Enhanced Weathering Screening Techno-Economic Analysis

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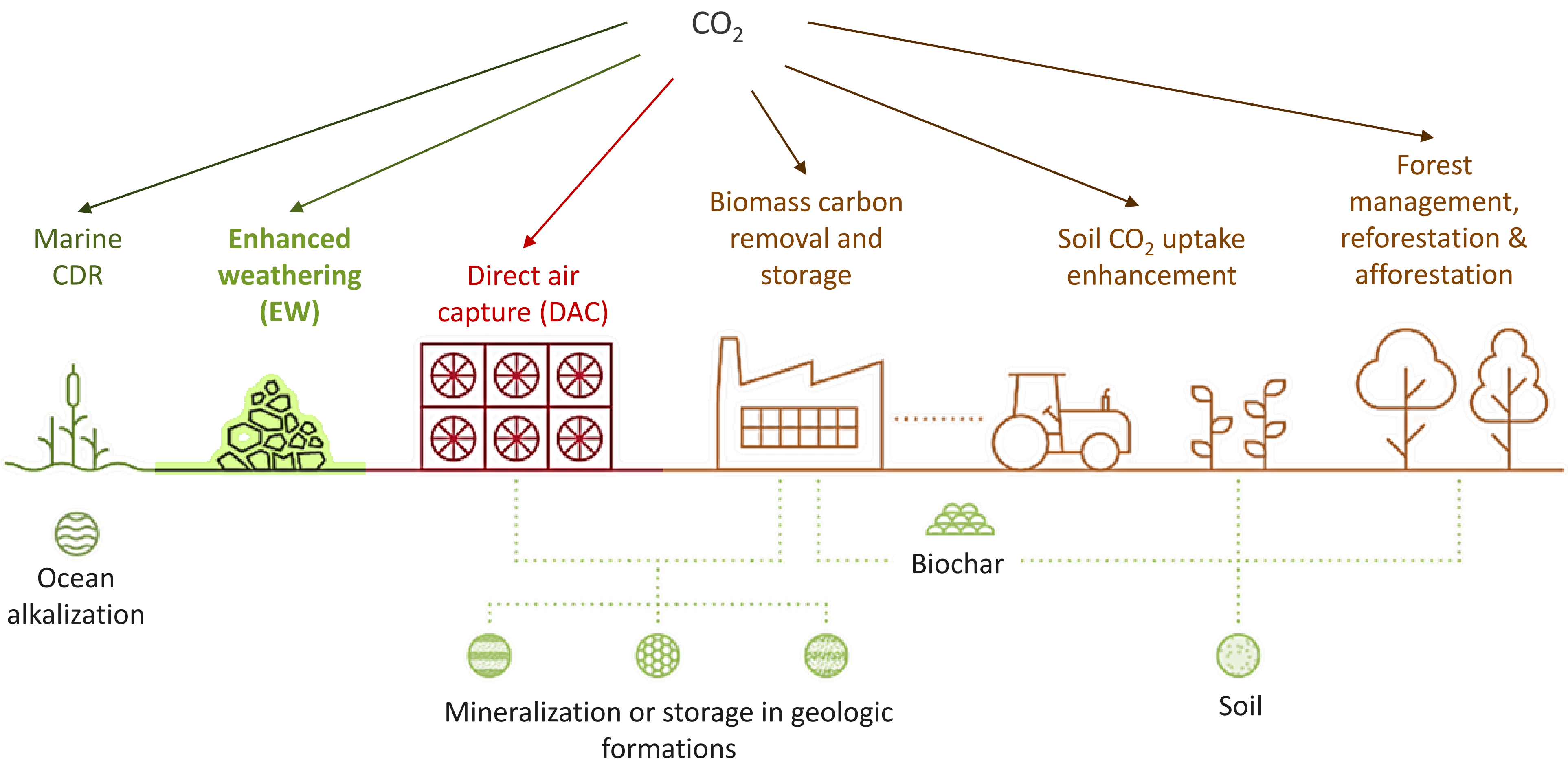
Carbon Dioxide Removal (CDR) Technology

