# Supporting information for

# Electrolytic Mineralization of $CO_2$

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**Supplementary Calculations.**

For this section, we provide the reader with a glossary of terms and variables (Supplementary Table 1).

**Supplementary Table 1:** Glossary of terms and variables used to express metrics in this study.

| Variable | Symbol | Meaning |
|---|---|---|
| Calcium transference efficiency | $\eta_{Ca,\,transfer}$ | $\eta_{Ca,\,transfer} = n_{Ca^{2+},\,catholyte} / n_{Ca^{2+},\,chemolyte} \times 100\%$<br><br>Ratio of mol $Ca^{2+}_{(aq)}$ ions in the catholyte, $n_{Ca^{2+},\,catholyte}$, to mol $Ca^{2+}$ liberated from silicates (e.g., $CaSiO_3$) in the chemical chamber, $n_{Ca^{2+},\,chemolyte}$, times 100%. |
| Calcium carbonation efficiency | $\eta_{Ca,\,carbonation}$ | $\eta_{Ca,\,carbonation} = n_{CaCO_3} / n_{Ca^{2+},\,chemolyte} \times 100\%$<br><br>Ratio of number of moles of $CaCO_3$ that precipitated in the cathode chamber after electrolysis, $n_{CaCO_3}$ to $n_{Ca^{2+},\,chemolyte}$, times 100%. |
| $CO_2$ mineralization efficiency | $\eta_{mineralization}$ | $\eta_{mineralization} = n_{CaCO_3} / n_{CO_2} \times 100\%$<br><br>Ratio between moles of $CaCO_3$ that precipitated in the cathode chamber after electrolysis ($n_{CaCO_3}$), and the total moles of $CO_2$ purged into the cathode chamber during electrolysis ($n_{CO_2}$) |
| $CO_2$ mineralization rate | $r$ | Tons of mineralized $CO_2$ per tons of silicate minerals per year, where $r_{CaSiO_3}$ represents wollastonite ($CaSiO_3$), $r_{Mg_2SiO_4}$ represents forsterite ($Mg_2SiO_4$). |

| | | |
|---|---|---|
| | $n_{Ca^{2+}, chemolyte}$ | Moles of soluble $Ca^{2+}$ in the chemolyte sourced from solid $CaSiO_3$. |
| | $n_{CaCO_3}$ | Moles of $CaCO_3$ that precipitated in the cathode chamber after electrolysis. This white solid is primarily $CaCO_3$, but may contain trace quantities of $Ca(OH)_2$. |
| | $n_{Ca^{2+}, catholyte}$ | Moles of soluble $Ca^{2+}_{(aq)}$ ions in the catholyte. |
| | $n_{e^-}$ | Moles of electrons used for electrolysis. |
| | $n_{CO_2}$ | Moles of $CO_2$ purged into the catholyte during electrolysis. |
| | $m_{CaCO_3}$ | Mass of $CaCO_3$ precipitated in the cathode chamber. |
| | $m_{CO_2}$ | Mass of $CO_2$ captured and converted into $CaCO_3$ in the weathering electrolyzer. |
| | $m_{CaSiO_3}$ | Mass of $CaSiO_3$ dissolved in the chemical chamber during electrolysis. |
| | $V_{catholyte}$ | Volume of catholyte for calcium transference efficiency determination test<br>(i.e., 0.5 L). |
| | $V_{CO_2}$ | Total volume of $CO_2$ purged into the catholyte during electrolysis. |
| | $V_m$ | Molar volume at operating temperature (24.055 L $mol^{-1}$ at 20 ºC). |
| | $t$ | Duration of electrolysis<br>(i.e., 1 hour). |
| | $t_W$ | Duration of weathering<br>(i.e., 1 yr) |
| | $[Ca^{2+}_{(aq)}]_{chemolyte}$ | $Ca^{2+}$ concentration in the chemolyte at any point in time during electrolysis. |
| | $[Ca^{2+}_{(aq)}]_{catholyte}$ | $Ca^{2+}$ concentration in the catholyte at any point in time during electrolysis. |

| | | |
|---|---|---|
| | $F$ | Faraday constant: 96485 C $mol^{-1}$,<br>where C = A•s. |
| | $i$ | Applied current density<br>(i.e., 0.1 A $cm^{-2}$). |
| | $k$ | Slope of [$Ca^{2+}_{(aq)}$] versus time (see Fig. 2B). |
| | $Q$ | Flow rate of gas |
| | $SA$ | Geometric surface area of electrodes<br>(i.e., 4 $cm^2$). |
| | $\chi_{CO_2}$ | Molar fraction of $CO_2$ in the purged gas. |

**Calcium transference efficiency ($\eta_{Ca,\ transfer}$)**

We set out to quantify the amount of $Ca^{2+}$ liberated from the silicate that passed through the $Ca^{2+}$-exchanged CEM into the catholyte. We define this term as the "calcium transference efficiency" ($\eta_{\text{Ca, transfer}}$).

$$\eta_{Ca,\, transfer} = \frac{n_{Ca^{2+},\, catholyte}}{n_{Ca^{2+},\, chemolyte}} \times 100\%$$

where $n_{Ca^{2+},\, catholyte}$ was measured by ICP-OES, and it was determined indirectly from the $Ca^{2+}$ concentration in the catholyte at any point in time during electrolysis (Fig. 2). The $n_{Ca^{2+},chemolyte}$ was calculated based on the number of moles of electrons used for electrolysis ($n_{e^-}$) and Faraday's law.

