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Large-scale electrolytic molten carbonate carbon capture and transformation to carbon nanotubes and other graphene nanocarbons

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Case Study

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Abstract

This study explores the development and scale-up of an emerging carbon capture technology using molten carbonate electrolysis, which converts CO_2 into high-value graphene nanocarbons (GNCs) and oxygen in a single step, offering a scalable and economically incentivized pathway to address global greenhouse gas emissions. Paths to large-scale carbon capture using molten carbonate electrolysis that splits CO_2 into GNCs and O_2 are studied and advanced. GNCs include carbon nanotubes, carbon nano-onions and other zero-, one-, two- and three-dimensional graphene nanoallotropes. The CO_2 to carbon nanotechnology (C_2CNT) carbon capture utilization process directly removes the greenhouse gas CO_2 over a wide range of concentrations (from 400 ppm to pure CO_2), incentivizing the capture by providing a value-added product. Scale-up of the original lab-scale discovery of the transition metal nucleated electrolytic splitting of CO_2 to an industrial process is documented. The scale-up includes a three-order-of-magnitude increase in the size of the electrolysis electrodes, an increase in the individual electrolysis modules to 100-tonne CO_2 annually, and a new industrial-scale production extraction unit separating the molten electrolyte from the GNC product. The molten carbonate electrolyte has evolved from costly pure lithium carbonate to multicomponent carbonate electrolytes, predominantly based on 10-fold less expensive strontium carbonate. Other advances include the introduction of a new direct cathode press for separation and extraction of the GNC product, as well as specialized modifications of C_2CNT for carbon capture, utilization and storage of industrial processes (Genesis CCUS), direct air capture (Genesis DAC) and the separate recovery of the oxygen product (Genesis O_2).

Impact statement

Global warming and climate change caused by the principal greenhouse gas CO_2 are an existential threat to the planet. To date, CO_2 abatement processes have been ineffective on a large scale as planetary CO_2 emissions continue to rise. Industrial scaling and exciting advances in a new decarbonization process, CO_2 to carbon nanotechnology (C_2CNT), are discussed/presented. C_2CNT decarbonization utilizes a recently discovered chemistry to remove CO_2 through transition metal-nucleated electrochemical splitting, producing carbon and oxygen. The carbon product is valuable graphene nanocarbons (GNCs), such as useful carbon nanotubes, which are composed of concentric graphene cylinders. Additionally, the value of GNCs provides an economic incentive for carbon capture and removal.

Introduction

CO_2 emissions reached a record 37.4 Gt in 2024 (GCO 2024). Carbon capture, utilization and storage (CCUS) offers CO_2 removal and conversion into useful products (Ampoman et al. 2024; Memon et al. 2024). However, most industrial decarbonization relies on energy-intensive CO_2 concentration methods, such as amine-based solvents or membrane systems (Du et al. 2024; Navik et al. 2024; Rochelle 2024; Wang et al, 2024a, 2025; Zheng et al. 2024a) or lime-based reactions (Afani et al, 2024; Kumar et al. 2024; Zhang et al. 2024a,b). These systems are still only sporadically deployed, concentrating only on CO_2 rather than storing it and offer negligible and unproven sequestration capacity (Djlegarski et al. 2023).

CO_2 to carbon nanotechnology (C_2CNT) is a large-scale CCUS process that converts CO_2 into graphene-based nanocarbons (GNCs) by molten carbonate electrolysis (Ren et al. 2015b; Ren et al. 2019; Licht et al. 2020–2025; Liu et al. 2022a,b). The resulting zero-, one-, two- and three-dimensional (3D) symmetry graphene nanomaterials possess exceptional mechanical and electronic properties. GNCs are stable for geological timescales, as exemplified by graphite.

Molten carbonate electrolysis of CO_2 was introduced in 2009–2010 (Licht 2009; Licht et al. 2010b; Licht and Wang 2010; Licht et al. 2011), and evolved from prior work on solar-to-chemical energy conversion (Li et al. 2015a,b; Licht 2005; Licht et al. 1996, 1998, 1999, 2003, 2010a, 2010b, 1996–2010a, 2014–2019). By 2015, CO_2 was shown to convert directly into carbon nanofibers and nanotubes via transition-metal nucleation (Ren et al. 2015a, b; Ren et al. 2019; Licht et al. 2020–2025; Liu et al. 2022a,b,c). Electrolysis requires 0.8–2.0 V at 0.05–0.6 A/cm^2 (Licht et al. 2010b; Ren et al. 2015a). The carbonate electrolysis reactions are:

$$CO_3{}^{2-} \rightarrow C_{GNC} + O_2 + O^{2-} \tag{1}$$

CO_2 reacts with the oxide, releasing heat that rapidly and continuously regenerates the carbonate, as occurs with Li_2CO_3 or mixed $SrCO_3$ and Li_2CO_3 electrolytes.

$$\begin{aligned}&CO_2 + O^{2-} \rightarrow CO_3{}^{2-}:\\&Li_2CO_3 : CO_2 + Li_2O \rightarrow Li_2CO_3 \quad \Delta H(770\,°C) = -158{,}000\,J/mol\end{aligned} \tag{2}$$

$$\text{Net reaction} : CO_2 \rightarrow C_{GNC} + O_2 \tag{3}$$

Heat from CO_2 oxide reactions, and electrolysis overpotential, sustains the 650–800 °C operating temperature (Wang et al. 2020; Liu et al. 2022a,b,c). Unlike other systems, C$_2$CNT does not require CO_2 preconcentration. This article presents recent advances, including decarbonization from dilute CO_2, direct air capture (DAC) and separate O_2 collection for oxy-fuel use.

Results and discussion

C$_2$CNT capture of 5% CO_2

Industrial flue gases contain N_2, O_2 and H_2O and are largely insoluble in molten carbonates such as Li_2CO_3. In contrast, CO_2 dissolves and reacts readily in CO, enabling selective uptake (Figure 1A). CO_2 flows into the electrolysis chamber, reacts in the electrolyte and is converted to GNCs at the cathode. The oxide produced reacts with incoming CO_2, maintaining the electrolyte as a carbon sink.

