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Assessing the Synergies of Thermochemical Energy Storage with Concentrated Solar Power and Carbon Capture

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ABSTRACT

As greenhouse gas emissions continue to increase worldwide, the growing energy demand must be met using low-carbon technologies. Renewable energy and carbon capture and storage are the two important technologies that can mitigate CO_2 emissions. The two technologies have been primarily developed independently. However, their hybridization can offer complementary benefits and lower the costs of greenhouse gas abatement. Accordingly, in this article, we develop a novel carbon-neutral process that combines concentrated solar power (CSP) and fuel-based combustor with redox-based thermochemical energy storage (TCES) materials. The TCES materials are used for energy storage and as a source of oxygen (O_2) for combusting fuel. We optimize the process' economic performance considering variability in solar irradiance by developing a two-stage stochastic programming model. We illustrate that compared to the CSP-TCES process employing the Mn_2O_3/Mn_3O_4 TCES system, the proposed hybrid process has a 25% lower levelized cost of electricity (LCOE) for an 80% capacity factor. We also compare the economic performance of our process with another hybrid configuration containing CSP-TCES, boiler for fuel combustion, and air separation unit (ASU) to produce O_2, which is then used to combust fuel. We conclude that the LCOE of the proposed process is 11.5% lower than the LCOE of the process with an ASU.

Keywords: Concentrated solar power, energy storage, stochastic programming, carbon capture and storage, hybrid energy systems

1. INTRODUCTION

As the energy demand continues to increase, there is an urgent need to develop technologies to reduce CO_2 emissions. Two classes of technology that can mitigate CO_2 emissions are carbon capture and storage (CCS) and renewable energy generation from sources such as solar and wind. While CCS aims to prevent CO_2 from being released into the atmosphere, renewable energy generation technologies avoid CO_2 emissions. While using a combination of photovoltaic (PV) or wind power with battery can provide reliable electricity, another promising strategy to deliver cost-effective, reliable, and dispatchable renewable power is integrating concentrated solar power (CSP) with thermal energy storage (TES). Among various TES technologies, thermochemical energy storage (TCES) is reported to be especially appealing for the next generation CSP plants because of their high energy density and ability to deliver heat at a high temperature (> 1000 °C). A recent material screening study concluded that due to the low energy density of TCES materials, even the most economically favorable reaction system leads to more than 50% higher levelized cost of electricity (LCOE) than the monthly average electricity retail price [1]. This is mainly due to a lower energy density of the TCES materials. Thus, hybridizing CSP with energy-dense fossil fuel power plants equipped with carbon capture can reduce the cost of producing clean power.

Attempts have been made to integrate solar thermal energy into post-combustion CO_2 capture (PCC). Parvareh et al. [2] showed that by utilizing solar thermal energy to support the thermal demand of the stripper, the energy penalty can be reduced, and more power can be produced. Qadir et al. highlighted the potential of dynamic, flexible operation to reduce CO_2 capture costs [3]. Hong and Jin used solar thermal energy as a heat source to drive the endothermic reaction of a metal oxide with CH_4 [4] and reported that solar energy can be converted to chemical energy at a low temperature and released at a higher temperature. Jafarian et al. [5] proposed the use of metal oxide for thermal energy storage and reported a lower fuel consumption and reduced CO_2 emissions by 50% compared to natural gas combined cycle with carbon capture.

Kumar and Tiwari summarized the potential of solar thermal energy in coal-fired power plants retrofitted with a PCC system. Specifically, they discussed various PCC and solar thermal integration techniques, economic and environmental impacts, benefits and challenges [6]. Dalvi et al. indicated that solar thermal systems can be easily integrated into Rankine-cycle power plants. They further showed that solar heat can offset up to 50% of fossil fuel consumption and this strategy is more economical than installing CCS for mitigating an equivalent amount of GHG emissions [7]. Most previous studies focussed on the feasibility aspect of hybridizing renewable energy and carbon capture, often ignoring the optimization of both the design and operational decisions.

