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## Separation of rare earth elements and nickel harnessing electrochemistry and reactive CO<sub>2</sub> capture and mineralization†

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**The aim is to probe the chemical mechanisms underlying the use of multifunctional solvents to simultaneously capture and convert CO<sub>2</sub> into insoluble rare earth element (REE)-carbonates, while forming soluble complexes with nickel for separation. Subsequent nickel electro-deposition regenerates the CO<sub>2</sub>-loaded solvent for reuse.**

Advances in technologies that harness CO<sub>2</sub> emissions for the recovery of energy relevant metals are crucial for a sustainable and secure energy future.<sup>1</sup> The growing demand for critical metals such as REEs and nickel, driven by their limited supply and rapid depletion of conventional high grade ores,<sup>2</sup> has sparked interest in recovering these metals from unconventional sources such as industrial residues<sup>3</sup> and recycled materials.<sup>4</sup> Current methods including pyrometallurgy (heat-based extraction)<sup>5</sup> and hydrometallurgy (chemical leaching and liquid-liquid extraction) are used for separation.<sup>6–8</sup> Despite significant progress, the greenhouse gas footprint associated with heating, or the use of these reagents is significant,<sup>9</sup> and alternative environmentally sustainable pathways are needed. One promising approach involves the capture and use of CO<sub>2</sub> for metal separations. Metal chelating amine ligands have been demonstrated for simultaneous CO<sub>2</sub> mineralization and recovery of metals such as Ni, Fe, and Cr in the solution phase.<sup>10</sup> However, the use of CO<sub>2</sub> capture solvents for the separation of REEs and transition metals such as Ni remains less explored.

In this context, it is well-known that REE-carbonates have low solubilities in water and can be preferentially separated *via* crystallization using CO<sub>2</sub> capture solvents that solubilize CO<sub>2</sub> and regenerate upon REE – carbonate precipitation. The separation of

La, Ni, and Co was reported using diethylenetriamine and carbon dioxide – bearing flue gas.<sup>4</sup> After lanthanum carbonate precipitation, ethanol and CO<sub>2</sub> were used to separate Ni<sup>2+</sup> and Co<sup>2+</sup> ions. While effective, this approach relies on multiple solvent-based techniques for sequential separation and requires efficient solvent regeneration for cost-effectiveness. An alternative approach would be to utilize multifunctional solvents that can effectively capture CO<sub>2</sub>, precipitate REE-carbonates, and serve as an effective medium for Ni precipitation without undergoing degradation. This approach eliminates the need for additional solvents for Ni recovery and instead regenerates the multifunctional solvent which can be looped multiple times for separating REEs (La<sup>3+</sup>, Pr<sup>3+</sup>, Nd<sup>3+</sup>, Eu<sup>3+</sup>, Dy<sup>3+</sup>) ions from Ni<sup>2+</sup> ions.

These scientific possibilities and challenges motivate the investigation of CO<sub>2</sub> capture solvents such as aqueous ammonium hydroxide (NH<sub>4</sub>OH), aqueous monoethanolamine (MEA), and aqueous diethylenetriamine (DETA). NH<sub>4</sub>OH is effective in forming soluble complexes with Ni,<sup>11</sup> MEA efficiently captures CO<sub>2</sub> and converts it to REE-carbonates,<sup>12</sup> and DETA has been reported for separating La and Ni in solvent – based extraction<sup>4</sup> though its effectiveness in electroplating remains unexplored. Despite these advances, the following specific research questions remain unexplored: (1) what are the chemical mechanisms associated with the use of amine bearing CO<sub>2</sub> capture solvents for REE and Ni separations? (2) After the recovery of REE-carbonates, what is the efficacy and associated coulombic efficiencies of Ni electrodeposition? (3) What is the influence of chemical speciation on product yields, purities, and morphologies? Addressing these questions will unlock new insights into the multifunctional role of solvents in capturing CO<sub>2</sub>, enabling the separation of REEs as water – insoluble carbonates, and mediating Ni electrodeposition (see Fig. 1).