Figure 1B shows a bench-scale C$_2$CNT system with a 12 × 12 × 15 cm carbon pot. CO_2 concentration is monitored with an external sensor cooled by a 304SS tube. Electrolysis at 5.0 A and 750 °C using Li_2CO_3 with a 25 cm² brass cathode reduced the exhaust CO_2 concentration from 5% to under 0.2% (Figure 1C), indicating over 75% capture efficiency.

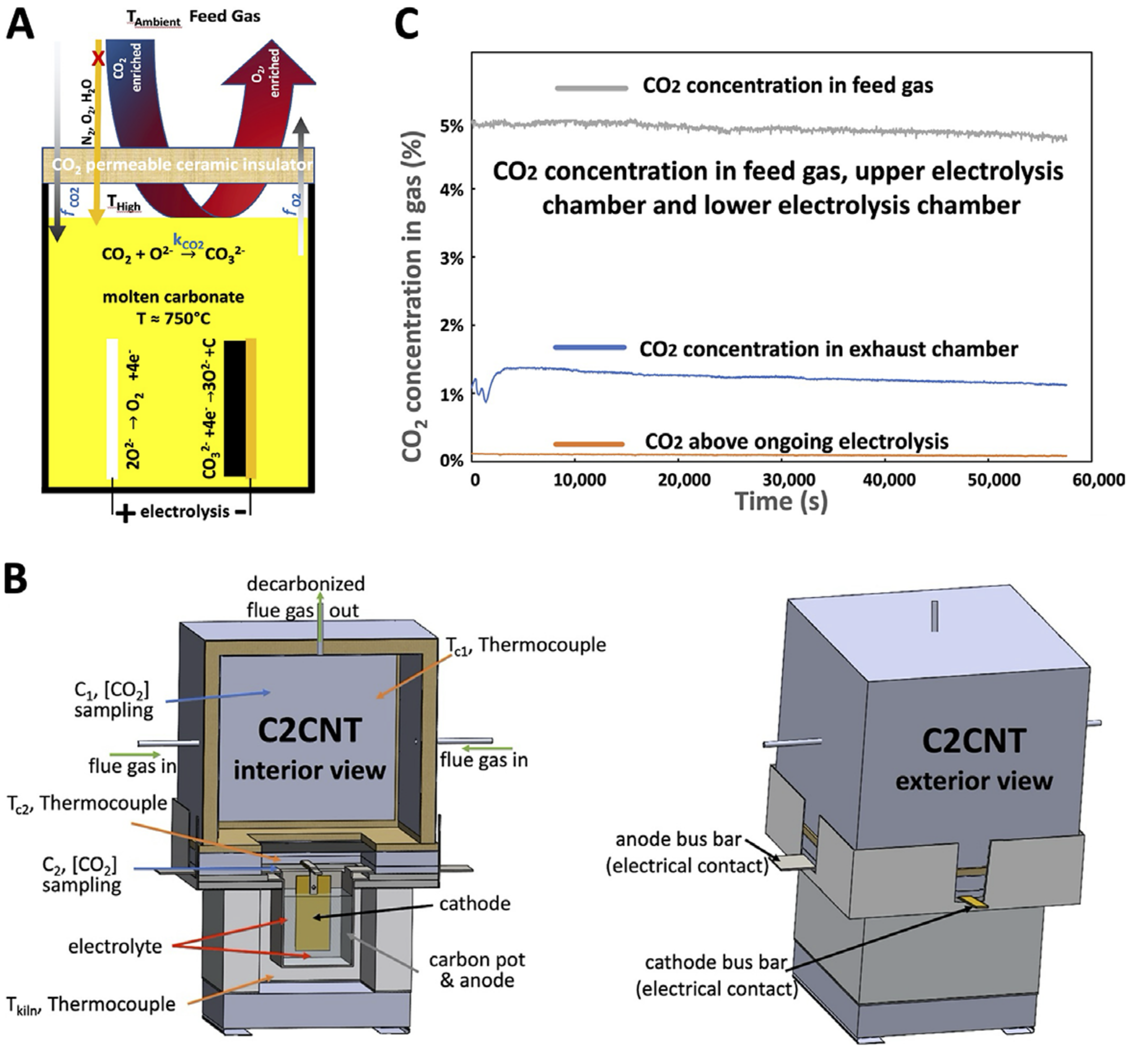

Figure 1. C$_2$CNT decarbonization. (A) The oxide-laden electrolyte of C$_2$CNT is a carbon sink, drawing in CO_2 while excluding the other insoluble components of flue gas, such as N_2, O_2 and H_2O. (B) The Genesis CCUS captures CO_2 from flue gas without the need to preconcentrate the CO_2. The flue gas is separated by a planar insulation membrane from the hot carbon sink electrolyte in the inner electrolysis chamber.

Industrial scale-up of C_2CNT decarbonization

Figure 2A shows the industrial C_2CNT system operating at the Shepard Centre Natural Gas Power Plant in Calgary. Each Genesis kiln module captures 100 t CO_2/year and produces 25 t/year GNCs. Electrodes have been scaled from 5 to 11,000 cm^2 (Ren et al. 2015b). Electrolytes have evolved from costly Li_2CO_3 to multicomponent systems using cheaper carbonates (Liu et al. 2022a,b,c,e).

Figure 2B shows the Muntz brass cathode before and after electrolysis at 770 °C and 0.6 A/cm^2. GNCs, such as carbon nanotubes (CNTs) and carbon nano-onions, resist oxidation up to 600 °C. Scanning electron microscopy (SEM), transmission electron

