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Novel Use of Concentrated Solar Thermal Energy for Producing Highly Thermal Activated Materials for CCUS via Mineral Carbonation of Mine Waste

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Abstract. An assessment of the levelised cost and associated $CO_{2\text{-eq}}$ emissions for the thermal activation of serpentine mine tailings to be used as activated feedstock for CCUS processes via mineral carbonation, is reported here for the first time. Two main technological scenarios were assessed, based on either direct fuel sources heating (natural gas and hydrogen) or indirect, CST-based heating with a back-up burner and storage to provide continuos operations, for a 200 ton/hr of processed ore and a targeted roasting ore temperature of 700°C. For CST-based systems, 3 different solar input scales, namely 50, 150 and 450 MW_{th}, were considered, and simulations performed over a year timeline with a 10 minutes time step, using Mt Keith Nickel mine in Western Australia as the reference location. The analysis highlighted that the proposed CST-hybrid plant layout can achieve similar cost to that of fuel-only cases with current Australian fuel prices for natural gas and hydrogen, with lower $CO_{2\text{-eq}}$ emissions, and a parity cost with fuel-only scenarios of some 16 USD/GJ. The proposed CST-hybrid plant layout was also identified as the potential, preferred route over direct CST routes to achieve 24/7 continuos heat supply while retaining fine tuning of activation temperature, given a very narrow temperature window of activation for the chosen mine tailings for mineral carbonation processes.

Keywords: Concentrated Solar Thermal, Techno-Economic Analysis, Mineral Carbonation, Carbon capture, Hydrogen

Introduction

Carbon capture, utilisation and storage (CCUS) refers to a suite of technologies that can play a diverse role in meeting global energy and climate goals. In the IEA Net-Zero Scenario [1], CCUS can facilitate the transition to net-zero CO_2 emissions by tackling emissions from existing assets, particularly large CO_2 point sources from hard to abate sectors, by providing a pathway to produce low-carbon hydrogen, and/or by allowing CO_2 removal directly from atmosphere. Among all CCUS technologies proposed to date, ex-situ mineral carbonation (MC), a process mimicking natural weathering phenomena, offers unique advantages of permanent disposal via geologically stable and environmentally benign materials (e.g., carbonates and silica) [2] while also providing recovery of valuable by-products.

Magnesium and calcium-rich minerals are ideal candidate feedstock for MC processes, with serpentine-type minerals found in both readily minable deposits and ultramafic mine waste/tailings (e.g., from nickel processing), at relatively low-cost. At global scale, the annual amount of mining tailings (mainly serpentine and olivine) produced could potentially offset some 1.5% of current global CO_2 emissions. At site level, the Mount Keith Nickel mine (owned by BHP Billiton) in Western Australia has been among the most studied mines globally for potential MC integration, [3], with the mine producing some 11Mt per year of ultramafic tailings per year. The full MC capacity of these tailings represents some 4MtCO_2/year, which is approximately 10 times the annual emissions of the mine, making the mine a carbon sink. Serpentine typically requires thermal activation to produce an activated feedstock for MC. While the majority of R&D work has focused on optimizing the heating step to maximise activation and enhance rate of kinetics, there is only a limited understanding of the impact of the heating source selection on the overall techno-economics and emissions of the thermal activation step. In particular, no data are available for hydrogen-based and concentrated solar thermal-based (CST) heating, with no information on the impact of solar plant type, scale and location on process performance. Therefore, the present paper aims to meet this need by providing the very first techno-economic assessment and emission analysis of a CST-based heating plant for serpentine activation to produce activated feedstock materials for CCUS processes via mineral carbonation. A comparison with fossil fuel-based, and hydrogen-based heating is also considered in this work.

Methodology

Two main technological scenarios were assessed here, based on either direct fuel sources heating or indirect, CST-based heating with a back-up burner and storage to provide continuos operations (Figure 1). A first-order mass/energy balance, a transient system modeling using an expanding solar vortex receiver (SEVR) [4] as solar receiver technology, and techno-economic assessments (TEA) [5-7] were then developed and used to systematically analyse the process performance. The transient CST system with a year of simulation with 10 minutes time steps for a range of CST conditions was proposed previously [6], which was used in the this study for the CST heat input. The combustion energy sources are natural gas, termed NG; hydrogen produced by a steam reforming plant equipped with a CCUS facility and a capture rate of 90%, termed H_2(B); and a low-carbon hydrogen produced via electrolysis using renewable electricity (assuming 50-50% wind and PV), termed H_2(G).