$$n_{Ca^{2+},\, catholyte} = [Ca^{2+}_{(aq)}]_{catholyte} \cdot V_{catholyte}$$

$$n_{Ca^{2+},\, chemolyte} = \frac{n_{e^-}}{N} = \frac{it}{NF}\, SA$$

$$n_{Ca^{2+},\, chemolyte} = \frac{n_{e^-}}{N} = \frac{iAt/F}{N}$$

where, $i$ is the applied current density (i.e., 100 mA $cm^{-2}$); $SA$ is the geometric surface area of electrodes (i.e. 4 $cm^2$); $t$ is the duration of electrolysis (i.e. 1 h); $F$ is Faraday constant (96485 C $mol^{-1}$), $N$ is the number of transferred electrons per dissolved $Ca^{2+}$ (i.e., 2). The volume of catholyte for calcium transference efficiency determination test ($V_{catholyte}$, i.e. 0.5 L).

Substitution yields:

$$\eta_{Ca,\, transfer} = \frac{[Ca^{2+}_{(aq)}]_{catholyte}}{t} \frac{NFV_{catholyte}}{i\, SA} \times 100\%$$

The slope of $[Ca^{2+}]$ versus time in Fig. 2, $k$, was expressed:

$$k = \frac{[Ca^{2+}_{(aq)}]_{catholyte}}{t}$$

Thus, substitution yields:

$$\eta_{Ca,\,transfer} = k\frac{NFV_{catholyte}}{i\,SA} \times 100\%$$

*Sample calculation:*

The slope obtained from Fig. 2 is 0.246 mmol $L^{-1}$ $min^{-1}$, or $4.10 \times 10^{-6}$mol $L^{-1}$ $s^{-1}$ in SI units.

$$\eta_{Ca,\,transfer} = k\frac{NFV_{catholyte}}{i\,SA} \times 100\%$$

$$= 4.10 \times 10^{-6} mol\,L^{-1}s^{-1} \quad \times \frac{0.5\,L \times 2 \times 96485\,C\,mol^{-1}}{0.1\,A\,cm^{-2} \times 4\,cm^{2}} \times 100\%$$

$$= 4.10 \times 10^{-6} mol\,L^{-1}s^{-1} \quad \times 2.41 \times 10^{5}\frac{L\,(A\,s)\,mol^{-1}}{A} \times 100\% = 98.9\%$$

This high calcium transference efficiency shows effectively quantitative permeance of dissolved $Ca^{2+}$ through the Ca-CEM into the cathode chamber. We note that in order to determine $\eta_{Ca,\ transfer}$, we performed electrolysis without supplying any $CO_2$ supplied to the cathode, and ensured that all of the $Ca^{2+}$ that passed through the membrane remained soluble in the catholyte by adding 20 mM of ethylenediaminetetracetic acid disodium (EDTA-2Na, Sigma Aldrich) the catholyte, and using a larger catholyte recirculating volume of 500 mL. During electrolysis, 2 mL of chemolyte and catholyte were taken out by a syringe at variable time periods and filtered with a member filter unit (Millipore, 0.22 μm). A volume of 1 mL of the filtered solutions were diluted with 3% nitric acid (10 times for catholyte and 100 times for chemolyte). The acidic dilute solutions were tested by inductively coupled plasma optical emission spectroscopy (ICP-OES) to determine [$Ca^{2+}_{(aq)}$].

**Calcium carbonation efficiency ($\eta_{Ca,\ carbonation}$)**

We define the calcium carbonation efficiency ($\eta_{Ca,\ carbonation}$) as:

$$\eta_{Ca,\ carbonation}\ (\%) = \frac{n_{CaCO_3}}{n_{Ca^{2+},\ chemolyte}} \times 100\%$$

where $n_{CaCO_3}$ was calculated using the following equation.

$$n_{CaCO_3} = \frac{m_{CaCO_3}}{M_{CaCO_3}}$$

where $m_{CaCO_3}$ is the mass of $CaCO_3$ that precipitated in the cathode chamber after electrolysis and $M_{CaCO_3}$ is the molar mass of $CaCO_3$. Substitution yields:

$$\eta_{Ca,\ carbonation}\ (\%) = \frac{\frac{m_{CaCO_3}}{M_{CaCO_3}}}{\frac{it}{NF}\ SA} \times 100\% = \frac{NFm_{CaCO_3}}{it\ SA\ M_{CaCO_3}} \times 100\%$$

*Sample calculation:*

For example, when simulated flue gas was purged into the catholyte over 1 h of electrolysis, the obtained $CaCO_3$ in the cathode chamber was 0.4992 g. Thus, $\eta_{Ca,\ carbonation}$ can be calculated as follows:

$$\eta_{Ca,\ carbonation}\ (\ \%) = \frac{NFm_{CaCO_3}}{it\ SA\ M_{CaCO_3}} \times 100\%$$

$$= \frac{2\times 96485\ C\ mol^{-1} \times 0.4992\ g}{0.1\ A\ cm^{-2} \times 4\ cm^{2} \times 1\ h \times 100.09\ g\ mol^{-1}} = \frac{2\times 96485\ A\ s\ mol^{-1} \times 0.4992\ g}{0.4\ A \times 3600\ s \times 100.09\ g\ mol^{-1}}$$

$$= \frac{96330\ A\ s\ g\ mol^{-1}}{144130\ A\ s\ g\ mol^{-1}} \times 100\% = 67\%$$

