SYNERGISTIC INTEGRATION OF CARBON CAPTURE UTILIZATION AND STORAGE WITH ORGANIC RANKINE CYCLE AND SOLAR TECHNOLOGIES AIMED AT ZERO EMISSION AND INDEPENDENT ENERGY SYSTEM

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ABSTRACT

Carbon capture, utilization and storage (CCUS) are widely used in various industries for CO_2 emission management. The required CO_2 compression work at high operating pressures and temperatures is very energy-intensive, requiring power for the compressors and cooling capacity for the intercoolers. This research aims to integrate CCUS technologies with an Organic Rankine Cycle (ORC) capable of producing electrical power from heat sources at low to medium temperature levels. In the proposed scheme, a modified energy-efficient CO_2 removal unit is presented in which the ORC unit is integrated with the intercoolers of the compression stages and the condenser of the CO_2 capture stripper.

In addition, Parabolic Trough Collector (PTC) technologies and photovoltaic (PV) systems are also integrated to provide the heating and/or power demands. The proposed conceptual design can be used for a decentralized energy system operating under zero-emission conditions with distinct purposes. The thermodynamic analysis presents the proposed system, which can produce all of its 330 MW heating demand and generate 16 MW power using methanol as the working fluid that, more than the necessity of the system, can be exported or stored. In addition, this zero-emission energy system can separate up to 130,000 kg/h of CO_2 from flue gases. Furthermore, the sensitivity analysis shows that the total heating demand and power consumption of the system are very sensible in altering the CO_2 molar fraction.

1 INTRODUCTION

According to the recent IPCC (Intergovernmental Panel on Climate Change) report, it has been recommended that to effectively control global warming by 2050, it is imperative to reduce one billion tonnes of carbon dioxide (Pörtner et al. 2022). It is now imperative for industries with high levels of greenhouse gas emissions to prioritize decarbonization as an obligatory measure. Such industries include carbon and energy-intensive sectors such as iron and steel, cement, oil refining, blue hydrogen production, and paper production. The installation of decarbonization system units is essential to effectively manage and reduce greenhouse gas (GHG) emissions in these industries (Leeson et al. 2017, Antzaras and Lemonidou 2022). Adopting low-emission technologies, such as replacing fossil fuels with renewable energy sources, presents a feasible solution to reduce greenhouse gas emissions at reasonable costs. However, certain GHG emissions may be inevitable or require costly and complex modifications, leading to residual emissions. To achieve a zero-emission state, it is indispensable to compensate for these remaining emissions by capturing carbon dioxide (Davis et al. 2018, Shu et al. 2023). Renewable energy production experienced a 7% increase in 2021. However, it remains unchanged that a 1% increase in global GDP is still correlated with a 0.5% increase in carbon dioxide emissions. Therefore, it is imperative to accelerate the transition from a fossil fuel-based to a zero-emission economy. This step will become increasingly crucial in mitigating climate change and environmental damage (Li et al. 2022, McCauley et al. 2019).

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Gas compression is an essential process used in a wide range of industries, particularly the oil and gas sector, as well as natural gas and CO_2 separation, processing, and compression units (Chen et al. 2022). One of the primary challenges we face is the high-energy demand associated with the capture, storage, and utilization steps. Specifically, these steps require thousands of watts to power, heat, and cool the system. (Allahyarzadeh-Bidgoli et al. 2021, Sun et al. 2021). Furthermore, it is worth noting that their operational efficiency from a thermodynamic standpoint is suboptimal, as they are designed to function at elevated pressures and temperatures (Mehr et al. 2021, Kourgiozou et al. 2021)

In light of strict environmental regulations and increasing energy costs, it has become imperative to recuperate waste heat and employ sustainable techniques to use energy carriers (Shi et al. 2018, Yang and Yeh 2015). Organic Rankine cycles (ORCs) have been proven to be a successful and promising technology for generating electricity from low to medium temperatures (Li et al. 2017). Parabolic trough solar collectors (PTCs) are a widely recognized and respected form of solar technology. They are often paired with ORC systems to create a highly efficient means of generating electricity. PTCs are particularly well-suited to applications that require moderate to elevated temperatures, up to 400 °C (Reddy and Kumar 2012, Jebasingh and Herbert 2016, Hafez et al. 2018).

