To avoid dangerous climate change, new technologies must remove billions of tonnes of CO$_2$ from the atmosphere every year by mid-century. Here we detail a land-based enhanced weathering cycle utilizing magnesite (MgCO$_3$) feedstock to repeatedly capture CO$_2$ from the atmosphere. In this process, MgCO$_3$ is calcined, producing caustic magnesia (MgO) and high-purity CO$_2$. This MgO is spread over land to carbonate for a year by reacting with atmospheric CO$_2$. The carbonate minerals are then recollected and re-calcined. The reproduced MgO is spread over land to carbonate again. We show this process could cost approximately $46–159 \text{tCO}_2^{-1}$ net removed from the atmosphere, considering grid and solar electricity without post-processing costs. This technology may achieve lower costs than projections for more extensively engineered Direct Air Capture methods. It has the scalable potential to remove at least 2–3 GtCO$_2$ year$^{-1}$, and may make a meaningful contribution to mitigating climate change.
The atmospheric concentration of CO₂ has reached 410 parts per million by volume (ppm), an increase of almost 20 ppm in the last 10 years. As current emission levels exceed 35 GtCO₂/year, a diverse portfolio of CO₂ mitigation technologies must be developed and strategically deployed to avoid more than a 2°C increase in Earth’s temperature. Due to global reliance on fossil fuels, and because it is unlikely our global economy will completely eliminate all emissions, this portfolio will include technologies that remove CO₂ from the atmosphere (negative emission technologies, NETs). Some NETs propose accelerating natural processes such as CO₂ uptake in oceans and terrestrial carbon sinks (soils, forests, minerals), or bioenergy with carbon capture and storage. The work described here is germane to NETs that use sorbents to scrub greenhouse gases from the atmosphere, also known as direct air capture (DAC) with storage. Prior to deployment of these technologies, it is important to understand their potential economic, social, political, and environmental impact. This study presents an overview of, and technoeconomic analysis for, a process that pairs enhanced weathering with calcination for the repeated use of mineral feedstocks to remove CO₂ from the atmosphere.

Enhanced weathering, emulating and accelerating natural weathering processes, was first proposed by Walter Seifritz in 1990. In natural weathering, silicate minerals are transformed into alkalinity-containing carbonate minerals on geologic timescales. The generalized natural weathering reaction is described below in Eq. (1):

\[
\text{MeO(SiO}_2\text{)} + \text{CO}_2 \rightarrow \text{MeCO}_3 + \text{SiO}_2 + \text{Energy.} \tag{1}
\]

Where Me represents a divalent metal cation (typically magnesium (Mg²⁺) and calcium (Ca²⁺)), where suitable feedstocks include rocks (containing olivine and serpentine) as well as industrial byproducts, such as mine tailings and steel slag. Since natural weathering occurs on geological timescales, researchers have explored methods to accelerate CO₂ mineralization. Conversely, in calcination, solid carbonate minerals are heated to decompose into metal oxides and CO₂. The generalized calcination reaction is shown below in Eq. (2):

\[
\text{MeCO}_3 + \text{Energy} \rightarrow \text{MeO} + \text{CO}_2. \tag{2}
\]

By pairing enhanced weathering with calcination, mineral feedstocks can be repeatedly used to capture and evolve CO₂.

Systems for CO₂ removal using carbonation reactions have been previously investigated. In 2011, the American Physical Society (APS) evaluated a system where CO₂ is absorbed by sodium hydroxide (NaOH) and subsequently reacted with calcium hydroxide (Ca(OH)₂) to produce solid calcium carbonate (CaCO₃). The CaCO₃ is calcined in an oven to form CaO. Keith et al. propose a continuous looping process consisting of an aqueous potassium hydroxide (KOH) sorbent coupled with a calcium recovery loop. The KOH sorbent reacts with CO₂ in air to produce aqueous potassium carbonate (K₂CO₃). K₂CO₃ then reacts with Ca(OH)₂ produced by calcining solid CaO, to form KOH and CaCO₃. These types of aqueous looping systems have been primarily evaluated using calcium-based sorbents. Calcium looping systems have also been demonstrated for flue gas capture, where the CO₂ concentration typically ranges from 4% (natural gas combined cycle) to 10–15% (pulverized coal combustion). Manovic and Anthony explored using CaO/CaO-based solid sorbents for capture of CO₂ from concentrated streams. Additionally, Kheshgi, Renforth et al., Renforth and Kruger propose an ocean liming process that deposits lime (CaO produced by calcining carbonate minerals) into the ocean to react with carbonic acid currently in the ocean. This process increases oceanic alkalinity and leads to storage of carbon in the ocean as bicarbonate ions, reducing atmospheric CO₂ concentration. Alternative systems consider reactions between minerals and concentrated CO₂ in high temperature/pressure reactors or through multistep extraction.

Researchers have also investigated using magnesia (MgO) in looping processes. The calcination temperature of magnesite (MgCO₃) is lower than CaCO₃, with a 66% lower enthalpy of decarbonization, potentially leading to a lower energy cost. Magnesium is also attractive as there are large deposits of magnesium silicate minerals throughout the world. Song et al. synthesized MgO from magnesite by varying calcination temperatures from 400 to 600°C when calcining for 2 h. MgO synthesized at higher calcination temperatures had a lower surface area, larger pore size, and a decrease in overall CO₂ uptake capacity. Researchers have also investigated forming MgO with properties optimized for CO₂ capture at ambient conditions, achieving higher specific surface areas (330.5 m² g⁻¹) than commercially available MgO and increased CO₂ uptake capacity (6.18 wt% at 25°C). Additional work focused on CO₂ uptake by powdery MgO promoting by sodium salts, such as NaNO₃ and Na₂CO₃, as well as KNO₃, demonstrating capture capacities of up to 19.8 mmol g⁻¹ (or 80% of the theoretical capacity).

