Techno-Economic Screening Analysis of CO_2 Removal Through Enhanced Weathering

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Background

According to the National Academy of Sciences and the International Panel on Climate Change, decarbonization alone will not be sufficient to reach current climate goals; several gigatons of carbon dioxide (CO_2) will need to be removed from the atmosphere to achieve these goals [1]. Enhanced weathering is one of the emerging technologies that can aid in the direct removal of CO_2 from the atmosphere. This poster presents NETL's active work on the techno-economic analysis (TEA) of enhanced weathering.

What is Enhanced Weathering?

"Weathering" is the natural breakdown of alkaline rocks in the presence of rainwater, temperature changes, and/or living organisms. Weathered rocks contain silicate, hydroxide, and carbonate minerals that react with CO_2 during this process to produce aqueous bicarbonate ions.

$$M(OH)_2 + 2CO_2 \rightarrow M^{2+} + 2HCO_3^-$$
$$MSiO_3 + 2CO_2 + H_2O \rightarrow M^{2+} + SiO_2 + 2HCO_3^-$$
$$MCO_3 + H_2O + CO_2 \rightarrow M^{2+} + 2HCO_3^-$$

where M is typically Ca or Mg

The removed atmospheric CO_2 in the form of aqueous bicarbonate ions is eventually transported to the oceans where it can remain in solution for >100,000 years. Enhanced weathering accelerates this process by mining and crushing alkaline rocks to increase the exposed surface area. The crushed rocks can be spread across coastal regions, tropical areas, and agricultural fields where pH, temperature, and water exposure can enhance weathering rates.

TEA Design Basis

This study assesses enhanced rock weathering (ERW). All cases are assessed under ISO conditions. Case 1 uses igneous rock—specifically, dunite and basalt. Case 2 uses industrial waste—specifically, cement kiln dust and biomass ash. For all cases, a base case is developed based on the average parameters, and sensitivities are performed on these parameters to account for the different materials or scenarios. Financial assumptions are in line with already released direct air capture (DAC) case studies [2, 3].

Enhanced Rock Weathering (ERW)

Purchased Rock/Waste → Crushing and Milling → Transportation → Application → Measurement

Enhanced weathering base cases

	Case 1: Igneous Rock	Case 2: Waste Material
Material amount, tonne/yr	250,000	144,000 (18,000/plant)
Rock size, micron	20	-
Specific surface area, m²/kg	1.69	2
Comminution energy, kWh/tonne	57	-
Weathering potential, kg CO_2/tonne	800	600
Weathering rate, mol/m²/s	$1x10^{-10}$	$1x10^{-9}$
Material coverage, kg/m²	21	21
Average farm, hectares	153	153
Material transport, miles	250	250
Material cost, $/tonne	25	0
Transport cost, $/tonne	35	35
Material application cost, $/tonne	6	6
Purchased power, $/MWh	67	67
MVR, $/hectare/year	150	150