The integration of energy systems entails the connection of various energy sources and technologies to establish a more flexible and resilient energy supply. This approach could potentially reduce the dependence on fossil fuels and improve the availability of energy. The integration opportunities presented by synergistic systems can unlock energy harvesting and environmental protection possibilities that would otherwise be inaccessible in standalone or island configurations. For example, combining renewable energy sources with energy storage systems helps balance supply and demand fluctuations, while integrating ORC with processes using local energy streams can result in significant improvements in energy efficiency (Liu et al. 2020). Various research studies have been conducted to explore the advantages of integrating solar energy systems into thermal and cooling processes (Ferry et al. 2020, Meraj et al. 2021, Masera et al. 2023). An external compound parabolic concentrator can warm the temperature of an HTF (heat transfer fluid) of up to 150 C in 500 kWh/m^2 (Ferry et al. 2020). However, the Parabolic Trough Collector (PTC) is a more suitable collector for the integration of solar thermal energy systems (Masera et al. 2023). In addition, using PTC in series can improve its application and efficiency(Meraj et al. 2021).

To the author's knowledge, no previous work has assessed the utilization of an Organic Rankine Cycle (ORC) that employs various working fluids to harness waste heat from low to medium-temperature sources, such as intercoolers of gas compression enhancing with a solar energy source. Furthermore, integration of these systems has not been explored to leverage the cooling demand of a Carbon Capture and Storage (CCS) unit that is based on monoethanolamine (MEA) for power generation. At present, there is no sustainable or zero-emission integrated system available that can meet all energy demands.

In this study, we address the identified gaps and explore possibilities by integrating an energetically efficient CO_2 removal unit based on MEA with supercritical CO_2 compression and injection and an ORC system. This integration presents a genetic conceptual design that allows us to utilize the energy conversion potential of intercoolers and condensers for power generation. As an enhancement and alternative heat source for the ORC cycle, we integrated a PTC system. In addition, we install rooftop photovoltaic panels in the occupied space of the system to further enhance power generation. Finally, we conduct a thermodynamic analysis of the integrated units and perform sensitivity analyses.

2 PROCESS CONFIGURATION AND SYSTEM STATEMENT

2.1 System description

Fig. 1 illustrates an integrated system that combines carbon capture, utilization, and storage (CCUS) with solar energy technologies such as Parabolic Trough Collectors (PTC), Organic Rankine Cycle (ORC), Photovoltaic (PV), and energy storage. This integration enables efficient utilization of waste energy for both power consumption and storage. By harnessing waste and sustainable resources from various energy sources, we can optimize energy utilization and minimize waste. For instance, the cooling needs of CCUS are utilized as a heat source in the evaporator of the ORC, as shown in Fig. 1. This approach improves the utilization of available energy and minimizes waste. Furthermore, a multi-

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vector power management system is implemented to efficiently manage and distribute the generated power. This system governs the allocation of power for internal consumption and exportation. Additional details regarding this power management system will be provided in subsequent explanations.

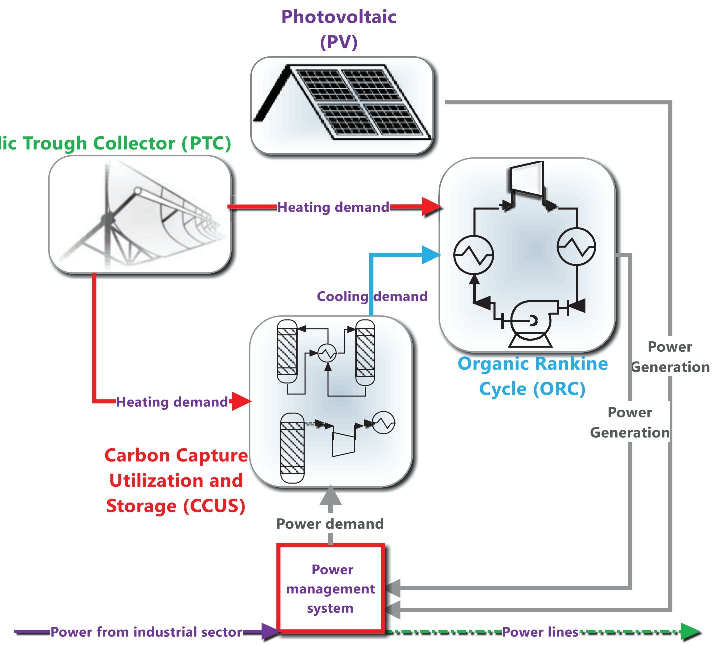

Figure 1: Conceptual flow diagram of the proposed system

This system consists of several units: CCUS, ORC, PTC, PV, energy storage, and a power management unit.

