

Perspective

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Gas-Diffusion Electrodes for Carbon-Dioxide Reduction: A New Paradigm

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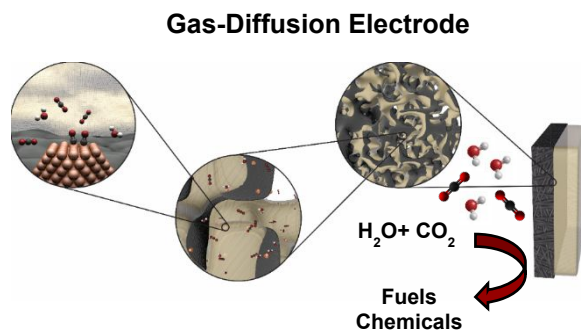
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Abstract

Significant advances have been made in recent years discovering new electrocatalysis and developing a fundamental understanding of electrochemical CO₂ reduction processes. This field has progressed to the point that efforts can now focus on translating this knowledge towards the development of practical CO₂ electrolyzers, which have the potential to replace conventional petrochemical processes as a sustainable route to produce fuels and chemicals. In this perspective, we take a critical look at the progress in incorporating electrochemical CO₂ reduction catalysts into practical device architectures that operate using vapor-phase CO₂ reactants, thereby overcoming intrinsic limitations of aqueous-based systems. Performance comparison is made between state-of-the-art CO₂ electrolyzers and commercial H₂O electrolyzers—a well-established technology that provides realistic performance targets. Beyond just higher rates, vapor-fed reactors represent new paradigms for unprecedented control of local reaction conditions, and we provide a perspective on the challenges and opportunities for generating fundamental knowledge and achieving technological progress towards the development of practical CO₂ electrolyzers.

TOC Image



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5 The development of new technologies that reduce greenhouse gas emissions while producing fuels and
6 commodity chemicals has the potential to mitigate the devastating impacts of climate change by
7 transforming the petrochemical sector towards sustainability. Electrochemical CO₂ reduction (CO₂R)
8 coupled with renewably generated electricity (wind, solar, hydro) provides an attractive approach for the
9 carbon-neutral production of valuable hydrocarbon, alcohol, and carbonyl products that find widespread
10 use in the energy and chemical sectors. For this artificial photosynthesis process to be implemented at
11 scale, highly active and selective CO₂R catalysts must be developed and ultimately integrated into devices
12 that can achieve high conversion rates and energy-conversion efficiencies to the desired product(s).
13 Vapor-fed CO₂ devices represent a promising platform for such a technology.
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17 On a fundamental level, there has been much progress understanding electrochemical CO₂R in the liquid
18 phase, where CO₂ molecules are solubilized in an aqueous electrolyte and reduced on the surface of a
19 catalyst (Figure 1a). The unprecedented level of synergy between theoretical and experimental research
20 towards aqueous-phase CO₂R has led to improved understanding regarding the impact of electrolyte
21 ions,¹⁻³ pH,⁴ mass transport,⁵⁻⁷ temperature,⁸ and pressure⁸⁻⁹ on activity and selectivity. As a result, activity
22 descriptors¹⁰⁻¹¹ and mechanistic insight into reaction pathways¹²⁻¹³ has guided catalyst design efforts,
23 leading to the discovery of new compositions¹⁴⁻¹⁶ and morphologies that are more active and selective to
24 desired CO₂R products. A succinct overview of these advances has been provided in a recently published
25 perspective piece.¹⁷ It is furthermore expected these efforts will be accelerated with the implementation
26 of machine learning processes for catalyst discovery.¹⁸⁻¹⁹
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30 While these referenced studies have been critical in establishing a deeper understanding of CO₂R, they
31 have traditionally relied upon aqueous-phase CO₂R reactors designed for fundamental investigations
32 (Figure 1a). From an applied standpoint, however, these test reactors have many practical limitations that
33 must be addressed. Most notably, the poor solubility (ca. 34 mM) of CO₂ in aqueous electrolytes, along
34 with acid/base buffer (CO₂/HCO₃⁻/CO₃⁻²) equilibria lead to intrinsic challenges towards achieving high
35 conversion rates and energy efficiencies.²⁰ Moving towards practical reactor designs that operate using
36 CO₂ delivered to the cathode in the vapor phase (Figure 1b,c) can help to overcome these performance
37 and solubility challenges. Such gas-diffusion electrodes (GDEs) can achieve this by employing a porous
38 catalyst layer along with diffusion media to facilitate reactant transport and distribution. GDEs have been
39 used in other electrochemical energy-conversion devices such as fuel cells and electrolyzers, where the
40 architecture has been optimized for high current density and low transport losses. However, the
41 adaptation to CO₂R will require further advancement, as different operating strategies and
42 understandings are needed to address product selectivity considerations, which is important to avoid the
43 need for costly downstream separations.²¹ Furthermore, the actual electrolyte can either be aqueous to
44 form a catalyst/liquid electrolyte interface (Figure 1b), or ideally an ion-conducting polymer that can
45 transport charged species (e.g., H⁺ or OH⁻) and form a catalyst/polymer electrolyte interface (Figure 1c).
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50 A recently published article²² provides a critical overview of various electrolyzer designs that can be
51 considered, along with a review of the technological achievements made in recent years on
52 electrochemical CO₂R reactor designs. In this perspective, we discuss the challenges and opportunities
53 facing GDE development for electrochemical CO₂R. We provide context in terms of CO₂R electrocatalysis,
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and include a discussion of the intrinsic advantages and unexpected opportunities of GDEs in an effort to motivate researchers to translate current understanding towards new GDE designs. The purpose of this perspective is not to provide a comprehensive review on the topic of electrochemical CO₂R or GDE development. Instead, the goal is to provide a forward-looking perspective to inspire and provide direction for these fields of research, using the technology maturation process of commercial water electrolyzers as realistic performance targets. We identify areas deemed important for developing a fundamental understanding of the underlying chemistry, processes, and phenomena occurring in GDEs. This insight is essential for advancing the state of electrochemical CO₂R technologies towards commercial viability.