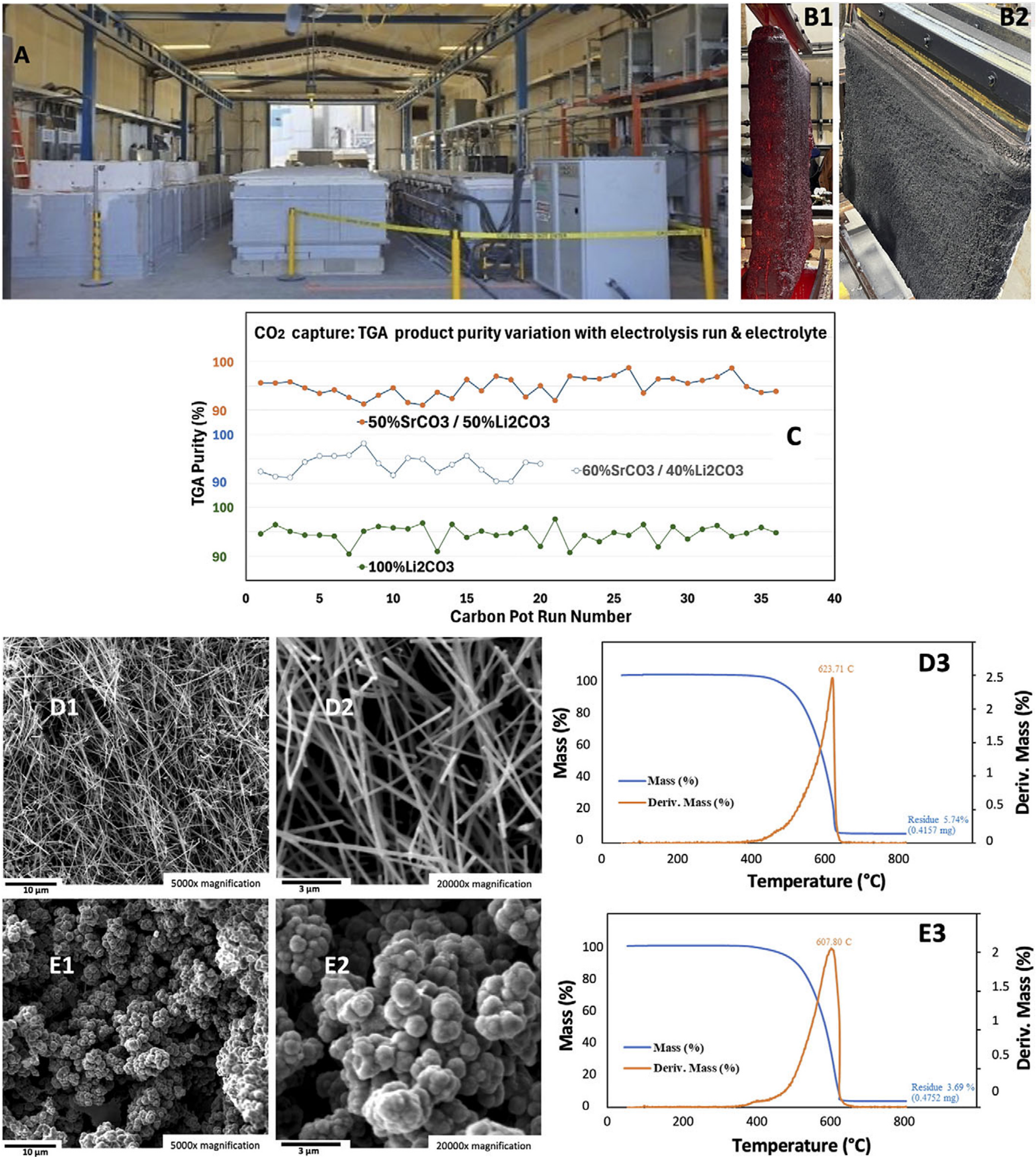

Figure 2. Industrial carbon capture by molten carbonate electrolytic splitting of CO_2. (A) The Genesis Device® kiln used for large-scale CO_2 molten carbonate electrolysis. (B1 and B2) The cathode, with an active area of 11,000 cm^2, upon lifting from the electrolyte and cooling. (C) TGA purity of captured CO_2 product measured from multiple carbon capture electrolysis runs in various lithium or mixed strontium/lithium carbonate electrolyte. (D) Carbon nanotube product: SEM and TGA of a 770 °C 60% $SrCO_3$/40 wt% Li_2CO_3 electrolyte 16-h electrolysis at $J = 0.2$ A/cm^2. (E) Carbon nano-onion product: SEM and TGA of a 770 °C 54% $SrCO_3$, 41% Li_2CO_3, 5 wt% Na_2CO_3 electrolyte electrolysis 4-h at $J = 0.6$ A/cm^2.

microscopy (TEM), Raman and X-ray Diffraction (XRD) analyses confirm morphology and purity (Supplementary Information; Johnson et al. 2017; Liu et al. 2021; Liu et al. 2022a,b,c). Thermogravimetric analysis (TGA) measurements (Figure 2C) confirm high-purity carbon with residual mass < 5%.

Figures 2D and 2E show how varying conditions produce different GNCs: CNTs at 770 °C in 60% $SrCO_3$/40% Li_2CO_3 for 16 h at 0.2 A/cm^2 and nano-onions in a 54% $SrCO_3$/41% Li_2CO_3/5% Na_2CO_3 mixture for 4 h at 0.6 A/cm^2 (Liu et al. 2019; Licht et al. 2024e).

Industrial separation of the electrolyte from the carbon capture product

During electrolysis, GNCs form a carbanogel – a matrix of product and electrolyte – on the cathode (Wang et al. 2021; Licht et al. 2024c,d). The product content ranges from 2 to 5% for CNTs from 8 to 20% for nano-onions. Loose electrolyte drips off the cathode post-electrolysis, while tightly bound electrolyte requires pressure extraction.

As shown in Figure 3, separation evolved from manual (Figure 3A) to vertical hydraulic presses (Figure 3B), and to the Carbanogel Harvester and Electrolyte Recycler (CHER) system (Figure 3C), which scrapes, presses and recycles electrolyte while forming compressed GNC pucks. A video of the scraper unit separating the carbanogel from the cathode is Movie 1 (https://www.youtube.com/watch?v=dMDOBgx2taM), and a full demonstration of the action of the CHER extraction unit is Movie 2 (https://www.youtube.com/watch?v=-SODerJNsYY), both of which are available in the Supplementary Information. Extraction efficiencies up to 98% were achieved by optimizing pressure (up to 3,000 psi), time and temperature (Figure 3D1, D2).