To elucidate the importance of CO<sub>2</sub> capture solvents in enhancing CO<sub>2</sub> solubility, and facilitating REE separation, two control experiments are conducted with solutions bearing 588 ppm La and 1176 ppm Ni. In the first control experiment, CO<sub>2</sub> is bubbled directly through the aqueous La/Ni solution for 12 hours resulting in no precipitation. Consequently, no carbonate formation is

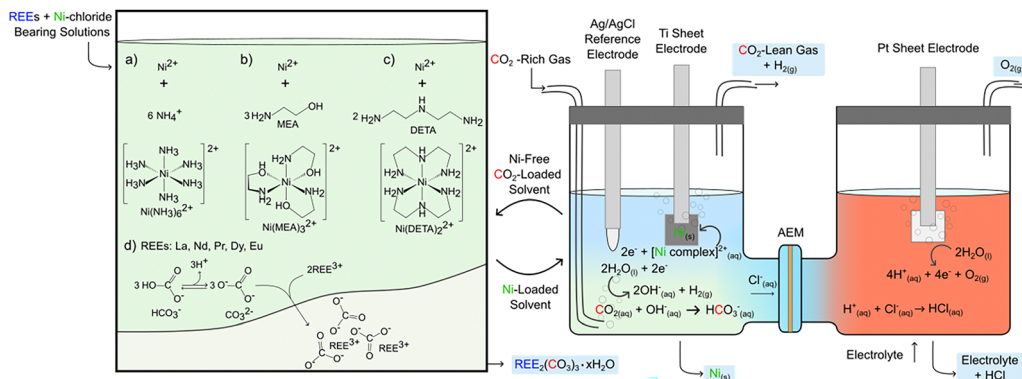
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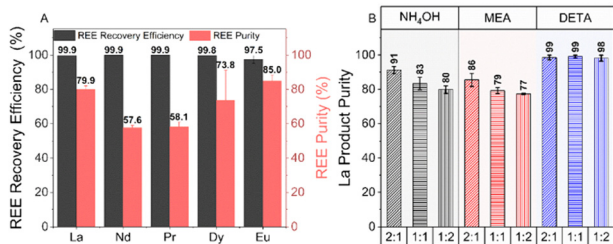
**Fig. 1** Proposed approach to separate La and Ni using CO<sub>2</sub> and multifunctional solvents. Preferred reactions illustrated with (a) ammonium hydroxide (NH<sub>4</sub>OH), (b) monoethanolamine (MEA) and (c) diethylenetriamine (DETA) are based on the most stable complexes shown in ESI† Table S2. Products include REE-carbonates, electrodeposited nickel, H<sub>2</sub>, O<sub>2</sub>, and regenerated solvent for the next cycles. All measurements are performed at room temperature.

observed due to the low solubility of CO<sub>2</sub> in pure water, indicating that CO<sub>2</sub> capture solvents are needed. In the second control experiment, equal volumes of CO<sub>2</sub> loaded aqueous NaOH, and aqueous La/Ni solution are mixed, which resulted in La recovery efficiencies as lanthanum carbonate up to 99.9 (±0.1)%. However, this is also accompanied by 70.7% (±0.5)% of Ni precipitation resulting in La-carbonate purity and separation factor ( $\beta$ ) of 46.4 (±0.7)% and 370.5 (±8.2), respectively. These base case separation factors are within a similar range of 314.6–3827.8 for La/Ni separation reported using other separation processes.<sup>6–8</sup> Nonetheless, more selective separation of La and Ni can be achieved by co-utilizing CO<sub>2</sub> and soluble metal chelating agents, which motivated the investigation of NH<sub>4</sub>OH, MEA, and DETA.

As shown in Fig. 2 and Table S1 (ESI†), La recovery efficiencies exceeding 99.5% are reported with NH<sub>4</sub>OH, MEA, and DETA. In addition, suppressed Ni co-extraction is observed (0–17.53% co-recovery efficiencies) at similar conditions with the control experiments (1:2 for La: Ni) resulting in separation factors of (4524–11630), (2131–4457), and (8784 – no Ni detected in carbonate phase) for NH<sub>4</sub>OH, MEA, and DETA, respectively. Increasing Ni co-extraction efficiency is reported in the order of DETA < NH<sub>4</sub>OH < MEA. Notably, this trend in Ni co-extraction efficiency is significantly influenced by the ability for Ni to form stable complexes in solution. Table S2 (ESI†) shows that Ni-DETA complexes have higher stabilities compared to those with NH<sub>4</sub>OH or MEA. The formation of this soluble complex is also evident from the change in the colour of the solution bearing Ni from green to

