Direct carbonate electrolysis into pure syngas†

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Syngas, a mixture of carbon monoxide (CO) and hydrogen (H2), is a feedstock for a wide variety of chemical processes and is currently produced from fossil fuels. The need to reduce carbon dioxide (CO2) emissions motivates the production of syngas from atmospheric CO2, powered by renewable electricity. Current CO2 electrolyzers require costly separation processes to purify the CO2 reactant stream and to remove unreacted CO2 from the product stream. We demonstrate direct carbonate electrolysis (DCE) in a reactive capture system that avoids the initial CO2 purification process and produces pure syngas with sufficient CO content for direct industrial use (H2/CO ratios of 1–2). The DCE system incorporates a composite CO2 diffusion layer (CDL) that attains high CO selectivity by achieving high alkalinity and available CO2 concentration at the cathode. Applying this strategy, we produce pure syngas in the cathode outlet gas stream with a H2/CO ratio of 1.16 at 200 mA cm−2, corresponding to a CO faradaic efficiency (FE) of 46% and an energy intensity of 52 GJ tsyngas−1. By eliminating intensive upstream and downstream processes, DCE achieves syngas production with 13% less energy than CO2 electrolysis combined with water electrolysis, 39% less energy than past carbonate reduction work, and 75% fewer emissions than the conventional fossil fuel based route.

Broader context
The electrochemical conversion of captured CO2 into CO could reduce CO2 emissions while producing the carbon content of a valuable feedstock, syngas, for upgrade into long-chain hydrocarbons. Most CO2 electrolyzers require pure gaseous CO2 streams, and, thus, incur substantial capital and operational costs for CO2 capture liquid regeneration and CO2 purification. Additionally, CO2 reactant can be lost to carbonates in the electrolyzer which crossover to the anode, regenerate, and mix with the O2 rich anode gas stream. Excess CO2 in the cathode gas product stream also demands separation. These sequential purification steps are costly and limit the viability of electroproduced chemicals and fuels. We demonstrate a reactive capture system that produces pure syngas with an industrial H2/CO ratio through direct electrolysis of a CO2 post-capture solution. We designed a CO2 diffusion layer that achieves high local CO reactant concentration and high alkalinity favourable for CO2 conversion. This report illustrates the potential for the renewable electroproduction of syngas in a net-zero emissions future.

Introduction
Syngas is a commodity feedstock used in the production of hydrocarbons and oxygenates via methanol routes and Fischer–Tropsch synthesis.1,2 Syngas is currently produced from fossil-fuels via coal gasification and/or methane reforming.3,4 These pathways are energy intensive and have high CO2 emission intensities (1.5 tCO2e tsyngas−1).5

Electrochemical syngas production methods use renewable electricity to produce syngas with a lower carbon footprint. These methods combine CO from CO2 electrolysis and H2 from water electrolysis.6–8 However, current CO2 electrolyzers require high-purity gaseous CO2 feeds,9–12 and sourcing this CO2 from air – via direct air capture – or from industrial sources, is costly.13–16 Within current electrolyzers, utilization of reactant CO2 is low, and CO2 is lost to carbonates and crossover to the anode.17–19 As a result, both the anodic and the cathodic outlet streams require CO2 separation.20,21 Reactive capture is an electrolysis approach that shortens this process (Fig. 1A). This pathway avoids the thermally-driven
capture liquid regeneration from the post-capture solution (carbonate electrolyte in the case of hydroxide-based direct air capture) and the subsequent CO₂ dehydration, compression, and transportation steps. In the electrolyzer, protons are generated by the anodic oxygen evolution reaction (OER) and transported to the cathode through a cation exchange membrane (CEM) (Fig. 1B). The protons then react with the carbonate ions to regenerate CO₂ in situ. Syngas is produced through co-synthesis of CO from the regenerated CO₂ and H₂ from the aqueous solution. Unreacted CO₂ is recaptured by hydroxide ions (OH⁻), a by-product of CO and H₂ evolution, to form carbonate.