The CCUS unit is a modified version of the MEA-based carbon capture technology, which consumes less power. This unit uses saturated water to prepare the input flue gas (Shi 2014). The exhaust gases, which contain carbon dioxide, oxygen, and nitrogen, are first saturated with water and then transported to the absorption tower to separate the carbon dioxide. The absorption tower has 30 separation steps and is included in the model. In the sixth stage, lean MEA enters the tower, and the solution present in the tower absorbs the carbon dioxide. Water is added to the top of the absorber to reduce solvent waste and extract MEA from the gas flow. The treated gas is released from the top section of the absorber, while the bottom section releases the concentrated solvent, which is then transferred to the stripper tower. The concentrated MEA solution is heated to 80 °C before entering the stripper tower. The stripper tower comprises twenty separation stages, with the initial stage commencing when the rich MEA enters the tower. During this stage, carbon dioxide is removed from the column's rich MEA, replenishing the amine stream. The absorber receives the recovered lean-MEA from the bottom of the stripper. It is imperative to note that the reboiler's heating demand is met via the intercoolers, PTC, and the condenser of the ORC cycles.

The system operates using flue gas containing a molar fraction of 2.63% CO_2 (1.14×10^5 kg/h) at a temperature of 50°C, as indicated by Table 1. A heat exchanger can adjust the operating temperature of the system to enter the absorber system. The performance of the system has been evaluated, and the results reveal that it can accommodate up to 3% CO_2 molar fraction or a mass flow rate of 1.3×105 kg/h of CO_2 for the design of the input flue gas. The system can operate under off-design conditions with a CO_2 molar fraction of up to 10%. Additionally, the minimum MEA concentration required for this CO_2 removal unit is 30%.

For utilization and storage purposes, a four-stage CO_2 compression unit with four intercooling heat exchangers is utilized. This unit receives the separated CO_2 and prepares it for injection under

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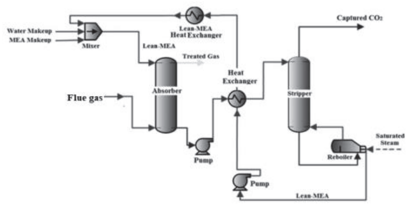
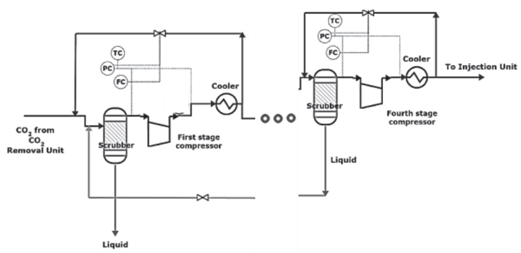
supercritical conditions. As presented in Table 1, the discharge pressure of the last compression stage for injection is 200 bar, which is suitable for both storage and utilization applications. Furthermore, Table 1 indicates that the CO_2 requires cooling to 40 °C after each compression step. The nominal power consumption of the injection system under the design condition is 14.1 MW.

Table 1: Operating conditions of MEA-based CO_2 removal unit with saturated water and CO_2 Injection unit

Section	**Description** CO_2 injection	**Value**
MEA-based CO_2 removal unit with saturated water and CO_2 injection	Mass flow rate of flue gas	800 kg/s
	CO_2 fraction	2.63 %
	Input and output temperature of CO_2	50 and 41°C
	MEA concentration	30%
	Number of pumps	2
	Overall required power of CO_2 removal unit	1.49 kW
	Number of stages	4
	Operating pressures	400 – 20000 kPa
	Operating temperature of intercoolers	40-270 °C
	Mass flow rate of CO_2	32.2 kg/s
	Overall required power	14.1 MW

An Organic Rankine Cycle (ORC) is employed to utilize the waste heat from the CCUS system in a highly effective manner. Methanol is chosen as the organic stream due to its simplicity and high-temperature suitability. To make the best use of the waste heat at the expander outlet, a regenerating ORC arrangement is implemented, which includes a superheater, evaporator, and economizer to raise the temperature of the organic fluid. The ORC uses over 4.63 × 107 kJ/h of heat from the last intercooling and PTC to generate 11.9 MW of power. According to Table 2, the vapor is supplied to the turbine at 290 °C and a pressure of 3033 kPa. The pump requires 124 kPa of power to reach the operating pressure for ORC. Therefore, the net power production is approximately 11.78 MW.