**$CO_2$ mineralization efficiency ($\eta_{\text{mineralization}}$)**

We define the $CO_2$ mineralization efficiency as:

$$\eta_{mineralization}\ (\%) = \frac{n_{CaCO_3}}{n_{CO_2}} \times 100\%$$

The $n_{CO_2}$ is calculated on the basis of the total volume of $CO_2$ purged into the catholyte during electrolysis ($V_{CO_2}$) and the molar volume at operating temperature ($V_m$), which is calculated as 24.055 L mol$^{-1}$ at 20 ºC.

$$n_{CO_2} = \frac{V_{CO_2}}{V_m} = \frac{\chi_{CO_2} Q t}{V_m}$$

where $\chi_{CO_2}$ is a molar fraction of $CO_2$ in the purged gas (i.e., 0.04% for air and 10% for flue gas); $Q$ is the flow rate of gas. Substitution yields:

$$\eta_{mineralization}\ (\%) = \frac{m_{CaCO_3} V_m}{\chi_{CO_2} Q\ t\ M_{CaCO_3}} \times 100\%$$

*Sample calculation:*

For example, with 0.2 L min$^{-1}$ simulated flue gas (10% $CO_2$) flowing into catholyte, we collected 0.4992 g $CaCO_3$ in the cathode chamber and we calculated $\eta_{\text{mineralization}}$.

$$\eta_{mineralization}\ (\%) = \frac{m_{CaCO_3} V_m}{\chi_{CO_2} Q\ t\ M_{CaCO_3}} \times 100\%$$

$$= \frac{0.4992\ g \times 24.055\ L\ mol^{-1}}{10\% \times 0.2\ L\ min^{-1} \times 1\ h \times 100.09\ g\ mol^{-1}} = \frac{0.4992\ g \times 24.055\ L\ mol^{-1}}{10\% \times 0.2\ L\ min^{-1} \times 60\ min \times 100.09\ g\ mol^{-1}}$$

$$= \frac{12.008\ g\ L\ mol^{-1}}{120.108\ L\ g\ mol^{-1}} \times 100\% = 10\%$$

**<u>$CO_2$ mineralization rate of natural rock weathering</u>**

It has been estimated that 0.127 Gt of $CO_2$ is removed annually by the natural weathering of silicates.[1] For this exercise, we assumed that all of this $CO_2$ is mineralized by a single silicate mineral, either wollastonite ($CaSiO_3$) or forsterite ($Mg_2SiO_4$). We can then express the $CO_2$ mineralization rate of natural weathering by the mass of $CO_2$ being mineralized to the mass of silicate minerals per year.

For example, the natural weathering of $CaSiO_3$ is expressed as.

$$CaSiO_{3(s)} + CO_{2(g)} \rightarrow CaCO_{3(s)} + SiO_{2(s)}$$

Thus, the $CO_2$ mineralization rate of natural weathering with wollastonite ($r_{CaSiO_3}$) can be calculated as follows:

$$r_{CaSiO_3} = \frac{m_{CO_2,W}}{m_{CaSiO_3,W}t_W} = \frac{m_{CO_2,W}}{m_{CO_2,W}t_W\frac{N_{CaSiO_3/CO_2}M_{CaSiO_3}}{M_{CO_2}}} = \frac{M_{CO_2}}{M_{CaSiO_3}N_{CaSiO_3/CO_2}t_W}$$

where $m_{CO_2,W}$ is the mass of $CO_2$ removed per year through natural weathering (0.127 Gt), $m_{CaSiO_3,W}$ is the mass of wollastonite needed to remove all this $CO_2$ through natural weathering (i.e., 0.335 Gt); $t_W$ is the duration of weathering (i.e., 1 yr); $M_{CO_2}$ and $M_{CaSiO_3}$ are the molar masses of $CO_2$ (44.01 g mol$^{-1}$) and $CaSiO_3$ (116.16 g mol$^{-1}$), respectively; $N_{CaSiO_3/CO_2}$ is the stoichiometric ratio of Ca to $CO_2$ (*i.e.,* 1).

Using these assumptions, the $CO_2$ mineralization rate of natural weathering with wollastonite is estimated as follows:

$$r_{CaSiO_3} = \frac{M_{CO_2}}{M_{CaSiO_3} N_{CaSiO_3/CO_2} t_W} = \frac{44.01\ g\ mol^{-1}}{116.16\ g\ mol^{-1} \times 1 \times 1\ yr}$$

$$= 0.379\ g_{CO_2}\ g_{CaSiO_3}^{-1}\ yr^{-1} = 0.379\ ton_{CO_2}\ ton_{CaSiO_3}^{-1}\ yr^{-1}$$

The same procedure can be used to estimate the $CO_2$ mineralization rate of natural weathering with forsterite ($r_{Mg_2SiO_4}$).

$$Mg_2SiO_{4(s)} + 2\ CO_{2(g)} \rightarrow 2\ MgCO_{3(s)} + SiO_{2(s)}$$

$$r_{Mg_2SiO_4} = \frac{m_{CO_2,W}}{m_{Mg_2SiO_4,W} t_W} = \frac{m_{CO_2,W}}{m_{CO_2,W} t_W \frac{N_{Mg_2SiO_4/CO_2} M_{Mg_2SiO_4}}{M_{CO_2}}} = \frac{M_{CO_2}}{M_{Mg_2SiO_4} N_{Mg_2SiO_4/CO_2} t_W}$$

where $m_{Mg_2SiO_4,W}$ is the mass of forsterite needed to remove all this $CO_2$ through natural weathering, i.e. 0.203 Gt; $M_{Mg_2SiO_4}$ the molar mass of $Mg_2SiO_4$ (140.69 g mol$^{-1}$); $N_{Mg_2SiO_4/CO_2}$ is the stoichiometric ratio of $Mg_2SiO_4$ to $CO_2$ (i.e., 0.5).