While there is consensus on the economic and environmental benefits of integrating solar thermal heat and carbon capture technologies, no previous work has sought to employ TCES materials for energy storage and as a source of oxygen for fuel combustion. Accordingly, in this article, we develop a novel carbon-neutral process referred to as CSP-TCES-OFC. The process combines CSP and fuels-based combustor to generate power and redox-based TCES materials for energy storage and a source of oxygen, which is used to combust fuel, like an oxy-fuel combustion (OFC) process. The process has three advantages. First, the power cycle can be operated at a higher temperature during the night compared to a standalone CSP-TCES process, wherein the reversible reaction temperature limits the temperature of the power cycle. This would lead to higher overall efficiency of the CSP-TCES-OFC process compared to CSP-TCES. Second, oxygen separation occurs using thermal energy, a low-grade energy source compared to electricity, the primary energy source for an air separation unit used in a traditional OFC process. Third, the process enables energy storage and carbon capture simultaneously. We develop a stochastic programming-based optimization model that considers variability in solar irradiance to minimize the levelized cost of electricity (LCOE). We also compare the economic performance of our processes with other processes and show that our process results in a lower LCOE.

2. SYSTEM DESCRIPTION

Figure 1(A) shows the schematic of the CSP-TCES-OFC process. The system operates as follows. During the day, the collector focuses sunlight onto a receiver, where photons are absorbed, and the heat transfer fluid (HTF) is heated. The flow of HTF is split such that a part of it flows through the reactor (R1) to provide heat to the forward endothermic decomposition reaction ($\mathrm{M_xO_z} \leftrightarrow \mathrm{M_xO_y} + \frac{z-y}{2}\mathrm{O_2}$), and the remaining flows through the power block to provide heat to the working fluid (WF). The oxygen (O_2) released due to the forward endothermic reaction is compressed and stored. It is then used for fuel combustion when solar energy is unavailable. Since O_2 from R1 is at a high temperature and compressing a gas at a lower temperature results in a lower power consumption, its sensible heat is extracted using a sensible heat storage unit. A multistage compressor is employed to compress O_2. An intercooler is used after each compressor so that the temperature of O_2 after each stage is 35 °C. The compressed O_2 is stored underground or in a pressure vessel.

During the night, the reverse exothermic reaction occurs in the presence of air to regenerate the metal oxide in a higher oxidation state. The heat stored in the sensible heat storage unit is used to increase the temperature of air entering R2. The energy from the high-pressure O_2 is recovered using a pressure recovery turbine (PRT) such that the pressure of O_2 entering the combustor is 1 atm. In the combustor, O_2 is combusted with fuel to produce heat. In this article, we consider natural gas as the fuel. Thus, energy is obtained during the night operation by reversible exothermic reaction, combusting fuel, and recovery energy from compressed O_2 using PRT. After exchanging heat with the combustor and R2, WF is sent to a power cycle to generate electricity. Since natural gas is combusted in the presence of O_2, the exhaust from the combustor mainly contains CO_2 and H_2O. The CO_2/H_2O stream is at a high temperature, and the stored O_2 is at a lower temperature. We employ a heat exchanger to increase the O_2 stream temperature and decrease the CO_2/H_2O stream temperature because increasing the O_2 temperature will result in a higher PRT efficiency, and decreasing the CO_2/H_2O stream temperature will aid in separating CO_2 and H_2O. The CO_2/H_2O stream temperature is further decreased to room temperature and separated using a flash column. The CO_2 stream is then compressed to 150 bar by four multistage compressors with intercoolers. The compressed CO_2 is then transported and stored underground.

3. ALTERNATIVE PROCESSES

We compare the economic performance of CSP-TCES-OFC with two alternative processes. The first process is the CSP-TCES with redox-based TCES material, illustrated in Figure 1(B). There are two key differences