Table 2: Operating Specification of Organic Rankin Cycle

Section	**Description**	**value**

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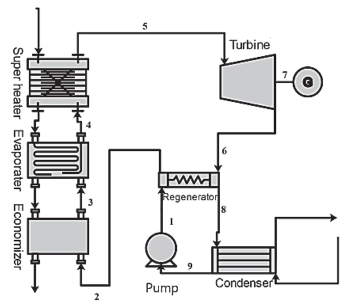
Organic Rankin Cycle 	Operating fluid	Methanol
	Critical Temperature	239.45 ^oC
	Critic Pressure	8103.5 kPa
	Boiling point	64.49 ^oC
	Inlet pressure of steam turbine	3033 kPa
	Inlet temperature of steam turbine	290 ^oC
	Heating sources	Two intercoolers and PTC
	Power generation	11.9 MW
	Overall required power	124 kPa

The Parabolic Trough Collector (PTC) comprises three main components: an absorber tube, a glass cover, and a heat transfer fluid. The heat transfer process in a typical PTC device is shown in Figure 2. When concentrated solar energy is directed towards the absorber tube, the temperature of the tube increases, causing heat to transfer to the heat transfer fluid and the surrounding atmosphere. The diagram in Figure 2 identifies the external diameter of the absorber tube as "D_{ro}," the internal diameter of the absorber tube as "D_{ri}," the internal diameter of the glass cover as "D_{ci}," and the external diameter of the glass cover as "D_{co}."

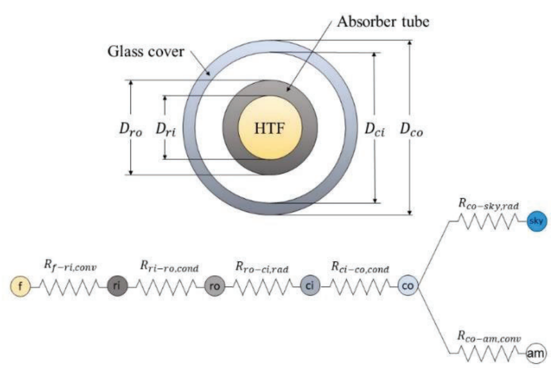


Figure 2: Drawing of a conventional receptor showing the plan for overall heat transfer resistance and the absorber tube and glass cover (da Costa Filho et al. 2024).

The specification of both the design and operating parameters for the PTC modules adopted herein and its applied structure is based on the research of da Costa Filho et al. (da Costa Filho et al. 2024).
Photovoltaics (PV) is a sustainable source of energy that can be used for power generation as a complementary source. Integrating PV systems into rooftop spaces is an efficient use of space. The proposed PV system can be installed on the roof, and it is estimated that half of the required area for the proposed Carbon Capture, Utilization, and Storage (CCUS) and Organic Rankine Cycle (ORC) units, approximately 20,000 m^2, can be used for rooftop PV panels. The ideal beam radiation for optimal PV performance is 500 W/m^2 or more. On average, 200 W per square meter can be generated in the installation area, which could result in up to 4 MW of power (Wimmer 2024). It is important to note

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that PV systems use DC-AC inverters that are integrated into the multi-vector power management unit. These inverters convert DC power to AC power for export and can also store DC power for future use.

Table 3: Specification of rooftop photovoltaic system considered in this research.

Section	Description	Value
Photovoltaic	Installation type	Rooftop type
	Installation area	Approximately 20000 m^2 (Hardisty, Sivapalan and Brooks 2011, Board, National Academies of Sciences and Medicine 2019) of CCS+ORC
	Irradiance	≥500 W/m^2
	Total power generation	Up to 4MW

Figure 3 shows a general schematic of the applied integration of CCUS with ORC and PTC using a power management system. As can be seen in Figure 3, the heating demand of CCUS is primarily provided by its cooling demand and, finally, by the PTC. The cooling demand of the PTC and intercoolers is the heat source of the ORC for power generation. As explained above, a rooftop PV is designed to use the necessary space of ORC and CCUS for power generation from solar energy. A power management system is considered to control the usage and export of power generation at different times of the day.

