Solar-induced mineral carbonation of mine waste: techno-economics and emission analysis

L. Lee[1], W. Saw[2], E. Lewis[1] and A. Chinnici[1]

[1] *School of Electrical and Mechanical Engineering, The University of Adelaide, Adelaide, Australia*
[2] *School of Chemical Engineering, The University of Adelaide, Adelaide, Australia*
alfonso.chinnici@adelaide.edu.au

Introduction

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 carbon capture, utilisation and storage (CCUS) processes via mineral carbonation, is reported here for the first time. Two main technological scenarios were assessed (Figure 1), 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 transient CST system analysis was adapted from a previous work (Nathan et al., 2023), using an expanding solar vortex receiver (SEVR) (Chinnici et al., 2017) as solar receiver technology. The combustion energy sources considered here are natural gas, NG, hydrogen produced by a steam reforming plant equipped with a CCUS facility and a capture rate of 90%, H_2(B), and a low-carbon hydrogen produced via electrolysis using renewable electricity (assuming 50-50% wind and PV), termed H_2(G). A first-order mass/energy balance was developed for all scenarios and used to build the techno-economics and performance analysis models.

To activate the material, a net thermal energy of 636 MJ/t_{Ser} is required for all cases (Balucan et al., 2013). Therefore, the thermal input required for the heat activation, Q_{req}, was estimated to be 35.3 MW_{th}, after including for some 80% of heat recovery. The levelised cost of heat from the CST system was calculated using the same method previously proposed (Nathan et al., 2023). A sensitivity on fuel price was also included here, with the fuel cost ranging from 3 to 30 USD/GJ. The estimated $CO_{2\text{-eq}}$ 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 (IEA, 2021).

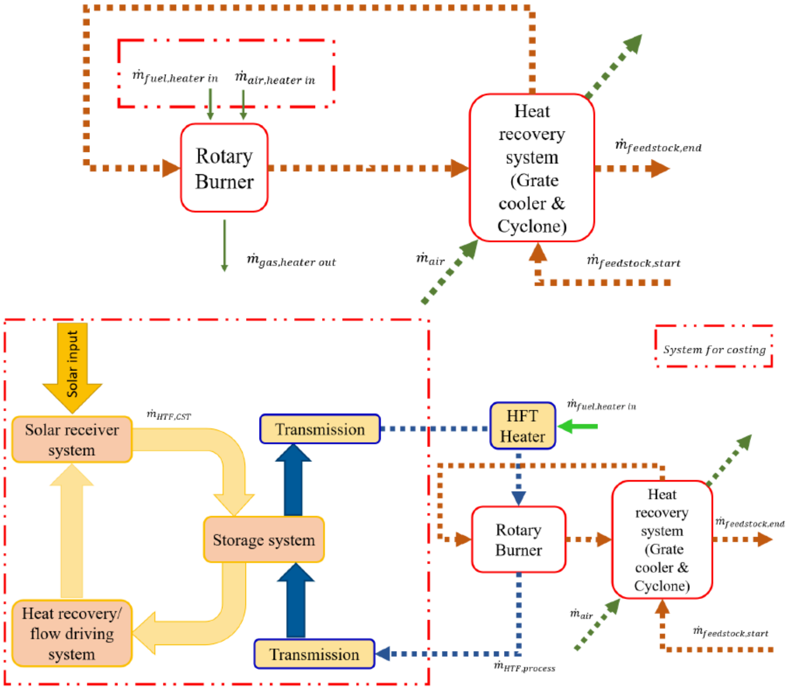

Figure 1. Process diagram for the thermal activation of serpentine waste, with top) fuel-only (either NG or H_2), and bottom) CST with back-up fuel hybrid system.

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 (Pasquier et al., 2016). 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.

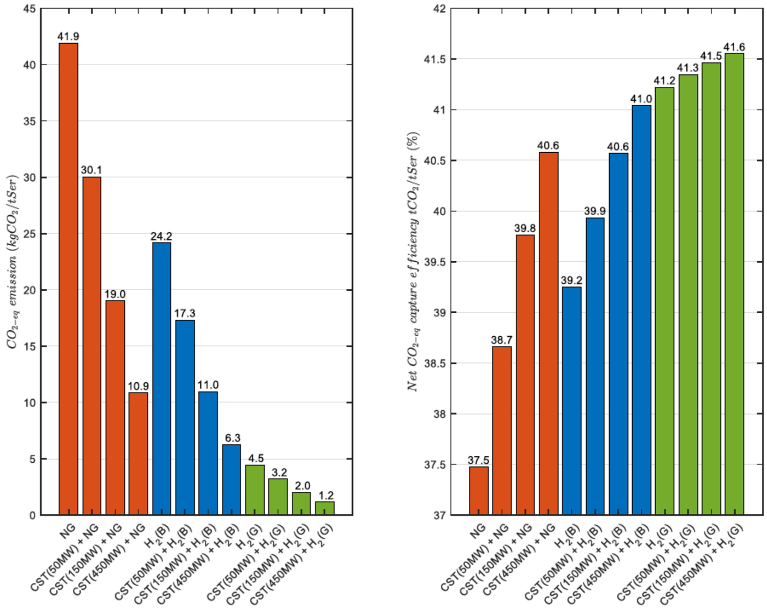

Figure 2. Process diagram for the thermal activation of serpentine waste, with top) fuel-only (either NG or H_2), and bottom) CST with back-up fuel hybrid system. Left) Comparison of $CO_{2\text{-eq}}$ emissions from activating a tonne of serpentine, right) net CO_2 capture efficiency using various heating methods.

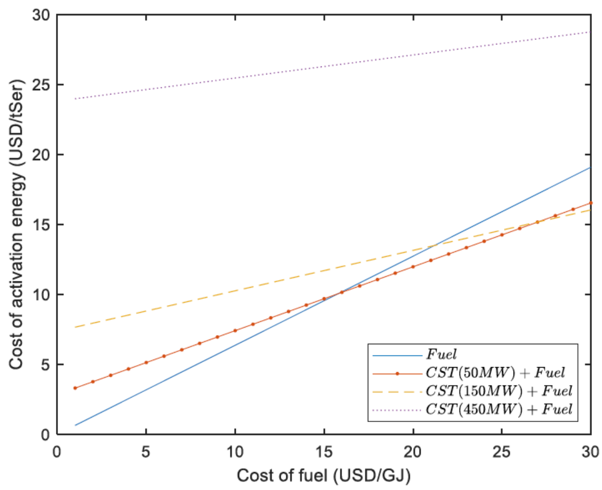

Figure 3. Effect of fuel price and energy source on thermal activation cost, for a plant processing

200 ton/h of serpentine tailings, and a roasting temperature of 700 C.

Conclusions

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 $CO_{2\text{-eq}}$ 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 >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.

References

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