Previous studies of reactive capture using bicarbonate electrolyte have demonstrated high CO selectivity (CO faradaic efficiency (FE) > 50%). However, the limited CO₂ recapture capacity of bicarbonate electrolyte results in a product gas stream diluted with CO₂. Direct electrolysis of carbonate (rather than bicarbonate) electrolyte allows for the collection of high-purity gaseous products, evidenced by the lack of CO₂ (<400 ppm) detected in the gas stream. Carbonate electrocatalytic conversion into syngas has previously been achieved with a H₂/CO ratio of 3 (CO FE of 25%) and energy intensity of 86 GJ tsyngas⁻¹. However, this mixture does not have sufficient CO content to meet industrial syngas standards.

Here, we present an adlayer strategy that modulates the cathode pH and maximizes CO₂ conversion to produce syngas with a H₂/CO ratio in the industrially relevant range (1–2, and corresponding to a CO FE between 33% to 50%). We develop a composite CO₂ diffusion layer (CDL) that enables cathode alkalinity to favour CO₂ electrolysis and increases CO selectivity by limiting the diffusion of protons to the cathode. We achieve a H₂/CO ratio of 1.16 (CO FE of 46%) at a current density of 200 mA cm⁻². An energy intensity of 52 GJ tsyngas⁻¹ was achieved, resulting in a 39% energy saving compared to the previous carbonate electrolysis report.

**Results & discussion**

**Increasing CO₂ conversion**

Previous (bi)carbonate electrolyzers have employed a bipolar membrane (BPM) to dissociate water and provide protons and
OH\(^-\) to the cathode and anode, respectively.\(^{26,29,35}\) To reduce the membrane overvoltage, thereby reducing the required energy input, we used a cation exchange membrane (CEM) to transport protons directly from the anolyte or anodic OER, resulting in a voltage reduction of ca. 0.5 V (Fig. S1, ESI\(^\dagger\)). A zero-gap configuration was first investigated by assembling the electrolyzer with an Ag electrocatalyst directly in contact with the CEM. We found that the maximum FE towards CO was 17% (H\(_2\) /CO ratio of 4.88) at 100 mA cm\(^{-2}\) (Fig. 2A). The only other carbon-based product detected was methane with <0.2% FE. Hydrogen evolution reaction (HER) accounted for the remaining FE.

We hypothesized that the low CO FE was caused by a CEM-induced acidic environment in which the kinetically more favourable HER outcompetes CO\(_2\) electrolysis,\(^{36-38}\) and, thus, modulating the cathode pH would improve CO\(_2\) conversion.\(^{39-41}\) We confirmed that CO\(_2\) was the electroreduction reactant, as opposed to the (bi)carbonate ions, by replacing the acidic anolyte with an alkaline electrolyte to suppress in situ CO\(_2\) regeneration. The only product detected was H\(_2\) (Fig. S2, ESI\(^\dagger\)). To increase CO\(_2\) conversion, we hypothesized that a CO\(_2\) diffusion adlayer between the CEM and the catalyst would limit proton diffusion to the cathode and separate the acidic CO\(_2\) regeneration region from the alkaline CO\(_2\) electrolysis region.

We developed multi-physics models of the carbonate electrolyzer with varying CDL thicknesses of 0 (zero-gap configuration), 10, 25, and 50 \(\mu\)m (Supplementary note 2, ESI\(^\dagger\)). We found that increasing the CDL thickness increased the pH at the cathode which favoured CO\(_2\) reduction over HER (Fig. 2B).\(^{42,43}\) However, increasing the CDL thickness also reduced the CO\(_2\) concentration at the cathode due to the recapturing of in situ CO\(_2\) within the extended alkaline region (Fig. 2C). The CDL must achieve high local cathode alkalinity and CO\(_2\) concentration to produce syngas with sufficient CO content for direct industrial application.