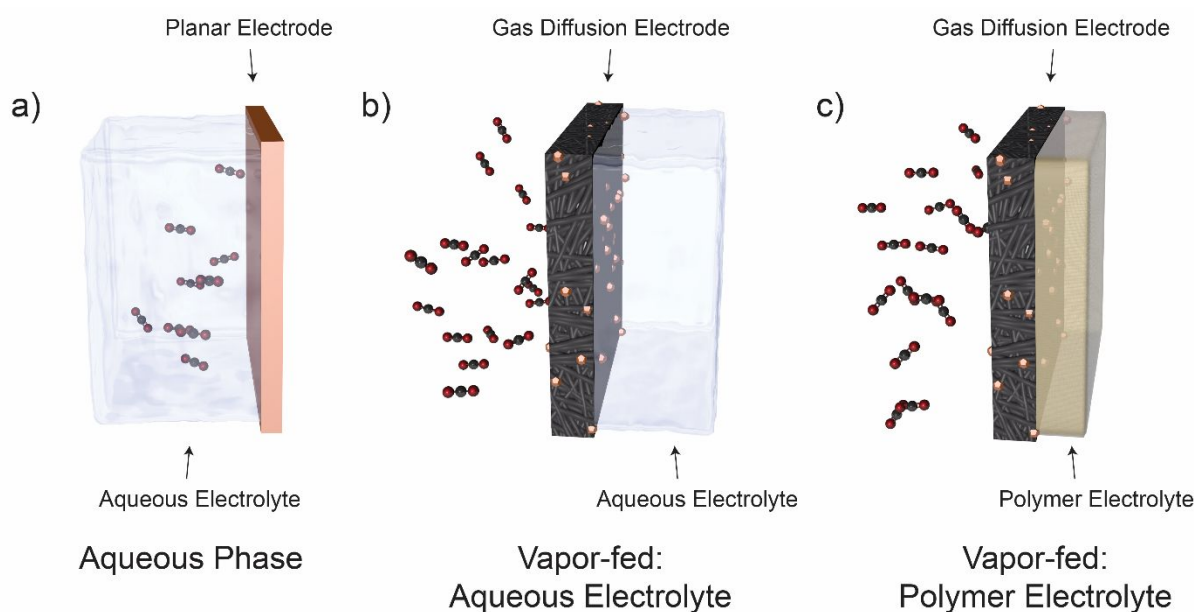


Figure 1: Different electrochemical CO₂R reactor schemes. **(a)** Aqueous-phase CO₂R, where CO₂ is first solubilized in an aqueous electrolyte and then reduced at a catalyst surface. Vapor-fed CO₂R employing an **(b)** aqueous or **(c)** polymer electrolyte.