Previous investigations of Ca- and Mg-looping focused on rapid carbon mineralization, for example, in fluidized bed reactors. The costs of building and operating such reactors contribute significantly to integrated looping cost. In this analysis, to reduce costs and ensure simple scalability, we do not include an engineered sorption/desorption-based process. Instead, we focus on land-based, enhanced weathering that could remove significant quantities of CO₂ from air at a relatively low cost, with an area requirement comparable to other potential CO₂ removal methods. Specifically, we consider using magnesite (MgCO₃) as the source of MgO in a looping system that removes CO₂ from air via enhanced weathering. We show that this process could cost approximately $46–$159 CO₂−¹ net removed from air, considering both grid and solar electricity resources without including postprocessing costs. This technology may achieve lower costs than optimistic projections for other more highly engineered DAC methods and may be used to remove significant amounts of CO₂ from air.

**Results**

**Process concept and overview.** In this process, MgCO₃ is calcined to produce caustic MgO and high-purity CO₂. The MgO is spread over land to react with atmospheric CO₂ to form magnesite (MgCO₃) and other Mg-carbonate minerals over the course of a year. After renewed formation of Mg-carbonate minerals, the weathered material is collected and calcined again, producing a nearly pure stream of CO₂ together with an amorphous, solid MgO residue (caustic magnesia, i.e. caustic MgO). The resulting MgO can be exposed to weathering again, and so on.

The produced MgO is assumed to have the same reactivity as mineral brucite (Mg(OH)₂). The rate of formation of magnesium carbonate via reaction of aqueous brucite is on the order of 3 x 10⁻⁸ moles m⁻² s⁻¹ when mineral dissolution kinetics are rate limiting. Thus, for example, grains of brucite with a diameter of 10–100 μm (1.7 x 10⁻¹⁰–1.7 x 10⁻⁷ moles, 1.25 x 10⁻⁵–1.25 x 10⁻⁷ m³, assuming spherical grains), are predicted to be completely transformed to magnesite in less than a year. In practice, larger porous grains with a higher surface area to volume ratio than spheres would also be transformed in a year.

Existing data suggest that under conditions of near 100% relative humidity, conversion of MgO to Mg(OH)₂ can occur on the order of hours, indicating that over the course of a year the hydration reaction is not rate limiting. This conversion is...
Further dependent on the specific surface area and relative humidity of the system (or water vapor partial pressure) with higher partial pressures resulting in faster conversion. Since conversion of MgO to Mg(OH)₂ in the presence of water is much faster than the rate of carbonation of Mg(OH)₂, we assume the carbonation step is rate limiting. Thus, the rate of carbonation can be assumed to be the effective rate for the system.

Based on these considerations, we made the conservative assumption that 20 µm particles of caustic magnesia achieve 90% carbonation in a year. The number of carbonation plots in our analysis is optimized to keep the calciner continuously operational, avoiding startup and shutdown expenses. Overall, the process analyzed here is divided into five main steps: mineral acquisition, magnesite calcination, onsite transportation, caustic magnesia carbonation, and mineral recollection (Fig. 1). A complete mass and energy balance for the system is shown in Supplementary Fig. 1 and described in Supplementary Note 1.

The major process assumptions and parameters for the upper and lower bounds of the analysis are outlined in Table 1. For CO₂ (i.e., compression, transportation, geological sequestration or utilization) is not accounted for in this analysis. The upper and lower bounds correspond to the effect of each parameter on overall process cost, not necessarily the magnitude of each parameter value.

Three scenarios are explored in this analysis, related to the type, cost and emissions of electricity used. The first scenario uses grid electricity, assuming electricity is taken directly from the commercial grid. The second scenario uses solar electricity, assuming electricity is obtained via utility solar plants at the current market price. The third scenario uses a projected cost of solar electricity, assuming a decrease in utility solar electricity cost by 2030 as projected by the DOE.

For this analysis, magnesite is considered to be the feedstock material, with 50,000 tons of raw mineral per carbonation plot. The emissions from mining magnesite are 10 kgCO₂ tMgCO₃⁻¹, within the high end of the typical range of 1.3–12.5 kgCO₂ tmineral⁻¹. The process costs are not sensitive to the feedstock cost or to the mining emissions, due to repeated reuse of MgO from the feedstock. For this analysis, it is assumed the feedstock is available at the desired particle size of 20 µm or that this particle size is attained in the first calcination step.

Magnesite feedstock is generally calcined at 500–1200 °C. For this analysis, two sets of calcination conditions are used: 600 °C for 2 h (lower bound) and 1200 °C for 0.5 h (upper bound). Calcining at 600 °C for 2 h yields a higher specific surface area (93.07 m² g⁻¹ for a 2–5 mm feed precalcination), which aids in subsequent carbonation reactions. Calcination at 1200 °C for 0.5 h results in a decreased surface area (10.9 m² g⁻¹ for a 2–5 mm feed precalcination). Calcination yields MgO and a high-purity stream of CO₂. The calciner is continuously operational with a capacity factor of 90% to account for routine maintenance. The number of carbonation plots was determined to meet this operational capacity. Additionally, an oxy-fired calciner was used. The oxy-fired calciner requires two additional pieces of equipment: an air separation unit (to feed high-purity oxygen to the system) and a condenser (to condense water from the calciner exhaust stream).