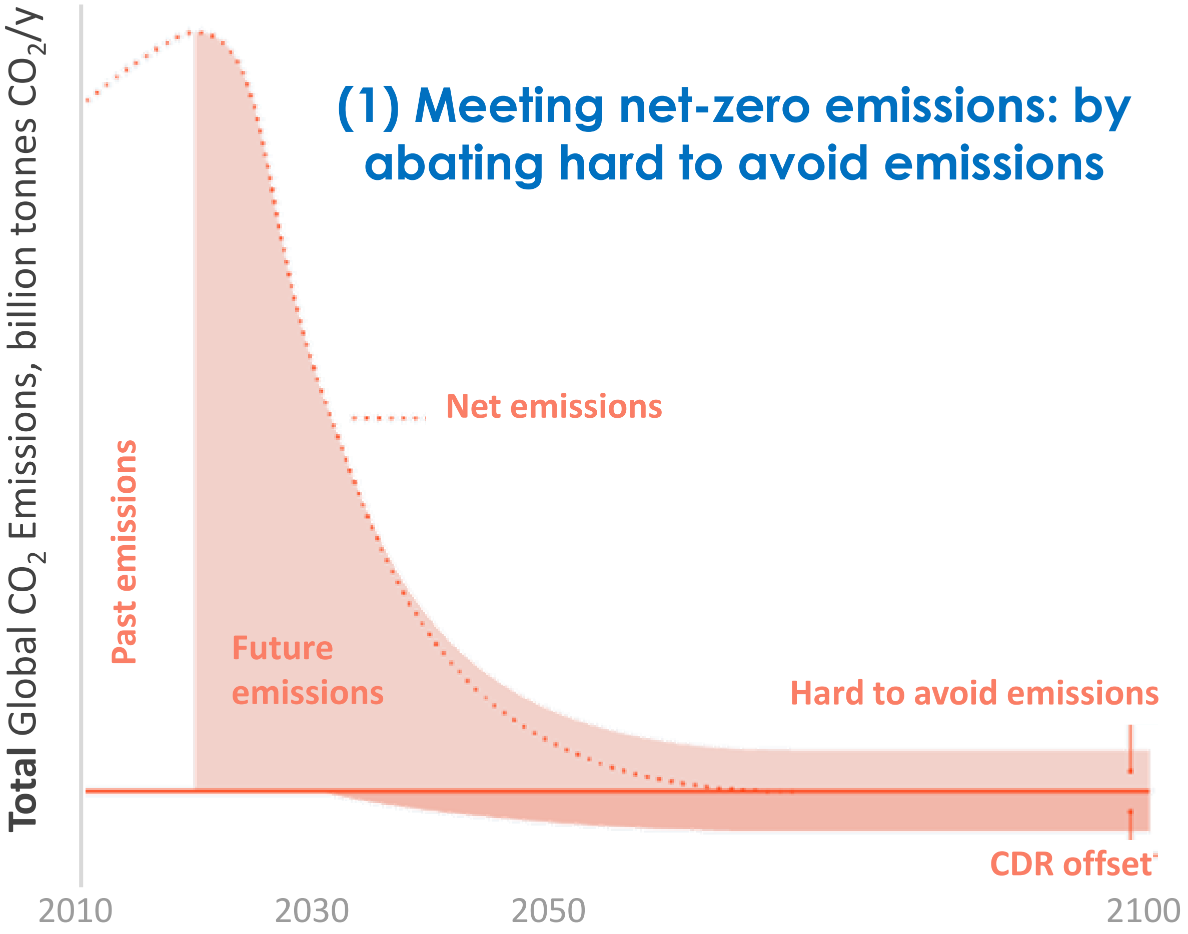
CDR technologies pull CO_2 from the atmosphere.

The removed CO_2 is stored to achieve negative emissions.



Adapted with permission from the Carbon Dioxide Removal Primer (2021)

Role of CDR Technology



(1) Meeting net-zero emissions: by abating hard to avoid emissions

Adapted with permission from the Carbon Dioxide Removal Primer (2021)

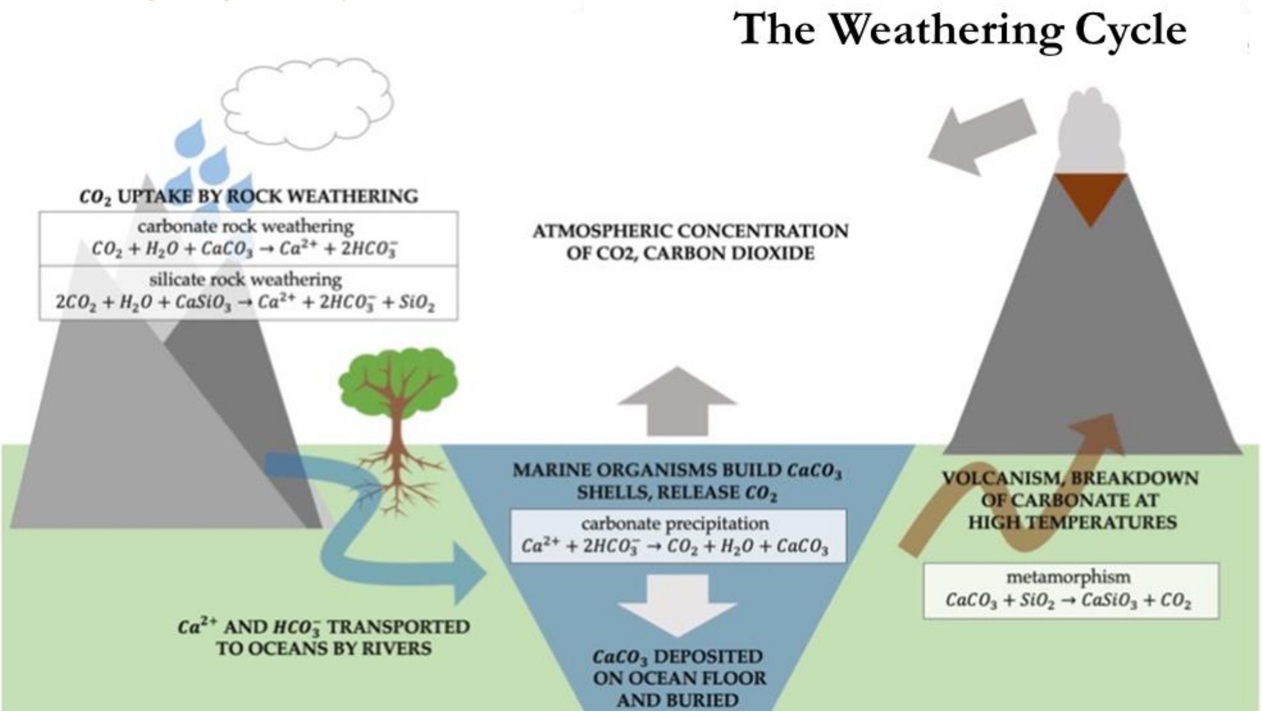
(2) Meeting climate goals: by abating legacy emissions

Most pathways highlighted by the Intergovernmental Panel on Climate Change for limiting global warming to 1.5 °C require **net negative** global CO_2 emissions to abate emissions overshoot.