New C_2CNT carbon capture advances to be scaled-up

Direct cathode press (DCP) electrolyte removal

The DCP (Figure 4) removes electrolyte directly from the cathode without scraping. Hydraulic pressure extracts the molten electrolyte, which can be returned immediately to the electrolysis chamber. This method minimizes processing time and oxidation loss. A higher-pressure version using 8″ hydraulic cylinders is under development (Supplementary Information). Movies 3 and 4 demonstrate DCP operation. Movie 3 (https://www.youtube.com/watch?v=_UFVd210aec) is a simple animation of the DCP in action, and Movie 4 https://www.youtube.com/watch?v=BmbukaCVJko) is a demonstration of an operational DCP, both of which are available in the Supplementary Information.

Eliminating active concentration of CO_2: Genesis CCUS

Conventional decarbonization relies on energy-intensive CO_2 concentration using lime or amine-based systems, which add CO_2 burden. The Genesis CCUS process (Figure 5A–C) offers a passive alternative, eliminating the need for active CO_2 concentration. It introduces a gas-permeable, high-temperature insulation membrane between the gas feed and molten carbonate electrolyte, establishing a diffusion-dominated intermediate zone. As shown in Figure 5A, CO_2 diffuses through this membrane into the electrolyte, which acts as a carbon sink, while N_2, O_2 and H_2O remain insoluble.

This porous membrane also thermally insulates the gas feed from the ~750 °C electrolysis chamber. High CO_2 diffusivity through thermal insulations, such as aluminosilicate and calcium–magnesium silicate, has been demonstrated (Licht et al. 2024b), as shown in Figure 5B. Figure 5C illustrates a Genesis CCUS configuration where CO_2 from 5 and 30% flue gas concentrations is effectively captured and converted into CNTs without preconcentration (Licht et al. 2025a).

Direct air electrolysis to CO_2 to CNTs: Genesis DAC

DAC is challenged by the need to process air containing only 0.04% CO_2, without heating the remaining 99.96% to high temperatures. The Genesis DAC system (Figure 5D–F) introduces a passive, membrane-insulated design that allows CO_2 to diffuse from ambient air into the electrolysis chamber, converting it to CNTs (Licht et al. 2025b,c). This is the first DAC approach to meet all of the following: (1) no active CO_2 concentration, (2) conversion to high-value product and (3) thermal insulation of the gas feed.

Compared to planar membranes used for flue gas, Genesis DAC employs large-area, open-channel porous insulations to maintain sufficient CO_2 flux from air while minimizing heat loss. Figure 5D shows the use of a 3D porous insulation to establish a diffusion-dominated zone between the feed and electrolysis chambers. Sustained electrolysis rates were experimentally measured and compared with diffusion-based models (Figure 5F), confirming effective DAC performance, with possible underestimation by up to a factor of 2 (Licht et al. 2025b,c).

Separate harvesting of O_2 and nanocarbons from CO_2: Genesis O_2

Oxy-fuel combustion improves fuel burning efficiency, heat recovery and combustion temperature, concentrates CO_2 for mitigation and decreases NO_x pollutants and flue gas volume. An obstacle has been the production of the necessary concentrated O_2. A facile CCUS molten carbonate process for producing concentrated O_2 is demonstrated by splitting CO_2 into separately harvested GNCs and oxygen. When C_2CNT decarbonization is integrated with a fossil fuel combustion process, oxygen is produced at a rate matching its consumption in the combustion process, providing a source for the fossil fuel process to be oxy-fuel driven.

A wide range of processes, including traditional power plants, cement, iron and ammonia production, to large-scale refineries and smaller-scale processes, such as engines, ovens and furnaces, rely on the air combustion of fossil fuels. Concentrated O_2 combustion of fuel (oxy-fuel combustion), rather than air, offers several advantages over conventional air combustion, such as in coal power plants (Tu et al. 2021; Rogalev et al. 2022; Shiquan et al. 2022; Guo et al. 2024), other industrial plants (Uwizeyimana et al. 2019; Abubakar et al. 2021; Raho et al. 2022; Wang et al. 2024a, b) or even internal combustion engines (Li et al. 2021). These include improved fuel efficiency, heat recovery, CO_2 concentration for mitigation, reduced NO_x pollutants and decreased flue gas volume (and related lowering of flue gas processing costs) (El Sheikh et al. 2020; Koohestanian and Shahraki 2021; Rong et al. 2022; Yadav and Mondal 2022; Bazooyar and Jomekian 2024). However, widespread implementation has been limited by the challenge of producing concentrated oxygen at scale. To date, oxy-fuel combustion has been primarily used in applications like glass production and welding, which benefit from the higher combustion temperatures attainable with oxygen combustion (Singh et al. 2021; Zier et al. 2021).

The first CCUS configuration, which, in addition to removing CO_2, simultaneously separates and produces high-concentration O_2, is presented here and termed Genesis O_2. The oxygen-harvesting Genesis O_2 configuration is shown in Figure 5G and incorporates a separate exhaust for the O_2

