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Screening analysis of enhanced weathering of igneous rocks and industrial waste materials

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Abstract

Enhanced weathering (EW) is a promising emerging carbon dioxide removal approach that involves harnessing and accelerating the natural weathering process by which atmospheric CO_2 passively reacts with exposed alkaline minerals and is removed from the atmosphere. This manuscript reports on a screening level techno-economic analysis of EW. Two primary cases utilizing different sources of alkaline material are considered: (1) utilizing naturally occurring mined igneous rocks, and (2) utilizing industrial waste materials. The modeled EW process encompasses material purchase, comminution, transport, distribution of material on farmland, and measurement, reporting and verification of CO_2 removal. Detailed sensitivities are performed to highlight promising scenarios for application. The analysis highlights that utilizing materials with high weathering potential in suitable locations may result in relatively low levelized cost of captured (less than $100 per total tonnes of CO_2 captured from the atmosphere). NETL is publishing a detailed and transparent report titled "Enhanced Weathering: Techno-Economic and Life Cycle Screening Analysis" that includes more detail on the screening level techno-economic analysis and includes a life cycle analysis.

Keywords: Enhanced weathering; carbon dioxide removal; techno-economic analysis

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1. Introduction

Carbon dioxide removal (CDR) technologies address legacy CO_2 emissions present in the atmosphere and offer a means to decarbonize hard-to-abate contemporary CO_2 emissions. Enhanced weathering (EW) is a promising emerging CDR approach. Enhanced weathering involves harnessing and accelerating the natural weathering process by which atmospheric CO_2 reacts with alkaline minerals—containing hydroxide, silicate, and/or carbonates—to form aqueous bicarbonates. The bicarbonates are transported with water and eventually reach the ocean where the CO_2 can remain in solution and ultimately form stable carbonates keeping the CO_2 from re-entering the atmosphere for more than 100,000 years. Accelerating the weathering process is accomplished by increasing the exposed surface area of the alkaline material, by crushing and grinding the materials, and distributing the particles across coastal regions, tropical areas, and agricultural fields where pH, temperature, and water exposure can enhance weathering rates.

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Screening level techno-economic analysis (TEA) is a valuable tool for assessing the performance and cost of emerging technologies under different scenarios; screening level TEA can highlight promising scenarios for application and potential avenues for cost reduction. Literature examining the performance and cost of EW is limited due to the nascence of the technology. Existing sources report EW costs ranging \$30–800/tonne of CO_2. [1, 2, 3, 4, 5, 6, 7, 8] Many of these analyses are high-level, and do not clearly discuss the financing structure assumptions, do not clearly define the basis used when calculating dollars per tonne, or do not account for monitoring, reporting, and verification (MRV) costs.

NETL has completed a transparent and independent screening level TEA and life cycle analysis (LCA) for an EW project. This paper highlights select TEA results that will be presented in the upcoming NETL report titled "Enhanced Weathering: Techno-Economic and Life Cycle Screening Analysis". Two primary cases utilizing different sources of alkaline material are considered: (1) utilizing naturally occurring mined igneous rocks such as basalt (a mafic rock) and dunite (an ultramafic rock), and (2) utilizing industrial waste materials such as biomass ash and cement kiln dust. The modeled EW process encompasses material purchase, comminution, transport, distribution of material on farmland, and MRV of CO_2 removal.

Nomenclature

CDR	carbon dioxide removal
DAC	direct air capture
EW	enhanced weathering
LCA	life cycle analysis
LCOC	levelized cost of CO_2 captured
MRV	measurement, reporting and verification
NETL	National Energy Technology Laboratory
O&M	operation and maintenance
tCO_2	metric tons (tonnes) of CO_2
TEA	techno-economic analysis
y	year