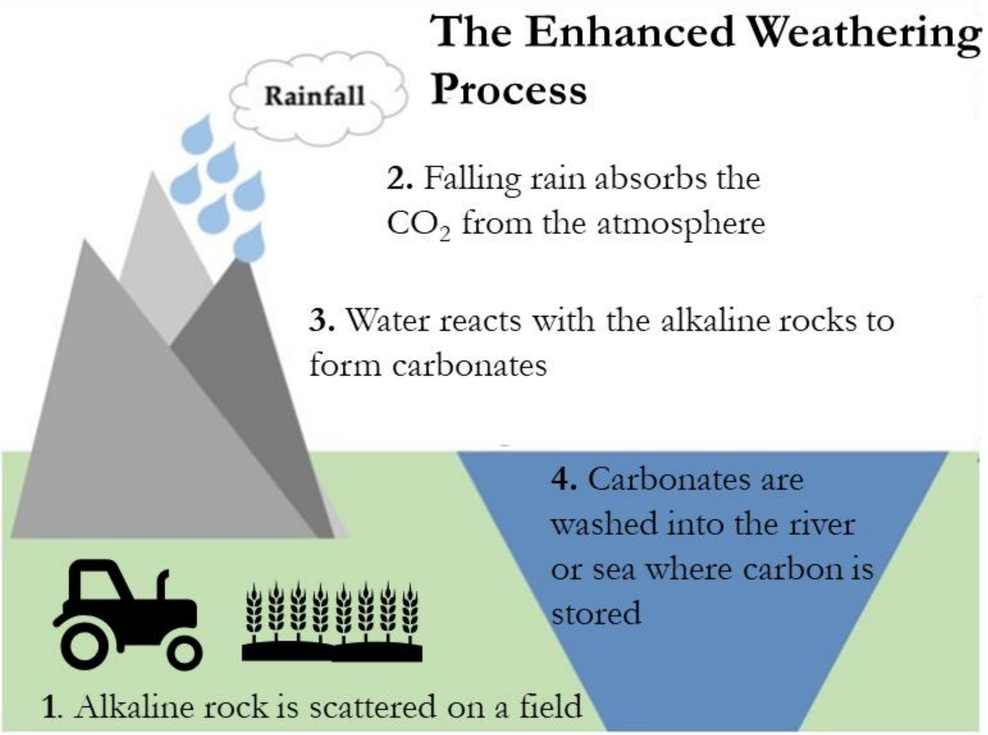
IPCC Special report on Global Warming of 1.5°C (2018)

Background

What is EW?



Used with permission from Gretashum [2]



Adapted with permission from Gretashum [2]

“Weathering” is the natural breakdown of alkaline rocks in the presence of rainwater, temperature changes, and/or living organisms.

Enhanced rock weathering (ERW) speeds this process by mining and crushing (↑ surface area) rocks that contain suitable minerals and spreading them in suitable areas to enhance weathering rates.

Removed atmospheric CO_2, in the form of aqueous bicarbonate ions, is eventually transported through soil, groundwater, and river water to the oceans where it can remain in solution for >100,000 years.

Background

What Alkaline Materials Are Suitable for Weathering?

	Ultrabasic	**Basic**	**Intermediate**	**Acidic**
Rocks	Dunite Lherzolite Harzburgite Wehrlite	Basalt Gabbro Dolerite	Andesite Adakite	Dacite Rhyolite Diorite Granite
Essential Minerals	Olivine Orthopyroxene Clinipyroxene	Ca-Plagioclase Augite	Plagioclase	Alkali feldspars Quartz
Type Minerals	Pyroxene Chromite	Low Ca-pyroxene Olivine Nepheline	Augite Enstatite Olivine Hornblende	Horblende Biotite Garnet Pyroxene

Note: Data from P. Renforth, 2012; USGS, 2022

Reactive and cation-rich (Mg^{2+} and Ca^{2+}) igneous rocks are the most suitable for ERW; specifically, ultrabasic (ultramafic), or basic (mafic) igneous rocks such as dunite and basalt.

- Industrial waste material can also contain reactive and cation-rich (Mg^{2+} and Ca^{2+}) alkaline material.
- Using industrial wastes for weathering takes advantage of waste that currently presents a disposal problem.
- Many alkaline waste sources exist, including cement industry waste streams, fly ash and bottom ash residue from biomass combustion, mine tailings, metallurgical slag, and red mud.

Biomass ash has a history of being spread onto agricultural land as an alternative liming agent, and cement kiln dust is a relatively 'clean' lime source.

