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Optimization of an improved calcium-looping process for thermochemical energy storage in concentrating solar power plants

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ABSTRACT

The calcium-looping (CaL) process comprises an endothermic calcination reaction, where CaO and CO_2 are generated from $CaCO_3$, and its reverse exothermic carbonation reaction. CaL is promising for thermochemical energy storage (TCES) in concentrating solar power plants. The CaL-TCES process includes: a calciner where solar energy is transformed into thermochemical energy; a carbonator where the stored energy is released; turbines for electrical power generation; and tanks where the reaction products are stored. In this work, the CaL-TCES process is simulated and optimized using gPROMS Process. The innovation lies in identifying process improvements: make-up and purge streams to reduce CaO deactivation after cycling; a water separation process at the calciner outlet to allow calcination with water vapor as fluidizing gas; and the use of several degrees of freedom for process optimization. The goal is to maximize the thermal-to-electrical efficiency. By optimizing the carbonator and main turbine outlet pressures, the efficiency is improved from 38.1 % in the literature to 39.2 %. When make-up and purge streams are considered, the savings in power supply owing to the purged CaO allow improving the efficiency to 43.0 %. The water separation process reduces the thermal-to-electrical efficiency to 34.7 %, but allows a higher solar-to-thermal efficiency or a smaller calcination reactor.

1. Introduction

The variability of some types of renewable energy is considered one of the main obstacles to their widespread adoption. Energy storage is essential to deal with this issue. Concentrating solar power (CSP) systems rely on the concentration of solar energy in a receiver, allowing high-temperature thermal energy storage (TES) and power dispatchability. The most common solution for TES relies on nitrate-based molten salts as heat transfer and storage medium, the operational limitations of which do not allow high efficiencies since they need to be kept between 220 °C and 560 °C. An alternative method for TES in CSP systems is thermochemical energy storage (TCES), which is based on reversible reactions. For example, a promising option is the calcium-looping (CaL) process for TCES, which relies on a cycle that comprises (i) an endothermic calcination reaction, with a standard enthalpy of reaction of 178.4×10^3 J mol^{-1}, in which CaO and CO_2 are generated from $CaCO_3$ in a solar reactor, and (ii) an exothermic carbonation reaction, in which $CaCO_3$ is formed from CaO and CO_2. The reaction products are stored in tanks until the reverse reaction is carried out. This process is advantageous with respect to the use of molten salts since CaO precursors such as limestone are cheap, abundant, and harmless, the energy density is large (> 3 GJ m^{-3}), and carbonation can occur at high temperatures, which improves the efficiency in CSP plants [1]. A main disadvantage is CaO deactivation after several cycles, which decreases

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INTRODUCTION

❖ BACKGROUND

- ➢ The research aims to optimize the Calcium-Looping (CaL) process for thermochemical energy storage in concentrating solar power plants.
- ➢ The CaL-TCES process proposed by Ortiz et al. is used as a benchmark and starting point for the simulation and optimization study.
- ➢ The research introduces three innovative aspects: *optimization of key variables*, *consideration of make-up and purge streams*, and *a proposed water separation process*.

INTRODUCTION: Literature Comparison & Gaps

COMPARISON	***GAPS***
Maximizing the efficiency of carbonation and maintaining optimal outlet pressures for the main turbine, all without the need for purging or a water separation process.	The oversight of incorporating makeup and purge streams has led to missed opportunities for enhanced efficiency.
Taking into account the calcination process in the presence of water vapor while optimizing the fraction of solids purge.	Failed to explore the tradeoff between thermal-to-electrical and solar-to-thermal efficiency due to the absence of a detailed heat integration analysis.
Suggesting a method for separating water in order to utilize water vapor in the solar calcination process.	Overlooked the impact of enhanced residual conversion of a $CaCO_3/CaO$ mixture on overall efficiency.