**CDL design strategy**

We first inserted commercially available hydrophilic microporous filters of different thicknesses between the catalyst and the CEM to separate the acidic CO\(_2\) regeneration region from the alkaline electrolysis region. We found that the filters increased the selectivity towards CO (Fig. S6, ESI\(^\dagger\)). However, the performance of the inserted filters was inconsistent due to trapped CO\(_2\) bubbles and material incompatibilities with the high and low pH extremes in this system (11 < pH < 2). We were motivated to design a robust and tuneable composite CDL. The engineered CDL needed to facilitate (bi)carbonate diffusion, hinder proton transport to the catalyst, sustain both high and low pH conditions, and have porous networks that allow mass transfer of in situ generated CO\(_2\). We selected TiO\(_2\) particles as the main substrate in view of their chemical stability and hydrophilic nature.\(^{44,45}\) For a substrate binder, we chose a hydrophilic ionomer that is anion-permeable to transport (bi)carbonate ions to the CEM.\(^{46,47}\) The wettability of the substrate and ionomer is important because hydrophobic elements will hinder ion transport, limiting the availability of carbonate ions in the CO\(_2\) regeneration region.\(^{48}\) When a hydrophobic substrate or ionomer was incorporated into the CDL, the CO FE was lower than the fully hydrophilic system (Fig. S7A and B, ESI\(^\dagger\)). The TiO\(_2\) and ionomer mixture was airbrushed evenly onto an Ag-catalyst layer (Fig. 3A and B) with corresponding energy dispersive X-ray (EDX) spectroscopy images confirming a distinct and uniform CDL (Fig. 3C).

To optimize the CDL for high CO FE, we screened TiO\(_2\) particle sizes (5, 25, 200, and 1500 nm) and TiO\(_2\)/ionomer weight ratios between 5–25 (Fig. S7C and D, ESI\(^\dagger\)). We found that a combination of 25 nm TiO\(_2\) and a TiO\(_2\)/ionomer ratio of 15 balanced the diffusion of (bi)carbonate ions and protons and enabled the local generation of CO\(_2\) to result in peak CO FE. The size of TiO\(_2\) nanoparticles and the ionomer volume fraction contribute to the permeability of the CDL. A high permeability failed to sufficiently hinder proton transport and resulted in hydrogen generation. A low permeability resulted in insufficient in situ regeneration of reactant CO\(_2\).\(^{49}\)

We varied the CDL thickness between 10 to 50 \(\mu\)m and achieved a maximum CO FE of 46% (H\(_2\) /CO ratio of 1.16) at 200 mA cm\(^{-2}\) with a 25 \(\mu\)m CDL (Fig. 3D). Achieving a high CO FE requires both a sufficiently alkaline local pH and adequate
CO₂ availability. Thinner CDLs have a smaller gap between the catalyst and the CEM which shortens the proton diffusion distance and results in a lower cathode pH. Despite having the highest CO₂ concentrations in our simulations, the selectivity of the system with thinner CDLs was not optimal and approached the performance of the zero-gap configuration due to insufficient cathode alkalinity (Fig. 2B). As the CDL thickness is increased, the pH at the cathode increased but the local CO₂ concentration decreased (Fig. 2C). With the cathode pH plateauing at thicknesses greater than 25 μm, this CDL thickness provided sufficient CO₂ availability while maintaining an alkaline cathode environment to suppress HER.

We compared the difference in iR-compensated voltage of a zero-gap configuration to an otherwise identical system with a 25 μm CDL, with both experiments using an identical hydrogen-evolving catalyst (Supplementary note 3, ESI†). At 200 mA cm⁻², a voltage increase of 117 mV was observed for the CDL system which corresponded to an increase in pH of 2, consistent with the multi-physics model which predicted a pH increase of 1.7 (Fig. 2B and Fig. S8, ESI†). These findings suggest that the CDL increases the pH of the cathode environment to favour CO₂ conversion and thereby yielded a higher CO FE.

We screened the selectivity and full cell voltage of the optimized 25 μm CDL at current densities between 50 to 300 mA cm⁻² with carbonate electrolyte flowrates between 0.35 to 17.5 mL min⁻¹ showing an increase in CO FE with decreasing flowrate. With carbonate electrolyte flowrates between 10 to 65 mL min⁻¹ showing an increase in CO FE with increasing flowrate. Typical carbonate electrolyte flowrates are provided in the ESI† (Table S5). Error bars represent the standard deviation of at least three samples measured under identical conditions.