State-of-the-art

In comparison to electrodes studied in aqueous-phase electrochemical reactors, various types of vapor-fed CO₂R electrodes have been shown successful in improving the partial current densities and energy efficiencies for CO₂R.²³ This has been achieved by taking the most selective catalysts identified through fundamental aqueous-phase reactor investigations, and integrating them into vapor-fed device designs. This research translation trend is depicted in Figure 2a, which summarizes state-of-the-art Faradaic efficiencies versus partial current densities achieved for CO, formate, ethylene, and ethanol production.

Performance obtained from vapor-fed GDEs²⁴⁻³⁶ (solid symbols) are shown in comparison to similar catalyst compositions tested in aqueous-phase reactors^{1, 14, 37-47} (hollow symbols). While different reactor designs and catalyst configurations were used throughout these studies, this comparison shows the general trend of vapor-fed GDE research successfully improving partial current densities beyond those achievable in aqueous-phase investigations, while retaining similar selectivity. Amongst these major products shown, the highest Faradaic efficiencies and partial current densities are generally reported for CO and formate, as there are a number of different catalyst types that are intrinsically selective to these 2e⁻ reduction products.^{36, 48-52} On the other hand, data for the further reduced (>2e⁻) products, ethylene and ethanol, demonstrates that selectivity is still a major challenge. This selectivity challenge is largely because ethylene and ethanol are competitively co-produced on Cu-based catalysts through very similar mechanistic reaction pathways. However, improvements in ethylene selectivity have been observed by implementing Cu-based catalysts in vapor-fed GDEs for electrochemical CO₂R,^{24, 26} along with similar results demonstrated for electrochemical carbon monoxide reduction.⁵³⁻⁵⁴ This observation suggests that vapor-fed conditions are a promising avenue for tuning the local environment and reaction conditions that control CO₂R selectivity (*vide infra*), while simultaneously achieving higher partial current densities. However, altering the local CO₂ environment is largely underexplored for GDEs and presents an opportunity for increased understanding compared to solely aqueous-phase reactor investigations.

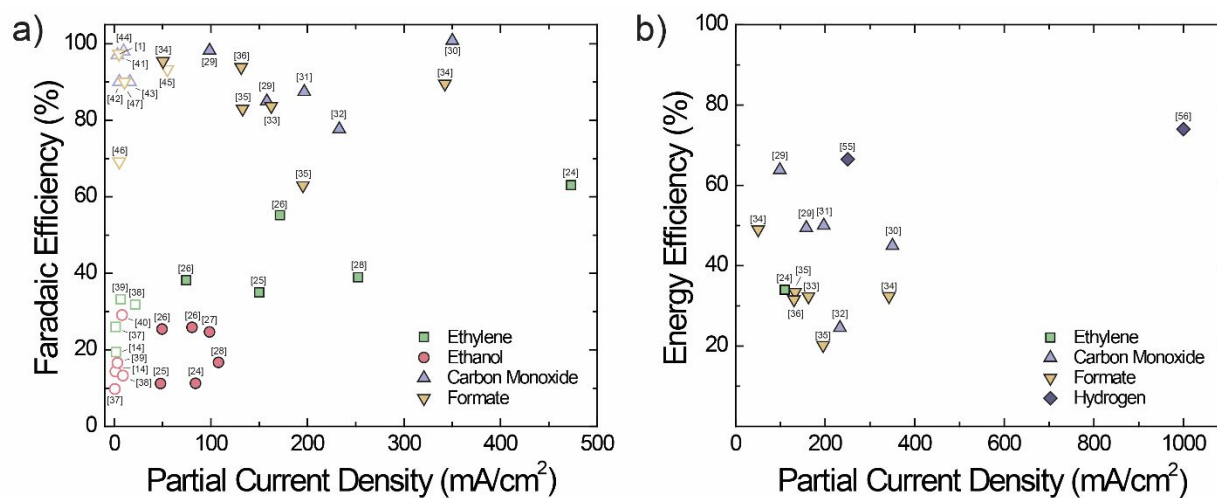


Figure 2: State-of-the-art performance of vapor-fed CO₂ devices. **(a)** Faradaic efficiencies versus partial current densities to ethylene, ethanol, carbon monoxide, and formate. **(b)** Energy efficiencies versus partial current densities to ethylene, carbon monoxide, formate, and hydrogen. Performances obtained for vapor-fed CO₂R electrodes are shown in solid symbols, while performance for electrodes in aqueous-phase CO₂R reactors are shown in hollow symbols. All energy efficiencies were calculated as voltage efficiencies using the formula:

$$\text{Energy Efficiency} = \frac{(E_{anode}^0 - E_{cathode}^0) \cdot FE}{V_{cell}}; \text{ where } E_{anode}^0 \text{ and } E_{cathode}^0 \text{ are the reversible potentials, } FE \text{ is the Faradaic efficiency for the CO}_2\text{R product, and } V_{cell} \text{ is the uncompensated cell voltage.}$$