2. Methodology

The scope of the analysis for Case 1, which considers utilizing igneous rock as the weathering material, is depicted in Figure 1. The scope of the analysis for Case 2, which considers utilizing industrial waste as the weathering material, is depicted in Figure 2. The modeled system is sized to utilize the average annual amount of igneous rock available from one mine (~250,000 tonnes/year) or the average annual amount of suitable industrial waste produced at an industrial hub (~150,000 tonnes/year). For the base case utilizing igneous rock, the rock is processed to 20 μm particles at a remote location prior to transport to the application site. The energy requirement for comminution and the resulting surface area is determined using equations published by Strefler et al. [2] For the industrial waste material case, comminution is not required. The material is transported by truck, with the cost calculated as a function of material quantity and transportation distance. This function considers the fuel, capital, and labor costs using the methodology outlined in the Quality Guidelines for Energy System Studies document, "Fuel Prices for Selected Feedstocks in NETL Studies". [9] A Midwestern location is selected with nearest material sources mapped. For both cases it is assumed that existing farming infrastructure will be leveraged for material application, and therefore this equipment is not included in the capital cost. The material is reapplied on a yearly basis and a 30-year project lifetime is assumed.

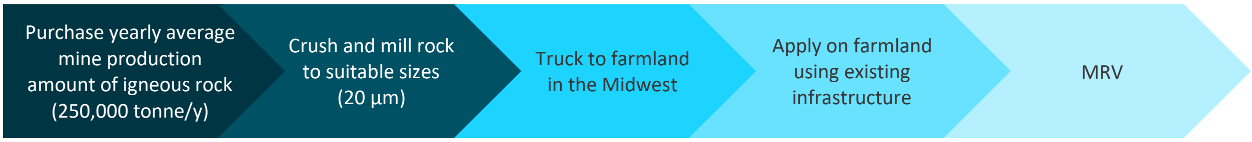


Fig. 1. EW of igneous rock screening analysis study scope: Case 1.

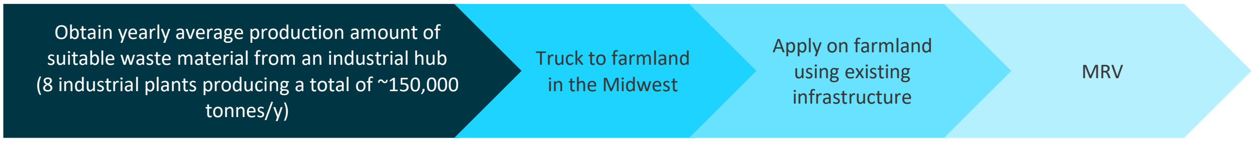


Fig. 2. EW of industrial material screening analysis study scope: Case 2.

The primary figure of merit used is the levelized cost of CO_2 captured (LCOC). LCOC is calculated by dividing EW process annualized capital, operation and maintenance (O&M), power, and fuel purchase costs by the total amount of CO_2 captured from the atmosphere on a yearly basis. Note that the CO_2 emissions associated with the process have not been accounted for when calculating the levelized cost of CO_2 captured. Financial assumptions are in line with NETL's direct air capture (DAC) case studies. [10, 11] System capital costs include equipment for comminution, material handling, and material storage. Operating costs include rock or industrial waste material costs, transport costs, energy requirements, labor costs, and MRV. System capital and operating costs are calculated by leveraging in-house cost estimating references, engineering judgement, and literature reported values. Costs are presented in May 2023 real dollars. The uncertainty of the capital cost estimates is +100%/-50% (consistent with the AACE Class 5 cost estimates).

Table 1. Base case assumptions.

	Case 1: Igneous Rock	**Case 2: Waste Material**
Initial rock use, tonne	250,000	144,000 (18,000/plant)
Rock size, micron	20	-
Specific surface area, m^2/kg	1.69	2
Comminution energy, kWh/tonne	57	-
Weathering potential, kg CO_2/tonne	800	600
Weathering rate, $mol/m^2/s$	$1x10^{-10}$	$1x10^{-9}$
Material coverage, kg/m^2	21	21
Average farm, hectares	153	153
Material transport, miles	250	250
Material price, $/tonne	25	0
Transport price, $/tonne	35	35
Material application price, $/tonne	6	6

Base case assumptions are summarized in Table 1. Due to limitations regarding publicly available literature reporting EW performance, and the variability of performance in different environments and for different alkaline materials, the base cases presented in this report are not representative of specific expected scenarios. Instead, the base cases serve as a reference for informative sensitivity analyses. Sensitivity analyses detail the impact of material weathering rate and potential on cost, with analyses ranges spanning reported performance ranges for different materials applied in different environments. Sensitivity analyses are also performed on the amount of alkaline material applied per year, material cost, site application cost, energy price, MRV price, and transportation distance. For the igneous rock case, a sensitivity analysis is performed on rock size. For the industrial waste case, a sensitivity analysis is performed on material specific surface area; specific surface area is dependent on the waste material source.