purple on DETA addition (Fig. S1(d), ESI†). The effectiveness of harnessing NH<sub>4</sub>OH for separating other REEs such as praseodymium (Pr), neodymium (Nd), europium (Eu), and dysprosium (Dy) is also investigated. From a thermodynamic standpoint, the respective stability constants of REE-carbonates are similar, which is an indicator of similar behaviour as with La while keeping all other factors constant. Fig. 2(A) and Table S1 (ESI†) also show that recoveries exceeding 98% are also observed for all the four REEs of interest. Moreover, the regeneration of the CO<sub>2</sub>-free solvent can be achieved at higher REE concentrations as demonstrated with MEA in Fig. S2(a)–(d) (ESI†).

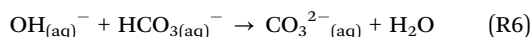
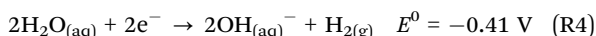
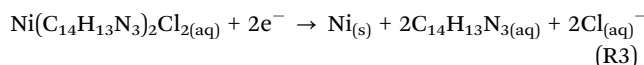
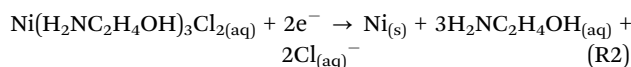
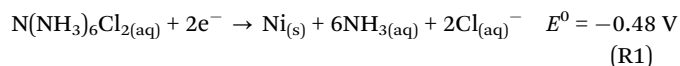
Evidence of REE carbonate formation is determined by investigating the thermal decomposition behaviour using TGA (Fig. S3, ESI†). Weight losses in the range of 80–240 °C accounts for ~6.7%, 7.2% and 5.7% of the sample weight in NH<sub>4</sub>OH, MEA and DETA respectively are associated with the loss of H<sub>2</sub>O molecules implying the presence of hydrated carbonate species.<sup>13,14</sup> Higher loss of H<sub>2</sub>O observed with MEA and NH<sub>4</sub>OH is likely due to the presence of hydrated Ni-carbonate. This observation is confirmed by the weight loss in the temperature range of 210–430 °C associated with the loss of CO<sub>2</sub> in Ni-carbonate.<sup>14</sup> Fig. S4(a) (ESI†) shows the TGA, DTG and DSC profile of pure hydrated Ni-carbonate for comparison. It is important to note that Ni-hydroxide and Ni-carbonate decompose at overlapping temperature ranges.<sup>14</sup> However, FTIR analyses confirm the absence of the characteristic OH stretching vibrations of Ni(OH)<sub>2</sub>, typically observed at 3645 (±3) cm<sup>-1</sup> (ref. 15) as shown in Fig. S4(b) (ESI†). In the next step, at temperatures in the range of 260–580 °C, lanthanum carbonate La<sub>2</sub>(CO<sub>3</sub>)<sub>3</sub> decomposes into La<sub>2</sub>O<sub>2</sub>(CO<sub>3</sub>), releasing CO<sub>2</sub>.<sup>13</sup> The fourth weight loss is perhaps the most distinct characteristic weight loss feature of lanthanum carbonate which represents the decomposition of La<sub>2</sub>O<sub>2</sub>CO<sub>3</sub> to release CO<sub>2</sub> and produces La<sub>2</sub>O<sub>3</sub>.<sup>13</sup> DETA is observed to have the highest weight loss (~7%) compared with ~4% in MEA and NH<sub>4</sub>OH implying a relatively higher purity of La-carbonate. This observation is further confirmed by the distinct green colour of Ni in the final product recovered from experiments performed using NH<sub>4</sub>OH and MEA (Fig. S5, ESI†) contrasted with a product free of any coloration obtained from DETA post separation. SEM images shown in Fig. S3(d)–(f) (ESI†) reveal the presence of aggregated clusters with rosette and flat morphologies in La-carbonate produced.<sup>3,10,16–18</sup>



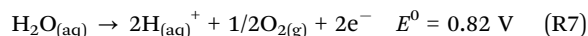
**Fig. 2** (A) Recovery efficiencies and product purity for REE/Ni separation using NH<sub>4</sub>OH at REE: Ni of 1:2. (B) The product purity at different concentration ratios for NH<sub>4</sub>OH, MEA and DETA.