Fig. 3 Optimization of the CDL for industrial H₂/CO ratio. (A–C) Cross-sectional scanning electron microscopy (SEM) image of the CDL evenly air-brushed onto the Ag catalyst atop a silicon wafer (A), with seamless interfacial contact between the CDL and Ag catalyst (B), and corresponding energy dispersive X-ray (EDX) spectroscopy elemental mapping of Ti, O, and Ag (C). (D) FE towards CO and H₂/CO ratio at 200 mA cm⁻² with thicknesses of the CDL between 0 and 50 μm. (E) FE towards CO and H₂ at current densities between 50 to 300 mA cm⁻² with 25 μm CDL. Corresponding full cell voltages are noted on the secondary y-axis. (F) One-dimensional multi-physics modelling of pH at distances from the cathode and current densities of 50, 200, and 300 mA cm⁻² for 25 μm CDL. (G) One-dimensional multi-physics modelling of CO₂ concentration at distances from the cathode and current densities of 50, 200, and 300 mA cm⁻² for 25 μm CDL. Accompanying models of HCO₃⁻ and CO₃²⁻ concentrations are provided in the ESI† (Fig. S5). (H) FE towards CO and H₂/CO ratio at 50 mA cm⁻² with carbonate electrolyte flowrates between 0.35 to 17.5 mL min⁻¹ showing an increase in CO FE with decreasing flowrate. (I) FE towards CO and H₂/CO ratio at 300 mA cm⁻² with carbonate electrolyte flowrates between 10 to 65 mL min⁻¹ showing an increase in CO FE with increasing flowrate. Typical carbonate electrolyte flowrates are provided in the ESI† (Table S5).
300 mA cm$^{-2}$ and found that the CDL resulted in minimal voltage penalties while significantly increasing CO FE compared to the zero-gap configuration (+0.23 V and +35.3% CO FE at 200 mA cm$^{-2}$) (Fig. 3E). Above 200 mA cm$^{-2}$, the CO selectivity decreased, and the CO partial current plateaued, which indicated a CO$_2$ mass transfer limit at the cathode (Fig. S9, ESI†). We hypothesized that the decrease in CO FE at the lower and higher current densities were due to an imbalance of cathode alkalinity and CO$_2$ concentration at these extremes. The multi-physics model showed that compared to operating at 200 mA cm$^{-2}$, the pH is lower at 50 mA cm$^{-2}$, while the CO$_2$ concentration is lower at 300 mA cm$^{-2}$ (Fig. 3F and G). To investigate further, we decreased the carbonate flow rate while operating at 50 mA cm$^{-2}$ and found that the CO FE increased (Fig. 3H). A slower flow rate increases the local pH due to the accumulation of OH$^-$. At 300 mA cm$^{-2}$, the CO FE increased as the carbonate electrolyte flow rate increased up to 30 mL min$^{-1}$; however, further increases in flow rate resulted in similar, or slightly decreased, CO FE (Fig. 3I). This result suggests that at high current densities, the local environment is excessively alkaline, and CO$_2$ availability is low. Increasing the carbonate electrolyte flow rate lowered the local pH and thereby increased the availability of CO$_2$ for reaction.

To assess the long-term stability of the engineered CDL, we operated the DCE system with continuous CO$_2$ capture and

![Fig. 4](image)

**Fig. 4** Long-term operation of DCE over 23 hours with CO FE, H$_2$/CO ratio, full cell voltage, and capture solution pH noted. Experiment conducted at a constant current density of 100 mA cm$^{-2}$ with a 1 cm$^2$ active area. Schematic and picture of the experimental set-up are provided in the ESI† (Fig. S10A and B).

![Fig. 5](image)