Focus

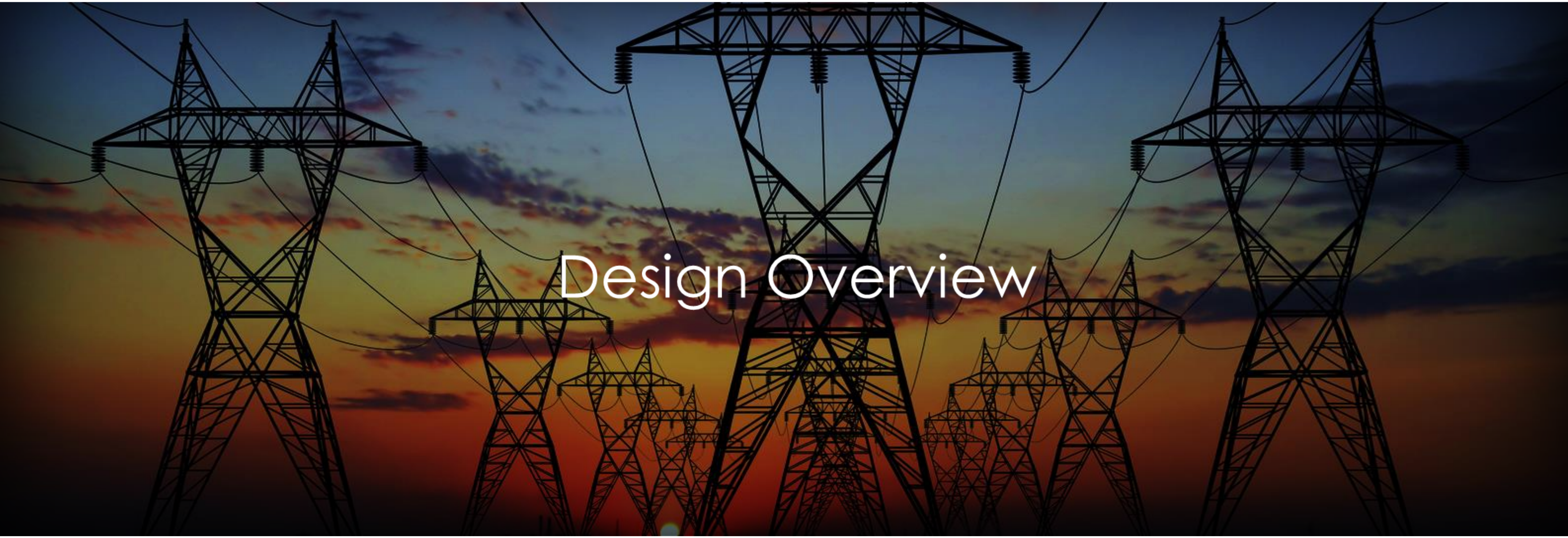
A literature search on EW revealed that

1. There is a gap in U.S. centered studies
2. Published studies focus on forecasting the cost of removal assuming the technology is used to its full potential and applied on a global scale
3. Published studies lack transparency regarding energy pricing and financing assumptions

This work takes a more focused lens and examines the cost of CO_2 captured associated with a single EW project deployed in the Midwest United States.

This presentation reports results from screening-level techno-economic analysis (TEA) case studies examining:

1. ERW of igneous rocks (basalt and dunite)
2. EW of industrial waste (biomass ash and cement kiln dust)



Design Overview

Levelized Cost of CO_2 Captured

- The levelized cost of capture (LCOC) is used as the metric for comparison.
- All costs are developed in May 2023 year-dollar.
- Performance models are developed to estimate the overall mass and energy balances.
- NETL cost modeling methodology is used to estimate the capital, O&M, and cost of capture. [3]

$$\frac{Annualized\ Capital + Fixed + Variable + Fuel + Power}{CO_2\ Captured\ per\ Year} = LCOC$$

EW

Approach

ERW of Igneous Rock Case

Purchase yearly average mine production amount of igneous rock (250,000 tonne/y)

Crush and mill rock to suitable sizes (20 μm)

Truck to farmland in the Midwest

Apply on farmland using existing infrastructure

Measurement, verification, and reporting (MVR)

EW of Industrial Waste Case

Obtain yearly average production amount of suitable waste material from an industrial hub (8 industrial plants producing a total of ~150,000 tonnes/y)

Truck to farmland in the Midwest

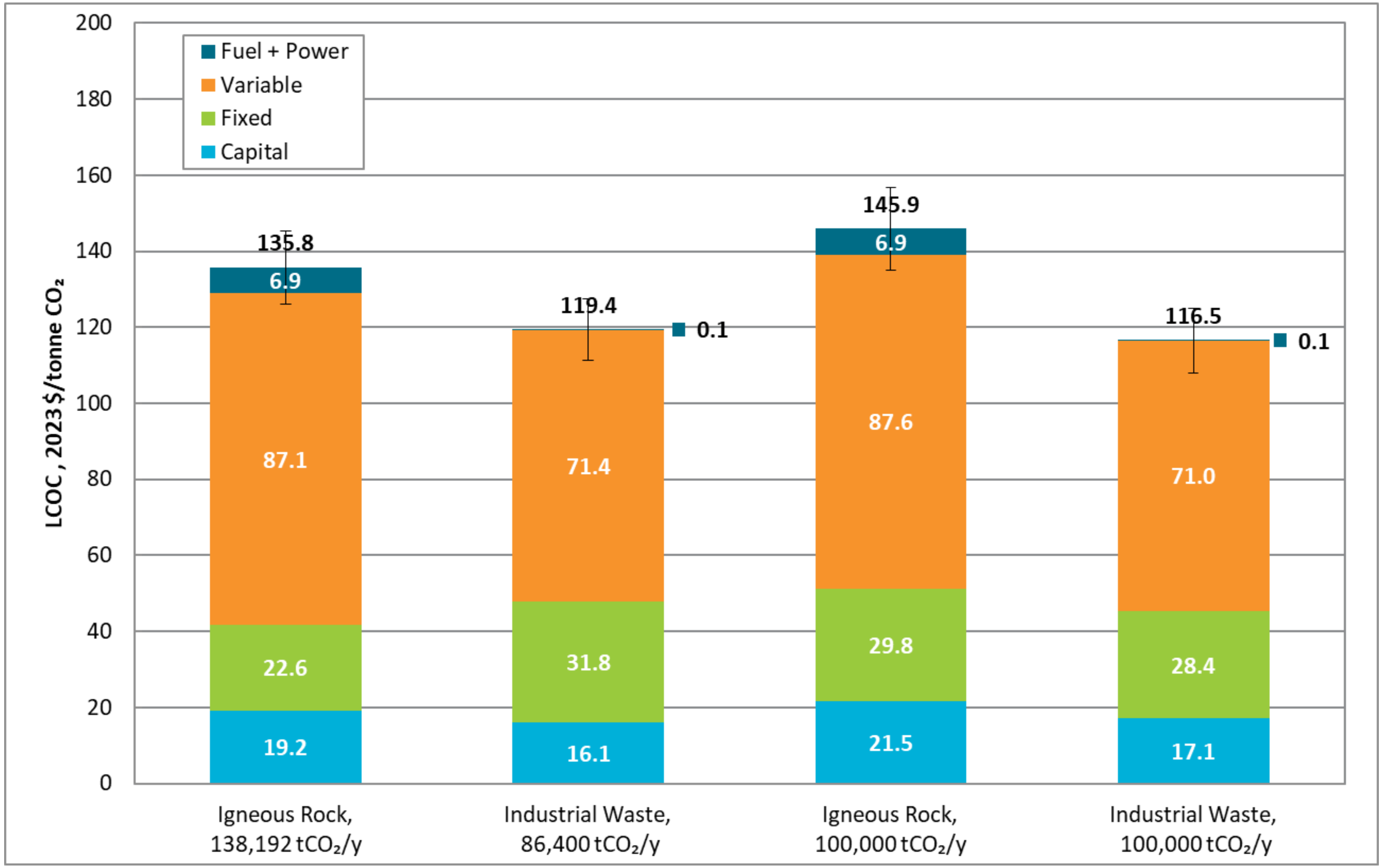
Apply on farmland using existing infrastructure