Cathodic reactions  $E^0$  vs. SHE, pH = 7



Anodic reactions  $E^0$  vs. SHE, pH = 7



The reactions proposed for Ni recovery are shown in (R1)–(R8). Ni deposition at the cathode is facilitated by decomplexation through a gain of electrons to deposit solid Ni species as shown in (R1)–(R3). Thermodynamic plots shown in Fig. S6 (ESI†) show the possibility for Ni to form complexes of varying oxidation states including  $[\text{Ni}(\text{NH}_3)_x]^{2+}$ ,  $[\text{Ni}(\text{H}_2\text{NC}_2\text{H}_4\text{OH})_x]^{2+}$ , and  $[\text{Ni}(\text{C}_{14}\text{H}_{13}\text{N}_3)_x]^{2+}$ , where  $x$  typically varies from 1–6, 1–3, and 1–2 in  $\text{NH}_4\text{OH}$ , MEA, and DETA, respectively. Nonetheless, the most stable Ni complexes in this study are those with  $x = 6$ , 3, and 2 for  $\text{NH}_4\text{OH}$ , MEA, and DETA, respectively (see Table S2, ESI†). One key side reaction to consider is the hydrogen evolution reaction (HER) at the cathode, which competes for electrons (R4). HER requires a similar number of electrons as Ni electrodeposition which implies that neither has a kinetic advantage. However, HER is favoured at higher potentials, and lower Ni concentrations,<sup>19</sup> due to rapidly depleting supersaturation around the electrode surface leading to lower Ni electrodeposition Coulombic efficiencies (CE).<sup>16</sup>

To evaluate the effect of  $\text{NH}_4\text{OH}$ , MEA, and DETA on the electrochemical reduction of Ni, linear sweep voltammetry (LSV) curves are obtained in Fig. S7 (ESI†). Two significant differences were observed among the three solvents. First, the reduction potentials for Ni were more negative for DETA ( $-0.638 \text{ V}$  vs. RHE) compared to MEA ( $-0.496 \text{ V}$  vs. RHE) and  $\text{NH}_4\text{OH}$  ( $-0.454 \text{ V}$  vs. RHE). The more negative reduction potential with DETA is attributed to the formation of more stable Ni complexes, requiring greater energy for Ni deposition. Although Ni–MEA complexes are less stable than Ni– $\text{NH}_3$ , MEA shows a more negative reduction potential, likely due to slower mass transport of the bulkier Ni–MEA complex, resulting in diffusion-limited behavior. Second, the slopes of the LSV curves decrease in the order:  $\text{NH}_4\text{OH} > \text{MEA} > \text{DETA}$ , consistent with decreasing mass transport rates of Ni ions toward the electrode surface.<sup>11</sup>

Since regeneration of the impurity-free  $\text{CO}_2$  loaded solvent is of importance, it is essential that these reactions are carried out in a two-chamber cell to facilitate the migration of  $\text{Cl}^-$  ions. It has been reported that the chlorine evolution reactions could occur in a

one-chamber cell at the anode leading to the evolution of chlorine gas.<sup>16</sup> Moreover the formation of  $\text{Cl}_2$  gas could result in a homogeneous reaction with  $\text{NH}_3$  to produce  $\text{N}_2$  leading to ammonia consumption.<sup>11</sup> Ammonia consumption through this reaction has been reported in the order of 0.193 kg of  $\text{NH}_3$ /kg of Ni.<sup>11</sup> Furthermore, the buildup of  $\text{Cl}^-$  ions could lead to increased acidity and solvent degradation. These side reactions can be avoided by the proposed two chamber cell configuration with an AEM to facilitate the migration of  $\text{Cl}^-$  ions to the anode. At the anode, oxygen evolution reaction (OER) occurs producing protons that stabilize the  $\text{Cl}^-$  ions to generate HCl as shown in (R7)–(R8).