Combustion energy and CO₂ outputs are estimated for oxidation of pure methane. Following combined combustion and calcination, the gas stream is fed into the condenser where water is removed. Since oxy-fired calcination is used, the flue gas is mainly composed of CO₂ and water vapor, yielding a high-purity stream of CO₂ after H₂O condensation. The condensation step produces 0.3 tonnes of H₂O per tCO₂ captured from air, which can be sold as a byproduct. CO₂ removed from Mg-carbonates, and CO₂ produced from combustion, can be compressed and permanently stored or sold. The cost of compression—not included in our analysis—may add ~$8 tCO₂⁻¹ to the net removed cost, depending on proximity to, and infrastructure at, a storage site.

To move calcined MgO to the plot of land used for weathering, an electric conveyor is used, as is ubiquitous in the mineral extraction industry. These conveyors act as connections between the calcination plant and carbonation plots for spreading MgO. Additionally, the conveyors will transport weathered, carbonated product from the plots to the calcination plant each year. A potential layout of the carbonation plots is shown in Supplementary Fig. 2. Transportation operating costs are related to electricity used by the conveyor system which was determined using motor power details for commercially available mining conveyors (373 kW (500 HP) with a capacity of 454 t h⁻¹).

Weathering in this process takes place on land at ambient conditions. MgO is spread on land in layers 0.1 m thick and stirred daily. Since stirring equipment for large plots of land is not industrially available, values for the capital costs of this equipment are approximated using costs of large-scale agricultural tillage equipment (Table 2).

The system analyzed here has between 3504 (lower bound) and 10,512 (upper bound) carbonation plots, each with ~21,500 tMgO from the original 50,000 tMgCO₃ feedstock. The number of carbonation plots is optimized for continuous calciner operation. Since the upper bound and lower bound have 30-min and 2-h calcination cycles, respectively, more plots are processed per year in the upper bound scenario. Since each plot is populated with MgO at different times during the year, they will also be recollected and calcined at different times. Additionally, it was assumed that 90–95% of the MgO will be recollected as MgCO₃.
or unreacted MgO, while 5–10% of this material will be lost to the environment. We calculate that losses of MgCO3 will be 0.03–0.05% per year and MgO losses will be 3–4% per year (assumptions and results in Supplementary Note 2).

For recollection and delivery to conveyors, the associated pieces of equipment are assumed to be commercially available front-loading tractors. The conveyors will bring MgCO3 from the pieces of equipment are assumed to be commercially available (assumptions and results in Supplementary Note 2).

We calculate that losses of MgCO3 will be throughout the year. This also allows for more CO2 capture ment can be used continuously for multiple carbonation plots staggering plot maturation times, the central calcination equip-ment can be used continuously for multiple carbonation plots back to the calcination plant and the MgO will 0.03

\( 0.03 \times 10^9 \) or unreacted MgO, while 5–10% of this material will be lost to the environment. We calculate that losses of MgCO3 will be 0.03–0.05% per year and MgO losses will be 3–4% per year (assumptions and results in Supplementary Note 2).

For recollection and delivery to conveyors, the associated pieces of equipment are assumed to be commercially available front-loading tractors. The conveyors will bring MgCO3 from the carbonation plots back to the calcination plant and the MgO will be regenerated in the calcination reactor for continued use. By staggering plot maturation times, the central calcination equip-ment can be used continuously for multiple carbonation plots throughout the year. This also allows for more CO2 capture without increasing the required operational scale (i.e., equipment sizing or throughput).

After undergoing repeated calcination, sintering may have a significant effect on MgO reactivity\(^47\). Studies evaluating capacity losses for magnesium-based adsorbents suggest that after ten cycles, CO2 uptake capacity diminishes by 5–7%\(^48,49\). This would correspond to a capacity loss between 2 and 17% over the plant lifetime, depending on the amount of makeup material and the number of cycles undergone by material lost to the environment (assumptions and results in Supplementary Table 1 and Supplementary Note 3). This analysis assumes 5–10% losses in each cycle, accounting for both environmental losses and possible sintering effects so the initial MgO lasts for 10–20 cycles. The periodic replacement of MgO via addition of MgCO3 feedstock is included in the system operating costs as makeup minerals, but capacity losses are not accounted for.

**Cost calculations.** The cost estimates presented in this section include capture of CO2 from ambient air and subsequent evolution of CO2 via a mineral calcination process, not including postprocessing CO2 costs. The largest contributions to the capital costs of the system are raw material costs at 81–86% of capital costs, the oxy-fired calciner at ~10% of capital costs, and the air separation unit and condenser at 2–7% of the capital costs. The costing method and scaling factor used for each piece of equipment are presented in Table 2. Each capital cost value is scaled to the individual process conditions. Here, the upper bound is processing 0.18 Gt CO2 year\(^{-1}\) using 10,512 carbonation plots, while the lower bound is processing 0.06 Gt CO2 year\(^{-1}\) using 3504 carbonation plots. Since the upper bound is processing about three times more CO2 than the lower bound, the capital cost per tonne CO2 is significantly less for the lower bound compared to the upper bound.