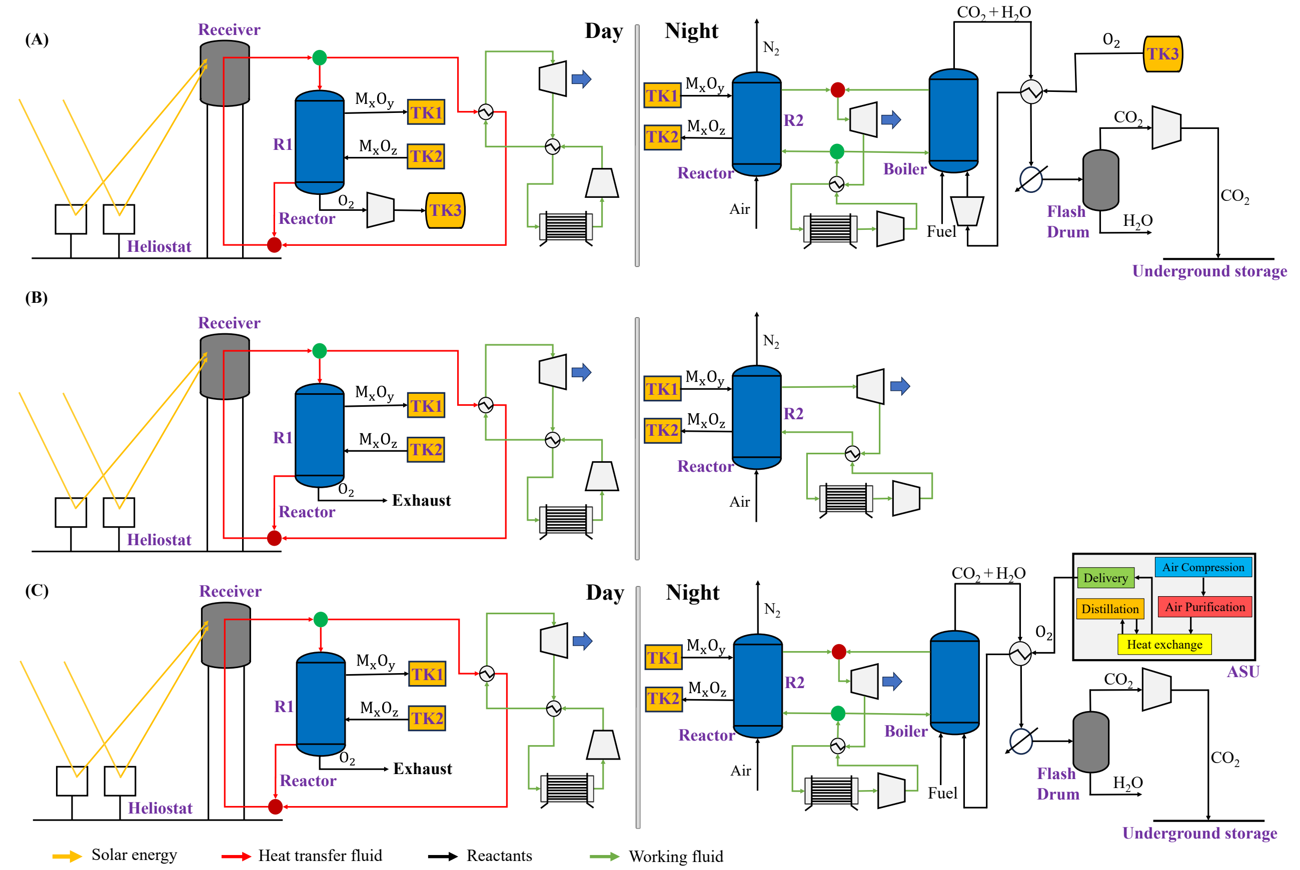

Figure 1. Schematic of (A) CSP-TCES-OFC, (B) CSP-TCES, (C) CSP-TCES-ASU processes.

between the CSP-TCES and CSP-TCES-OFC processes. First, oxygen is not stored, and second, no fuel is combusted. The proposed process has several advantages over the CSP-TCES process. First, the power cycle can be operated at a higher temperature at night than a standalone CSP-TCES process. Second, oxygen separation occurs using thermal energy, a low-grade energy source compared to electricity, which is the primary energy source for an air separation unit used in a traditional OFC process. Third, the process enables energy storage and carbon capture simultaneously. Fourth, there is no direct contact between metal oxide and CO_2, thus avoiding the carbonation of the metal oxide and improving reversibility.

The schematic of the second process, referred to as CSP-TCES-ASU, is shown in Figure 1(C). Instead of storing oxygen formed during the forward endothermic reaction, an ASU produces oxygen needed to combust fuel during the night. We assume that 250 kWh of electricity is needed to produce 1 tonne of O_2.