2.2 System assumptions and modeling

The following assumptions are adopted for numerical simulations:

- Separators, pumps, mixers, and splitters are considered adiabatic.
- A polytropic efficiency of 85% is considered for all centrifugal turbomachines (Allahyarzadeh-Bidgoli et al. 2018).
- The isentropic efficiency of 90% is defined for expanders (Allahyarzadeh Bidgoli, Hamidishad and Yanagihara 2022).
- Due to the different operating pressures, temperatures, and compositions of each unit, a multi-EoS simulation (PR (Peng DY 1976), Span-Wagner (Span R 1996), and Acid Gas (Austgen DM 1989)) is used to consider thermodynamic properties in the simulation environment of Aspen HYSYS (Tech. 2017). For PTC and Therminal VP1, thermodynamic properties are used from EES (da Costa Filho et al. 2024).
- The pressure penalty of 50 kPa and the minimum approach temperature are designed for heat exchangers.
- The four working fluids of methanol, n-pentane, i-pentane, and R134a are analyzed for ORC.

3 METHODOLOGY

This section presents methodologies for energy balances and heat transfer relations of applied equipment and systems. First, the heat transfer relation of the PTC (Parabolic Trough Collector) is introduced.

The mass equilibrium and thermal efficiency of the gas turbine are presented in Equations 1 and 2 as follows:

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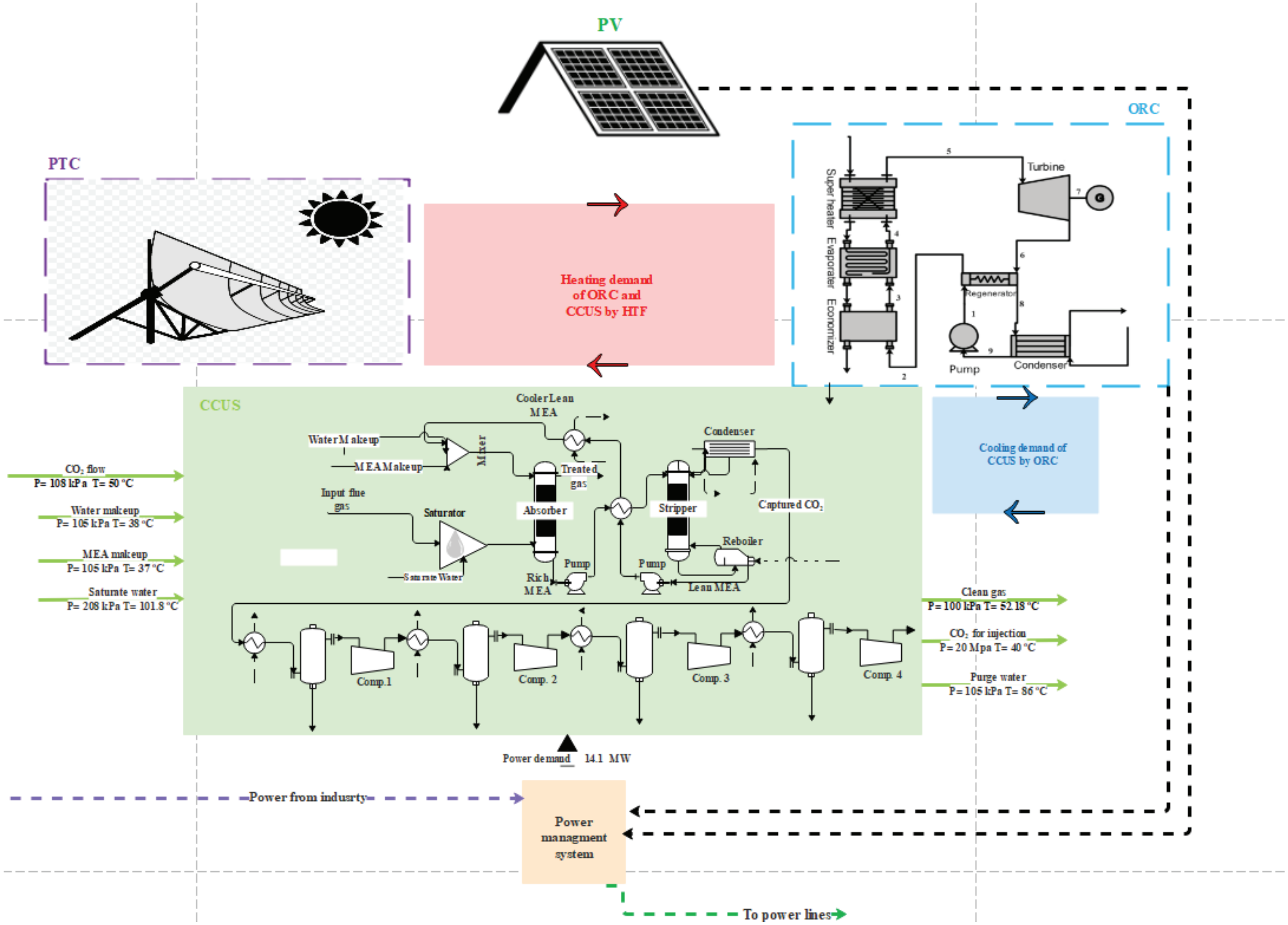