### Table 1 Assumptions and parameters used for the upper and lower bounds in the process model.

| Parameter/Assumption | Value | Comments |
|----------------------|-------|----------|
| **Calcination**      |       |          |
| Calcination temperature \( [^\circ \text{C}] \) | 600 | 1200 | Literature values from 500 to 1200 \( ^\circ \text{C} \)\(^45\) |
| Calcination time \( [\text{h}] \) | 2 | 0.5 | Literature values from 0.5 to 4 \( \text{h} \)\(^45\) |
| Time between calcination loads \( [\text{h}] \) | 0.25 | 0.25 | Literature value\(^70\) |
| Heat of decarbonation \( [\text{kJ mol}^{-1}] \) | 118 | 118 | Assumed industry state-of-the-art |
| Kiln efficiency [%] | 90 | 90 | At 600 \( ^\circ \text{C} \), the decomposition is completed within 2 \( \text{h} \). At 800 \( ^\circ \text{C} \), the decomposition is completed within 30 \( \text{min} \)\(^45\). Additional studies show decomposition efficiencies near 90% using 600 and 650 \( ^\circ \text{C} \) for 1.5 \( \text{h} \)\(^71\). |
| Calcination efficiency [%] | 90 | 90 | Calculated from MgCO3 to MgO conversion yields at 800 \( ^\circ \text{C} \)\(^58\). |
| **Carbonation**      |       |          |
| CO2 uptake capacity \( [\text{mol CO2 molMgO}^{-1}] \) | 1 | 1 | Assumed stoichiometric value consistent with magnesite formation |
| MgO layer thickness \([\mu \text{m}]\) | 0.1 | 0.1 | Literature value\(^72\) |
| Particle size \([\mu \text{m}]\) | 20 | 20 | Determined to keep the calciner operating continuously at the given calcination conditions |
| Environmental losses [% cycle\(^{-1}\)] | 5 | 10 | Literature value\(^56\) |
| Carbonation efficiency [%] | 90 | 90 | Determined to keep the calciner operating continuously at the given calcination conditions |
| Stirring equipment [acres unit equipment\(^{-1}\)] | 125 | 125 | Literature value\(^56\) |
| Number of plots | 3,504 | 10,512 | Literature value\(^56\) |
| **Energy costs and emissions** |       |          |
| Natural gas \([\$ \text{GJ}^{-1}]\) | 3.5 | 3.5 | Literature value\(^7,20\) |
| Natural gas \([\text{kgCO2 GJ}^{-1}]\) | 59 | 59 | Literature value\(^26\) |
| Gasoline \([\text{kgCO2 gallon}^{-1}]\) | 2.60 | 2.60 | Average market price for 2019 from EIA\(^73\) |
| Grid electricity \([\$ \text{GJ}^{-1}]\) | 8.89 | 8.89 | Literature value from EIA\(^74\) |
| Solar electricity \([\$ \text{GJ}^{-1}]\) | 16.7 | 16.7 | Literature value\(^20\) |
| Solar electricity \([\$ \text{GJ}^{-1}]\) | 150 | 150 | Literature value\(^26\) |
| Solar electricity \([\text{kgCO2 GJ}^{-1}]\) | 16.7 | 16.7 | US national average for utility-scale solar ($0.06 \text{kWh}^{-1}$)\(^44\) |
| Solar electricity \([\text{kgCO2 GJ}^{-1}]\) | 150 | 150 | Projected value ($0.03 \text{kWh}^{-1}$)\(^44\) |
| Raw material (mining) emissions \([\text{kgCO2 gallon}^{-1}]\) | 6.9 | 6.9 | Literature value\(^7\) |
| Gasoline \([\text{kgCO2 gallon}^{-1}]\) | 8.89 | 8.89 | Literature value from EIA\(^26\) |
| Natural gas \([\text{kgCO2 GJ}^{-1}]\) | 150 | 150 | Literature value\(^72\) |
| Natural gas \([\$ \text{GJ}^{-1}]\) | 125 | 125 | Literature value\(^72\) |
| **Economic parameters** |       |          |
| Capacity factor [%] | 90 | 90 | Consistent with Keith et al.\(^20\) |
| Plant economic lifetime [yr] | 20 | 20 | Consistent with Keith et al.\(^20\) |
| Discount rate [%] | 4 | 11 | Similar to 7.5 and 12.5% used in Keith et al.\(^20\) |
| Capital recovery factor [%] | 7.4 | 12.6 | Similar to 7.5 and 12.5% used in Keith et al.\(^20\) |
Table 2 Estimated capital expenditures (CAPEX) for the MgO looping process.

| CAPEX                      | Cost [M$]          | Comments                                                                 |
|----------------------------|--------------------|--------------------------------------------------------------------------|
|                            | Lower bound | Upper bound |                                                                 |
| Raw mineral                | 8,760          | 110,376      | Lower bound: Estimated based on open pit mining cost ($10 tonne\(^{-1}\))\(^{75}\) and inflated to represent the required size reductions. Upper bound: cost of calcined magnesia\(^{76}\). |
| Air separation unit and condenser\(^a\) | 785           | 2,260        | Lower bound: scaled from Keith et al. installed calciner cost\(^{20}\). Upper bound: scaled from NASEM Report (built-in installation costs)\(^{7}\). Lower bound: Scaled from Keith et al.\(^{20}\). Upper bound: Scaled from NASEM Report (Built-in 4.5× factor for new technology)\(^7\). |
| Oxy-fired calciner\(^a\)   | 930           | 12,202       |                                                                 |
| Land                       | 129           | 1,796        |                                                                 |
| Transportation (Conveyor System)\(^a\) | 129           | 1050         | Price from mining cost data\(^{46,77}\). Lower bound: 1.5× factor to account for commercial possibility. Upper bound: 4.5× factor to account for new technology application. |
| Stirring equipment         | 28            | 84           | Price quote for industrial farming equipment with a 1.5× factor for new equipment application. |
| Recollection equipment     | 22            | 67           | Price quote for industrial farming equipment with a 1.5× factor for new equipment application. |
| Total CAPEX [M$]           | $10,783       | $127,835     | CRF of 7.4% used for lower bound and 12.5% used for upper bound. Only includes CO\(_2\) captured directly from the air. Includes CO\(_2\) captured directly from the air and produced via calcination. |
| CAPEX Annualized [M$ year\(^{-1}\)] | $794          | $16,053      |                                                                 |
| CO\(_2\) capture from air [GtCO\(_2\) year\(^{-1}\)] | 0.064       | 0.18         |                                                                 |
| Total CO\(_2\) capture [GtCO\(_2\) year\(^{-1}\)] | 0.12         | 0.34         |                                                                 |
| CAPEX [$ tCO\(_2\)\(^{-1}\) captured] | $12           | $89          |                                                                 |
| CAPEX [$ tCO\(_2\)\(^{-1}\) produced] | $7            | $47          |                                                                 |

\(^a\)Assumed a scale-up factor\(^{68}\).