MVR

- Material is re-applied to the same farmland on a yearly basis, and the project has a 30-year life. Financing assumptions are consistent with the NETL DAC case studies.
- CO_2 emissions associated with the process have not been accounted for when calculating the CO_2 LCOC. However, a life cycle analysis (LCA) was completed and will be included in the associated report when published. [4]

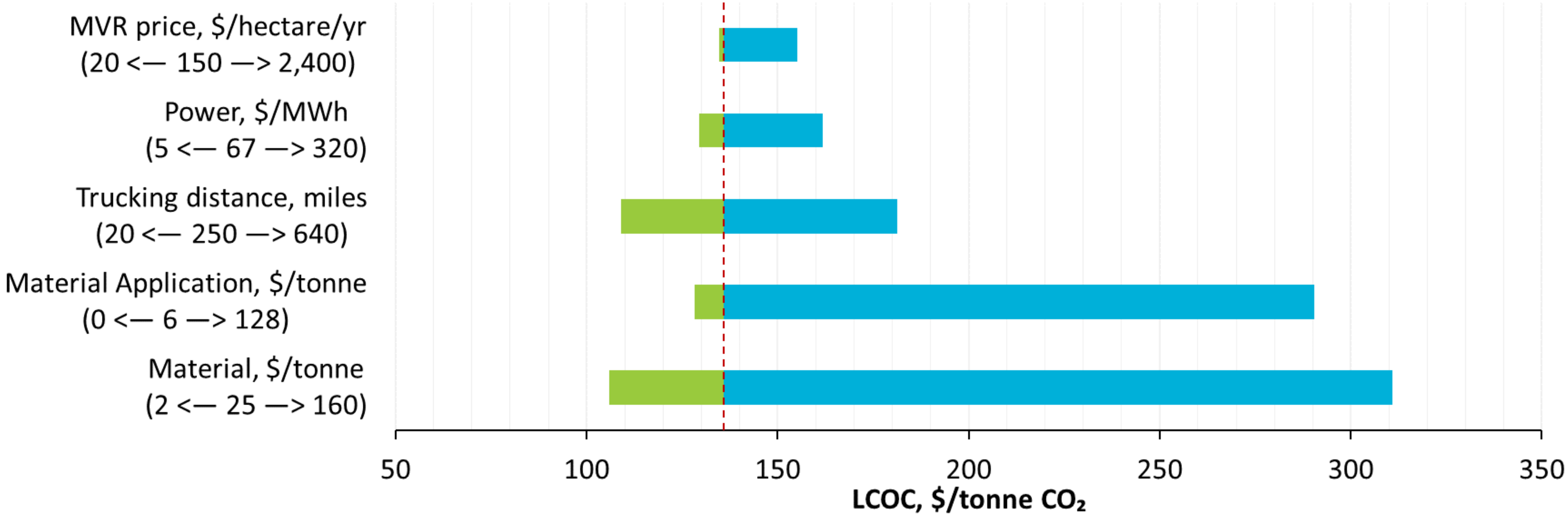
Results

Levelized Cost of Capture (LCOC)



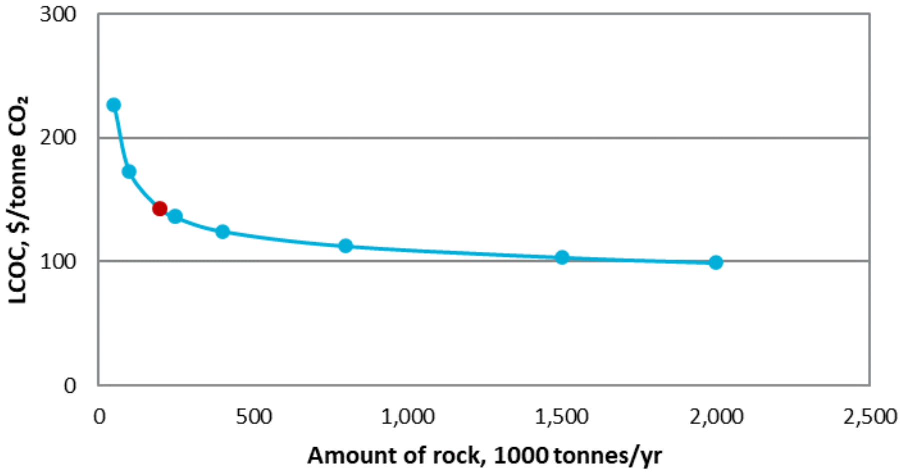
- The capital estimate represents an AACE Class 5 estimate, with an uncertainty range of +/- 50 percent.
- When both cases are adjusted to capture 100,000 tonnes of CO_2/y, the impact on the economy of scale is reflected.