GOALS & OBJECTIVES

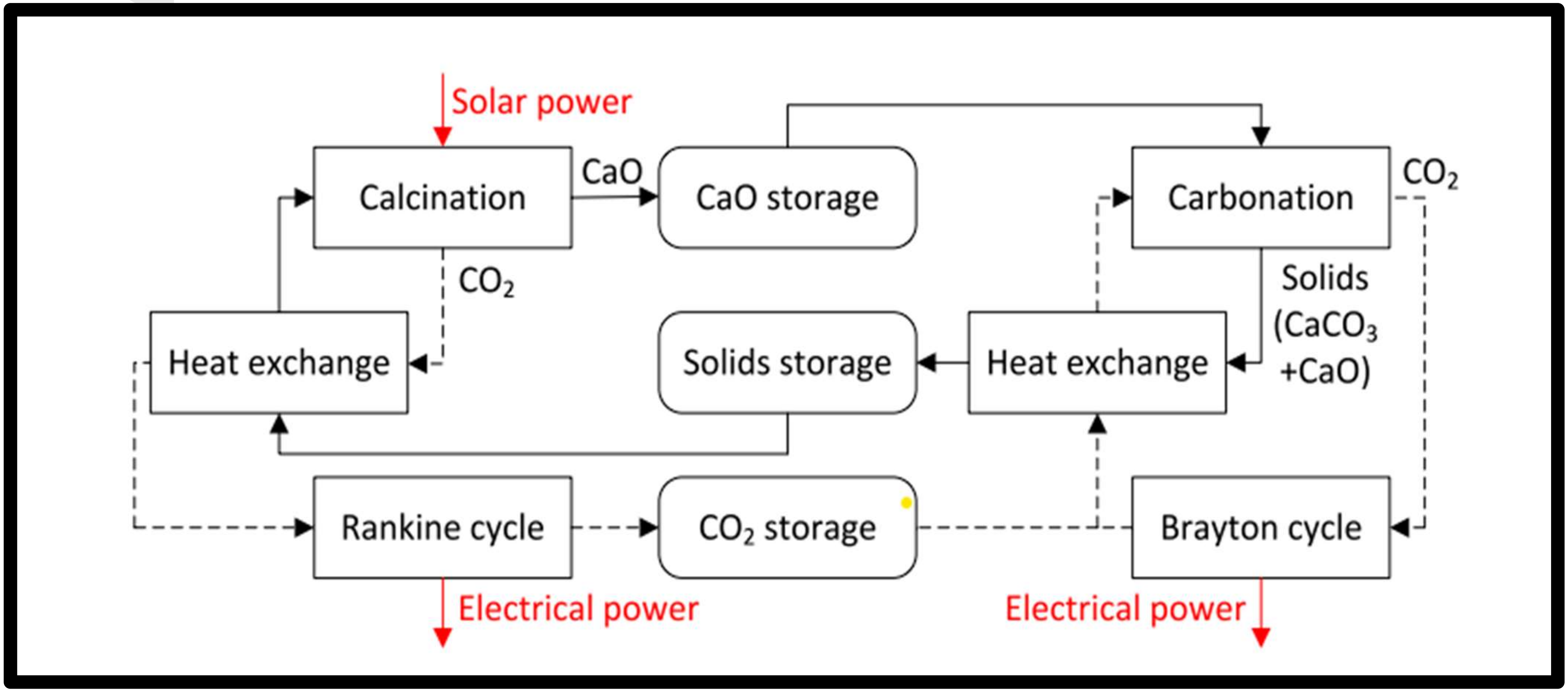
1. *Enhancing thermal-to-electrical efficiency through the optimization of carbonator and main turbine outlet pressures.*
2. *Investigating the influence of different solids purge split fractions on the efficiency of the CaL-TCES process.*
3. *Examining the balance between maximizing thermal-to-electrical efficiency and solar-to-thermal efficiency in the CaL-TCES process.*

Process Modelling & Optimization

1. Description

- This process uses sunlight to heat a mixture of substances, turning one of them into another and releasing a gas called CO_2. This CO_2 is then used to make hot air and steam.
- When there's sunlight, the CO_2 is squeezed and stored at high pressure. When there's no sunlight, this stored CO_2 is used to power a special machine.
- One part of the process works all the time, changing one substance into another. It also warms up the CO_2 used by the machine and some of the CO_2 coming out of it. The solid stuff that comes out of this part is used to heat up more CO_2.
- The whole process is explained in detail in gPROMS Process software. The part that changes substances works non-stop, while the part that uses sunlight only works when there's sunlight.

Schematic Diagram of Process



Description of the ***water separation process***

- **No More Pure CO_2**: Instead of using only CO_2, the process now mixes in water vapor for better efficiency.
- **Separation Goal**: It splits the gas from the reactor into two parts: one with lots of water to recycle and one with lots of CO_2 for backup.
- **Efficient Separation**: This is done using stages and compressors to save energy.
- **Heating Step**: Finally, both streams are heated to 900°C with the hot reactor gas for recycling water and using CO_2 efficiently.

Optimization

- **Optimization Goal**: The study focuses on maximizing the thermal-to-electrical efficiency of the CaL-TCES process, addressing constraints and obtaining a more efficient process.
- **Key Improvements**: It introduces improvements compared to prior research by optimizing carbonator and turbine pressures, considering make-up and purge streams, and proposing a water separation process for better efficiency.
- **Decision Variables**: The study treats carbonator and turbine pressures, make-up and purge streams, and compressor pressure ratios as decision variables, optimizing them to minimize power consumption and enhance overall efficiency.

