nanofluid density  
\[ \Sigma \] Sum  
\[ \mu \] Nanofluid dynamic viscosity  
\[ \phi \] Nanoparticles volume fraction  
\[ \int \] Integration  
\[ \Delta \] Difference  

Subscripts and superscripts:

Ch Chemical  
ex Exergy  
i Inlet  
Min Minimum  
n Number of stream  
o Outlet  
P Pressure component
REFERENCES

1. Shirmohammadi R, Aslani A, Ghasempour R, Romeo LM, Petarakopoulou F. Process design and thermoeconomic evaluation of a CO2 liquefaction process driven by waste exhaust heat recovery for an industrial CO2 capture and utilization plant. *J Therm Anal Calorim*. 2021;145(3):1585-1597.

2. Hosseini SM, Saifoddin A, Shirmohammadi R, Aslani A. Forecasting of CO2 emissions in Iran based on time series and regression analysis. *Energy Rep*. 2019;5:619-631.

3. Styring P, Quadrelli EA, Armstrong K. Carbon dioxide utilisation: closing the carbon cycle. Elsevier; 2014.

4. Shirmohammadi R, Aslani A, Ghasempour R, Romeo LM. CO2 utilization via integration of an industrial post-combustion capture process with a urea plant: Process modelling and sensitivity analysis. *Processes*. 2020;8:1144.

5. Aliyoon K, Mehrpooya M, Hajinezhad A. Comparison of different CO2 liquefaction processes and exergoeconomic evaluation of integrated CO2 liquefaction and absorption refrigeration system. *Energy Convers Manage*. 2020;211:112752.

6. Aliyoon K, Hajinezhad A, Mehrpooya M. Energy assessment of coal-fired steam power plant, carbon capture, and carbon liquefaction process chain as a whole. *Energy Convers Manage*. 2019;199:111994.

7. Seo Y, You H, Lee S, Huh C, Chang D. Evaluation of CO2 liquefaction processes for ship-based carbon capture and storage (CCS) in terms of life cycle cost (LCC) considering availability. *Int J Greenhouse Gas Control*. 2015;35:1-12.

8. Yoo B-Y, Lee S-G, Rhee K-P, Na H-S, Park J-M. New CCS system integration with CO2 carrier and liquefaction process. *Energy Procedia*. 2011;4:2308-2314.

9. Ghorbani B, Salehi G, Ebrahimi A, Taghavi M. Energy, exergy and pinch analyses of a novel energy storage structure using post-combustion CO2 separation unit, dual pressure Linde-Hampson liquefaction system, two-stage organic Rankine cycle and geothermal energy. *Energy*. 2021;233:121051.

10. Yoo B-Y. The development and comparison of CO2 BOG re-liquefaction processes for LNG fueled CO2 carriers. *Energy*. 2017;127:186-197.

11. Roussanaly S, Deng H, Skaugen G, Gundersen T. At what pressure shall CO2 be transported by ship? An in-depth cost comparison of 7 and 15 barg shipping. *Energy*. 2021;14:5635.

12. Ghorbani B, Zendezhkhbidi S, Moradi M. Development of an integrated structure of hydrogen and oxygen liquefaction cycle using wind turbines. *Kalina power generation cycle, and electrical energy conversion system involving weather and energy demand variations. Chem Eng Process Process Intensification*. 2020;157:108114.

13. Rodríguez CEC, Palacio JCE, Venturini OJ, et al. Exergetic and economic comparison of ORC and Kalina cycle for low temperature enhanced geothermal system in Brazil. *Appl Therm Eng*. 2013;52:109-119.

14. Jonsson M, Yan J. Ammonia-water bottoming cycles: a comparison between gas engines and gas diesel engines as prime movers. *Energy*. 2001;26:31-44.

15. Vera D, Baccioli A, Jurado F, Desideri U. Modeling and optimization of an ocean thermal energy conversion system for remote islands electrification. *Renewable Energy*. 2020;162:1399-1414.

16. Hernández-Romero IM, Nápoles-Rivera F, Flores-Tlacaualhuac A, Fuentes-Cortés LF. Optimal design of the ocean thermal energy conversion systems involving weather and energy demand variations. *Chem Eng Process Process Intensification*. 2020;157:108114.

17. Khanmohammadi S, Baseri MM, Ahmadi P, Al-Rashed AA, Afzand M. Proposal of a novel integrated ocean thermal energy conversion system with flat plate solar collectors and thermo-electric generators: Energy, exergy and environmental analyses. *J Clean Prod*. 2020;256:120600.