ERW Single Parameter Sensitivities Impact on LCOC



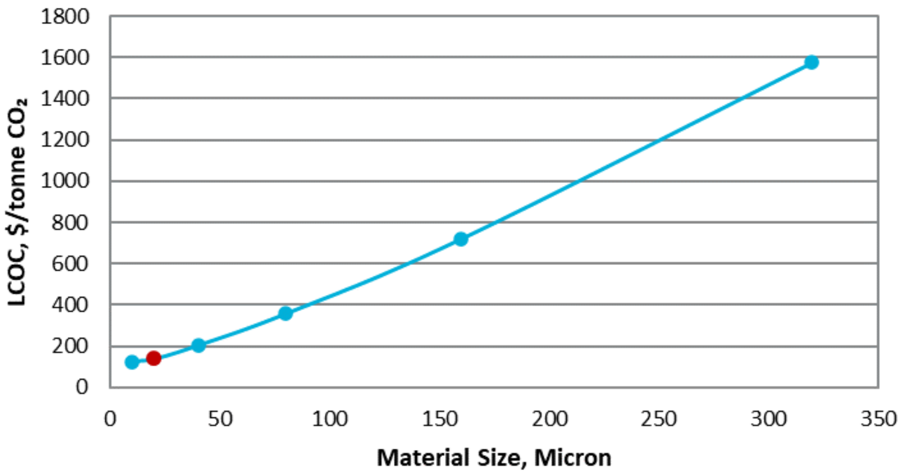
Sensitivity ranges were determine based on literature and engineering judgement.

ERW Single Parameter Sensitivities Impact on LCOC

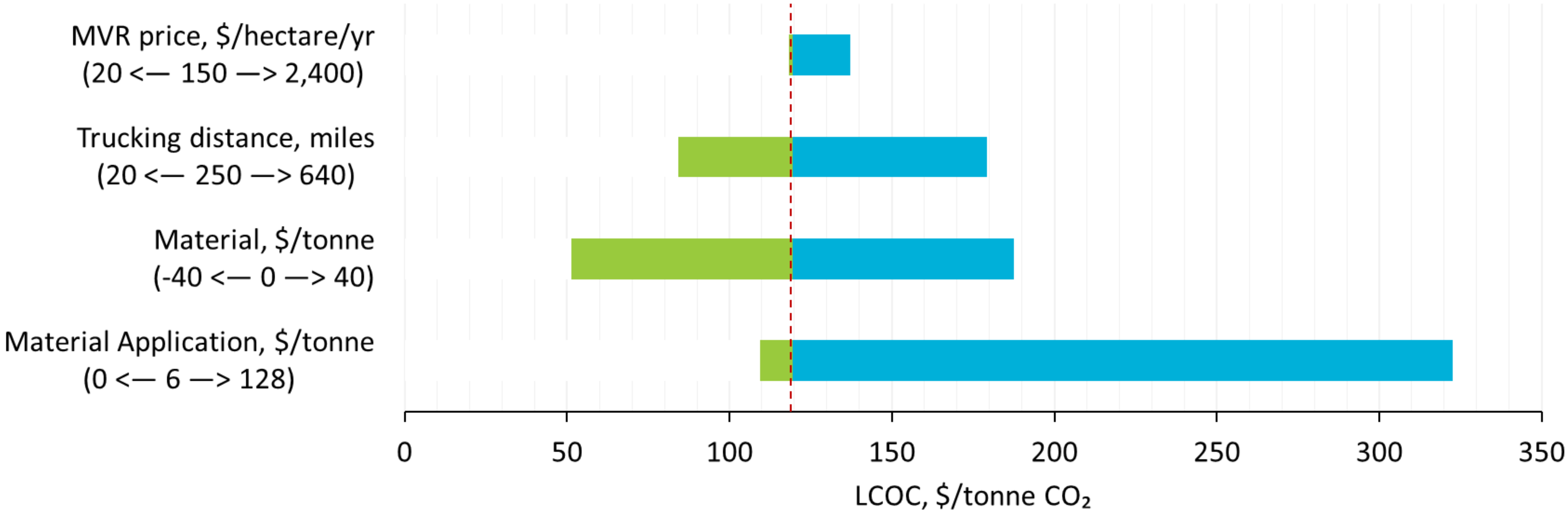


The amount of rock determines the potential amount of CO_2 captured but would increase the size of the plant, thus, demonstrating how this technology can benefit from the economy of scale.

The rock size impacts the specific surface area (SSA) of the rock and auxiliary load of the plant. The SSA impacts the reaction rate of the material, thus, affecting the amount of CO_2 captured per year and the LCOC of the technology.