3. Results

Table 2 presents the performance results for the bases cases examined. Figure 3 presents the LCOC for the base cases. Additionally, two cases are included where the amount of material is varied to obtain a total CO_2 capture rate of 100,000 tonnes of CO_2 (tCO_2) per year (y). Variable cost (material cost, application cost, material transport cost, and MRV) is the largest contributor to the LCOC for all cases.

Table 2. Base case performance.

	Case 1: Igneous Rock	**Case 2: Waste Material**
CO_2 captured, tonne/yr	138,192	86,400
Initial rock use, tonne	250,000	144,000
Rock makeup, tonne/yr	172,740	144,000
Auxiliary load, MWh/yr	14,148	-
Land needed, hectares	1,190	686
Number of farms	8	5

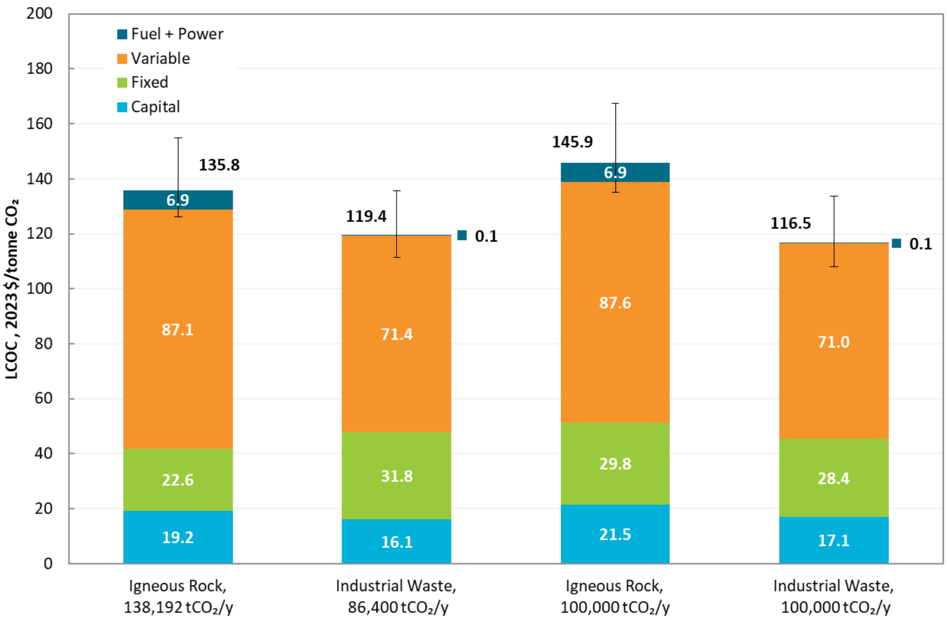


Fig. 3. Base case LCOC.

Sensitivity analysis results are presented in Figure 4, Figure 5, Figure 6, and Figure 7. The most impactful parameters on the EW LCOC are the weathering potential and weathering rate. The weathering rate is highly dependent on the pH and temperature conditions of the application site, and the weathering potential is dependent on the composition of the material. Together, these parameters determine the efficiency of the capture system and, thus, impact the LCOC. The typical weathering potential ranges for mafic and ultramafic rocks, cement kiln dust, and biomass ash are highlighted in Figure 5 and Figure 7.

For the igneous rock case, particle size was also found to significantly impact the levelized cost of CO_2 captured, with cost minimized at around 20 µm particle sizes. For the industrial waste case, availability of sufficient quantities of waste material in reasonable proximity to the application sites significantly impacts the LCOC. More details on the sensitivity analysis approach and limitations can be found in NETL's report titled "Enhanced Weathering: Techno-Economic and Life Cycle Screening Analysis". This work highlights that site selection is instrumental for EW since it impacts weathering rate, material availability and transportation costs.