**Fig. 5** Comparison of three syngas production methods. (A–C) Schematic showing process pathways, major chemical inputs and outputs, and energy source of rWGS (A), CE-WE (B), and DCE (C). (D) Energy intensity comparison to produce one tonne syngas using rWGS, CE-WE, and DCE. Syngas dehydration energies for CE-WE and DCE are too small to be seen in this figure. Detailed breakdown available in the ESI† (Table S3). (E) CO$_2$e emissions to produce one tonne syngas using rWGS, CE-WE, and DCE. The CO$_2$e associated with the energy input in each process is considered. Detailed breakdown available in the ESI† (Table S4).
recycling of regenerated alkaline capture fluid (Fig. S10A, ESI†). At a constant current density of 100 mA cm⁻², the full cell voltage, CO FE, H₂/CO ratio, and capture solution pH were stable for over 23 hours of operation (Fig. 4). The pH of the anode electrolyte remained constant, (Fig. S10C, ESI†) and negligible CO₂ was detected in the cathode and anode gas streams (<400 ppm), yielding a pure syngas (99.91 vol%, dry basis). Scanning electron microscopy (SEM) before and after prolonged operation showed minimal change in the CDL structure (Fig. S11, ESI†).

Comparison to alternative syngas production methods

We compared the energy intensity of syngas production via three CO₂ electrolysis pathways: thermocatalytic reverse water gas shift (rWGS) (Fig. 5A); low-temperature CO₂ electrolysis combined with water electrolysis (CE-WE) (Fig. 5B); and DCE (Fig. 5C) (Supplementary note 4, ESI†). In all cases, the feedstock CO₂ is captured from the atmosphere using an alkaline capture liquid.¹³ The rWGS pathway produces syngas with H₂/CO ratio of 1 and requires 57 GJ t⁻¹syngas⁻¹ (Fig. 5D). The CE-WE and DCE pathways produce syngas with H₂/CO of 1.16, requiring 60 and 52 GJ t⁻¹syngas⁻¹, respectively. Syngas production via DCE circumvents intensive upstream and downstream processes and thereby results in a 13% energy saving compared to the CE-WE pathway and 8% energy savings compared to the rWGS method. The capture and dehydration steps in the DCE required only 0.85% of the energy demand for the DCE pathway, because the most energy intensive step of the capture process (regeneration) is avoided, and the output syngas stream is pure.

Of the three syngas production methods, DCE is the only pathway that is fully electrically driven, whereas CE-WE requires thermal energy input during CO₂ capture and rWGS requires thermal energy in two major processes. Comparing the operational CO₂e emissions of the three syngas production pathways, DCE was the only method that offered a low CO₂ intensity (0.36 tCO₂e t⁻¹syngas⁻¹), while both CE-WE and rWGS exhibited high net CO₂ emissions (1.39 and 2.48 tCO₂e t⁻¹syngas⁻¹, respectively) even when using renewable electricity (Fig. 5E). Compared to the fossil-based method (1.5 tCO₂e t⁻¹syngas⁻¹), DCE offers a 75% reduction in CO₂e emissions.

Conclusions

We developed a strategy for the efficient electroproduction of syngas with sufficient CO-content and purity for direct industrial application. Through a one-dimensional multi-physics model, we found that the selectivity towards CO can be improved by separating the acidic CO₂ regeneration region from the alkaline CO₂ electrolysis region. We engineered a composite CDL positioned between the cathode and CEM of a DCE system to modulate the local pH and improve local CO₂ conversion. The CDL was comprised of TiO₂ nanoparticles bound by hydrophilic ionomer and was conformally coated onto the Ag catalyst. By determining the optimal CDL thickness that balanced the cathode alkalinity with CO₂ concentration, a H₂/CO ratio of 1.16 (CO FE 46%) was achieved with an energy intensity of 52 GJ t⁻¹syngas⁻¹ and a CO₂ intensity of 0.36 tCO₂e t⁻¹syngas⁻¹. Syngas production via DCE can provide a 13% energy saving compared to conventional CO₂ electrolysis methods, and a 75% CO₂e emissions reduction compared to fossil-fuel methods. These savings suggest that DCE is a promising pathway toward energy efficient syngas – a foundational feedstock for renewable chemicals and fuels in a net-zero emissions future.

Experimental

Reagents

Potassium hydroxide (KOH) (>85%) and sulfuric acid (H₂SO₄) were purchased from Bioshop. All reagents were of analytical grade and used without further purification. All solutions were prepared using Milli-Q grade water (18.2 MΩ).