Using these assumptions, $r_{Mg_2SiO_4}$ is estimated as follows:

$$r_{Mg_2SiO_4} = \frac{M_{CO_2}}{M_{Mg_2SiO_4} N_{Mg_2SiO_4/CO_2} t_W} = \frac{44.01\ g\ mol^{-1}}{140.69\ g\ mol^{-1} \times 0.5 \times 1\ yr}$$

$$= 0.626\ g_{CO_2}\ g_{Mg_2SiO_4}^{-1}\ yr^{-1} = 0.626 ton_{CO_2}\ ton_{Mg_2SiO_4}^{-1}\ yr^{-1}$$

## $CO_2$ mineralization rate of weathering electrolyzer

Our study centered on $CaSiO_3$, and thus the weathering reaction for wollastonite was used to calculate the $CO_2$ mineralization rate of our electrolyzer, i.e., $r_{CaSiO_3}$. We take the calculation of $r_{CaSiO_3}$ for our weathering electrolyser purged with simulated flue gas as an example.

Given that 0.4992 g of $CaCO_3$ precipitated in the cathode chamber, the mass of $CO_2$ captured and converted into $CaCO_3$ in the weathering electrolyzer ($m_{CO_2}$) was calculated based on the following equation,

$$m_{CO_2} = \frac{m_{CaCO_3} M_{CO_2}}{N_{CaCO_3/CO_2} M_{CaCO_3}}$$

$$m_{CO_2} = \frac{0.4992\ g \times 44.01\ g\ mol^{-1}}{1 \times 100.09\ g\ mol^{-1}} = 0.2195\ g_{CO_2}$$

where $N_{CaCO_3/CO_2}$ is the stoichiometric ratio of $CaCO_3$ to $CO_2$ (i.e., 1).

Then, the mass of dissolved $CaSiO_3$ during electrolysis ($m_{CaSiO_3}$) was calculated in the following equation.

$$m_{CaSiO_3} = \frac{it\ SA\ M_{CaSiO_3}}{N_{e/CaSiO_3} F}$$

$$m_{CaSiO_3} = \frac{0.1\ A\ cm^{-2} \times 4\ cm^{2} \times 1h \times 116.16\ g\ mol^{-1}}{2 \times 96485\ C\ mol^{-1}} = \frac{0.4\ A \times 3600\ s \times 116.16\ g\ mol^{-1}}{2 \times 96485\ A\ s\ mol^{-1}}$$

$$= \frac{167270\ A\ s\ g\ mol^{-1}}{192970\ A\ s\ mol^{-1}} = 0.8668\ g_{CaSiO_3}$$

where $N_{e/CaSiO_3}$ is the stoichiometric ratio of electrons to $CaSiO_3$ in Fig. 1 (i.e., 2).

Thus, the $CO_2$ mineralization rate of our weathering electrolyser over 1 hour of electrolysis was calculated as follows:

$$r_{CaSiO_3} = \frac{m_{CO_2}}{m_{CaSiO_3} t}$$

$$r_{CaSiO_3} = \frac{0.2195\ g_{CO_2}}{0.8668\ g_{CaSiO_3} \times 1\ h} = 0.2532 g_{CO_2}\ g_{CaSiO_3}^{-1} h^{-1}$$

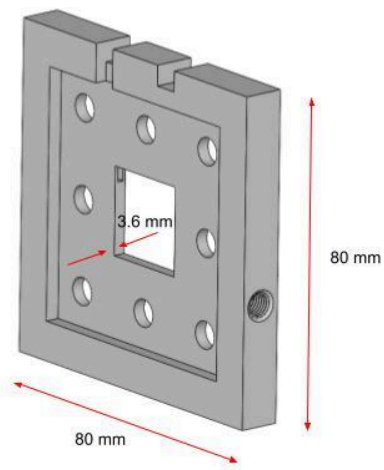
Lastly, to compare to natural weathering, we calculate the yearly $CO_2$ mineralization rate of our weathering electrolyzer operating at current density of 100 mA cm$^{-2}$ with simulated flue gas (10% $CO_2$) purging into catholyte:

$$r_{CaSiO_3} = \frac{0.2532\ g_{CO_2}}{g_{CaSiO_3} h} \times \frac{24 \times 365 h}{yr}$$