To provide the heat required for the thermal activation, models were developed for both the combustion heat sources and the CST hybrid cases, and performance compared them are presented. For all cases, it is assumed that the source of mine waste (serpentine) is located at the BHP Mount Keith Nickel mine, with the plant scale of 200 ton/h. To activate the material, a net thermal energy of 636 MJ/tSer is required [8], hence the thermal input required for the heat activation Q_{req} is 35.3 MW_{th}. The levelised cost of heat from the CST system $LCOH_{CST}$ is calculated using the same method previously proposed and the solar input scale of 50, 150 and 450MW were assessed. The fuel cost is ranged from 3 to 30 USD/GJ [9]. The estimated equivalent specific CO_2 emission used in this study are 65.9, 38.7 and 7.0 kg CO_2/GJ for NG, H_2(B) and H_2(G) respectively [10, 11].

The total energy cost C_{tot} and $CO_{2\text{-eq}}$ equivalent emission for the activation of 1 tonne of serpentinite are estimated for each heat source, from specific cost of fuel c_f, specific emission of fuel e_f, solar share SS and the Levelised Cost of Heat ($LCOH$) of the CST, using equation (1) and (2).

$$C_{tot} = c_f \cdot Q_{req} \cdot (1 - SS) + LCOH \cdot Q_{req} \cdot SS + Dis \cdot c_t \; [USD/tSer] \qquad (1)$$

$$E_{tot} = e_f \cdot Q_{req} \cdot (1 - SS) + e_{CST} \cdot Q_{req} \cdot SS + Dis \cdot e_t \; [\mathrm{kg\,CO_2}/tSer] \qquad (2)$$

The amount of tonne of $CO_{2\text{-eq}}$ that can be captured by one tonne serpentinite can be defined as the efficiency of the serpentinite η_{Ser}. The net efficiency of CO_2 captured is defined in

$$\eta_{net} = \eta_{Ser} - 1000E_{tot}\ [\%\ or\ \mathrm{tCO_2}/tSer] \quad (3)$$