Table 3 Energy requirements for the MgO looping process.

| Unit operation                     | Energy requirements | Energy type |
|------------------------------------|---------------------|-------------|
|                                    | Lower bound | Upper bound |
| Air separation unit and condenser\(^7\) [MJ tCO\(_2\)\(^{-1}\)] | 300         | 300         | Electricity |
| Oxy-fired calciner\(^\) [MJ tCO\(_2\)\(^{-1}\)] | 5890        | 7970        | Natural gas |
| Transportation [MJ tCO\(_2\)\(^{-1}\)] | 8           | 9           | Electricity |
| Stirring equipment [gallons tCO\(_2\)\(^{-1}\)] | 0.29        | 0.31        | Gasoline    |
| Recollection equipment [gallons tCO\(_2\)\(^{-1}\)] | 0.0051      | 0.0054      | Gasoline    |

Table 3 shows the energy requirements and energy type for each unit operation. The main energy demand of the process is for calcination, which depends on calcining temperature. Therefore, the energy requirements per tonne CO\(_2\) vary between the lower and upper bounds.

Table 4 details the operating costs for the MgO looping system, while Fig. 2 illustrates the breakdown of operating costs by type. There are no variations in the cost between grid and solar electricity scenarios as the cost of electricity is identical. Variations between these energy resource scenarios arise when considering CO\(_2\) emissions.

The largest contribution to operating costs is the natural gas required to power the calciner, making up 45–62% of operating costs for all scenarios. This indicates process operating costs are sensitive to the price of natural gas. Additionally, electricity makes up 8–16% of operating costs. Other major contributions to operation costs are maintenance (15–34%) and labor (5–10%), which are directly correlated to capital costs.

Cost of CO\(_2\). The cost of CO\(_2\) combines the capital and operating costs presented in the previous sections to develop a process cost per tCO\(_2\) as outlined in the “Methods” section. These costs are shown in Table 5. In addition, costs for a smaller scale system (10,000 tMgCO\(_3\) per plot) and reduced layer thickness (0.01 m) are provided in Supplementary Tables 2 and 3, respectively. The sensitivity of process costs to key parameters is shown in Supplementary Fig. 3 and discussed in Supplementary Note 4.

While the cost of capture for the solar electricity scenario is the same as for the grid electricity scenario, the cost of CO\(_2\) net removed is ~4% less for the solar scenario compared to the grid scenario. This minor difference is due to the lower CO\(_2\) emissions associated with solar versus grid electricity. Additionally, when accounting for projected cost reduction of solar electricity, the CO\(_2\) net removed process cost is reduced by ~7% compared to grid electricity.

Discussion

This study explores a process by which a magnesite feedstock can be repeatedly calcined and carbonated to remove CO\(_2\) from air, to evaluate the feasibility of this process as a DAC technology. Here, we discuss important factors affecting feasibility, including estimated costs, opportunities for cost reduction, land use, magnesite availability and potential use of alternative feedstocks.

For the process presented here, the cost of CO\(_2\) net removed ranges from $46 to $159 tCO\(_2\)\(^{-1}\) using current costs of grid and solar electricity, while the cost of CO\(_2\) produced ranges from $24 to $79 tCO\(_2\)\(^{-1}\). Using future cost projections for solar electricity yields $43–$149 tCO\(_2\)\(^{-1}\) net removed and $23–$77 tCO\(_2\)\(^{-1}\).
produced. These estimates can be compared to published values for other processes. Currently, DAC processes using synthetic sorbents or solvents have been demonstrated on pilot scales, with costs of CO₂ net removed reported to be $500–$600 tCO₂⁻¹ captured using low-carbon energy. Aside from industrial-scale initiatives, estimated costs of DAC technologies using combined carbonation and calcination processes have been described. The American Physical Society (APS) estimated a cost of $610 tCO₂⁻¹. By varying packing materials and optimizing the process around this new material, Mazzotti et al. estimated costs ranging from $94 tCO₂⁻¹ net removed for a similar process. Using potassium hydroxide, Keith et al. estimated costs ranging from $94 tCO₂⁻¹ net removed as $199 tCO₂⁻¹, $407, respectively. As technology continues to develop, there are multiple opportunities to reduce the cost of the enhanced weathering process analyzed here, perhaps most notably by using a solar calciner. The calcination step requires the most process energy. As an alternative to capturing emissions associated with oxy-fired calcination, solar calcination may largely avoid these emissions. Currently, solar calcination is not an industrially available technology. However, research is currently underway to develop high temperature solar kilns for calcination. Additionally, adoption and scale-up of industrial-scale electric calciners may allow for low-carbon energy to power the calcination step. Incorporating an experimental calcination process would increase initial capital investment. However, when solar or electric calcination technology becomes established, it could provide a lower-cost, sustainable alternative to oxy-fired calcination, aiding the transition away from fossil fuels.

The process evaluated in this study uses carbonation plots, each with ~21,500 tMgO in a layer 0.1 m thick, using 11 ha of land. For comparison, a small family farm in the US has an average size of 93 ha while large family farms average ~600 ha. Using this approximation, 0.15–0.9 MtCO₂ year⁻¹ could be removed from air on a family farm, equivalent to 160 kgCO₂ m⁻² year⁻¹. Additional information, biomass-based production usually removes between 1 and 10 kgCO₂ m⁻² year⁻¹. The upper bound in this analysis would require 0.11 Mha (sequestering 180 million tCO₂), while the lower bound would require 0.04 Mha.