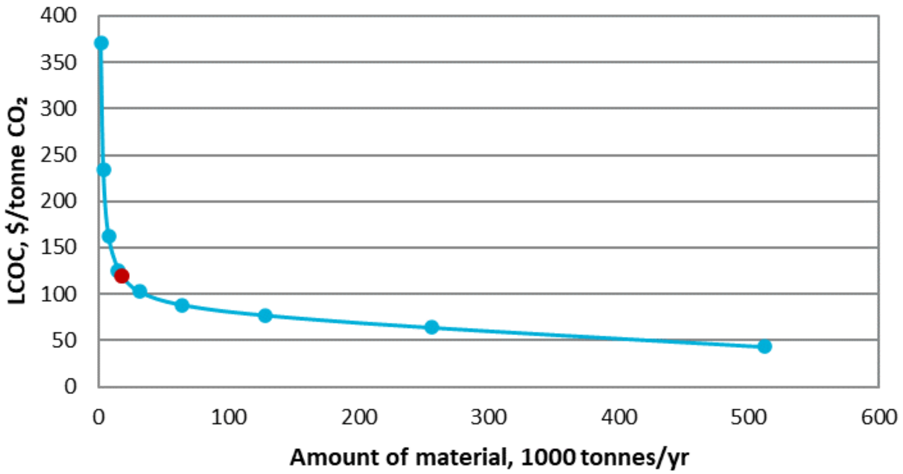


EW Single Parameter Sensitivities Impact on LCOC



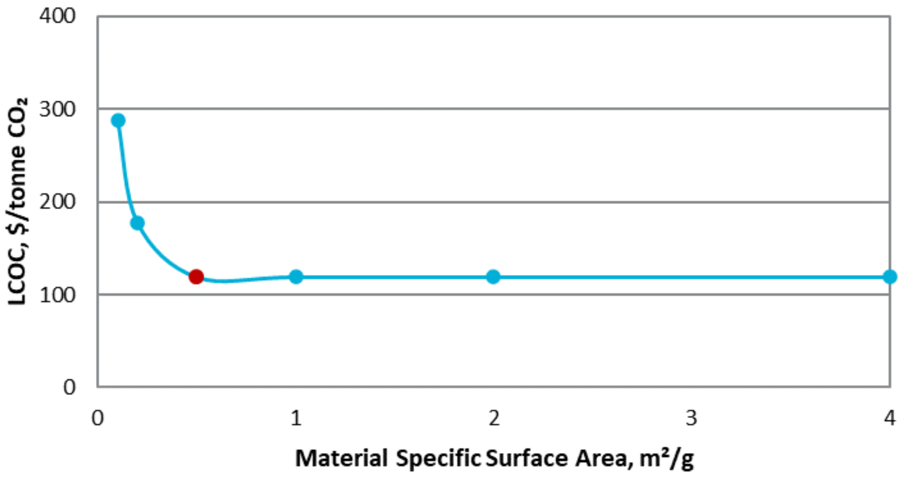
Sensitivity ranges were determine based on literature and engineering judgement.

EW Single Parameter Sensitivities Impact on LCOC



The amount of material determines the potential amount of CO_2 captured but would increase the size of the plant, thus, demonstrating how this technology can benefit from the economy of scale.

The SSA can vary drastically for industrial waste, ranging from 0.5 to12 m^2/g. The SSA impacts the efficiency of CDR and, thus, the LCOC.



Dual-Factor Sensitivity: Impact of Weathering Potential and Weathering Rate on LCOC

ERW of Igneous Rock

Weathering rate [mol·m^{-2}s^{-1}]

Weathering potential [kg CO$_2$/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	

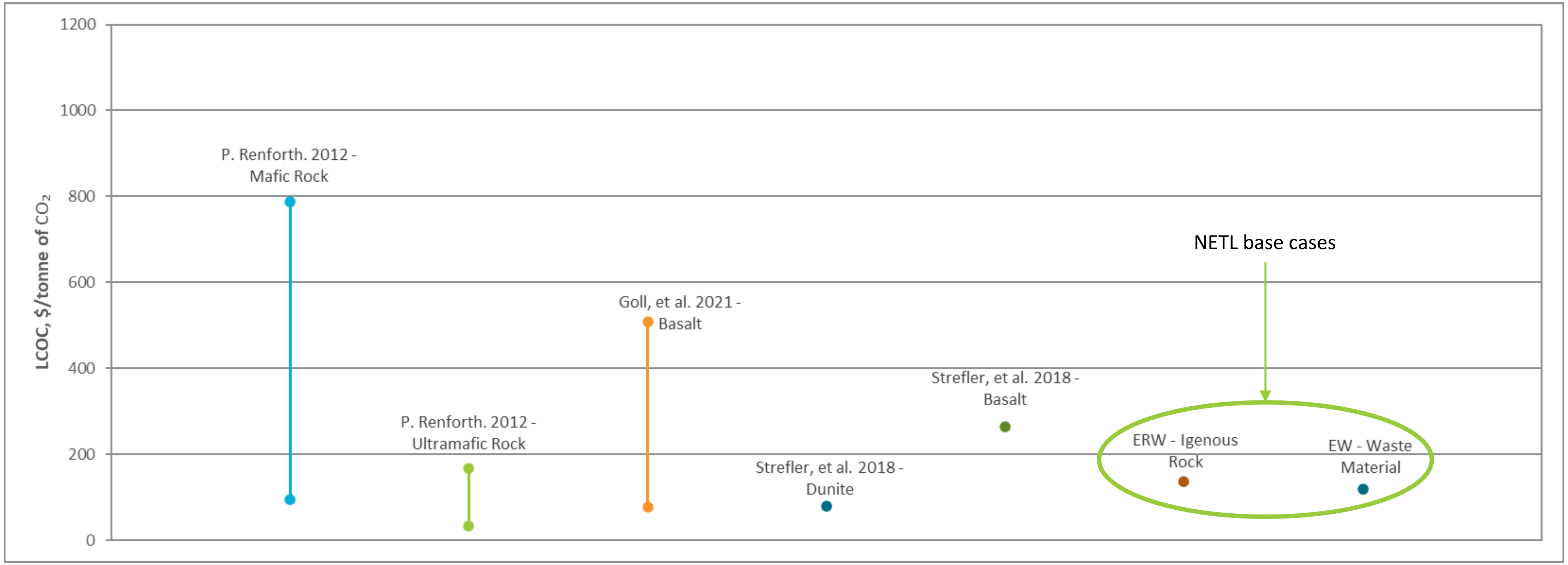
*The circle denotes the base case LCOC

EW of Industrial Waste

Weathering rate [mol·m^{-2}s^{-1}]