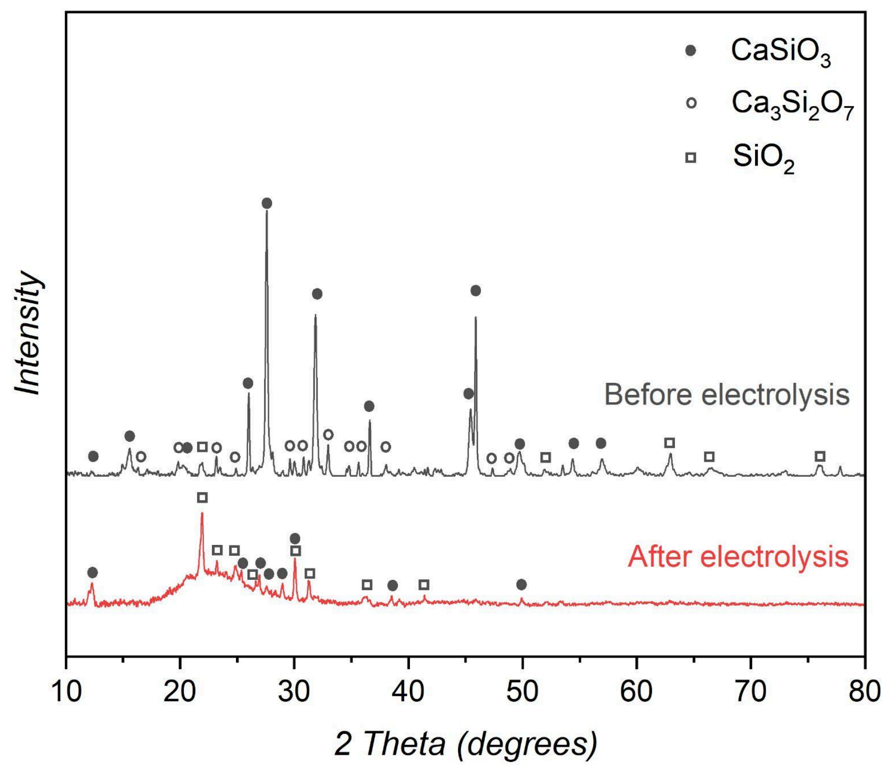
$$= 2218\ g_{CO_2}\ g_{CaSiO_3}^{-1} yr^{-1} = 2218\ ton_{CO_2}\ ton_{CaSiO_3}^{-1} yr^{-1}$$

Similarly, the $CO_2$ mineralization rate of our weathering electrolyser using $CaSiO_3$ and purging with ambient air is calculated to be 69.32 $ton_{CO_2}\ ton_{CaSiO_3}^{-1} yr^{-1}$.