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3 On a system level, Figure 2b shows a summary of state-of-the-art energy efficiencies versus partial current
4 densities, which takes into account transport resistances (ionic and electronic), along with kinetic losses
5 from both the anode and cathode.⁵⁵ A comparison is also provided to the performance of representative
6 alkaline⁵⁵ and proton-exchange membrane⁵⁶ (PEM) H₂O electrolyzers. It is interesting to note that all of
7 the vapor-fed CO₂R cells incorporate an aqueous electrolyte (Figure 1b), in part because alkaline
8 electrolytes can improve energy efficiencies by reducing cathodic overpotentials. Thus, a traditional
9 commercial H₂O electrolyzer with an aqueous alkaline electrolyte⁵⁵ likely provides the most appropriate
10 comparison. While the representative alkaline H₂O electrolyzer performance is superior to that of the
11 vapor-fed CO₂ cells shown in Figure 2b, the performance of CO₂R to CO cells has been recently closing the
12 gap. Comparing CO₂R cell data to the representative PEM H₂O electrolyzer shows the intrinsic advantages
13 of the PEM configuration (Figure 1c) for high current-density applications (Figure 2b) due to their more
14 efficient reactant management, high reaction area, and minimal distances for ion transport. Clearly, there
15 are opportunities to develop vapor-fed CO₂ devices in this configuration as there is currently a dearth of
16 such studies. Moving forward, it is necessary to understand and optimize transport properties and
17 reaction kinetics in vapor-fed CO₂R devices to advance the performance towards practical viability. While
18 we have focused on partial current density, Faradaic efficiency, and energy efficiency as immediately
19 important performance figures of merit, we note that other parameters such as CO₂ utilization and
20 component stability will also become increasingly important.
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29 **Challenges and Opportunities**

30 A crucial first step in the development of vapor-fed CO₂R devices relates to engineering the GDE
31 structures. Despite decades of studies, GDEs continue to be an active area of research in the fuel-cell
32 sector, and performance improvements are still being realized through GDE optimization strategies that
33 aim to address the many open questions that remain. GDEs in fuel cells may represent a simplified case
34 in comparison to those in CO₂R cells, as reaction selectivity and different product phases (vapor versus
35 liquid) are not as crucial considerations for fuel cells. The challenges and opportunities facing vapor-fed
36 CO₂R electrode development relate to understanding and optimizing the multitude of processes occurring
37 in 3-dimensional GDEs. These processes span different length- and time-scales (Figure 3), with the
38 complex interplay between phenomena ultimately having a governing effect on the CO₂ reaction
39 selectivity and the energy-conversion efficiencies and rates. As these research efforts are accelerated, it
40 will be necessary to translate fundamental knowledge from aqueous-phase CO₂R studies to vapor-fed
41 systems and identify gaps and emergent phenomena. The vapor-fed systems are inherently more
42 complex, due to the presence of a myriad of heterogeneous interfaces on the micro- and nanometer
43 scales. Future research and scientific challenges must be addressed by closely coupled experimental and
44 theoretical investigations. Areas deemed important for knowledge generation and technological process
45 are outlined herein.
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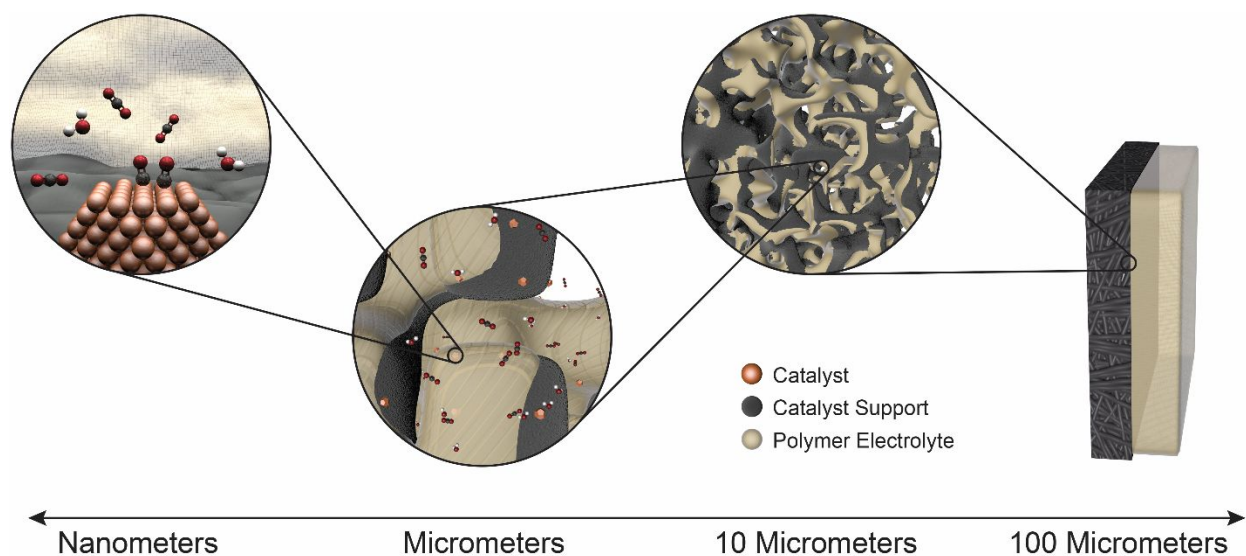