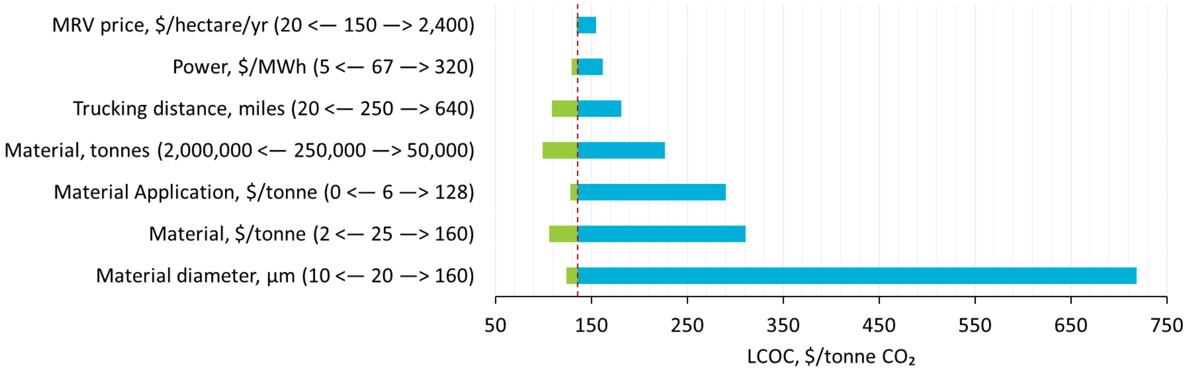
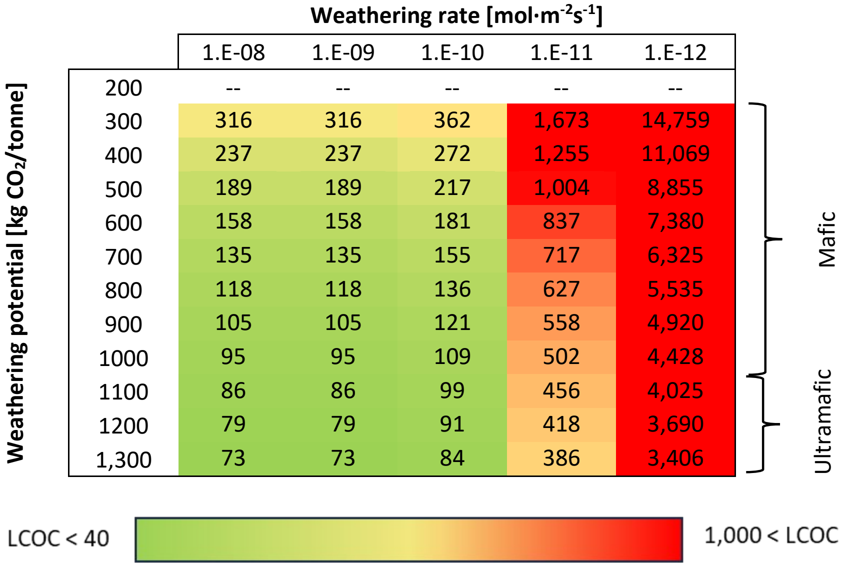


Fig. 4. Case 1 EW of igneous rock LCOC sensitivity.



Weathering rate [mol·m^{-2}s^{-1}]

Weathering potential [kg CO₂/tonne]	1.E-08	1.E-09	1.E-10	1.E-11	1.E-12	
200	--	--	--	--	--	
300	316	316	362	1,673	14,759	Mafic
400	237	237	272	1,255	11,069	
500	189	189	217	1,004	8,855	
600	158	158	181	837	7,380	
700	135	135	155	717	6,325	
800	118	118	136	627	5,535	
900	105	105	121	558	4,920	
1000	95	95	109	502	4,428	
1100	86	86	99	456	4,025	Ultramafic
1200	79	79	91	418	3,690	
1,300	73	73	84	386	3,406	

Fig. 5. Case 1 EW of igneous rock two factor sensitivity.

