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# Developing Reactors for Electrifying Bio-Methanation: A Perspective from Bio-Electrochemistry

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The integration of microbial synthesis with renewable electricity is an emerging route for both $CO_2$ utilization and seasonal energy storage in the form of stored bio-electrofuels. The major benefits of electrifying bioreactors include: using highly selective bio-catalysts for $CO_2$ conversion under mild reaction conditions; decoupling the production of more facile electrochemical intermediates, such as hydrogen, at the electrode from the production of bio-catalyzed multi-electron and/or carbon products, such as methane or acetate; using microbes as robust and self-regenerating catalysts enabling higher efficiency and durability in $CO_2$ conversion systems compared to inorganic catalysis. In this Perspective, we propose research aimed at developing electro-bioreactor components that will increase the productivity of the reactor while maintaining high energy efficiency and biocompatible reaction conditions to fully realize the benefits of electrified bioreactors. These developments include: flow reactors with tailored 3D electrodes to optimally use the reactor volume, electrocatalysts designed for peak performance in neutral pH electrolytes, high conductivity microbial media, and new membrane separator materials with high ion conductivity and low gas permeability. Production of methane via a hybrid electrical-biological approach is taken as a case study to motivate these developments. Finally, an iterative design-manufacture-test cycle, enabled by additive manufacturing and 3D printing technologies, is proposed to rapidly prototype components prior to large-scale manufacturing.

## 1. The promise of electrifying bioreactors

The ability to electrify chemical manufacturing using renewable energy is becoming increasingly important as nations and major corporations make pledges to become carbon neutral. Technologies for electrochemical conversion of nitrogen and carbon dioxide ($CO_2$) into a range of products have attracted great interest.[1–4] In particular, production of chemicals and fuels using $CO_2$ and renewable energy is increasingly important in decarbonizing chemical manufacturing, where $CO_2$ "waste" can be turned into a carbon containing feedstock for new products, reducing our reliance on petroleum-derived carbon.[1] While significant research efforts are focused on developing inorganic and non-biological electrocatalysts to facilitate *purely electrochemical* conversion of $CO_2$, the chemical selectivity and long-term stability of these systems poses a significant challenge for these types of catalysts. In contrast, *biological* catalysts, e.g. microbes and enzymes, often perform reactions with high energy efficiency, near 100% product selectivity even at high single-pass conversion efficiency, low operational energy demand, and the ability to self-regenerate, making them potentially attractive for some industrial chemical transformations.[2–14] The advantages of process electrification and biological catalysis could be simultaneously realized by electrifying bioreactors.

Commercial bioprocesses have achieved incredible selectivity and productivity in recent decades. For example, biological fermentation and oxidation of ethanol produces acetic acid,

contributing up to 10% of its global production.[15,16] Similarly, biological gas fermentation technologies are promising for small scale waste gas utilization due to mild operating conditions and relatively low capital costs, enabling rapid and widespread deployment.[17]

Separately, the development of high-performance $CO_2$-fed electrolyzers has undergone a renaissance over the past decade leading to record selectivity, current density, and single pass conversion.[2,18–21] These gains were realized in large part through the understanding that new electrolyzer designs were needed to improve the electrolyte and $CO_2$ transport to the catalyst surface creating efficient boundaries to improve the local catalyst environment. This allowed researchers to approach the intrinsic activity of the electrocatalysts.[20] We propose that a similar paradigm shift in reactor design and materials is needed to maximize the performance of biological catalysts in electrified bioreactors.

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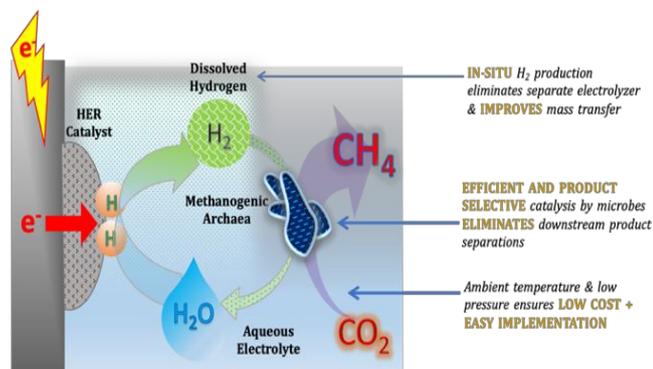
Figure 1. Electrification of bioreactors, exemplified by bio-methanation, can enable low-cost and low-emission energy conversion and synthesis of valuable products. Hydrogen produced in-situ in proximity with microbes in electrolyte facilitates efficient mass transport and rapid utilization by the microbes.