Figure 3: Schematic of a 3-dimensional GDE depicting the multiple length scales where phenomena are occurring during electrochemical CO₂R.

Transport of Reactants

In vapor-phase CO₂R electrodes, the delivery of relevant reaction species (CO₂, electrons and H⁺) can be readily optimized to achieve improved conversion rates. Most notably, vapor-fed cells overcome the intrinsic solubility challenges of CO₂ in aqueous electrolytes (ca. 34 mM). At these low concentrations, mass-transport limitations significantly hinder CO₂ conversion rates in aqueous-phase devices when current densities exceed ca. 10 mA/cm².²⁰ The type of catalyst and GDE fabrication process must be carefully selected to maximize the catalytically active surface area available, and micro- and nanoscale electrode architectures must be designed to optimize CO₂, ion, and product transport simultaneously.⁵⁷ If present, the properties of the diffusion media, including porosity, pore structure, hydrophilicity, and thickness also play a significant role governing electrode performance. These parameters have been explored and optimized in the case of fuel cells,⁵⁸ whereby H₂/O₂ fuel cells are able to reliably achieve current densities in excess of 1 A/cm². This provides a good basis for comparison, yet very limited understanding exists towards the design and development of high current density CO₂R electrodes, which must be established through concerted experimental and theoretical efforts.

The relative humidity and concentration of water in vapor-fed CO₂R reactors can be carefully controlled to overcome the intrinsic challenges associated with aqueous-phase CO₂R, where the concentration of water at the catalyst surface is ca. 55M, whereas in a typical ion-exchange membrane, water concentrations on the order of 1 to 25 M or so are obtainable via humidity control although there is tradeoff in ionic conductivity at low water contents.⁵⁹⁻⁶¹ Water can be a proton source for CO₂R as well as for the undesirable HER. As the reversible potentials for most electrochemical CO₂ reactions lie within 200 mV of the HER,³⁷ the HER provides competition to CO₂R by occupying electrocatalytically active sites and consuming electrons as well as the proton source, resulting in reduced CO₂ conversion rates and energy

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3 efficiencies towards the desired product(s). By delivering CO₂ to the cathode in the vapor-phase, the local
4 partial pressure of CO₂ can be decoupled from the concentration of water (provided an ionic transport
5 pathway remains), enabling strategies to steer selectivity by controlling reactant transport to tune the
6 coverage of intermediates on the catalyst surface. The impact of CO₂ partial pressure on vapor-fed device
7 performance is, however, not well understood and should be the focus of future studies. Parametric
8 investigations on well-characterized GDEs should be conducted and closely coupled to the development
9 of continuum mathematical models to understand transport processes throughout these 3-dimensional
10 porous electrodes and identify their impact on performance.
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14 *Polymer Electrolyte and Ionomer - Charge Carrier Transport and Catalyst/Electrolyte Interfaces*