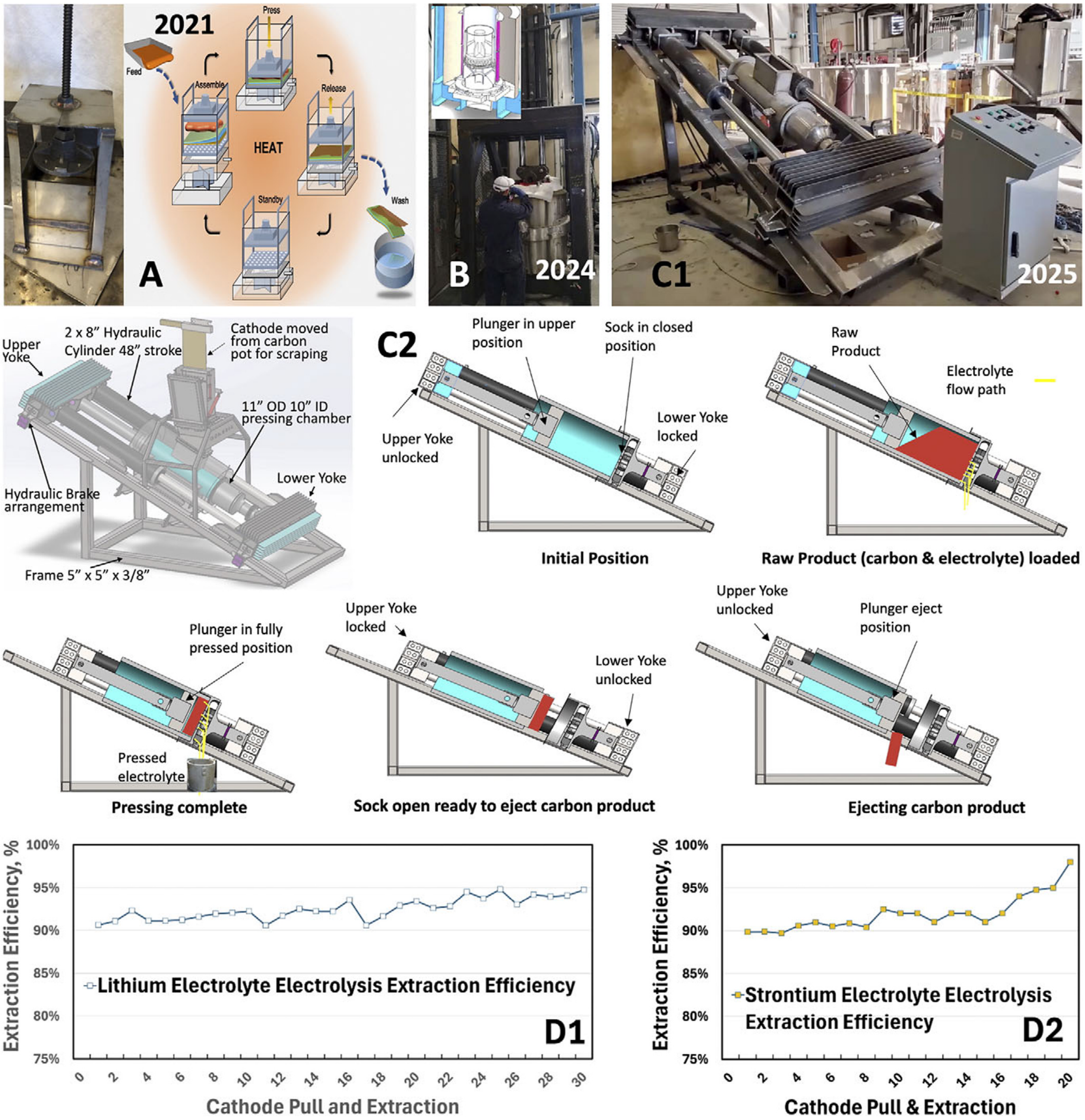

Figure 3. Extraction, subsequent to CO_2 electrolysis: separation of the raw product grown on the cathode from excess electrolyte. (A) A 2021 desktop manual press is used to filter the high-temperature carbanogel raw product into its separate product and electrolyte. (B) A 2024 large-scale hydraulic-driven vertical extraction press. (C) The 2025 industrial CHER extraction unit, designed to repetitively scrape the carbanogel from the electrolysis cathode, separate the GNC product from the excess electrolyte and recover the GNC product made from CO_2. (D) The CHER extraction efficiency of removing the electrolyte during repeat post-electrolysis insertion of the raw-product covered cathode.

generated during the electrolysis. This design offers the key advantage over the C_2CNT configuration: the highly concentrated O_2 output is available for oxy-fuel combustion as a separate product from the GNC. Another advantage is that the separate O_2 offtake provides a pressure differential to enhance CO_2 draw-in from the flue gas.

Figure 5H illustrates Genesis decarbonization action during electrolysis and distinguishes it from the regular single-exhaust Genesis process shown in Figure 5E. CO_2 from the flue gas enters the electrolysis chamber and exothermically reacts with oxide in the electrolyte to form carbonate. The carbonate is consumed at the cathode to regenerate oxide and simultaneously produce the GNC product, illustrated in black, that accumulates on the cathode, while O_2 is released from the anode reaction. The inner walls of the carbon pot collectively function as the anode and generate the O_2 as the CO_2-splitting byproduct. Evolved O_2 rises from the anode walls. In this new configuration, the produced O_2 is isolated within the additional O_2 channels shown on the right and left sides of the electrolysis chamber, and exits through a dedicated separate slit or pipe as shown. This harvested O_2 gas can be used for oxy-fuel