Though there are significant opportunities for microbiologists and bioengineers to improve the performance and operability of biocatalysts used in electrified bioreactors, the goal of this Perspective is to highlight the challenges and opportunities associated with reactor design and engineering.[22–26] We take electro-bio-methanation as a representative case study to emphasize the need for interdisciplinary research across materials science, chemical engineering, microbiology, and electrochemistry to enable developments for commercial deployment of hybrid electro-bioprocesses. These disciplines need to be brought together to overcome the central challenge: **the need to increase the productivity of electro-bioreactors within the bounds of biocompatible reactor conditions while maintaining high efficiencies.**[22–25] We motivate the development of new reactor components using guidance from technoeconomic analysis (TEA) and propose an iterative design-manufacture-test cycle, enabled by additive manufacturing and 3D printing technologies to rapidly push the field forward.

## 2. Case study: electrochemical methane production using microbes

Methanation can be performed using biological catalysts, such as methanogenic archaea (methanogens), to convert $CO_2$ into methane. Electrification of the bio-methanation process with renewable electricity allows production of a carbon-neutral fuel that can be easily distributed and stored for long durations using existing pipeline infrastructure. Of particular interests are hydrogenotrophic methanogens, which utilize hydrogen to reduce $CO_2$ (Reaction 1), and are promising biocatalysts for converting $CO_2$-rich biogas streams to pipeline-quality renewable natural gas (Figure 1).[26–29]

Electrification of bioreactors can be accomplished using reactor designs that take advantage of different processes: direct transfer of electrons from electrodes to biofilms or biocatalysts on the electrode surface (Reaction 2) or indirect transfer using electrochemically generated redox mediators such as hydrogen. In addition to electro-bio-methanation using hydrogenotrophic methanogens (Figure 1), examples of other indirect electro-bioreactor processes include acetogenic fermentation mediated

by in-situ generation of hydrogen and synthesis of formate using electrochemically regenerated cofactors.[7,30]

$$CO_2 + 4 H_2 \leftrightarrow CH_4 + 2 H_2O \qquad \Delta G=-131 \text{ kJ/mol (Reaction 1)}$$
$$CO_2 + 8 H^+ + 8 e^- \leftrightarrow CH_4 + 2 H_2O$$
$$E^{o'}=-240 \text{ mV vs NHE at pH 7 (Reaction 2)}$$
$$H^+ + e^- \leftrightarrow \tfrac{1}{2} H_2 \qquad E^o= \quad 0 \text{ mV vs NHE at pH 0 (Reaction 3)}$$
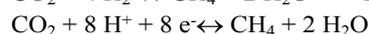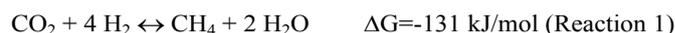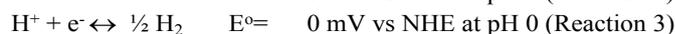
When the reducing equivalents are provided by surplus electricity, either directly as electrons or indirectly through the hydrogen evolution reaction (HER) (Reaction 3), to bio-catalytically produce gaseous fuels, it represents a promising "bio-power-to-gas" technology (P2G).[31] Power-to-methane technology may be an ideal solution for grid-balancing and storing renewable energy over seasonal timescales compared to utility-scale batteries. Additionally, electro-bio-methanation technology can be appropriate for upgrading a range of $CO_2$ sources, from biogas to ethanol fermentation, and at a range of scales.[24,29,32–34]