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16 As previously mentioned, a key challenge of aqueous-phase CO₂R is the CO₂/carbonate/bicarbonate
17 buffering equilibria that limits the range of operational pH values for CO₂R, and convolutes an accurate
18 depiction of the boundary-layer properties at the catalyst surface.²⁰ This leads to inflexibility in tuning the
19 chemical properties of the catalyst/electrolyte interface, despite the importance of these chemical
20 properties in dictating surface reaction kinetics, mechanisms, and charge-transport processes. For
21 example, electrolyte pH is known significantly impact CO₂R activity and selectivity. In particular, increased
22 activity towards valuable C-C coupled products are favored at high pH values,^{4, 62} which cannot be reliably
23 achieved for aqueous-phase CO₂R due to the above-mentioned equilibria. This presents a valuable
24 opportunity to develop and utilize polymer electrolytes that can operate in different pH regimes and may
25 exhibit very different ion concentrations due to their thinness as well as background charge. Furthermore,
26 advances in polymer electrolytes must be translated to the development of ionomers for incorporation
27 throughout the 3-dimensional structure of a GDE to create an interconnected thin-film network needed
28 for ionic species transport. Despite similar structures, the behavior of ionomer thin films in an electrode
29 can vary quite significantly from the bulk polymer,⁶⁰ and advances in their development and
30 understanding are needed.
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35 Solid-state polymer electrolytes (Figure 1c) pose many intrinsic advantages over liquid-phase electrolytes
36 (Figure 1b). Particularly, simplified device designs requiring fewer auxiliary components for electrolyte
37 circulation and replenishment, and the elimination of any mobile counter-ions other than protons and
38 hydroxyls are ideal from a sustainability and CO₂ utilization standpoint. Vapor-fed GDE based devices
39 employing polymer electrolytes also provide additional transport advantages versus aqueous electrolytes
40 as they enable shorter distances between the anode and cathode,⁶³ thereby minimizing ohmic resistances
41 through a “zero-gap” complete solid-state configuration. Avoiding the use of corrosive liquid electrolytes
42 also poses several safety advantages, including avoiding the risk of leaking or heat-induced pressure
43 buildup. Polymer electrolytes furthermore enable operation at higher pressures and potentially allow for
44 differential pressures to be used between the two electrodes, as reactant crossover can be suppressed.⁶³
45 Finally, they provide an opportunity for separation of volatile liquid-phase CO₂R products directly at the
46 site of generation. For example, when targeting alcohol products, in comparison to aqueous-phase CO₂R,
47 vapor-fed devices will avoid the formation of azeotropic alcohol/water mixtures that would require
48 energy intensive downstream separation processes.²¹ Clearly there is an immense opportunity for the
49 development of solid polymer electrolytes and their integration with vapor-fed CO₂R GDEs. Key challenges
50 include designing and integrating new polymer electrolytes that simultaneously satisfy the requirements
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3 of low cost, high ionic conductivity and selectivity, resistance to reactant/product crossover, CO₂
4 tolerance, and long-term chemical and mechanical stability under operating conditions.
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6 On the electrode level, the ionomer properties, including type (i.e., anionic, cationic), structure and
7 catalyst/ionomer interactions strongly influence CO₂R activity and selectivity, where the tethering of the
8 ionic groups hinder movement of their counterions as well as influence the reactivity of the ionic group
9 themselves relative to their behavior in liquid electrolytes. Ionic species (e.g., H⁺, OH⁻, HCO₃⁻) transport in
10 the ionomer phase is a crucial consideration, in addition to the distribution of the ionomer phase
11 throughout the 3-dimensional GDE structure. Particularly, optimized ionomer distributions can enable
12 good charge species transport and active site utilization, while nonideal distributions can adversely affect
13 performance through catalytic or transport resistances.⁶⁴ There also exists enticing opportunities to
14 modify ionomer structures to accommodate functional or ionic species that can provide promotional CO₂R
15 effects, such as increasing the local CO₂ concentration, decreasing selective site poisoning through blocky
16 architectures,¹⁵ or impacting reaction mechanisms and routes through chemical modification⁶⁵ and field
17 effects, where the local ion concentrations and distances can be more precisely controlled.²
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22 While recent advances have enabled understanding of how different parameters (i.e., pH, electrolyte
23 concentrations, catalyst functionalization) fundamentally affect aqueous-phase CO₂R catalysis, it is an
24 opportune time to translate and validate this current state of understanding to highly porous vapor-fed
25 GDEs. For example, polymer electrolytes exhibit different acid/base equilibria time constants than
26 aqueous electrolytes due to the existence of the polymer backbone.⁶⁶ Furthermore, while one may obtain
27 the desired high pH in aqueous electrolytes using high flowrates, that may provide challenges from a
28 practicality standpoint, and thin electrodes,²⁴ a similar effect may perhaps be obtained with polymer
29 electrolytes since their thinness and possibility for high current-density operation result in large hydroxide
30 fluxes and amounts in the electrode ionomer. Targeted approaches to understand polymer electrolyte
31 effects, ionomer distributions, ionomer/catalyst interactions and charge-carrier transport properties must
32 be carried out on model and/or prototype vapor-fed CO₂R systems, where the use of new polymer
33 electrolytes and ionomers provide an increased ability to control and manipulate the local reaction
34 environment at the catalyst surface. It is suggested that researchers leverage previous efforts on these
35 topics reported in the fuel cell or electrolyzer literature, especially as anion-exchange membranes and
36 ionomers become more prevalent and understood.
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42 *Opportunities for Fundamental Understanding*