Table 4 Operating expenditures (OPEX) for the MgO looping process.

| OPEX                  | Cost [M$] | Lower bound | Upper bound | Comments                          |
|-----------------------|-----------|-------------|-------------|-----------------------------------|
| Maintenance           | 323       | 3,835       |             | Calculated at 0.03 of total capital |
| Labor                 | 97        | 1,151       |             | Calculated at 0.3 of maintenance  |
| Makeup minerals       | 9         | 53          |             |                                   |
| Gasoline              | 50        | 151         |             |                                   |
| Natural gas           | 1,310     | 5,036       |             |                                   |
| Electricity           | 327       | 929         |             |                                   |
| Total OPEX [M$]       | $2,117    | $11,154     |             |                                   |
| Total OPEX [$ tCO₂⁻¹ captured] | $33 | $62 | | Using a value of $16.7 GJ⁻¹ for both solar and grid electricity |
| Total OPEX [$ tCO₂⁻¹ produced] | $17 | $32 | | |

Fig. 2 Distribution of operating costs for the enhanced weathering system. Color gradient indicates the difference between the lower and upper operating cost values. Two pie charts are presented representing the operating cost distribution for both the lower (darker color palette) and upper (lighter color palette) bounds of the analysis. Source data are provided as a Source Data file.
(sequestering 64 million tCO₂). To sequester 1 GtCO₂ would require ~0.61 Mha (6100 km²) of land area.

The land area for electricity generation can also be incorporated into this analysis. The process consumes 0.3 GJ of electricity per tCO₂ captured. The land area footprint for electrical generation, using natural gas combined cycle (NGCC) methods, is 0.14 ha MW⁻¹, while for solar electricity the land requirement is 12.7 ha MW⁻¹. Therefore, the upper bound would require 290 ha for NGCC electricity and 26100 ha for solar electricity to remove 180 million tCO₂ from air. The lower bound would require 91 ha for NGCC electricity and 8300 ha for solar electricity to remove 64 million tCO₂. To remove 1 GtCO₂ from the air per year with NGCC would require ~1500 ha (15 km²) for electrical generation, while a solar electricity generation would require ~0.14 Mha (1400 km²). The land energy requirements for the system coupled to solar and grid electricity are shown in Table 6.

In total, the lower and upper bound facilities using natural gas as the source for thermal and electrical requirements have a land area footprint between 0.04 and 0.11 Mha respectively. A facility using solar electricity and natural gas thermal energy has a land area footprint between 0.05 and 0.12 Mha for the lower and upper bounds. The small difference between the land area footprints arises from the small contribution of the footprint for electrical generation to the overall land area requirement (~2% for NGCC electricity and ~18% for solar electricity). To remove 1 GtCO₂ from air requires 0.61 Mha (~6100 km²) for natural gas electricity and thermal energy and 0.75 Mha for solar electricity and natural gas thermal energy (0.02% of the 3.25 billion ha of global marginal land).

These values are similar to the estimated footprints of DAC with synthetic sorbents or solvents. To put these requirements into context, the Nevada Test Site plus the surrounding Nevada Test & Training Range occupy 15,000 km², roughly enough to remove 2.5 GtCO₂ from air per year via weathering of MgO. That area is about 5.2% of Nevada (286,380 km²), 0.15% of the USA (9,833,520 km²), 0.05% of global marginal land (32,000,000 km²) or 0.01% of global land area (127,343,220 km²).

While this process would never be done on arable land, we used the cost of arable land here because price estimates are readily available. Additionally, our comparison to farm size is for illustrative purposes only. Since arable land is in high demand and is essential for food supplies, our proposed process would use inexpensive marginal land, so that our approximation yields an upper bound cost. Moreover, our upper bound for the cost of land in this analysis is still <1% of the overall capital costs.

When estimating magnesite requirements for this system, there are two main considerations: the initial supply of magnesite to each carbonation facility and the makeup supply of magnesite each subsequent year of facility operation. For the initial supply of magnesite, there are two cases: the lower bound utilizing 3,504 carbonation plots with 5% environmental losses and the upper bound utilizing 10,512 carbonation plots with 10% environmental losses. For both cases, the initial plots are each populated with 50,000 tMgCO₃. The upper bound requires 525 MtMgCO₃ to capture 180 MtMgCO₃, or 6.2% of global reserves (estimated to be 8.5 billion tons of known, economically and legally producible magnesite). A graphical representation of global magnesite reserves by country is provided in Supplementary Fig. 4. Additionally, with 10% environmental losses, the lower bound process would require 53 MtMgCO₃ in replacement magnesite each year or 0.6% of global reserves.

For the lower bound, the initial mineral requirement is 175 MtMgCO₃ or 2% of global magnesite reserves to capture 64 MtMgCO₃. For makeup minerals, the lower bound assumed 5% environmental losses, corresponding to an additional 8.7 MtMgCO₃ per year or 0.1% of global reserves. Removing 1 GtCO₂ from air per year would initially require 2.9 GtMgCO₃ or roughly 29% of global magnesite reserves. The makeup supply would require between 0.15 and 0.29 GtMgCO₃ per year, or roughly 1.7–3.4% of global magnesite reserves.

Magnesite is not the only mineral that can be used in this process. Another potential source of alkalinity is sodium carbonate, Na₂CO₃. According to the US Geological Survey, global reserves are about 25 billion tons, of which about 60 wt% is Na₂O. If all of this were used for CO₂ removal from air, that would yield almost 10 GtCO₂ per year. It is not clear how practical this might be, since sodium carbonate is very soluble in water, and only preserved in arid climates. Additionally, alkaline industrial wastes may be able to remove ~1 GtCO₂ per year, based on current production, and this may increase to more than 3 GtCO₂ capacity per year by 2100.