Compared to the conventional Sabatier process where alumina-supported nickel or ruthenium catalysts are used at high-temperature and high-pressure conditions for $CO_2$ methanation, the bio-methanation process generates methane under near ambient conditions (Table 1).[35,36] Moreover, bio-methanation can convert $CO_2$ to methane with significantly higher selectivity[34] and energy efficiency than can be achieved using inorganic catalysts.[27,28,31]

The state-of-the-art for commercial bio-methanation is a two-stage system where hydrogen is generated using an external electrolyzer and then compressed and bubbled with $CO_2$ into a separate bioreactor for methane generation. Electrochaea GmbH has deployed their two-stage technology for grid-scale energy storage via bio-methanation and has injected methane from their process into commercial gas grids in Denmark and Switzerland (Solothurn).[37] The latter demo site is developed and evaluated under the STORE&GO project using hydrogen and carbon dioxide volumetric inputs at 120 and 30 $m^3$/ hr rates respectively.[38] A range of volumetric productivity from 200-800 $L_{CH4}$ /L /day has been reported for the state-of the-art technology.[38,39] Despite the impressive productivity of two-stage systems achieved to date, the technology still faces some limitations to achieve such a performance level.

The major challenges to achieve higher productivity in two-stage bio-methanation systems are the poor solubility of input gases (both hydrogen and $CO_2$) in aqueous media and slow rate of diffusion of hydrogen bubbles.[32,40] These issues prevent the reactors from operating at the intrinsic turnover rate of the microbes, operating instead in a mass transport limited regime, and thus utilizing the reactors and the microbes sub-optimally.[41,42] Indeed, previous studies have shown that the microbial synthesis of hydrocarbons from $CO_2$ is limited by hydrogen uptake rather than $CO_2$ utilization, indicating that efficient supply of hydrogen to microbes is necessary to enhance the reaction rate.[43,44] Accordingly, high pressure hydrogen gas input systems, advanced gas diffusers, dispersion and recirculation systems, and large mixing/agitation rates are introduced to improve hydrogen utilization at the expense of

increased energy consumption.[26,42,45] Though effective, high pressure hydrogen storage and delivery to the bio-reactor present challenges for safe operation and cost-effectiveness of the technology.[41,46]

Alternatively, in a *single stage* electrified bioreactor which is the focus technology of this Perspective, the electrochemical generation of hydrogen occurs directly within the bioreactor, allowing hydrogen production to occur in close proximity to the microbes, making it readily available for uptake.[26,34,47] At low current densities, hydrogen bubbles formed at the cathode are small, or hydrogen remains dissolved, enabling more efficient gas transfer to the microbial media than larger hydrogen bubbles formed during hydrogen gas sparging into the solution.[30,44] Thus, operation of bio-methanation systems can be simplified by generating $H_2$ *in situ*, eliminating the requirement for separate

for neutral media operation tailored for efficient and productive electro-bio-methanation.

To facilitate comparison between different system configurations, we recommend standardizing testing conditions and reporting several key performance metrics—these guidelines are outlined in the Supplementary Information Section S1.

## 3. Electro-bio-methanation cost drivers

To identify the most important economic drivers that govern reactor design, we performed a technoeconomic analysis (TEA) that reflects one potential deployment of the electro-bio-methanation technology. TEAs are vital to understanding the viability of a process as reactor scale up progresses.[51] Our TEA

Table 1. Comparison of Performance Parameters for $CO_2$ Methanation Technologies

| Technology | Process Parameters | | | Energy Efficiency (%) | Performance Notes |
|---|---|---|---|---|---|
| | Catalyst | Temp. (°C) | Pressure (bar) | | |
| High temperature metal catalytic Sabatier process | Ni, Ru | 250-550 | 1-100 | 54-80 | Commercial process[27,28,31] Sensitive to biogas contaminants High temperature and pressure required |
| Electrocatalytic methanation | Cu, Cu-Bi nano alloy | 25 | 1 | 5-25 | Bench-scale technology[33–35] Low carbon selectivity and Faradaic efficiency |
| Photocatalytic methanation | Pt-Cu/TiO2 Halide perovskites | 25 | 1 | < 1 | Bench-scale technology[36,40,41] Significant challenges in light distribution and reactor scaling Activity degradation during cycling |
| Bio-catalytic methanation | Hydrogeno-trophic methanogen | 20-70 | 1-18 | 46-62 | Produces pipeline-quality RNG[42,43 48] No feed gas purification required Pilot plant demonstration [a] Adaptable to range of flow rates |