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44 With the seemingly overwhelming number of factors that govern the multiscale processes and
45 performance of a GDE, a detailed understanding of these phenomena will require experimental
46 approaches closely coupled with multiscale theoretical modeling and prediction. Comprehensive models
47 do not currently exist that simultaneously capture and bridge quantum- and molecular-level dynamics
48 with continuum models of reactant and product transport. The difficulty lies in the disparate length- and
49 time-scales between these processes that require the combination of non-linear partial differential
50 equations with complex boundary conditions. Robust numerical techniques that can accomplish this are
51 needed, which will enable the necessary multi-process understanding and optimization that will be
52 essential for guiding and understanding GDE approaches.
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3 In terms of experimental approaches, the increasing complexity of vapor-fed devices necessitates the
4 development and utilization of *operando*, *in-situ*, and *ex-situ* probes that probe interfacial phenomena in
5 highly porous electrodes. For this, simplified vapor-fed cells can potentially be designed to deconvolute
6 the influence of common experimental parameters.⁶⁷ This could serve to enable facile characterization
7 and CO₂R evaluation of catalyst and electrode structures, which will accelerate the implementation of
8 new GDE formulations in high-performance devices. Additionally, vapor-fed GDEs offer a promising
9 platform for experimentally characterizing the multi-scale properties of devices and processes occurring
10 during operation. By minimizing the use of liquids, challenges associated with beam attenuation and
11 refraction are avoided, enabling mechanistic probing of electrode processes using X-ray scattering,
12 absorption or photoelectron techniques. For example, the electronic or chemical structure of catalytically
13 active surface sites in GDEs under reaction conditions can be probed by *in-situ* X-ray absorption
14 spectroscopy⁶⁸⁻⁷⁰ or *in-situ* X-ray photoelectron spectroscopy⁷¹⁻⁷², respectively; meanwhile the effects of
15 electrode pore sizes, structures and surface properties on microscale transport processes can be
16 interrogated by X-ray computed tomography coupled with performance evaluation.⁷³⁻⁷⁷ Developing an
17 improved understanding of the effects of operating conditions and GDE configurations on performance
18 will provide opportunity to engineer devices to provide multi-variable optimization for achieving
19 unprecedented knowledge and performance.

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21 Beyond GDE designs to optimize the multiscale processes underlying their operation, electrode
22 integration into vapor-fed reactors provides an ideal opportunity for advanced understanding. The impact
23 of operational parameters such as relative humidity, reactant flow rates, temperature, and device
24 electrical potential on CO₂ conversion rates and efficiency remains largely unexplored, yet provide
25 additional levers to tune performance and selectivity. The type of polymer electrolyte (proton exchange,
26 anion exchange, bipolar) and anode design and materials are essential considerations for incorporating
27 GDEs into working devices,⁷⁸⁻⁷⁹ and GDE compatibility with electrolytes and anodes must be understood.
28 The stability of GDEs under operating conditions is also an important topic that has not been addressed
29 in detail here or in the literature, because vapor-fed CO₂R electrode design is a relatively early stage field
30 of research. Stable, long-term operation will be essential for achieving practicality of these devices. As
31 these devices will ideally be coupled with renewable sources of power, the question of variability and how
32 it relates to GDE performance and stability must also be understood and addressed. Furthermore,
33 engineering vapor-fed GDEs to be capable of accommodating low-grade or dilute CO₂ feed sources (e.g.,
34 atmospheric CO₂) improves the practicality of these devices to different applications and elucidation of
35 these effects is important.