Figure 3: The general schematic with the flow diagram of synergetic integration showing the input and output stream of the proposed system.

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$$\dot{m}_{out-GT} = \dot{m}_{input-air} + \dot{m}_{fuel} \quad (1)$$

$$\eta = \frac{\dot{W}_{net}}{\dot{m}_{fuel} \times LHV} \quad (2)$$

The energy balance and chemical reactions of MEA-CCS (monoethanolamine-carbon capture and storage) are used from (Allahyarzadeh-Bidgoli, Hamidishad and Yanagihara 2022).
The useful gain and heat losses from the PTC modules, as well as the numerical procedure showing the steps for the PTC parameter calculations, are described as follows (da Costa Filho et al. 2024):

$$Q_s = A_a G_b \quad (3)$$

The relation for heat transferred to heat transfer fluid of PTC is estimated according to Eqs. 4, 5 and 6:

$$Q_u = h_{HTF} A_{ri} (T_{ri} - T_{HTF,avg}) \quad (4)$$

$$h = \frac{Nu\, k_{HTF}}{D_{ri}} \quad (5)$$

$$Q_u = \dot{m} c_{p\,HTF} \left(T_{out} - T_{in} \right) \quad (6)$$

The other heat transfer formulations used in this research, including the Reynolds and Prandtl numbers range are from (da Costa Filho et al. 2024).

4 RESULTS AND DISCUSSION

This section presents the thermodynamic and sensitivity analyses of the proposed system using various terms.

4.1 Thermodynamic analysis of integrated system and subsystems

Figure 4 shows how the cooling requirements (condensers and intercoolers) of the Carbon Capture, Utilization, and Storage (CCUS) system can be used to generate power through the Organic Rankine Cycle (ORC). The high temperature of CO_2 after compression and CO_2 removal unit condenser preheats the working fluid of ORC, which allows it to reach the required temperature for power generation through heat transfer with the Heat Transfer Fluid (HTF) of the Parabolic Trough Collector (PTC). Moreover, the HTF of PTC and ORC's condenser provide the necessary conditions for fluid in the reboiler section, thereby eliminating the need for fossil fuel-based heating demands. By taking into account these heat transfers, which have minimal environmental impact, we present a zero-emission system capable of providing electricity in a multi-vector system that deposits its energy demand, and it can export power produced by renewable and waste heat sources.