MVR = Measurement, verification, and reporting

Results Analysis

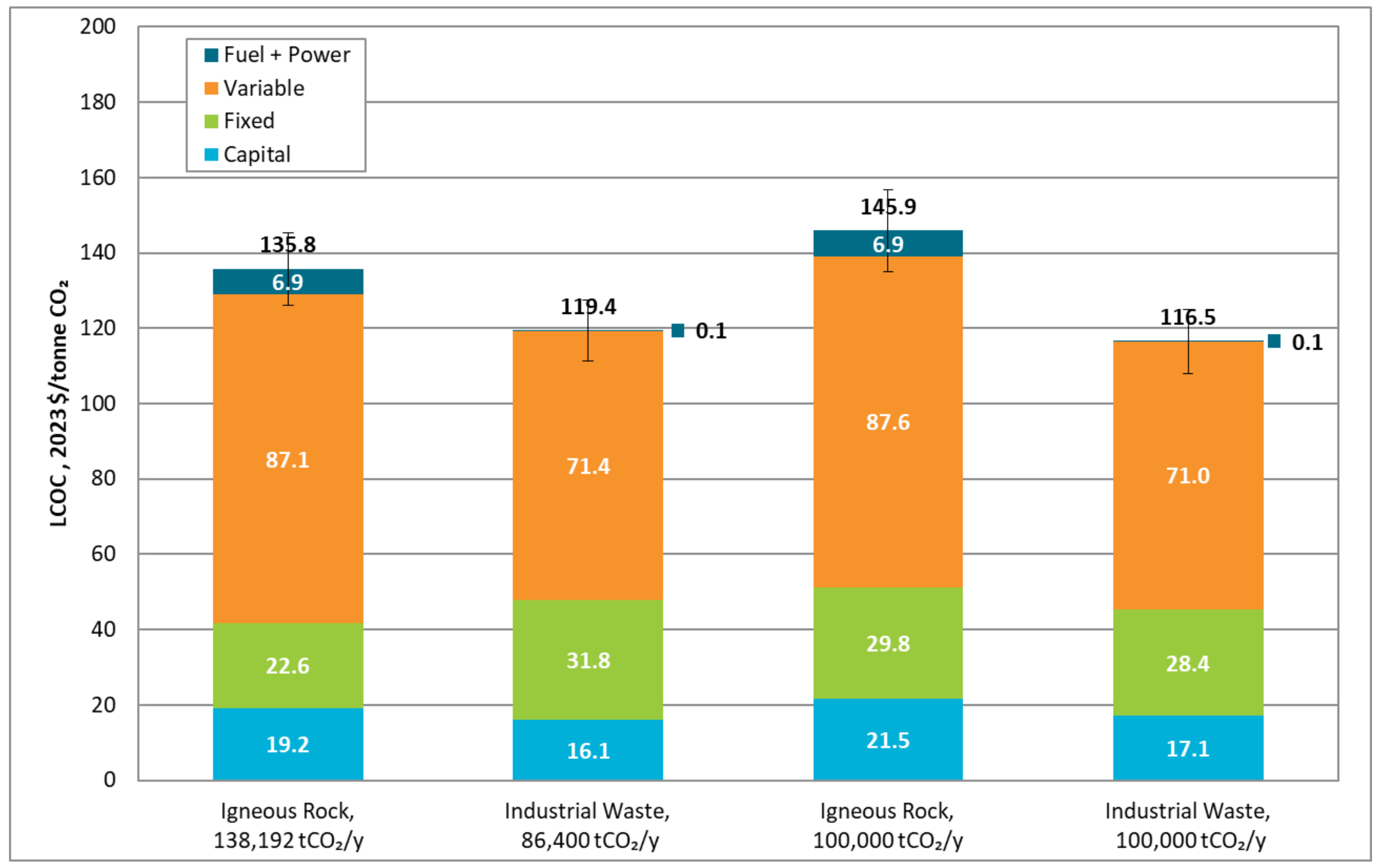
The amount of CO_2 captured in the base cases is determined by either the rock available from a mine (Case 1) or the waste material available from multiple plants in the vicinity (Case 2). To better compare these two cases, an additional case was developed for each scenario to capture 100,000 tonnes of CO_2/year, labeled as "comparison."

Enhanced weathering performance and cost results

	Igneous Rock		Waste Material	
	Case 1	Comparison	Case 2	Comparison
CO_2 captured, tonne/yr	138,192	100,000	86,400	100,000
Initial rock fill, tonne	250,000	180,908	144,000	167,000
Rock makeup, tonne/yr	172,740	125,000	144,000	167,000
Auxiliary load, MWh/yr	14,148	10,238	-	-
Land needed, hectares	1,190	861	686	794
# of farms	8	6	5	6
Total plant cost, $/1,000	26,001	21,129	13,318	16,331
Levelized cost of capture, $/tonne of CO_2	136	146	119	117

When both cases are adjusted to capture 100,000 tonnes of CO_2/year, the impact on the economy of scale is observed. For the industrial waste case, it is assumed that the same plants in the area can accommodate the material to achieve 100,000 tonnes of CO_2/year, and additional plants in the area do not need to be considered. The uncertainty of the capital cost estimates is +/-50 percent to be consistent with the AACE Class 5 cost estimates. Variable cost (material cost, application cost, material transport cost, and MVR) is the largest contributor to the levelized cost of capture (LCOC)for both cases.

Enhanced weathering LCOC breakdown



Sensitivity Analysis

The most impactful parameters on the LCOC of ERW is 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.

ERW with industrial waste (Case 2) LCOC ($/tonne of CO_2) sensitivity on weathering rate and weathering potential

Weathering rate [mol·m⁻²s⁻¹]; Weathering potential [kg CO_2/tonne]

(a)	1.E-07	1.E-08	1.E-09	1.E-10	1.E-11	
200	358	358	358	534	3,503	Biomass ash
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	Cement kiln dust
1000	72	72	72	107	701	
1100	65	65	65	97	637	
1,200	60	60	60	89	584	
1,300	--	--	--	--	--	

ERW with igneous rock (Case 1) LCOC ($/tonne of CO_2) sensitivity on weathering rate and weathering potential

Weathering rate [mol·m⁻²s⁻¹]; Weathering potential [kg CO_2/tonne]

(a)	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	

Conclusions

The weathering rate is highly influenced by ambient conditions and can, therefore, be slower or faster depending on location or material composition, thus highlighting the importance of location and material selection. ERW has the potential to offer an economical approach to CO_2 removal. Future work will incorporate more specific design parameters related to technology, materials, and location.

References: [1]"Carbon Removal." World Resources Institute. https://www.wri.org/initiatives/carbon-removal (accessed July 20, 2023). [2] J. Valentine, A. Zoelle, "Direct Air Capture Case Studies: Sorbent System," National Energy Technology Laboratory, Pittsburgh, PA, July 8, 2022. [3] T. Fout, J. Valentine, A. Zoelle, A. Kilstofte, M. Sturdivan and M. Steutermann "Direct Air Capture Case Studies: Solvent System," National Energy Technology Laboratory, Pittsburgh, PA, May 15, 2020.

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