4. METHODOLOGY

We evaluate the techno-economic performance of the CSP-TCES-OFC process via optimization of the energy system design, considering variability in solar irradiance. We develop a stochastic programming (SP) model to account for variability in solar irradiance. Based on the previous works [1,8], we extend the SP model developed for CSP-TCES to CSP-TCES-OFC. The inputs required by the model are (1) solar irradiance data, (2) plant capacity, (3) TCES and combustion reactions and properties (reaction enthalpy, equilibrium temperature), and (4) cost parameters.

We selected the plant location as Daggett, California. We used its solar irradiance data from the National Solar Irradiance Database and use k-means clustering to obtain six representative scenarios. We assume that the plant operates in day and night modes. The plant capacity is chosen to be 100 MW. The TCES system is Mn_2O_3/Mn_3O_4 because it is one of the most well-studied systems, and we assume that natural gas is combusted using O_2. The objective of the model is to minimize the LCOE subject to the constraints that include the physical model of the plant components (i.e., collector, receiver, TCES reactors, storage tanks, compressors, combustor, power cycle), unit mass and energy balances, equipment sizing, and cost correlations. The model solution results in optimal design and scenario-dependent operating variables. The overall framework is given in Figure 2. The resulting model is a mixed integer nonlinear programming model formulated and solved using Gurobi's Python API. The cost parameters and complete model equations for CSP-TCES-OFC and CSP-TCES-ASU can be found in the

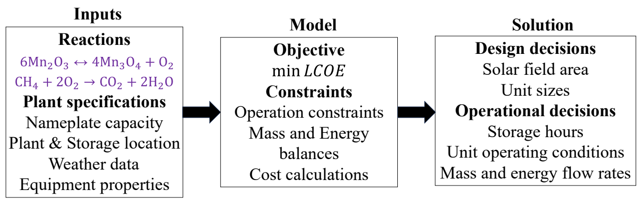

Figure 2. Overview of the optimization model for CSP-TCES-OFC process.

supplementary material, and the model for CSP-TCES can be found in the ESI of Bajaj et al. [1].

5. RESULTS

We consider two sets of cost parameters for transporting and storing CO_2 and O_2, which are given in Table 1. The two cases for CO_2 storage and transportation costs are the typical values given in the literature. The case 1 for storing O_2 corresponds to pressure vessel and case 2 corresponds to underground storage. Figure 3 shows the LCOE distribution for the three processes, and Table 2 lists the important decision variables. The subscript 'h' and 'l' denote the higher and lower cost parameters (case 1 and case 2), respectively. The LCOE of the CSP-TCES-OFC process ranges between 8.66 – 9.67 ¢/kWh, and lowest among the three processes, suggesting that the proposed integrated process synergistically combines energy storage and carbon capture. The capital investment required for CSP-TCES-OFC, CSP-TCES, and CSP-TCES-ASU are \$ 605.18 million, \$ 658.8 million, and \$ 711.9 million, respectively. The total electricity produced is 870 GWh, 649 GWh, and 897 GWh, respectively.

Table 1: Cost of storage and transportation of gases for CSP-TCES-OFC model considered for different cases.

Case	CO_2 storage price (\$/ton)	CO_2 transportation price (\$/km ton)	O_2 storage price (\$/m³)
1	15	2	5700
2	5	1	50

For all the processes, the solar field/collector and receiver are the main contributing factors to LCOE, followed by the power block. Compared to the CSP-TCES process, the LCOE contribution of solar field and receiver is lower for the CSP-TCES-OFC process because of their lower sizes (Table 2). This is primarily due to (1) the higher efficiency of the power cycle during the night due to a higher working fluid temperature (Table 2) and (2) energy production from low-cost and energy-dense natural gas and compressed O_2. The power cycle operates at a lower temperature in the CSP-TCES process because the thermal energy is provided by the reversible exothermic reaction, which due to thermodynamic limitations, can only occur at a temperature lower than the equilibrium temperature. Although the cost of the power block is the same for all the processes, its contribution to CSP-TCES-OFC is lower because of higher electricity production.