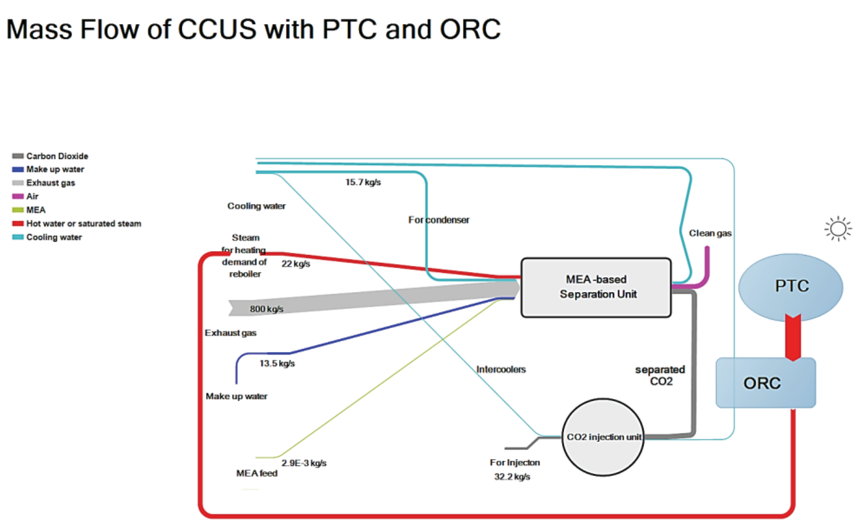

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Figure 4: Conceptual design for a zero-emission multi-vector electricity generation and carbon capture, utilization, and storage system using organic Rankine cycle, parabolic trough collector, and rooftop photovoltaic technologies presented as a Sankey mass flow diagram.

The proposed CCUS system is characterized by lower power consumption compared to conventional CCUS systems (Allahyarzadeh Bidgoli et al. 2022, Allahyarzadeh-Bidgoli et al. 2022, Sánchez and de Oliveira Jr 2015). In the MEA-based CO_2 removal unit, replacing the blower with saturated water has resulted in a notable reduction of 2 MW in power consumption. Table 7 outlines that the two pumps operating under the mentioned conditions consume only about 1.5 kW. The total heating and cooling demand for the MEA-based CO_2 removal unit is 1.949×10^9 kJ/h, whereas the intercooling demand for the CO_2 compression unit is 7.789×10^7 kJ/h, as indicated in Table 7.

Table 4: Total energy demand of CCUS

Energy consumption sector	value
Total power requirement of the MEA-based CO_2 removal unit	1.5 kW
Total power requirement of the CO_2 compression unit	14100 kW
Total heating and cooling demand of MEA-based CO_2 removal unit	1.949×10^9 kJ/h
Total cooling demand of CO_2 compression unit	7.789×10^7 kJ/h

4.2 Sensitivity analysis

This section aims to analyze the impact of altering the working fluid in the ORC1 cycle and the input flue gas in the CCUS on energy demand.

According to Figure 5, four working fluids were tested in the ORC cycle, and the power generated under various operating conditions was documented. Methanol was the most efficient fluid, generating a net power of approximately 12 MW when utilizing waste and solar sources. A generated power of 5.2 MW followed I-pentane. N-penetrate and R134a generated powers of 5.1 MW and 4.1 MW, respectively. It can be seen that methanol, as the working fluid, produces more power than the power required for the proposed system, which can be exported.

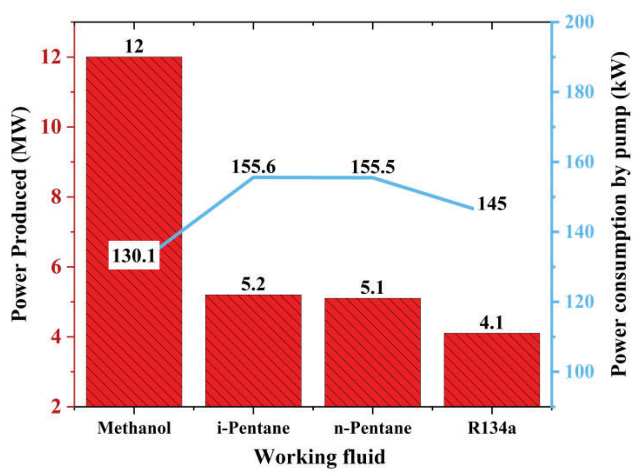

Figure 5: Power produced and power consumption of ORC using methanol, i-Pentane, n-Pentane, and R134a

Figure 6 illustrates the total energy demand associated with two different input flue gases in the CCUS section. Specifically, the investigation involved a mass flow rate of 114,000 kg/h of CO_2 (2.63%) and 130,000 kg/h of CO_2 (3%). The first condition, with a mass flow rate of 114,000 kg/h, requires a power of 14.1 MW for the

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separation, injection, and compression of CCUS. Similarly, the second condition, with a mass flow rate of 130,000 kg/h, requires 14.8 MW for these processes.
In the case of a CO_2 concentration of 2.63%, the total heating demand amounts to 1.20×10^9 kJ/h, and the system requires a cooling demand of 1.17×10^9 kJ/h, as shown in Figure 6. Additionally, when the CO_2 flow rate is 130,000 kg/h, the heating and cooling demands amount to 1.28×10^9 kJ/h and 1.24×10^9 kJ/h, respectively. It is presented that with an increase in a different operating scenario of the CCUS, the produced water by renewable sources is still more than necessary for the system.