Limestone (CaCO₃) and dolomite (CaMg(CO₃)₂) are highly abundant, much less labile sources of alkalinity. The reserves of rock commodities are such that they are simply described as very large by the US Geological Survey. Hayes and Waldbauer estimate that the inventory of sedimentary carbon in the Earth’s crust is ~10²⁴ mol. Much more than 10% of this is in limestone and dolomite, corresponding to more than 10⁸ billion tons of rock, about half of which is CaO and MgO.

Finally, or in parallel, Mg-silicates from ultramafic rocks—olivine-rich peridotite from the Earth’s mantle and its hydrated equivalent, serpentine—could be used as a source of MgO. For simplicity, peridotite can be simplified as nearly pure Mg-olivine (Mg₂SiO₄), and serpentine as serpentine (Mg₃Si₂O₅(OH)₄) and brucite (Mg(OH)₂). There are abundant legacy tailings of partially hydrated (serpentinized) peridotite, and on the land resource of

### Table 5 Summary of CO₂ capture costs for the MgO looping process using costs as defined in the section “Calculating the cost of CO₂”.

| Cost Type                               | Grid electricity | Solar electricity $0.06 kWh⁻¹ | Solar electricity $0.03 kWh⁻¹ |
|-----------------------------------------|------------------|-------------------------------|-------------------------------|
| Capture cost [$ tCO₂⁻¹]                 | 46–151           | 46–151                        | 43–148                        |
| Net removal cost [$ tCO₂⁻¹]             | 48–159           | 46–152                        | 43–149                        |
| Produced cost [$ tCO₂⁻¹]                | 24–79            | 24–79                         | 23–77                         |

### Table 6 Land area requirements for the MgO looping process.

| Requirement                                      | Lower bound | Upper bound | 1 GtCO₂ |
|--------------------------------------------------|-------------|-------------|---------|
| CO₂ captured [MtCO₂ yr⁻¹]                        | 60          | 180         | 1000    |
| Total plot land area [Mha]                       | 0.04        | 0.11        | 0.61    |
| Grid electricity land area [ha]                  | 91          | 286         | 1500    |
| Solar electricity land area [ha]                 | 8300        | 26100       | 138000  |
| Total land area (grid) [Mha]                     | 0.04        | 0.11        | 0.61    |
| Total land area (solar) [Mha]                    | 0.05        | 0.14        | 0.75    |
peridotite and serpentineite exceeds 100–1000 trillion tons within 3 km of the surface\textsuperscript{10}. There is a large literature on heat-treating serpentinite to create a reactive material for CO\textsubscript{2} capture and storage\textsuperscript{62–67}. To produce MgO for weathering as envisioned in this paper, one would calcine serpentinite, driving off H\textsubscript{2}O and minor CO\textsubscript{2}, to create reactive material composed of MgO and amorphous Mg\textsubscript{2}SiO\textsubscript{4}. After a few weathering and calcining cycles, this would become MgO and SiO\textsubscript{2}. One could then use MgO as described throughout this paper.

In summary, there are many natural sources of alkalinity (MgO, CaO, Na\textsubscript{2}O) that could be weathered and calcined, to remove CO\textsubscript{2} from air as described in this paper. For example, the US Geological Survey reports that resources from which magnesium compounds can be recovered range from large to virtually unlimited and are globally widespread\textsuperscript{68}. However, because the various feedstocks listed here undergo calcining and/or weathering at different rates and conditions compared to those for magnesite, additional calculations would need to be performed to investigate the economic feasibility using the alternatives.

CO\textsubscript{2} removal from air via the process described in this paper has a similar or lower cost than CO\textsubscript{2} removal using DAC with synthetic sorbents or solvents, within uncertainty of estimates for both techniques. The net removed cost associated with grid electricity ($48–$159 tCO\textsubscript{2}−1) is slightly higher than that of solar electricity ($46–$152 tCO\textsubscript{2}−1, or $43–$149 tCO\textsubscript{2}−1 when incorporating predicted cost decreases) due to the CO\textsubscript{2} emissions associated with grid electricity. The process is relatively simple and robust and is feasible at a reasonable cost using existing technology. Additionally, the proposed process integrates CO\textsubscript{2} capture from the oxy-fired calcination unit, so the cost of produced CO\textsubscript{2}, both removed from air and captured from combustion, is competitive with other sources. While addressing the greenhouse gas problem requires permanent storage of huge amounts of CO\textsubscript{2}, this is not currently profitable. For storage, the integrated CO\textsubscript{2} capture from the calciner will increase the costs associated with storage—with storage costs of approximately $9–$20 tCO\textsubscript{2}−1 stored\textsuperscript{7}. However, in the short term, sale of CO\textsubscript{2} may provide an income stream that attracts the investment required to support research and development of a range of technologies for CO\textsubscript{2} removal from air.

Finally, we wish to emphasize that DAC technologies, including the MgO looping process analyzed in this paper, are not as effective as point source emissions reductions. However, CO\textsubscript{2} removal from air will probably be required to limit global warming to less than 2 °C by 2100. In this context, MgO looping offers a practical and relatively inexpensive carbon dioxide removal method.