The TCES material requirement is the lowest for the CSP-TCES-OFC process due to additional lower-cost energy production sources (methane and compressed O_2) at night. This also results in lower reactor and solid storage tank costs. The operating cost is higher for the CSP-TCES-OFC process due to natural gas and cooling requirements. Additionally, the CSP-TCES-OFC requires compressors and gas storage infrastructure to store O_2 and CO_2. The LCOE contributions for both CSP-TCES-OFC and CSP-TCES-ASU processes differ mainly by the capital expenses needed for the air separation unit in the latter and the O_2 compressor and storage in the former. However, the cost associated with compressing and storing O_2 is much lower than that of an ASU. The analysis illustrates that it is more economical to use redox-based TCES materials for both energy storage and a source of O_2 for fuel combustion.

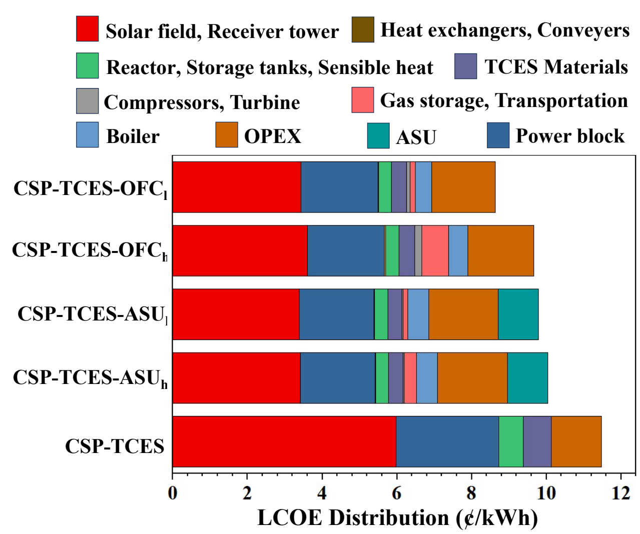

Figure 3. LCOE distribution for various processes.

A key decision variable is the storage pressure of O_2. While high storage pressure results in a lower tank cost and more power production by PRT, it also produces higher power consumption during the day and a higher compressor cost. We can observe from Table 2 that O_2 storage pressure is higher when O_2 is stored in a pressure

Table 2: Comparison of key decision variables of the three processes.

Decision variables	CSP-TCES-OFC$_l$	CSP-TCES-OFC$_h$	CSP-TCES	CSP-TCES-ASU$_l$	CSP-TCES-ASU$_h$
Power cycle temperature during day (TIT) (K)	1377.1	1382.5	1415.3	1385.2	1394.4
Power cycle temperature during night (TIT) (K)	1048.1	1048.3	967.3	1017.5	1007.8
Receiver temperature (K)	1273.3	1276.7	1314.3	1280.9	1284.1
Collector area (m^2)	913.1	955.4	1182.3	927.2	929.2
Receiver size (MWh$_t$)	493.7	514.9	635.5	497.9	500.3
CF (%)	79.8	78.9	74.1	81.1	80.8
Oxygen storage pressure (bar)	5.3	39.3	-	-	-
Yearly CH_4 consumption (10^3 tonnes)	25.9	27.6	-	33.4	33.6
Yearly O_2 consumption (10^3 tonnes)	103.6	110.5	-	133.6	134.1
Power generated at night (MW)	42.3 – Combustion 59.3 – Reactor 1.9 - PRT	44.1 – Combustion 62.7 – Reactor 3.6 - PRT	100.0 – Reactor	54.7 – Combustion 56.7 - Reactor	54.2 – Combustion 62.2 - Reactor
Power consumed at night (MW)	1.7 - Compressor	1.8 - Compressor	-	2.1 – Compressor 8.0 - ASU	2.2 – Compressor 8.1 - ASU

vessel (case 1), resulting in the production of a higher amount of power.

Capacity factor (CF) is the ratio of the actual amount of energy produced by the plant to the amount of energy that could have been produced by that plant when operated at its full power rating during the same period. Mathematically, CF is defined as follows:

$$CF = \frac{\sum_{t\in T} \pi_t \left(DT_t^c + NT_t^d\right)}{\sum_{t\in T} 24 \times \pi_t}$$

where π_t is the probability of occurrence of scenario t, DT_t^c is the charging time, and NT_t^d is the discharging time.