Electrode preparation

The cathode was fabricated by air-brushing an Ag nanoparticle ink onto commercially available hydrophilic carbon paper (AvCarb MGL190, Fuel Cell Store) on a hot plate at 75 °C to achieve a loading of approximately 3 mg cm⁻². The loading was measured by weighing the carbon paper before and after air-brushing. The catalyst ink was prepared with 150 mg of Ag nanoparticle (99.99%, 20 nm, metal basis, US Research Nanomaterials), 150 mg of Nafion dispersion (5 wt%, Fuel Cell Store), and 6 mL of methanol for a 25 cm² substrate and sonicated for 1 hour prior to air-brushing. A commercially available titanium-based anode was used (Magneto Special Anodes, Evoqua Water Technologies).

CDL preparation

Four sizes of TiO₂ nanoparticle were used: 5 nm (anatase, 99.5%, US Research Nanomaterials), 25 nm (Aeroxide TiO₂ P25, Evonik), 100 nm (anatase, 99.9%, US Research Nanomaterials), and 1500 nm (anatase, 99.9%, US Research Nanomaterials). Two ionomers were used: Nafion (Hydrophobic) and Aemion (Hydrophilic). Nafion ionomer can create strongly hydrophobic nanoporous networks due to its polytetrafluoroethylene (PTFE) (–CF₂–CF₂–) back-bone.⁵⁰,⁵¹ Aemion ionomer contains poly-(benzimidazole) units which are more hydrophilic than the PTFE in Nafion.⁵² The Aemion dispersion was prepared by adding 388 mg of ionomer powder (AP1-CNNS-00-X, Ionomr) to 40 mL of ethanol and 10 mL of acetone and sonicated until fully dissolved.

The CDL was fabricated by air-brushing a TiO₂ nanoparticle ink onto the fabricated cathode to achieve the desired thickness. For the optimized CDL, the ink was prepared with 50 mg of 25 nm TiO₂, 333 mg of the prepared Aemion dispersion, and 4 mL of ethanol for a 6.25 cm² cathode and was sonicated for 1 hour prior to air-brushing. The CDL coated cathode was cut to a 1 cm² size prior to electrolyzer assembly. CDLs were characterized using SEM at the Centre for Nanostructure Imaging at the University of Toronto using an FEI Quanta FEG 250 environmental SEM.
Two hydrophilic microporous membrane filters were used: 125 μm PVDF (Filter 1, 0.45 μm pore size) was purchased from Sigma Aldrich and 100 μm nylon (Filter 2, 5 μm pore size) was purchased from Sterlitech. Both filters were used as received.

Operation of the electrochemical cell

The carbonate electrolysis experiments were performed in a 1 cm² electrolyzer with serpentine flow channels ingrain in both the stainless-steel cathode and the titanium anode current collectors. The electrolyzer was assembled by placing a CEM (Nafion 117) over the cathode, then placing the anode on the membrane. In all experiments, unless otherwise specified, the cathode feedstock was a carbonate electrolyte prepared by purging CO₂ at 80 sccm into 85 mL of 2 M KOH for 40 minutes, similar to a previous report. The anode was fed with 0.05 M H₂SO₄. After starting the experiment, the carbonate electrolyte was continuously purged with Ar gas flowing at 20 mL min⁻¹. The first gas sample is typically collected 20 minutes after the start of the experiment to ensure complete purging of excess CO₂ from the electrolyte preparation process and even mixing of gaseous products. The electrochemical measurements were performed with a potentiostat (Autolab PGSTAT204) and the full cell voltages reported are not iR compensated unless otherwise specified.

Product analysis

The cathode gas outlet stream was analyzed in 1 mL sample volumes by a gas chromatograph (PerkinElmer Clarus 590) coupled with a thermos conductivity detector (TCD) and flame ionization detector (FID). The gas chromatograph used Ar gas as the carrier (99.999%, Linde) and was equipped with a Molecular Sieve 5A Capillary Column and a packed Carboxen 1000 Column. Liquid product detection was performed using proton nuclear magnetic resonance spectroscopy (¹H NMR) on an Agilent DD2 600 spectrometer in D₂O using water suppression mode, with dimethyl sulfoxide (DMSO) as the internal standard. Calculation of FE and energy efficiency are included in Supplementary note 1.

Conflicts of interest

There are no conflicts to declare.

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