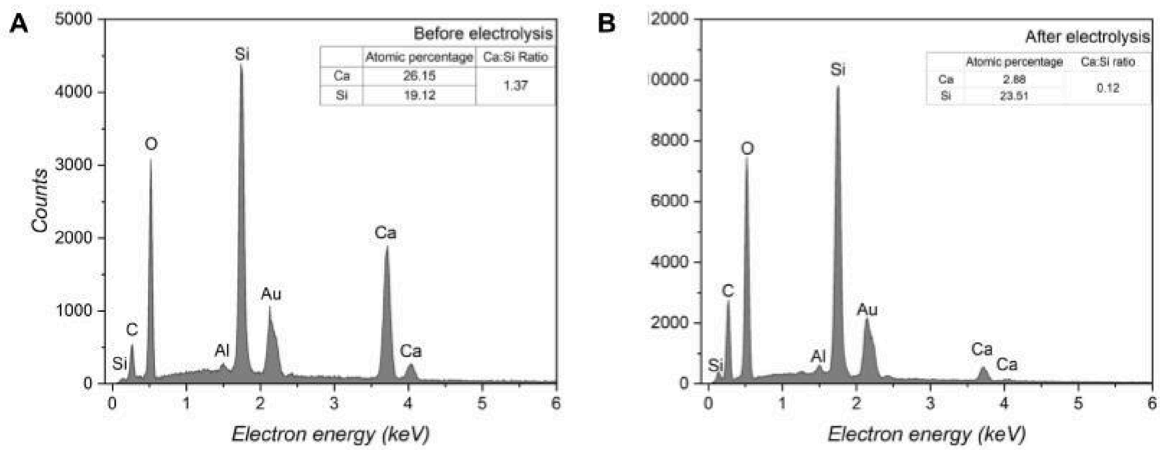
## Supplementary Figures



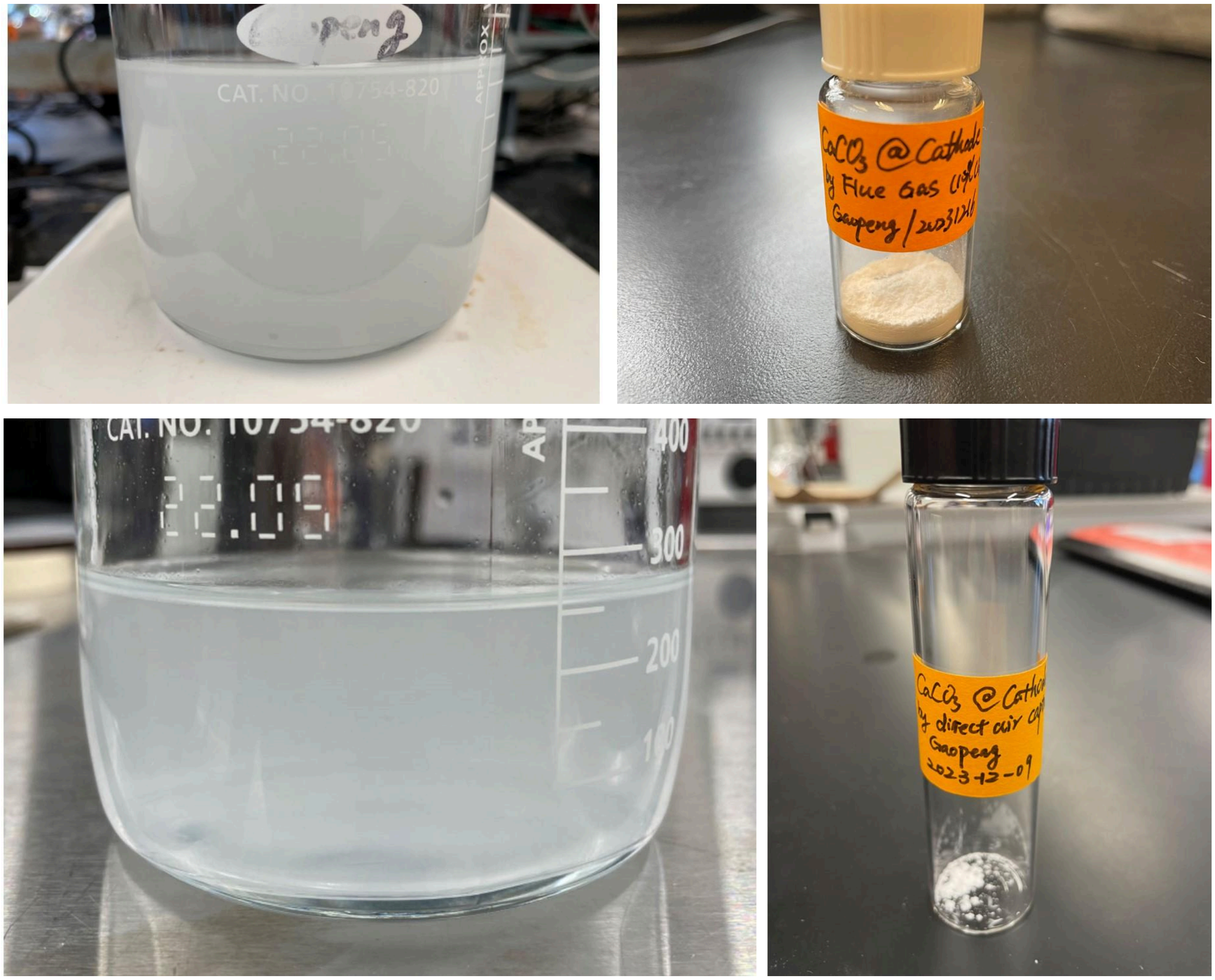

**Supplementary Figure 1:** Dimensions of the 3D-printed chemical chamber.




**Supplementary Figure 2:** XRD diffractograms of $CaSiO_3$ introduced into the chemical chamber before electrolysis,[2,3] and the solids collected in the chemical chamber after 1 hour of electrolysis. Note that the $CaSiO_3$ signals are less prominent after electrolysis, and the onset of the broad signal at 25 degrees is consistent with amorphous $SiO_2$.[4–6]