Figure 4 shows the variation of LCOE with CF. The LCOE of the CSP-TCES-OFC process is the lowest among the three processes for CF varying between 60 – 85%. The difference in LCOE between the CSP-TCES and CSP-TCES-OFC processes becomes larger as CF increases to more than 80%. The cost of the CSP-TCES process increases more with CF because as CF increases, power needs to be produced during low DNI scenarios, which requires a larger collector and receiver. Furthermore, increasing CF requires more energy storage to provide power during nighttime, resulting in more TCES material requirements, larger reactors, and storage tanks. The optimal CF for CSP-TCES, CSP-TCES-ASU, and CSP-TCES-OFC processes are given in Table 2. The corresponding charging and discharging times for the three processes are shown in Figure 5.

We observe that the charging time for the CSP-TCES process in all the scenarios is the highest, whereas the discharging time is the lowest. This occurs because of the lower energy density of TCES materials. However, the amount of material stored is still insufficient to provide power for longer discharging times. The presence of an additional source of energy (natural gas combustion) in CSP-TCES-OFC and CSP-TCES-ASU results in longer discharging times, resulting in a higher overall CF for the two processes.

6. CONCLUSIONS

We proposed a hybrid process that combines concentrated solar thermal and fossil-fuel-based power production with redox-based TCES materials for energy storage and carbon capture. We develop a stochastic programming-based optimization model that considers the variability in solar irradiance to evaluate the economics of the process. We compare the economic performance of our process with CSP-TCES and show that the optimal LCOE of our process is 15.9% – 24.6% lower. This illustrates that the redox-based TCES materials enable synergistic energy storage and carbon capture, reducing overall electricity production costs at higher capacity factors. Our analysis provides critical insights into the benefits of redox-based TCES materials, and we hope more experimental studies will follow to elucidate the O_2 formation and energy storage capabilities of TCES materials.

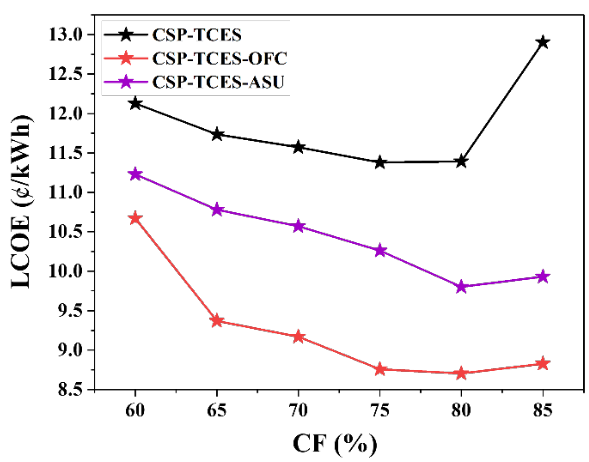

Figure 4. LCOE variation for different CF for the three processes.

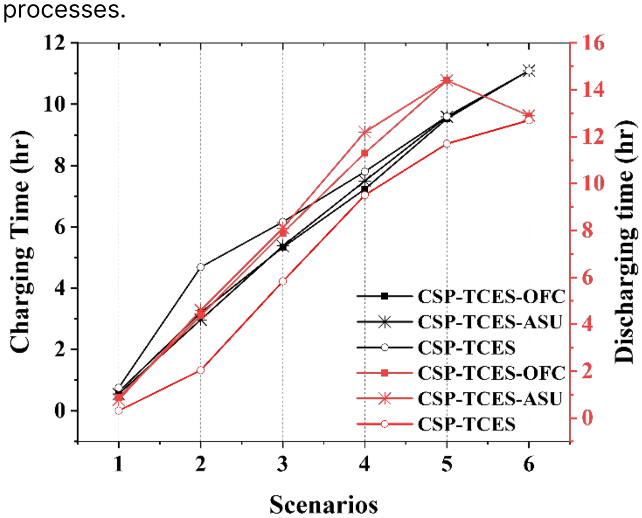

Figure 5. Charging and discharging times during various scenarios for the three processes.

DIGITAL SUPPLEMENTARY MATERIAL

The complete SP model for the CSP-TCES-OFC and CSP-TCES-ASU processes and CSP-TCES-ASU can be found in the Living Archive for Process Systems Engineering using the ID LAPSE:2025.0025v2

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