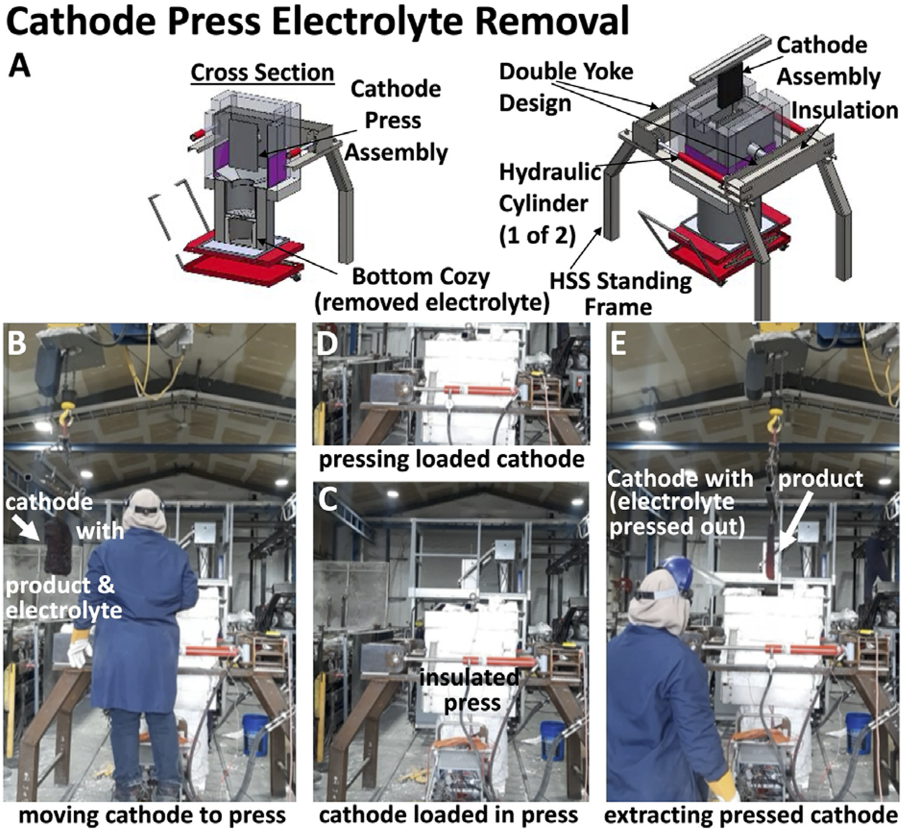

Figure 4. The direct cathode press electrolyte removal. (A) Illustration of the press and components. (B) Subsequent to electrolysis, the cathode, laden with product and electrolyte (raw product), is moved to the press, as shown in (C), loaded into the press. (D) The cathode is directly pressed (rather than scraped as illustrated in Figure 3), removing electrolyte and retaining the product. (E) The cathode, still retaining the product but with excess electrolyte removed, is lifted from the press. Further details of the direct cathode press, including an action animation and demonstration of actual operation, are provided in the Supplementary Information.

combustion. The product at the cathode forms a lattice of GNCs intermingled with the electrolyte.

Figure 5G Genesis O_2 configuration provides a contiguous trap of O_2 around the inner perimeter of the carbon pot, isolating the electrolyte interface and the anode headspace from the cathode headspace. Both O_2 and CO_2 concentrations are measured using CO2meter.com sensors, positioned outside the hot chamber through a 304 stainless steel tube that allows cooling to maintain the sensor's room temperature operation. With fascinating results, this design forms separate anode and cathode half-cell compartments. Unexpectedly, the concentration of CO_2 in the O_2 exhaust rose during electrolysis to a concentration higher than the inlet flue gas, displacing the O_2 product. In contrast to this headspace-separated configuration, high CO_2 concentrations are not observed in the regular configuration when there is a single shared headspace above the anode and cathode. However, this separate anode and cathode half-cell compartment process stopped producing CO_2 when 1 m Li_2O was added to the Li_2CO_3 electrolyte. From that point onward, the CO_2 concentration dropped quickly, and the O_2 purity in the manifold grew to 98% (±2%). It should be noted that in the future, rather than through chemical addition, oxide can be added electrochemically (in situ) by pre-electrolysis in a CO_2-deficient environment (without flue gas feed) as described by the reaction of Equation (1), without simultaneously adding CO_2 as described in equation 2. A proposed mechanism explaining the initial rise of CO_2 concentrations in the separated half-cell Genesis O_2 configuration is presented in the Supplementary Information.

The volume of O_2 gas produced in the exhaust during electrolysis in Li_2CO_3 with 1 m Li_2O electrolyte was studied and compared to the electrolysis charge (the time-integrated constant current). This high level of O_2 purity was maintained throughout the measurements, without further added Li_2O. The measured rate of gas volume collected over time t (s), $V_{20°C}$ (ml/s), is converted to moles per second, $R_{m\text{-}O2}$ (mol/s) of pure (98% to 99%) O_2, adjusted to 20 ° C rather than STP:

$$R_{m\text{-}O2} = V_{20\,°C} \times (293K/273K)/\left(2{,}414\,cm^3/mole\right)/t(s) \qquad (4)$$

The coulombic efficiency of oxygen generation, CE (%), is then determined from the measured volumetric rates of gas generation using the constant applied electrolysis current, I (A), where $n = 4$ moles electrons per mole of O_2 produced, and Faraday's constant, F = 96,485C/mol e^-:

$$CE(\%) = 4F100\%(R_{m\text{-}O2}/I(A)) \qquad (5)$$

Coulombic efficiency was measured at several constant electrolysis currents of 8.4A ($J = 0.1$ A/cm^2), 16.8A (0.2 A/cm^2), 33.6A (0.4 A/cm^2) and 50.4A (0.6 A/cm^2). It is noteworthy that a current density of 0.6 A/cm^2 is a high rate and is the same current density used in the commercial electrolytic molten electrolyte production of aluminum. In each case, the measured O_2 product concentration was 99% (±2%). The respective O_2 exhaust rates, measured at the increased electrolysis currents, were 0.39, 0.89, 2.03 and 3.11 ml/s. These rates of O_2 generated were used to determine coulombic efficiency from Equations (4) and (5).