Weathering potential [kg CO$_2$/tonne]	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	
1000	72	72	72	107	701	Cement kiln dust
1100	65	65	65	97	637	
1,200	60	60	60	89	584	
1,300	--	--	--	--	--	

Literature Comparison



Note: This chart only compares full techno-economic analyses (TEAs) from the literature; no back-of-the-envelope calculations were included

- Comparing the LCOC from this study to previous studies, the EW base cases fall at the lower end of the ranges.
- The sensitivities performed on the EW cases capture both the higher and lower ends of the LCOCs identified in the literature.

EW Conclusions

- Site selection is instrumental for this technology since it impacts weathering rate, transportation costs, and process emissions.
- An LCA has been completed and will be published alongside the TEA.
- The LCA indicates that it can be conservatively assumed that the net CDR rate is >50% of the CO_2 capture rate. The net cost of CDR is no more than double the reported CO_2 LCOC → utilizing ultramafic rock and/or cement kiln dust in suitable locations can be relatively low cost (approaching $100/tonne CO_2 gross removed).
- NETL will be publishing these screening-level analysis results in an upcoming report, which will become available by the end of the year. In addition, NETL is working to further refine this study.

Questions/ Comments

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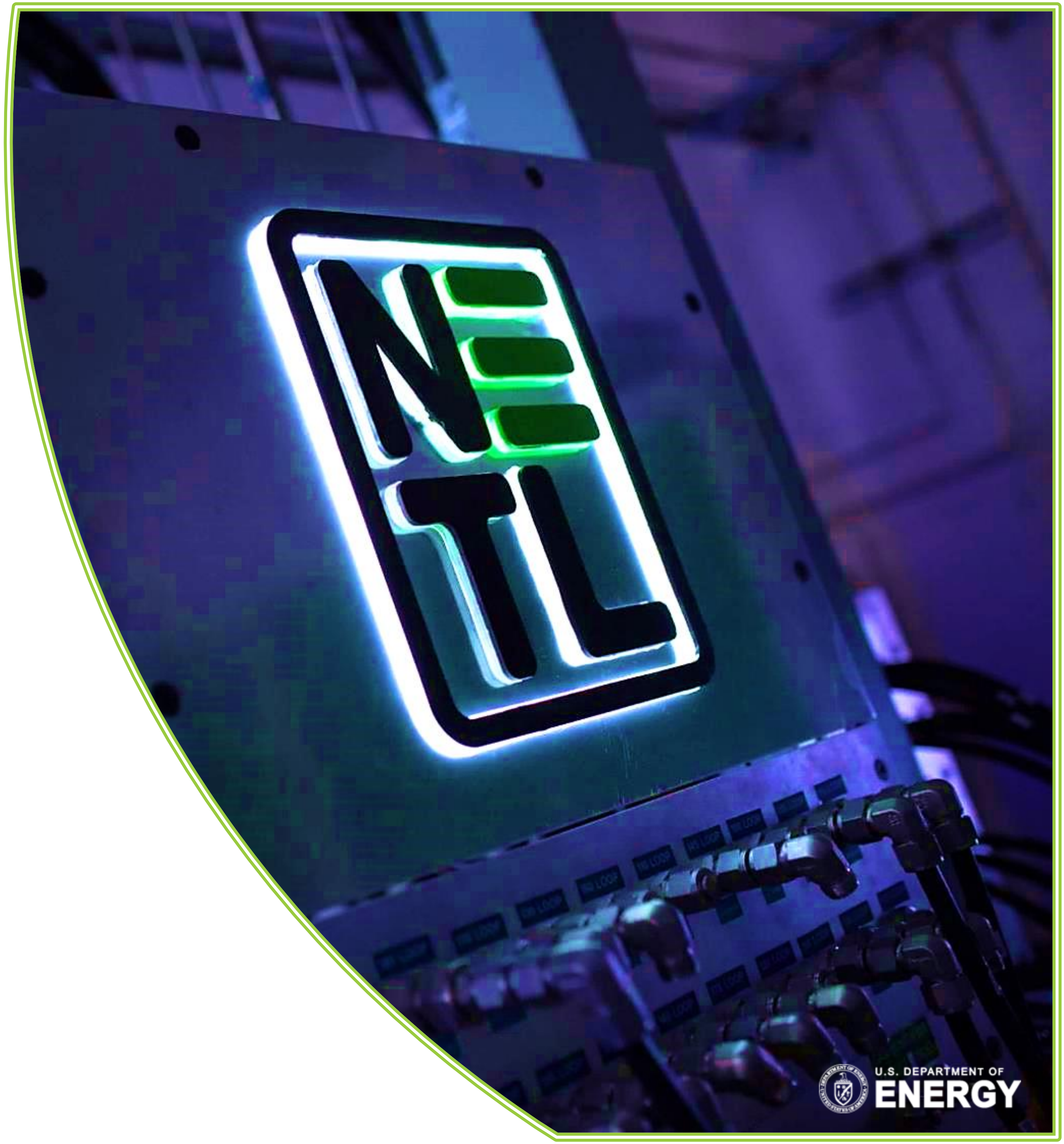

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Supplemental Slides

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