Fig. 3(A) shows the (CE) and the yield rate of Ni per unit area of titanium electrode for each solvent at a galvanostatic hold of 100 mA for 1 hour. The highest yield rates and CE of  $32 \text{ mg h}^{-1} \text{ cm}^{-2}$  and 29% respectively, are obtained with  $\text{NH}_4\text{OH}$ . The CE and rate of deposition of these systems is dependent on the starting concentration of Ni and the electrolyte.<sup>19</sup> CE of 45% have been reported for electrodeposition of 1700 ppm Ni from a single chamber cell in an ammoniacal buffer system consisting of  $(\text{NH}_4)_2\text{SO}_4$ ,  $\text{NH}_3$  and  $\text{H}_2\text{SO}_4$ .<sup>16</sup> Moreover the CE is observed to slowly decrease with time (Fig. S8, ESI†), which matches the asymptotic behaviour also observed with Ni recovery efficiencies as a function of time shown in Fig. 3(B). Up to 90% of Ni is electrodeposited after 4 hours of electrolysis from  $\text{NH}_4\text{OH}$  and MEA, and up to 4% with DETA. DETA shows early asymptotic behavior, resulting in slower deposition rates, likely due to the transformation of NiDETA into the more stable  $\text{Ni}(\text{DETA})_2$  complex as the pH rises due to competing hydrogen evolution reaction (HER) (Table S2, ESI†). A pH increase of 3.64 from neutral conditions is observed, suggesting that  $\text{Ni}(\text{DETA})_2$  complex becomes more prominent in this system according to thermodynamic speciation calculations shown in Fig. S6 (ESI†), implying that a buffer system is required. A similar slow pH increase is observed with  $\text{NH}_4\text{OH}$  and MEA which is detrimental for electrodeposition as

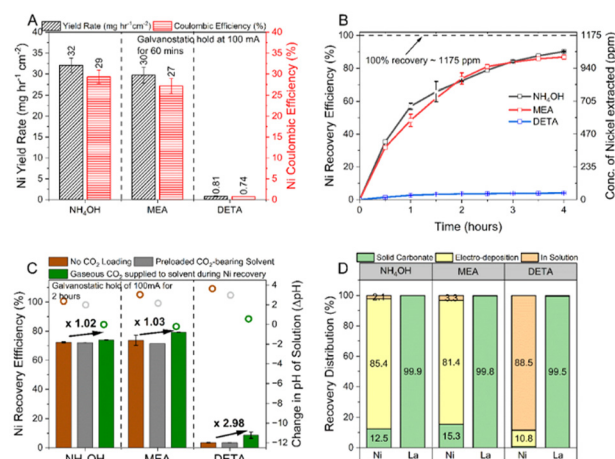


Fig. 3 (A) Ni yield rate and coulombic efficiencies in different  $\text{CO}_2$  capture solvents at galvanostatic hold of 100 mA for 1 h. (B) Ni recovery efficiency vs. time for  $\text{NH}_4\text{OH}$ , MEA and DETA. (C) Effect of  $\text{CO}_2$  loading on Ni recovery. (D) Integrated experiments showing product distribution as carbonates, electrodeposited material and unrecovered metal.



Ni species undergo hydrolysis at higher pH conditions to precipitate as hydroxides.

The pH in these systems is typically modulated by adding a buffer, with boric acid commonly used to both regulate pH and reduce overpotential by forming weak Ni borate complex ( $\text{Ni}(\text{H}_2\text{BO}_3)_2$ ) in solution.<sup>20</sup> Alternatively, we propose using  $\text{CO}_2$ , which dissolves and speciates into carbonate and bicarbonate, consuming  $\text{OH}^-$  ions from the HER (R4)–(R6), and controlling pH.  $\text{CO}_2$  also forms carbamate species with amine which could also aid in Ni extraction. As shown in Fig. 3(C), continuous  $\text{CO}_2$  supply during electrodeposition improves recovery efficiencies by 1.02, 1.03, and 2.98 times for  $\text{NH}_4\text{OH}$ , MEA and DETA respectively after 120 min. Further, the pH change was  $-0.01$ ,  $-0.21$ , and  $0.57$  for  $\text{NH}_4\text{OH}$ , MEA and DETA respectively, compared to 2.37, 3.03, and 3.64 obtained without  $\text{CO}_2$ . The relatively higher  $\Delta\text{pH}$  with DETA compared to MEA and  $\text{NH}_4\text{OH}$  is also an indication of the lower Ni extraction CE obtained in Fig. 3(A) due to HER. The effect of  $\text{CO}_2$  on Ni electrodeposition appears to be primarily through pH modulation, not complexation. Experiments performed using  $\text{CO}_2$  loaded solvent after REE separation showed no significant enhancement in Ni recovery, despite NMR analysis confirming the presence of similar amine- $\text{CO}_2$  species such as carbamates,  $\text{HCO}_3^-/\text{CO}_3^{2-}$  ions (Fig. S9, ESI<sup>†</sup>).