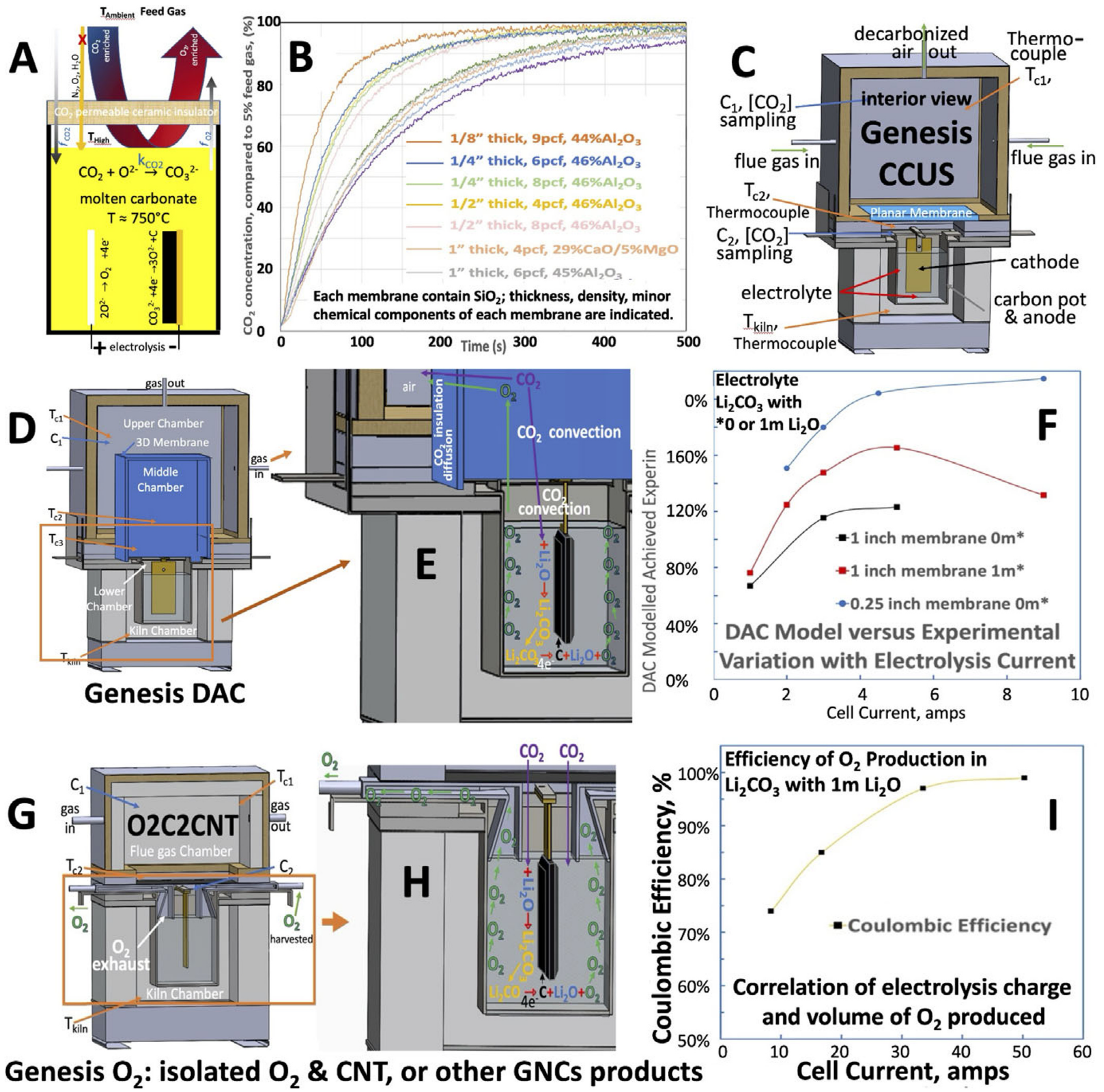

Figure 5. Recent advances in the C2CNT decarbonization process. (A–C) Genesis CCUS: (A) The addition of a porous, insulating membrane above the electrolyte carbon sink thermally isolates the feed gas from the electrolysis. (B) The CO_2 diffusion rate through several porous insulation materials. (C) The Genesis CCUS captures CO_2 from flue gas without the need to preconcentrate the CO_2. **(**D–F) The Genesis DAC expands the C_2CNT process to air as a source of CO_2 by expanding the feed gas/electrolysis chamber interfacial membrane for sufficient CO_2 diffusion. (G–I) The Genesis O_2 configuration separates the CO_2 splitting products, facilitating the separate collection of O_2 from the anode and carbon nanomaterials from the cathode.

Figure 5I correlates the electrolysis current with O_2 production coulombic efficiency. The conversion efficiency of the electrolytic charge to the O_2 product is observed to increase with increasing cell current. At a cell current of 33.6 A, the coulombic efficiency increases to 97%, and at the highest current, the coulombic efficiency increases to 99% at 0.60 A/cm^2.

Ongoing applications of CNTs made from CO_2 by the C_2CNT process

CNTs, due to their graphene-based, cylindrical morphology, exhibit exceptional tensile strength (up to 93,900 MPa), thermal conductivity, flexibility and electrochemical performance (Chang et al. 2010; Islam et al. 2024). Applications include batteries (Licht et al. 2013, 2016), low-carbon composites (Licht 2017; Licht et al. 2019) and emerging uses in polymers (Licht et al. 2024b,c) and plasmas (Licht et al. 2025a).

Comparison of C_2CNT decarbonization to amine or calcium-looping decarbonization

Traditional CCS methods, such as amine scrubbing and calcium looping (CaL), rely on CO_2 concentration and regeneration cycles, incurring substantial energy penalties. Amine-based systems require 6.1–14.5 GJ/t CO_2, factoring in solvent regeneration, compression and transport (Du et al. 2024; Rochelle 2024; Singh et al. 2025). CaL processes involve 8.1–16.5 GJ/t CO_2, limited by sorbent degradation and energy-intensive cycling (Kumar et al. 2024; Zhang et al. 2024b; Afani et al. 2024; Tan et al. 2024; Toledo et al. 2023).

In contrast, the **C_2CNT** process directly converts CO_2 into GNCs and oxygen via electrolysis, eliminating the need for preconcentration. Energy requirements range from 7.2 to 15.5 GJ/t CO_2 or from 26 to 57 GJ/t GNC, depending on process conditions (Ren et al. 2015a; Licht et al. 2019; Srinivasan 2019). Preferred electrolytes include lithium and lithium–strontium carbonates, which offer optimal CO_2 activity and electrochemical properties (Licht et al. 2024a,b,c,d,e,f).

C_2CNT additionally produces GNCs with applications in construction, electronics and polymers, replacing high-emission materials like steel or aluminum. Some GNCs (formed via Fe/Ni catalysis) are magnetic, enabling selective recovery and reuse. With Technology Readiness Level 7–8, the system is modular and compatible with aluminum smelting infrastructure, supporting scale-up to megatonne (Mt) CO_2 capture capacity.

Commentary on future challenges and factors to improve C_2CNT decarbonization

Large-scale deployment of C_2CNT faces both sociopolitical and technical barriers. Policy limitations, fossil fuel subsidies and insufficient climate urgency hinder adoption despite the growing impacts of CO_2 emissions. Technically deployable, advancing C_2CNT can include improving CO_2 uptake, increasing product yield, reducing energy use and adapting systems to a wide CO_2 concentration range – from ambient air (~0.04%) to fermentation gas (~90%).

Recent developments aim to enhance energy selectivity for CO_2 reduction by insulating non-CO_2 gas components from the electrolysis zone (b; Licht et al. 2024f, 2025a). Parallel efforts focus on localized carbon product generation at emission sources, such as on-site CNT production at cement plants or the use of carbon nano-onions in rubber and plastics (Licht 2017; Hofstetter et al. 2025).