36 37 38 39 40 41 42 43 44 45 46 47 **Outlook**

48
49 Recent efforts have demonstrated the potential of translating scientific advances made in electrochemical
50 CO₂ reduction research towards the development of practical CO₂ electrolyzers. Key challenges and
51 opportunities that remain involve the understanding and development of 3-dimensional vapor-fed CO₂
52 reduction electrodes that can achieve high conversion rates and energy efficiencies towards the desired
53 products. Particularly, there is an immense scientific opportunity to develop fundamental understanding
54 of the multi-scale processes occurring in 3-dimensional GDEs, and to optimize GDE performance through
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3 rational engineering approaches. Closely integrated experimental and theoretic investigations are
4 required to progress upon our current state of understanding and perpetuate the advancement of CO₂
5 electrolyzers towards practical relevance. The knowledge generated and progress made in catalyst
6 integration, electrode engineering and electrochemical device design will also be directly applicable to
7 other electrochemical conversion devices that could be of technological importance in the near future to
8 replace Gigatonne-scale, carbon intensive industrial processes. These include sustainable electrochemical
9 technologies for the production of fuels and chemicals from carbon-based feedstocks, or the synthesis of
10 ammonia-based fertilizers from ambient N₂.
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16 **Biographies**

17 Drew Higgins has been at Stanford University and SLAC National Laboratory since 2015, first as a Banting
18 Postdoctoral Fellow and then Associate Staff Scientist working on electrochemical catalyst development,
19 understanding and device integration. In January 2019, he starts a Faculty position at McMaster
20 University in the Department of Chemical Engineering. <https://www.higginslab.com/>
21
22

23 Christopher Hahn began his current position at SLAC National Accelerator Laboratory in 2015, where he
24 is conducting research with the Joint Center for Artificial Photosynthesis on catalyst discovery and
25 understanding reaction mechanisms for electrochemical CO₂ reduction.
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27 <https://suncat.stanford.edu/people/christopher-hahn>
28

29 Chengxiang (“CX”) Xiang and his team is working on development of testbed prototypes for
30 photoelectrochemical CO₂ reduction and water-splitting. <http://sunlight.caltech.edu/cx/>
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33 Thomas Jaramillo is an Associate Professor at Stanford and SLAC National Accelerator Laboratory and is a
34 Thrust Coordinator in JCAP overseeing electrocatalysis research. His laboratory focuses on fundamental
35 catalytic processes occurring on solid-state surfaces in both the production and consumption of energy.
36 <http://jaramillogroup.stanford.edu/>
37
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39 Adam Weber is currently a Staff Scientist at LBNL where he leads the Energy Conversion Group and is a
40 Thrust Coordinator in JCAP overseeing continuum modeling, multicomponent integration, and test-bed
41 construction and evaluation. He is a Fellow of the Electrochemical Society for his research on
42 understanding electrochemical technologies. <https://weberlab.lbl.gov/>
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49 SC0004993.
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Quotes

Moving towards practical reactor designs that operate using CO₂ delivered to the cathode in the vapor phase can help to overcome these performance and solubility challenges

The challenges and opportunities facing vapor-fed CO₂R electrode development relate to understanding and optimizing the multitude of processes occurring in 3-dimensional GDEs. These processes span different length- and time-scales, with the complex interplay between phenomena ultimately having a governing effect on the CO₂ reaction selectivity and the energy-conversion efficiencies and rates.

Particularly, there is an immense scientific opportunity to develop fundamental understanding of the multi-scale processes occurring in 3-dimensional GDEs, and to optimize GDE performance through rational engineering approaches.

There also exists enticing opportunities to modify ionomer structures to accommodate functional or ionic species that can provide promotional CO₂R effects, such as increasing the local CO₂ concentration, decreasing selective site poisoning through blocky architectures, or impacting reaction mechanisms and routes through chemical modification and field effects, where the local ion concentrations and distances can be more precisely controlled.