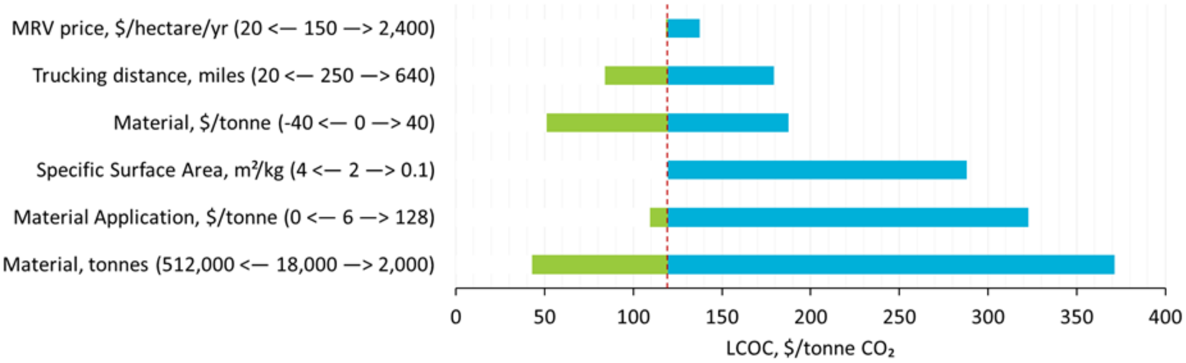
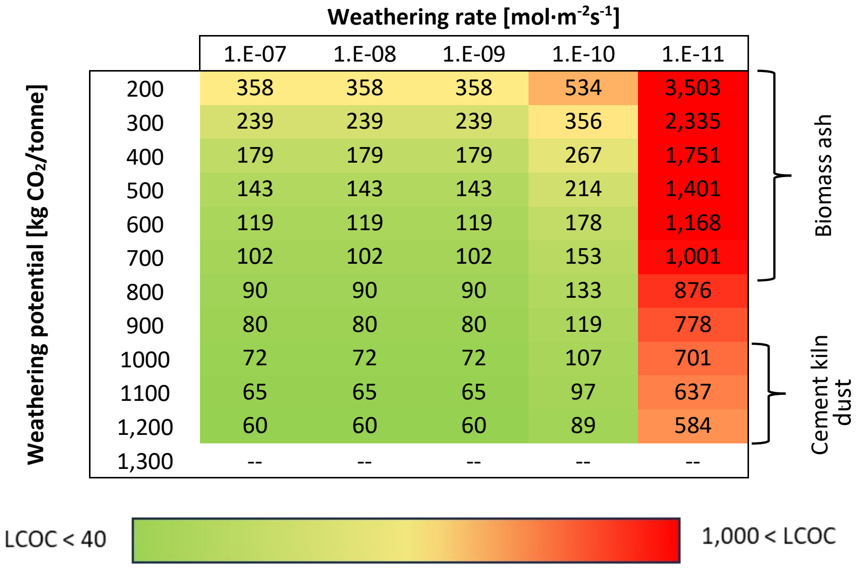


Fig. 6. Case 2 EW of industrial waste LCOC sensitivity.



Weathering potential [kg CO_2/tonne]	Weathering rate [mol·m^{-2}s^{-1}] 1.E-07	1.E-08	1.E-09	1.E-10	1.E-11
200	358	358	358	534	3,503
300	239	239	239	356	2,335
400	179	179	179	267	1,751
500	143	143	143	214	1,401
600	119	119	119	178	1,168
700	102	102	102	153	1,001
800	90	90	90	133	876
900	80	80	80	119	778
1000	72	72	72	107	701
1100	65	65	65	97	637
1,200	60	60	60	89	584
1,300	--	--	--	--	--

Fig. 7. Case 2 EW of industrial waste material two factor sensitivity.

4. Conclusions

Utilizing materials with high weathering potential in suitable locations can lead to relatively low levelized cost of captured (less than \$100/tCO_2 captured). Note that the CO_2 emissions associated with the process have not been accounted for when calculating the levelized cost of CO_2 captured. NETL is publishing a detailed and transparent report titled "Enhanced Weathering: Techno-Economic and Life Cycle Screening Analysis" summarizing the findings of the screening level techno-economic analysis. The report also contains LCA results and a second cost metric of interest, levelized cost of CO_2 removal, which takes into account cradle-to-gate LCA emissions. This study presents a first pass screening level TEA and has limitations. The analysis is high-level and focuses on highlighting the impact of various parameters on cost and CO_2 removal potential. A more detailed and specific analysis building on the results of this analysis and accounting for the variability and challenges expected for a specific project will be addressed in future work.

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