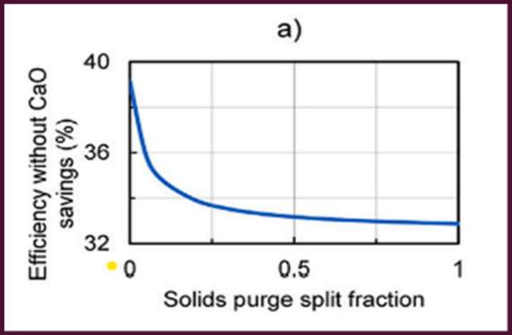
Process Configurations

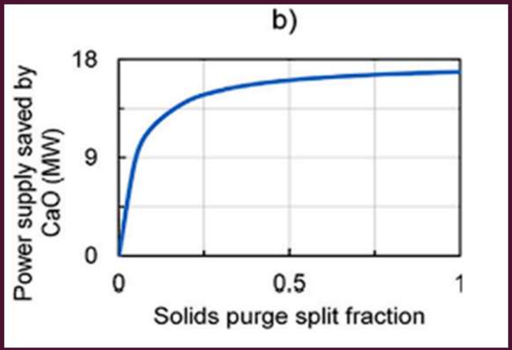
- **Pressure Optimization**: Focuses on optimizing carbonator and turbine pressures without purge or water separation, assuming 15% residual conversion in the carbonator and CO2 in the calciner.
- **Solids Purge Variation**: Introduces variable solids purge fraction (fp) from 0 to 1 while optimizing carbonator and turbine pressures, still using CO2 in the calciner.
- **Water Vapor Calcination**: Explores calcination with water vapor, maintaining the optimal fp from Case 2, and considering the efficiency impact of a water separation process.

Result and Discussions

***Optimization of the carbonator and main turbine outlet pressures*:-**

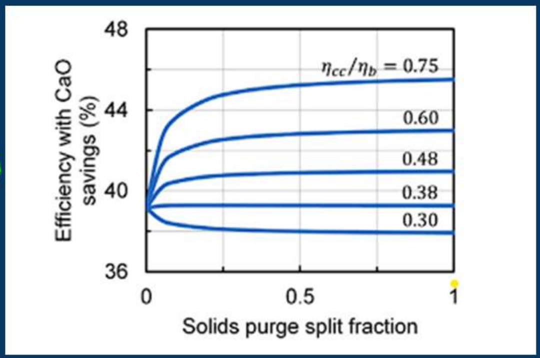
Changing carbonator pressures from 3 to 1.485 bar and turbine pressures from 1 to 0.293 bar significantly boosts efficiency of the CaL-TCES process i.e 38.1% to 39.2%. This depicts the importance of optimization of *decision variables* to enhance efficiency.

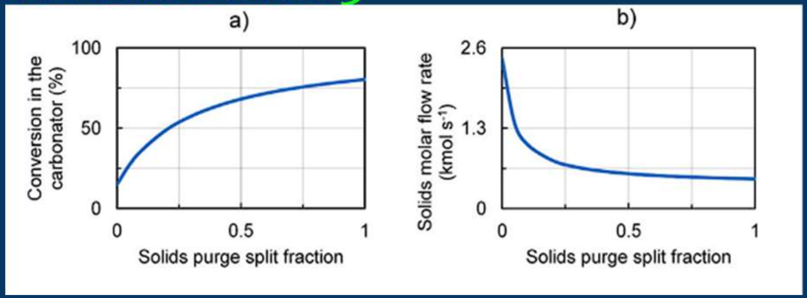




Effect of the solids purge split fraction

Increasing solids purge (fp) in the CaL-TCES process reduces efficiency but saves power. The ideal fp value depends on the efficiency ratio , with 43% efficiency achievable in the best case. As fp rises, carbonator conversion increases while solids flow decreases due to more CaCO3 turning into CaO.





Effect of the water separation process

- Using water vapor in calcination has a smaller effect on efficiency compared to increasing solids purge (fp).
- Even with water vapor, the best choice is fp = 1, giving an efficiency of **43%**. But there's a tradeoff between maximizing thermal-electrical efficiency and solar-thermal efficiency.
- The water separation process consumes power, reducing efficiency from **43.0% to 34.7%**. Calcination at 800°C has minor effects but some benefits.
- Water vapor generally improves the process due to lower temperatures, despite increased power consumption in water separation.

CONCLUSION

- This study aims to enhance the efficiency of a calcium looping process used for storing solar energy as thermochemical energy. The process involves a solar calciner, carbonator, turbines, and heat integration.
- Key innovations include adding streams to improve carbonator efficiency and a water separation process for using water vapor in the calciner.
- Optimizing pressures boosts efficiency from 38.1% to 39.2%. With additional streams, efficiency ranges from 32.9% to 43.0%, improving if certain efficiency ratios are met.
- A water separation process reduces efficiency to 34.7%, slightly impacted when lowering calcination temperature to 800°C.
- Future work will consider energy for transporting materials, variable solar input, integrating with cement production, and alternative configurations.

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