The chemical phases, structural and morphological features of the electrodeposited Ni, is discussed using XRD, SEM and XPS analyses. Fig. S10(a)–(c) (ESI<sup>†</sup>) shows the formation of dark shiny particles on the surface of the electrode indicating a successful electrowinning process. Ni particles of different sizes are observed in Fig. S11(a)–(f) (ESI<sup>†</sup>). The Ni deposit obtained for  $\text{NH}_4\text{OH}$ , MEA, and DETA at galvanostatic hold of 100 mA appeared to be a non-compact, silvery dark powder with spherical morphology which could be easily scraped off the titanium sheet electrode (Fig. S11(a)–(f), ESI<sup>†</sup>). It is important to also disclose that a different sheet-like morphology is observed when working at lower current densities  $< 5$  mA (see Fig. S12c, ESI<sup>†</sup>). XRD analysis on the scraped powder showed the presence of 111, 200, and 220 phases in Fig. S12 (ESI<sup>†</sup>) associated with pure metallic Ni (PDF 03-065-2865). This is confirmed by high resolution XPS scans which showed the characteristic binding energy of  $\text{Ni}^0$  for  $2\text{p}^{3/2}$  at 852.7 eV with  $\Delta E$  of 17.27 from  $2\text{p}^{1/2}$  indicating the presence of pure metallic Ni. This  $\text{Ni}^0$  peak decreased in intensity when comparing  $\text{NH}_4\text{OH}$  to MEA and could not be detected in the Ni species from DETA. XRD analysis on the Ti electrode bearing Ni for DETA confirms the presence of Ni oxides as opposed to pure metallic Ni observed with  $\text{NH}_4\text{OH}$  and MEA.

To illustrate the flexibility of this concept for integrated  $\text{CO}_2$  capture and the separation of REEs and Ni, we performed a stepwise separation of La and Ni using  $\text{CO}_2$  loaded aqueous  $\text{NH}_4\text{OH}$ , MEA and DETA. Lanthanum carbonate phases with  $> 99.5\%$  yield were observed in all solvents (Fig. 3(D)), however, 12.5% and 15.3% Ni-carbonates are also co-recovered. Product purity could be improved by controlling  $\text{CO}_2$  concentration in the solution. The similar stability constants of  $\text{NiCO}_3(\text{aq})$  and  $\text{Ni-NH}_4\text{OH}(\text{aq})/\text{Ni-MEA}(\text{aq})$  complexes led to partial Ni precipitation as carbonate. However, insignificant quantities of Ni are observed with DETA due to the formation of a significantly

stronger complex. This stronger complexation challenges electrochemical Ni recovery in the subsequent step. Ni recovery up to 85% and 81% is obtained using  $\text{NH}_4\text{OH}$  and MEA, but only 11% using DETA. To improve Ni electrodeposition, higher temperatures can enhance electrolyte conductivity, ion diffusivity, and charge transfer rates leading to better recovery efficiencies, however, the risk of solvent decomposition exists. Alternatively, solvents that binds Ni preferentially over REE ( $\log K$  values 10–18) could be explored, ensuring Ni binding is not too strong to hinder electrodeposition. Additionally, solvents must be chemically stable and efficient in  $\text{CO}_2$  capture.

In summary, using  $\text{CO}_2$  capture solvents to separate REEs and Ni is highly effective, achieving REE yields up to 99% with product purities of 80%, 79% and 98% for  $\text{NH}_4\text{OH}$ , MEA and DETA, respectively. While DETA is more effective for REE–Ni separation, its strong Ni-complex formation challenges nickel recovery during electrodeposition. Also, the supply of  $\text{CO}_2$  during electrodeposition improves Ni recovery by modulating pH and forming alternative complexes. Scalable deployment can be achieved by optimizing this approach to maximize  $\text{H}_2$  and  $\text{O}_2$  recovery and ensure efficient solvent regeneration over multiple cycles.

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## Data availability

The data supporting this article has been included as part of the ESI<sup>†</sup>.

## Conflicts of interest

G. G. co-founded Carbon To Stone to valorize emissions for producing high value products.

## Notes and references

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