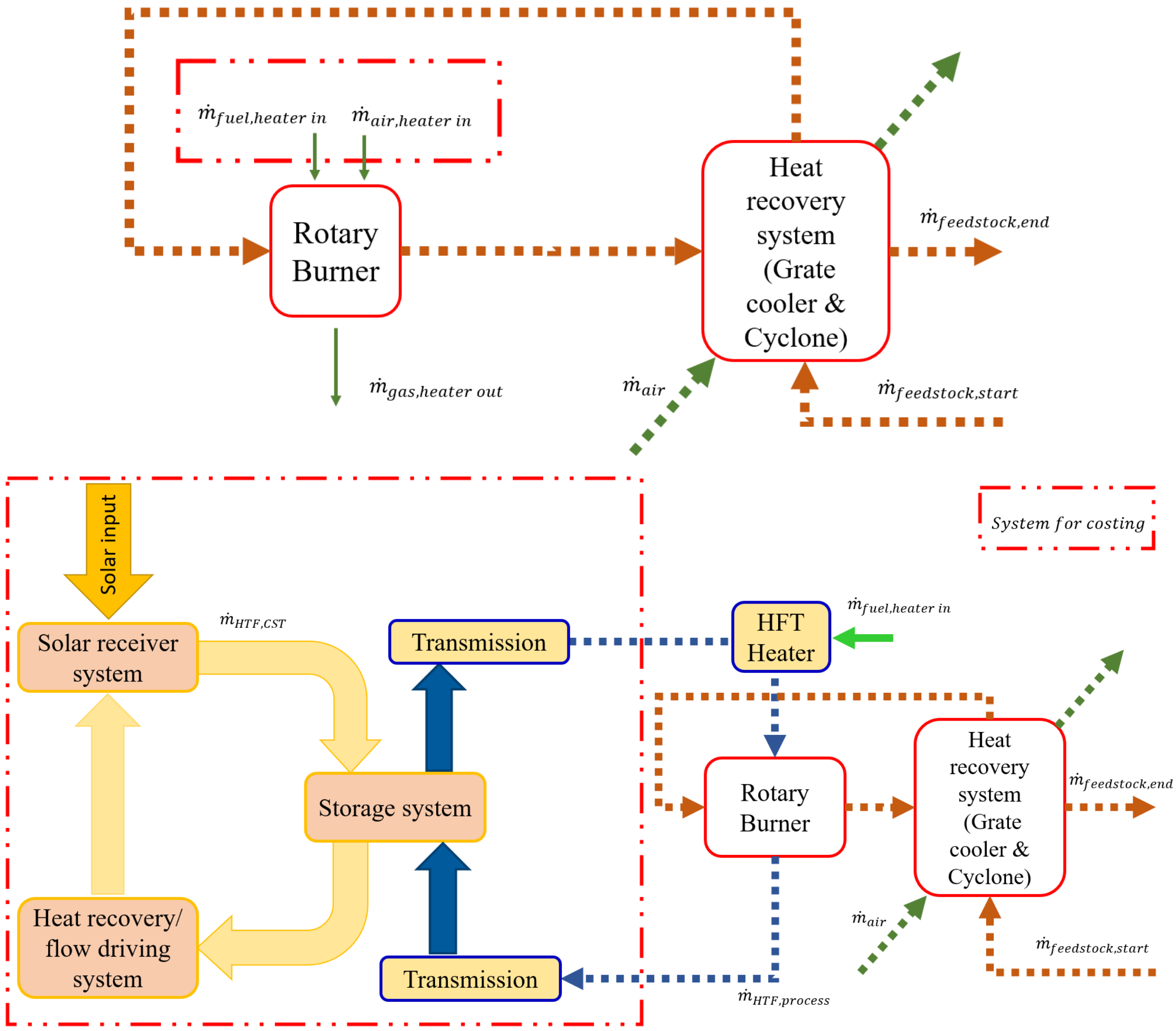

Figure 1. *Process diagram for the thermal activation of serpentine waste, with top) fuel-only (either NG or H_2), and bottom) CST with back-up fuel hybrid system.*

Results and Discussion

An assessment of a large number of CST configurations have been performed, including a sensitivity on storage capacity, thermal efficiency of the storage and thermal transmission system. The most suitable configurations for the 50, 150 and 450 MW solar input scale are shown in Table 1. The LCOH of the CST system and the annual solar share are also presented. These configurations are used to further assess both the cost and emission of the thermal activation process for the hybrid CST plant with back-up burner and thermal storage cases.

Table 1. *CST parameters to meet the energy requirement to thermally activate 200 t/hr of serpentine tailings at Mount Keith, and for a roasting temperature of 700°C*

CST Scale (MW)	Thermal demand (MW)	Solar multiple	Solar share (%)	LCOH of CST (USD/GJ)
50	35.3	1.42	28.3	15.8
150	35.3	4.25	54.6	21.2
450	35.3	12.7	74.1	50.5

Figure 2 presents the $CO_{2\text{-eq}}$ emissions associated with the energy required for the tailing activation, and the associated net CO_2 capture efficiency. The results show that, the calculated $CO_{2\text{-eq}}$ emissions of the CST-hybrid plant is much lower than that of the fuel-only plant, particularly for the 100% natural gas-based case.

Previous works highlighted that some 417kg of CO_2 can be captured and stored in 1 tonne of thermally activated serpentine [12]. Both the amount of CO_2 emitted during the activation process and the relative CO_2 supply chain emissions, influence the net CO_2 capture efficiency, which is reported in Figure 2 for each configuration assessed here. It can be seen that the net CO_2 capture efficiency could be improved by some 10% if a portion of the heat source is replaced with CST, in comparison with a fossil-fuel based operation.

Figure 3 shows the dependency of the cost of fuel on the overall cost of serpentine tailing activation, for different combinations of fuel and CST scenarios. Overall, the analysis highlights that the CST-hybrid plant has the potential to be the most cost-effective option to carry out the thermal activation process if the cost of fuel is >16 USD/GJ.