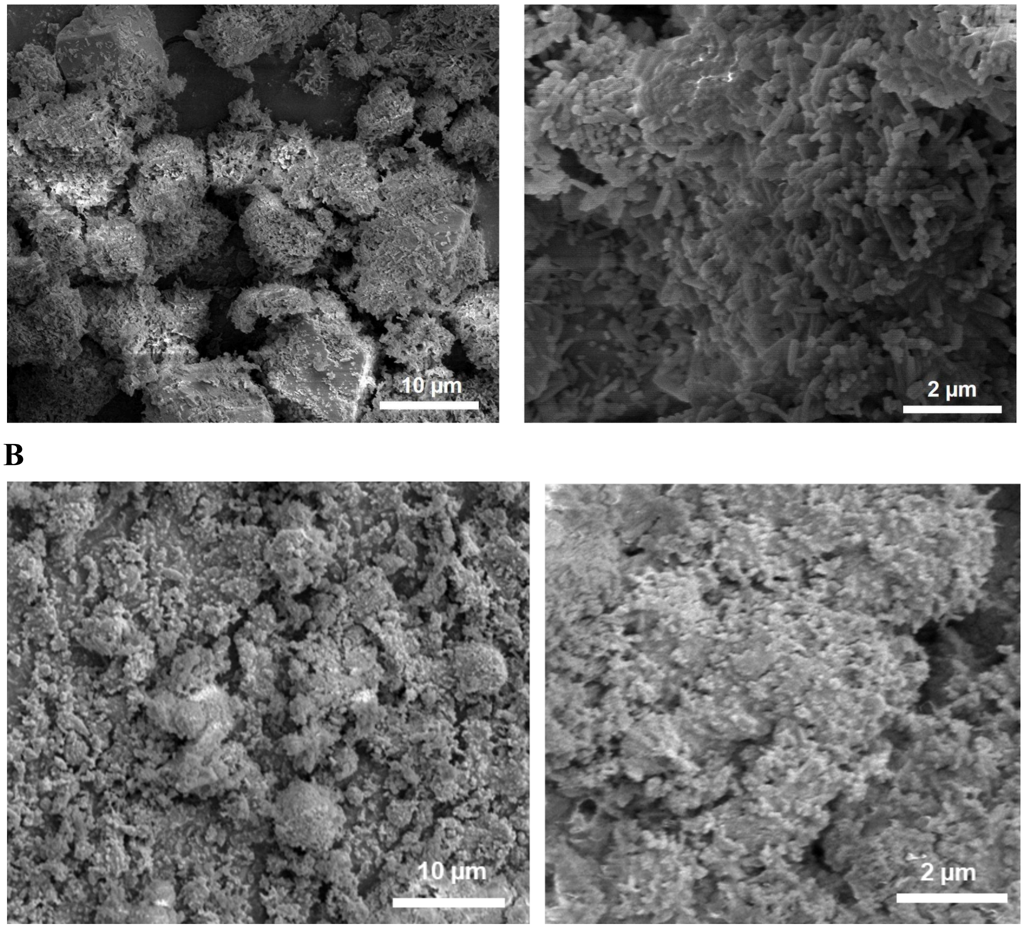



**Supplementary Figure 3:** EDX spectra of commercial $CaSiO_3$ (**A**) before and (**B**) after 60 minutes electrolysis. Gold sputtering was applied for SEM sample preparation. The detection of carbon and aluminum was assigned to conductive tape and aluminum sample stab.

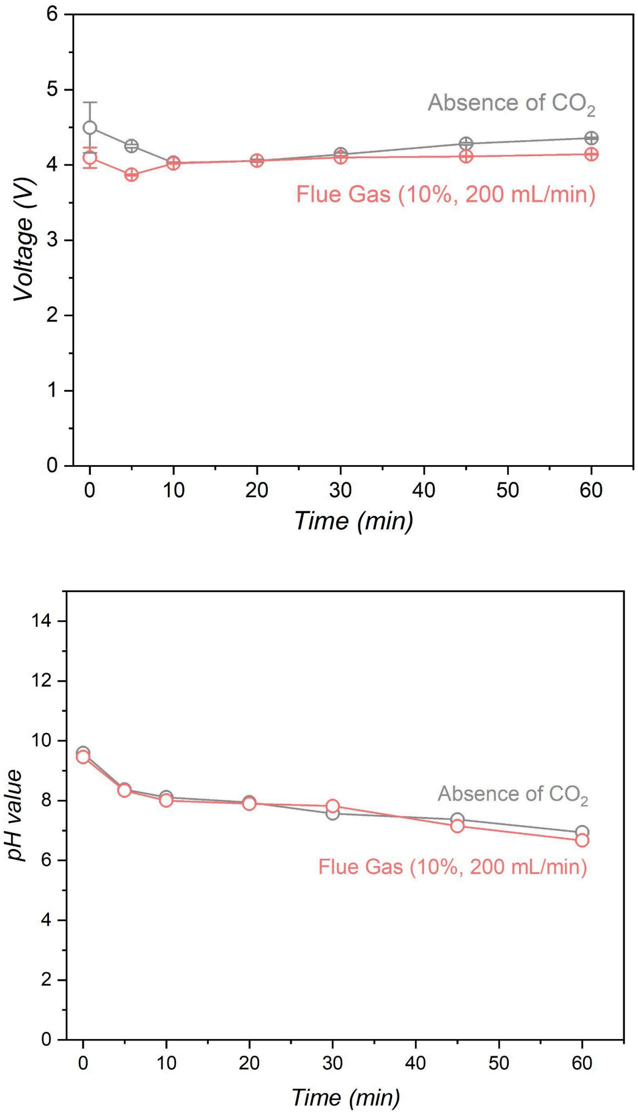



**Supplementary Figure 4:** Photographs of the catholyte (left) and $CaCO_3$ solid (right) after electrolysis at 100 mA cm$^{-2}$ in the presence of the simulated flue gas (10% $CO_2$, 90 % $N_2$) (top panel), and air (bottom panel).