Methods

Equipment scaling and capital costs. Major unit operations in this process include: physical preprocessing, air separation, condenser, oxy-fired calciner, land use, and transportation equipment. Costs for these were developed from two sources. First, quotes from industry for available equipment were used. This includes pricing for raw materials, the transportation conveyor system, and stirring and recollection equipment. For novel or new types of equipment, capital costs were determined based on corresponding literature values. Both of these types of equipment costs were scaled to process 30,000 tMgCO\textsubscript{2} feedstock per cycle per plot (or 18 ktCO\textsubscript{2} cycle−1 plot−1) using the relationship in Eq. (3).

\[
\frac{Cost_1}{Cost_2} = \left( \frac{Scale_1}{Scale_2} \right)^a
\]

where \(a\) is a scaling factor. Traditionally, 0.60 is used as a scaling factor for most industrial equipment. However, for reaction vessels, this scaling factor is conventionally 0.68\textsuperscript{88}. Additionally, to account for the installed cost of the equipment, a multiplication factor was included. This factor was 1.5× for commercially available equipment and 4.5× for new technology or new applications. Finally, capital expenditures for the process were annualized using capital recovery factors of 7.4% for the lower bound and 12.6% for the upper bound.

Energy requirements and operating costs. Energy costs associated with the process were calculated for each unit operation based on operating time, equipment capacities, and periodic nature of the process. Operations energy requirements were determined for a single carbonation cycle and scaled to the required number of plots. From the energy analysis on each unit operation, operating costs for the system were developed. The operating costs were determined using $16.7 GJ−1 for grid and utility solar electricity. Additionally, a third scenario was developed using a projected solar electricity cost of $8 GJ−1. Parameters for energy costs and associated emissions are outlined in Table 1.

Calculating the cost of CO\textsubscript{2}. The costs of CO\textsubscript{2} determined in this analysis considers three different scenarios. First, a general case is presented where grid electricity is used. Second, the current industrial cost of electricity generated by solar photovoltaic cells was used. Finally, process costs were anticipated using the projected price of solar electricity, which is expected to reach $8 GJ−1 ($0.03 kWh−1) by 2030\textsuperscript{94}. Solar electricity is not entirely carbon-free as there are emissions during fabrication, mainly associated with manufacturing of solar cells\textsuperscript{95}. While these emissions are significantly less than for a comparable amount of grid electricity, they must still be included in the analysis.

Three different costs of CO\textsubscript{2} are calculated for each scenario: the cost of capturing CO\textsubscript{2}, the cost of CO\textsubscript{2} net removed from the atmosphere, and the produced cost of CO\textsubscript{2}\textsuperscript{96}. The cost of capturing CO\textsubscript{2} is the direct cost of the process and is calculated in accordance with Eq. (4). This value represents how much it would cost for the process to remove 1 tCO\textsubscript{2} directly from the atmosphere.

\[
\frac{\text{Cost} [\text{tCO}_2^{-1}]}{\text{Process cost } [\text{s}]} = \frac{\text{CO}_2 \text{ capture from air } [\text{tCO}_2]}{\text{CO}_2 \text{ capture from air } [\text{tCO}_2]}
\]

The cost of CO\textsubscript{2} net removed takes the cost of capturing CO\textsubscript{2} and adjusts for emissions produced in the process, and not captured onsite. For each step in the process, some amount of energy in the form of electricity, natural gas, or fuel is required. With each energy source, there are associated CO\textsubscript{2} emissions. We have assumed that electricity will be generated off site, and that the emissions from generation are not captured. Since the goal of the process is to remove CO\textsubscript{2} from the atmosphere, it is important to consider emissions from the process itself. The cost of CO\textsubscript{2} net removed includes the emissions as a result of the process and scales the cost of capturing CO\textsubscript{2} to develop a cost that represents a net capture of 1 tCO\textsubscript{2} as follows:

\[
\frac{\text{Net removed cost} [\text{tCO}_2^{-1}]}{\text{Process cost } [\text{s}]} = \frac{\text{CO}_2 \text{ capture from air } [\text{tCO}_2] - \text{CO}_2 \text{ released by process } [\text{tCO}_2]}{\text{CO}_2 \text{ capture from air } [\text{tCO}_2]}
\]

Finally, the produced cost of CO\textsubscript{2} uses the cost of capturing CO\textsubscript{2} and adjusts for additional CO\textsubscript{2} captured onsite, specifically CO\textsubscript{2} captured from natural gas combustion in the oxy-fired calcination unit. Ultimately, the produced cost of CO\textsubscript{2} is equivalent to the price at which CO\textsubscript{2} could be sold for the process to break-even. This is described in Eq. (6).

\[
\frac{\text{Produced cost } [\text{tCO}_2^{-1}]}{\text{Process cost } [\text{s}]} = \frac{\text{CO}_2 \text{ capture from air } [\text{tCO}_2] + \text{additional CO}_2 \text{ captured by process } [\text{tCO}_2]}{\text{CO}_2 \text{ capture from air } [\text{tCO}_2]}
\]

Sensitivity analysis. A sensitivity analysis was performed on the proposed system with respect to six important parameters: carbonation efficiency, environmental losses, calcination temperature, calcination time, and the number of carbonation plots. The sensitivity analysis was performed in MATLAB by iteratively solving the process simulation between designated parameter values. This was performed for both the lower and upper bounds of the analysis. The complete sensitivity analysis is presented in Supplementary Fig. 3 and described in Supplementary Note 4.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files. The source data underlying all figures and tables in both the main text and supplementary information is provided as Supplementary Data.

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Author contributions

P.K. conceived of the process idea based on P.R.’s prior work. N.M. and J.W. further refined the process to the form presented in the current work. N.M. performed the techno-economic calculations and sensitivity analysis for the cost of CO2 removal. G.D. provided important input on the kinetics of carbonation of different kinds of MgO. N.M., P.K., G.D., P.R., and J.W. were involved in the development and revisions of the article.

Competing interests

The authors are all named inventors on Patent Application Systems and Methods for Enhanced Weathering and Calcining for CO2 Removal from Air, no. 62/865,708, filed on June 24, 2019, based on the technology described in this paper.

Additional information

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