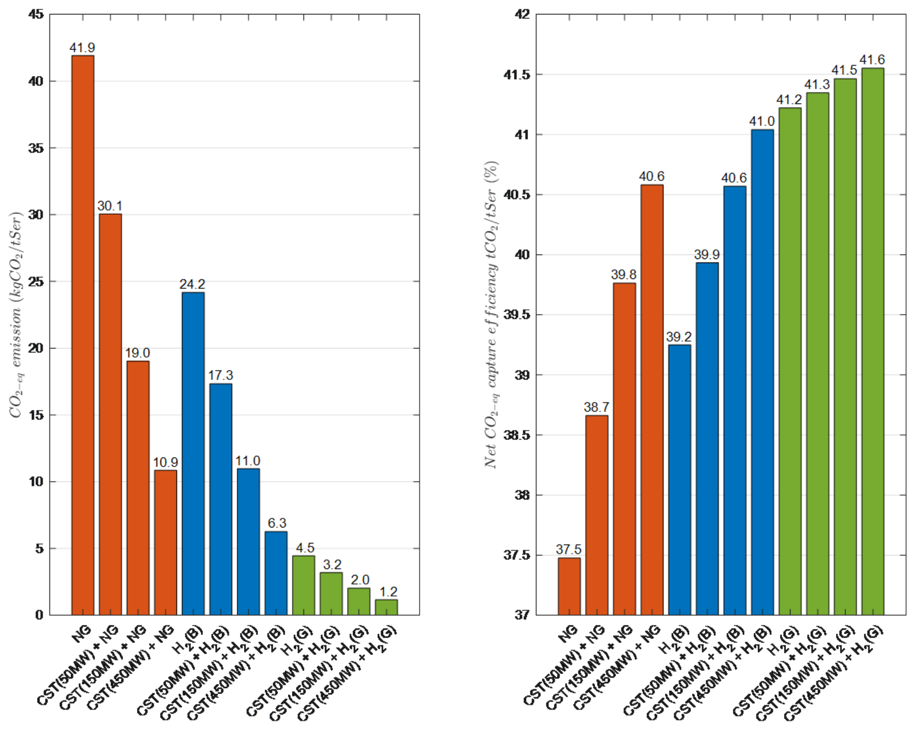

Figure 2. *Left) Comparison of CO_2-equivalent emissions from activating a tonne of serpentine, right) net CO_2 capture efficiency using various heating methods. H_2 (B) and H_2 (G) represent blue hydrogen (from methane reforming with CCUS with 90% capture rate), and electrolytic H_2 from renewable electricity. All calculations for 200 ton/h of serpentine.*

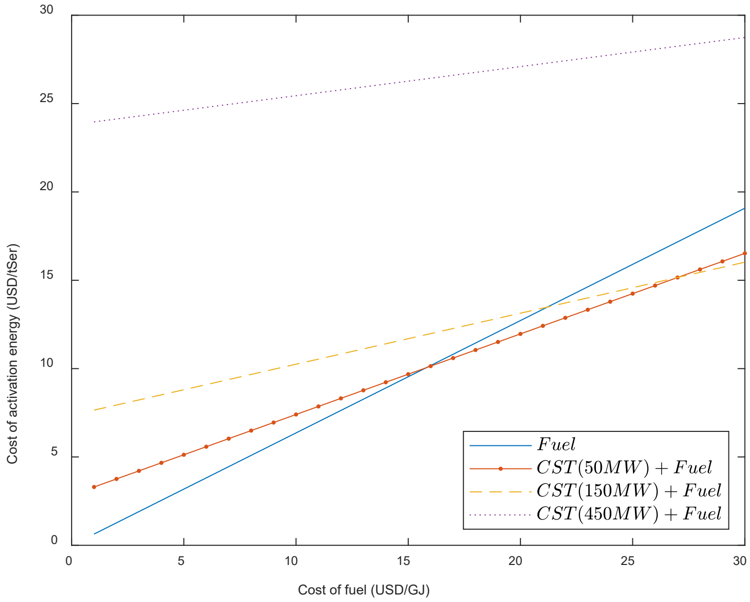

Figure 3. *Effect of fuel price and energy source on thermal activation cost, for a plant processing 200 ton/h of serpentine tailings, and a roasting temperature of 700 C.*

Conclusion

The key outcomes from this study are as follows:

- **A potential, attractive business case for CST:** use of CST as major source of heat avoids reduction in the net CO_2 sequestration efficiency of some 10% in comparison with fuel-only cases (due to avoidance of CO_2 emissions associated with fuel supply chain). By selecting an appropriate ratio between scales of the CST system and the thermal activation plant, the overall cost of heating for a CST-hybrid plant is similar to that of fuel-only cases, but with lower CO_2-equivalent emissions. In addition, CST-hybrid plant features both higher net CO_2 capture efficiency and lower cost of activation energy when the cost of fuel is above 16 USD/GJ.
- **Role of CST in a thermally assisted CCUS process:** the solar route can provide the heat required to sustain activation of serpentine for CO_2 mineral carbonation processes. An indirect (with the solar heat collector system being different from the thermal activation device), hybrid (CST with back-up burner and thermal storage) approach was identified as a potential, preferred route to achieve 24/7 continuos heat supply while retaining fine tuning of the activation temperature process for mineral carbonation of serpentine tailings.

Data availability statement

Data available upon request

Underlying and related material

Not available

Author contributions

Leok Lee: formal analysis, writing – original draft. Woei Saw: supervision, writing – review and editing. Elliott Lewis: writing – review and editing. Graham J. Nathan: supervision, writing – review and editing. Alfonso Chinnici: funding acquisition, project administration, supervision, writing – review and editing, conceptualisation

Competing interests

The authors declare that they have no competing interests

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