A key goal is scaling to Mt-level facilities. The Genesis Device® is designed for bolt-on, modular expansion, scaling from the current 100 to 1,000 t/y via larger reaction vessels. A future 1 Mt CO_2/y

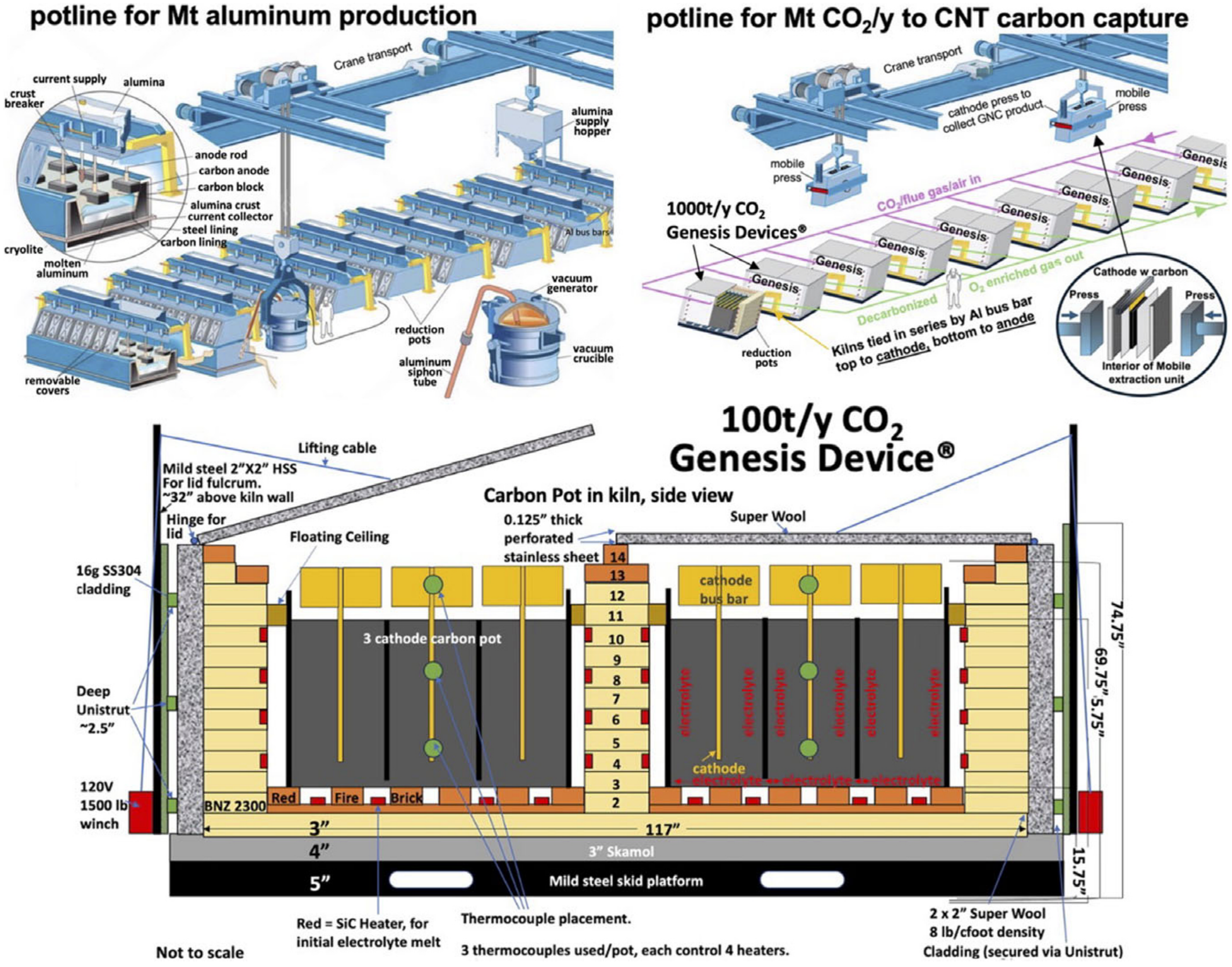

Figure 6. (Top) A commercially operational aluminum smelting plant, illustrating the industrial-scale infrastructure. (Bottom left) Schematic of the current Genesis Device® designed for the electrochemical conversion of 100 tonnes of CO_2 per year into graphene nanocarbon (GNC) products such as carbon nanotubes (CNTs). (Bottom right) Conceptual design of a future large-scale Genesis Device system targeting 1 megatonne (Mt) per year of CO_2 conversion, producing ~0.25 Mt of GNCs. This scale-up is modeled after aluminum smelting operations and involves a tenfold increase in capacity through the serial integration of kilotonne-per-year (kt/y) Genesis Device modules.

plant may consist of three potlines, each with several hundred Genesis Devices, analogous to aluminum smelting plants. Figure 6 illustrates both the current 100 t/y system and the proposed Mt-scale plant design.

Conclusions

This study introduces the discovery, scale-up and industrial deployment of a transition metal-nucleated molten carbonate electrolysis process – **C_2CNT** – for direct CO_2 conversion into high-yield, high-purity GNCs. The technology operates as a **single-pot system**, eliminating the need for CO_2 preconcentration by capturing from both dilute (e.g., air) and concentrated (e.g., flue gas) sources. Key benefits include: (1) simultaneous CO_2 capture and conversion into valuable GNCs, generating economic incentives for decarbonization; (2) long-term carbon storage as durable nanomaterials; and (3) downstream CO_2 offset via GNC incorporation into composites (e.g., plastics and cement) or as substitutes for carbon-intensive materials.

Reported advances include: (1) demonstration and industrial scaling of the C_2CNT process; (2) development of large-scale GNC separation systems; (3) introduction of a DCP for GNC extraction and tailored C_2CNT configurations for (4) flue gas decarbonization (Genesis CCUS), (5) DAC (Genesis DAC) and (6) independent oxygen product recovery (Genesis O_2).

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Data availability statement. The data supporting this article have been included as part of the Supplementary Information.

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Competing interests. The authors declare none. Direct Air Capture LLC and Carbon Corp both maintain mission statement commitments to mitigate climate change.

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