a: http://www.electrochaea. com

units to generate, store and introduce gaseous hydrogen at elevated pressure. Additionally, *in situ* $H_2$ generation can

 mitigate some of the solubility and mass transfer challenges of bubbling hydrogen gas, providing a pathway to increase the reaction kinetics and reactor productivity.[31,32,34,43,49]

Despite these advantages, direct integration of currently available commercial electrolyzers with microbial processes is not straightforward. State-of-the-art water electrolyzers typically operate under highly acidic or alkaline conditions, which is not compatible with microbes who require pH near 7 operation.[24] Thus, electrolyzers for bioreactor applications must be designed from the ground up to realize the opportunities and potential of biologically catalyzed electrochemical conversions.[25,50] A whole-of-system research approach to electrification of bioreactors can ensure that the performance can be increased to commercially viable levels while maintaining biocompatibility. From the reactor design and engineering perspective, this research should target improvements in 1) the design of flow reactors with electrodes, 2) the conductivity of the microbial media, 3) ion transport efficiency of separator and membrane materials and 4) performance stability of inexpensive electrodes

included: (1) a detailed process flow diagram, based on research data and rigorous material and energy balance calculations; (2) capital and project cost estimations for DOE-recommended reactor configurations using in-house models; (3) a discounted cash flow economic model; and (4) the calculation of minimum fuel selling price (MFSP). We calculated the MFSP, which is the minimum price at which the methane product must sell to break even on the process cost, given a 10% internal rate of return. In addition, a sensitivity analysis (Figure 2) on both market parameters (i.e., $CO_2$ and electricity price) and technology-specific parameters (i.e., productivity, cell voltage, methane selectivity, and $CO_2$ single-pass conversion) was developed to understand not only key cost drivers but also key strategies for cost reduction in the electro-bio-methanation system.[52–54] A process flow diagram and key assumptions in the model can be found in the Supplementary Information Section S2-S4.

Out of three electrolyzer reactors identified by DOE in hydrogen analysis (H2A) models for electrochemical water splitting, the alkaline water electrolyzer is the most similar configuration to our system based on lower current densities for hydrogen generation in biocatalytic systems which is dictated by the constraints for neutral pH environments. Thus, we have used it
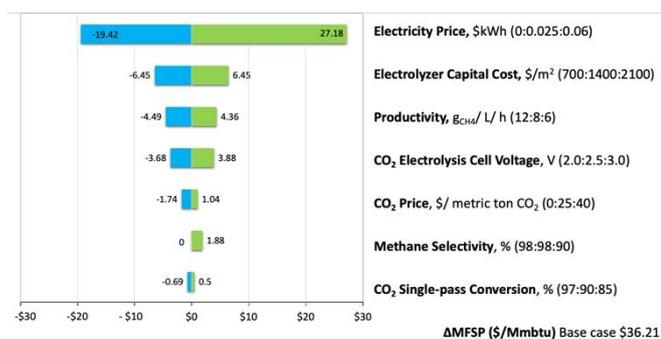
Figure 2: Technoeconomic sensitivity analysis for a single-stage electro-bio-methanation highlights the need to improve reactor productivity and use low-cost materials

as the most comparable cost number for the capital cost of the electro-bioreactor in present study.[55] Importantly, our technoeconomic analysis provides a baseline for evaluating how the overall cost of renewable methane production is affected by the improvements in the system, highlighting important areas for research and development.