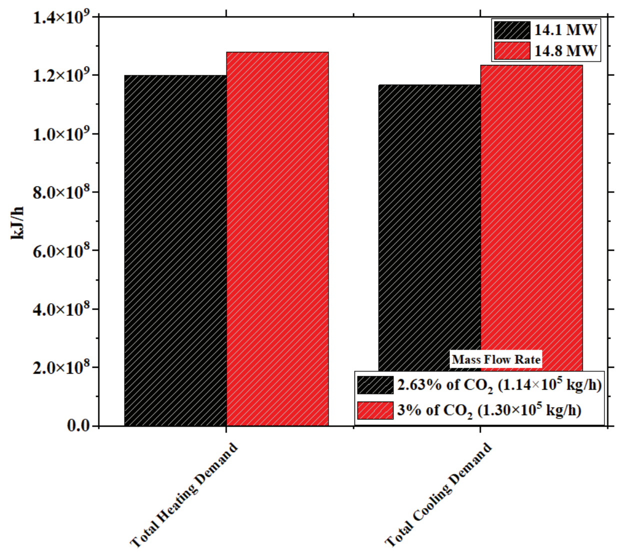

Figure 6: Total energy demand for both different mass flow rates at different operating conditions

5 CONCLUSIONS

This study introduces an innovative integration system that harmoniously integrates ORC and solar technologies to harness waste heat and generate electricity. Incorporating solar technologies ensures efficient utilization of installation space for additional power generation. Additionally, this system meets all energy requirements and can export or store surplus power. Overall, our proposed integration energy system cleverly uses varied energy conversions to produce power.

The ongoing research aims to integrate an MEA-based CO_2 removal unit, designed for low-energy consumption, with supercritical CO_2 compression and injection into an ORC system for power generation. Furthermore, the study proposes the incorporation of a PTC system designed to increase the heat capacity of heat sources sustainably. Additionally, the feasibility of installing a rooftop photovoltaic system in the occupied space is also considered.The proposed system possesses the capacity to effectively separate and process up to 130,000 kg/h of CO_2, for both storage and utilization purposes. In addition, the zero-emission unit can generate up to 16 MW of energy by combining Methanol ORC, PTC, and PV technologies. Furthermore, it can meet a total heating demand of up to 330 MW, representing a significant increase in energy output and efficiency.

On the basis of our analysis of specific design parameters, it has been discovered that utilizing methanol as a working fluid can significantly enhance the system's overall energy efficiency and performance. It is important to note that the design parameters of the CO_2 removal unit, including adjusting the separated mass flow rate of CO_2 and energy demands, can significantly affect the performance of non-solar sections.

This system can be seamlessly incorporated into various CCUS implementations in industries such as oil and gas, cement, mining, and more. We can determine the ideal operating conditions by optimizing the procedures, resulting in decreased energy consumption requirements.

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NOMENCLATURE

A	Surface area, m^2	CCUS	Carbon Capture Utilization and Storage
C_p	Specific heat capacity under constant pressure, J/kg.K	EES	Equation Engineering Solver
D	Diameter, m	Q_s	Available solar energy, W/m^2
f	Friction factor, -	Q_u	Useful gain, W
G_b	Solar beam radiation, W/m^2	Re	Reynolds number, -
h	Heat transfer coefficient, W/m^2K	T	Temperature, K
k	Thermal conductivity, W/m.K	HRSG	Heat Recovery Steam Generator
L	Absorber tube length, m	HTF	Heat transfer fluid
$\dot{m}$	Mass flow rate, kg/s	ORC	Organic Rankine Cycle
Nu	Nusselt number, -	PTC	Parabolic Trough Collector
Pr	Prandtl number, -	PV	Photovoltaic
Q_{loss}	Heat loss, W		

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