18. Tyagi H, Phelan P, Prasher R. Predicted efficiency of a low-temperature nanofluid-based direct absorption solar collector. *J Sol Energy*. 2009;131(4):041004. doi:10.1115/1.3197562

19. Ahmadi MH, Mirlohi A, Nazari MA, Ghasempour R. A review of thermal conductivity of various nanofluids. *Iran J Mech Eng Trans ISME*. 2016;17:5-18.

20. Boustani E, Mirab Dolah Lasavani A. The exergy optimization of a flat-plate solar collector using Al2O3-water, CuO-water and TiO2-water nanofluids by genetic algorithm. *Iran J Mech Eng*. 2018;265:181-188.

21. Shojaeizadeh E, Veyes F, Kamandi A. Exergy efficiency investigation and optimization of an Al2O3-water nanofluid based Flat-plate solar collector. *Energy Build*. 2015;101:12-23.

22. Aalawi OA, Kamar HM, Mallah A, et al. Nanofluids for flat plate solar collectors: Fundamentals and applications. *J Clean Prod*. 2021;291:125725.

23. Said Z, Saidur R, Rahim N. Energy and exergy analysis of a flat plate solar collector using different sizes of aluminium oxide based nanofluid. *J Clean Prod*. 2016;133:518-530.

24. Yousefi T, Veyes F, Shojaeizadeh E, Zinadini S. An experimental investigation on the effect of Al2O3–H2O nanofluid on the efficiency of flat-plate solar collectors. *Renewable Energy*. 2012;39:293-298.

25. Sint NKC, Choudhury I, Masjuki HH, Aoyama H. Theoretical analysis to determine the efficiency of a CuO-water nanofluid based-flat plate solar collector for domestic solar water heating system in Myanmar. *Sol Energy*. 2017;155:608-619.

26. Loni R, Askari Asli-ardeh E, Ghobadian B, Kasaeei AB, Gorjan S. Thermodynamic analysis of a solar dish receiver using different nanofluids. *Energy*. 2017;133:749-760.

27. Mahian O, Kianifar A, Sahin AZ, Wongwises S. Entropy generation during Al2O3/water nanofluid flow in a solar collector: Effects of tube roughness, nanoparticle size, and different thermophysical models. *Int J Heat Mass Transf*. 2014;78:64-75.

28. Ghasemi S, Ranjar A, Ramiar A. Numerical investigation of effect of al-water nanofluid on performance of solar parabolic collector. *Iran J Energy Technol*. 2013;5(14):100-107.

29. Kasaeei A, Sokhansefat T, Abbaspour M, Sokhansefat M. Numerical study of heat transfer enhancement by using Al2O3-synthetic oil nanofluid in a parabolic trough collector tube, World Academy of Science. *Eng Technol*. 2012;69:1154-1159.

30. Belloes E, Tzivanidis C, Said Z. A systematic parametric thermal analysis of nanofluid-based parabolic trough solar collectors. *Sustain Energy Technol Assessments*. 2020;39:100714.

31. Tong Y, Lee H, Kang W, Cho H. Energy and exergy comparison of a flat-plate solar collector using water, Al2O3 nanofluid, and CuO nanofluid. *Appl Therm Eng*. 2019;159:113959.
32. Noroozian A, Mohammadi A, Bidi M, Ahmadi MH. Energy, exergy and economic analyses of a novel system to recover waste heat and water in steam power plants. *Energy Convers Manage*. 2017;144:351-360.

33. Ashouri M, Ahmadi MH, Pourkiaei SM, et al. Exergy and exergo-economic analysis and optimization of a solar double pressure organic Rankine cycle. *Therm Sci Eng Progress*. 2018;6:72-86.

34. Mohammadi A, Ahmadi MH, Bidi M, Joda F, Valero A, Uson S. Exergy analysis of a combined cooling, heating and power system integrated with wind turbine and compressed air energy storage system. *Energy Convers Manage*. 2017;131:69-78.

35. Mousavi SA, Mehrpooya M. A comprehensive exergy-based evaluation on cascade absorption-compression refrigeration system for low temperature applications-exergy, exergoeconomic, and exergoenvironmental assessments. *J Clean Prod*. 2020;246:119005.

36. Vatani A, Mehrpooya M, Palizdar A. Advanced exergetic analysis of five natural gas liquefaction processes. *Energy Convers Manage*. 2014;78:720-737.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher’s website.

How to cite this article: Ghorbani B, Khatami Jouybari A. Development of a new CO2 liquefaction system using the Linde–Hampson process, Kalina power generation unit, and flat plate solar collectors with Al2O3/H2O nanofluid. *Energy Sci Eng*. 2022;10:4252–4272. doi:10.1002/ese.1034