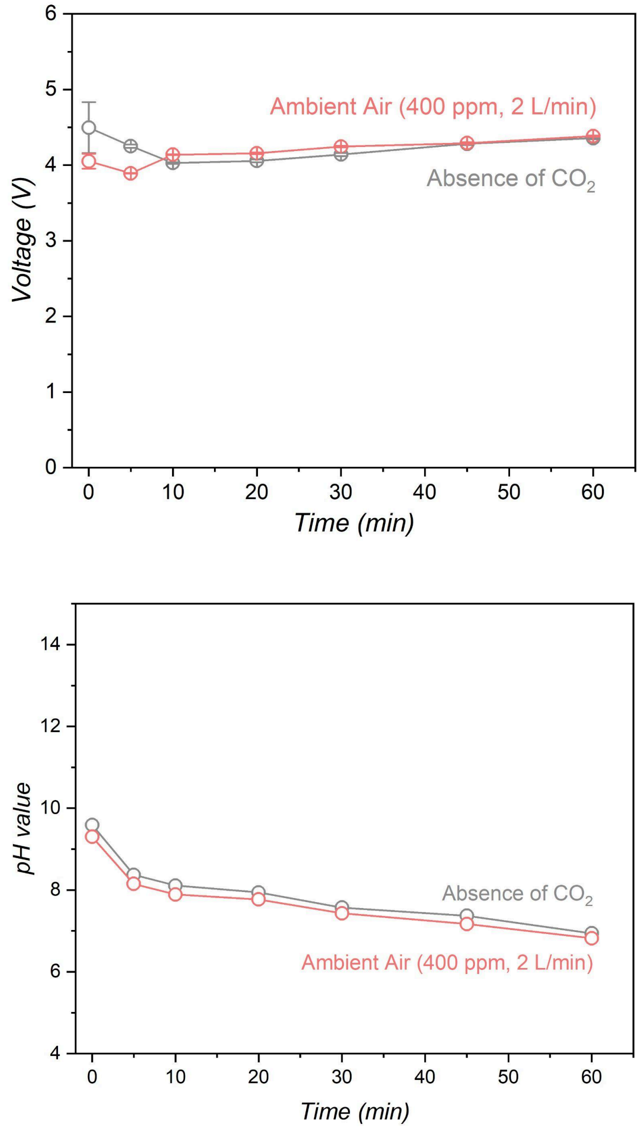
**A**



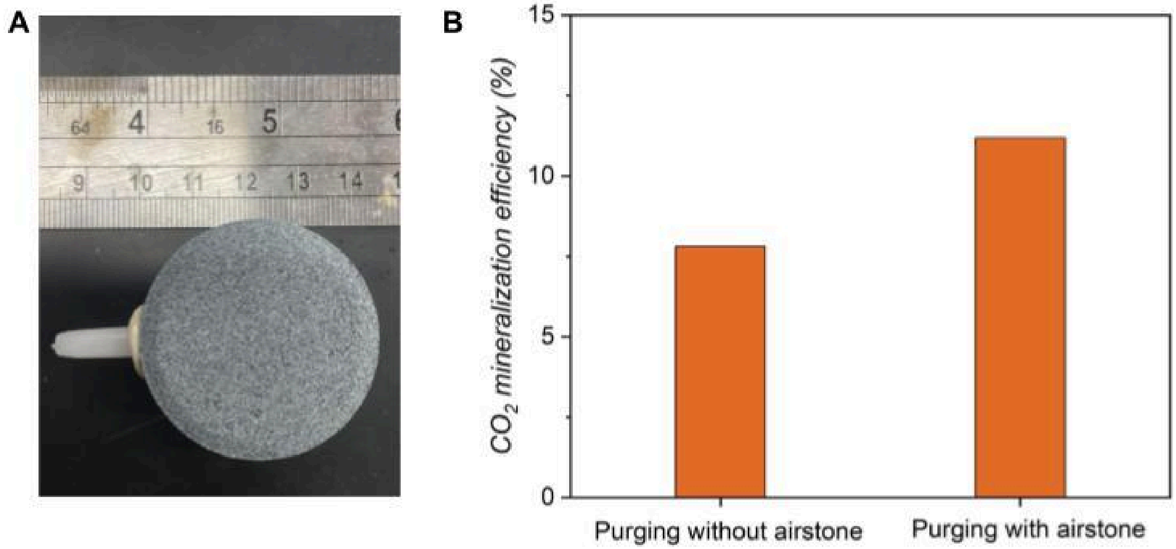

**Supplementary Figure 5:** SEM images of white solid recorded from the cathode chamber after electrolysis at 100 mA cm$^{-2}$ in the presence of (**a**) simulated flue gas (10% $CO_2$, 90 % $N_2$) and (**b**) ambient air.




**Supplementary Figure 6:** Cell voltage (top) and catholyte pH (bottom) versus time for electrolysis at 100 mA $cm^{-2}$ without a $CO_2$ supply, in the presence of the simulated flue gas (10% $CO_2$, 90 % $N_2$).




**Supplementary Figure 7:** Cell voltage (top) and catholyte pH (bottom) versus time for electrolysis at 100 mA cm$^{-2}$ with and without a $CO_2$ supply, in the form of air.




**Supplementary Figure 8:** (**A**) The commercial airstone (diameter = 4 cm) used to purge ambient air. (**B**) The $CO_2$ mineralization efficiency of the weathering electrolyzer at 100 mA $cm^{-2}$ supplied with air, with and without the airstone.

## References


1. Sanna, A., Hall, M. R. & Maroto-Valer, M. Post-processing pathways in carbon capture and storage by mineral carbonation (CCSM) towards the introduction of carbon neutral materials. *Energy Environ. Sci.* **5**, 7781–7796 (2012).
2. Zhao, H., Park, Y., Lee, D. H. & Park, A.-H. A. Tuning the dissolution kinetics of wollastonite via chelating agents for $CO_2$ sequestration with integrated synthesis of precipitated calcium carbonates. *Phys. Chem. Chem. Phys.* **15**, 15185–15192 (2013).
3. Monasterio-Guillot, L., Di Lorenzo, F., Ruiz-Agudo, E. & Rodriguez-Navarro, C. Reaction of pseudowollastonite with carbonate-bearing fluids: implications for $CO_2$ mineral sequestration. *Chem. Geol.* **524**, 158–173 (2019).
4. Yu, L. Y., Huang, Z. X. & Shi, M. X. Synthesis and characterization of silica by sol-gel method. *Adv. Mat. Res.* **1030**, 189–192 (2014).
5. Guo, Q. *et al.* Synthesis of dispersed amorphous $SiO_2$ nanoparticles via sol–gel process. *Ceram. Int.* **43**, 192–196 (2017).
6. Biswas, R. K. *et al.* Study of short range structure of amorphous silica from PDF using Ag radiation in laboratory XRD system, Raman and NEXAFS. *J. Non-Cryst. Solids* **488**, 1–9 (2018).