Under current state-of-the-art performance, microbial synthesis from $CO_2$ is not yet economically viable mainly due to high operational cost for energy input.[25,56] Our cost sensitivity analysis of electro-bio-methanation (Figure 2) indicates that this is also true for methane production – the cost of electricity dominates the overall cost. However, if the electricity supply is free, which may occur if reactors are operated when there is an oversupply of renewable electricity to the electrical grid, the cost is primarily dependent on the cost of the electrolyzer. Decreasing the capital cost of the electrolyzer by 50% from the base case can lower the cost of methane production by about 20%. This suggests that one key research focus should be on developing inexpensive electrolyzer components, such as electrodes for HER that are compatible with biocatalysts and noble-metal-free anodes for the oxygen evolution reaction (OER) near neutral pH using abundantly available materials.

Our TEA suggests that a 50% increase in reactor productivity can reduce the cost of methane by about 12%. This may be done by increasing the surface-area-normalized current density, but as will be detailed in the next section, increasing the current density while maintaining biocompatible conditions is challenging. Therefore, we propose that increasing productivity should be accomplished by designing flow reactors with electrodes that intelligently optimize the surface area to reactor- and electrolyte-volume ratio while allowing the solution-phase microbes to access the hydrogen produced *in situ*. Another cost sensitive factor considered in our TEA is the cost for $CO_2$. Our TEA implies that methane production cost can be reduced by 5% if free $CO_2$ waste stream can be used.

Development of the bioreactors and reactor components to reduce cost and improve methane productivity should be performed while maintaining high efficiencies. However, there is a lack of literature reporting both the whole cell potential, which is directly related to the energy efficiency, and single-pass $CO_2$ conversion efficiency. Both high methane selectivity and $CO_2$ conversion efficiency lead to lower system and operational costs associated with downstream gas purification. In the electro-

bio-methanation process, the potential cost reductions from improvements in these two parameters are almost negligible since the demonstrated selectivity and conversion efficiency are already above 98% and 90%, respectively.[34]

These insights from the TEA highlight the need for development of inexpensive reactors and reactor components to increase the productivity of an electro-bio-methanation system, while maintaining high energy efficiency and biocompatible reactor conditions. In the next section, we detail research areas from the perspective of reactor design and engineering that would benefit electrification of bioreactors.

## 4. Designing and engineering key elements of electrified bioreactors

We identified three general reactor designs that have been tested in the literature for electro-bio-methanation: membrane-less single to multi-chamber reactors, membrane-separated reactors (H-cell, bubble column reactors, or flow cell), and electrolyzer stacks.[33,36,57–59] All these configurations operated with electrochemical approaches have four essential components:

1. a cathode where a reduction half-cell reaction occurs to produce reducing equivalents, typically as molecular hydrogen;
2. an anode where an oxidation half-cell reaction occurs;
3. microbes to catalyze substrate conversion; and
4. electrolyte and media to support ionic conductivity, maintain pH and supply nutrition for the microbes.

For electrified bioprocesses where hydrogen evolving electrodes are in the microbial media, maintaining biocompatible conditions must be balanced against the kinetics of hydrogen evolution and the overall productivity of the reactor. Figure 3(A) highlights key challenges in coupling bioreactors with electrolysis. In mass transport unrestricted regions, the voltaic efficiency of the system varies with current density due to charge transport kinetic barriers and internal resistance, including: ohmic polarization, low salinity microbial media, contact resistance of electrodes, and poor ion conductivity through membranes. At higher current densities, efficiency improvement in electro-bioreactors is mainly reliant on lowering the mass transport resistance. However, achieving comparable current densities for HER achievable in alkaline electrolyzers, 100-200 $mA/cm^2$, at >50% energy efficiency (or single cell voltage < 2.5 V) for improving methane productivity appears challenging in typical flow reactors in neutral media.[24,25,50] Strategies to maintain biocompatibility and increase the reaction rates through selection of reactor component and operating conditions are shown in Figure 3(B). The most important engineering and electrochemical concepts are discussed below.

### Maximizing reactor utilization with solution phase bio-catalysis

Selecting microbes that remain suspended in the electrolyte, rather than forming a biofilm, is an approach for increasing electro-bioreactor productivity and/or efficiency. Electrodes that are coated with biofilms grant the microbes direct access to *in-situ* generated hydrogen at the electrode surface. However,
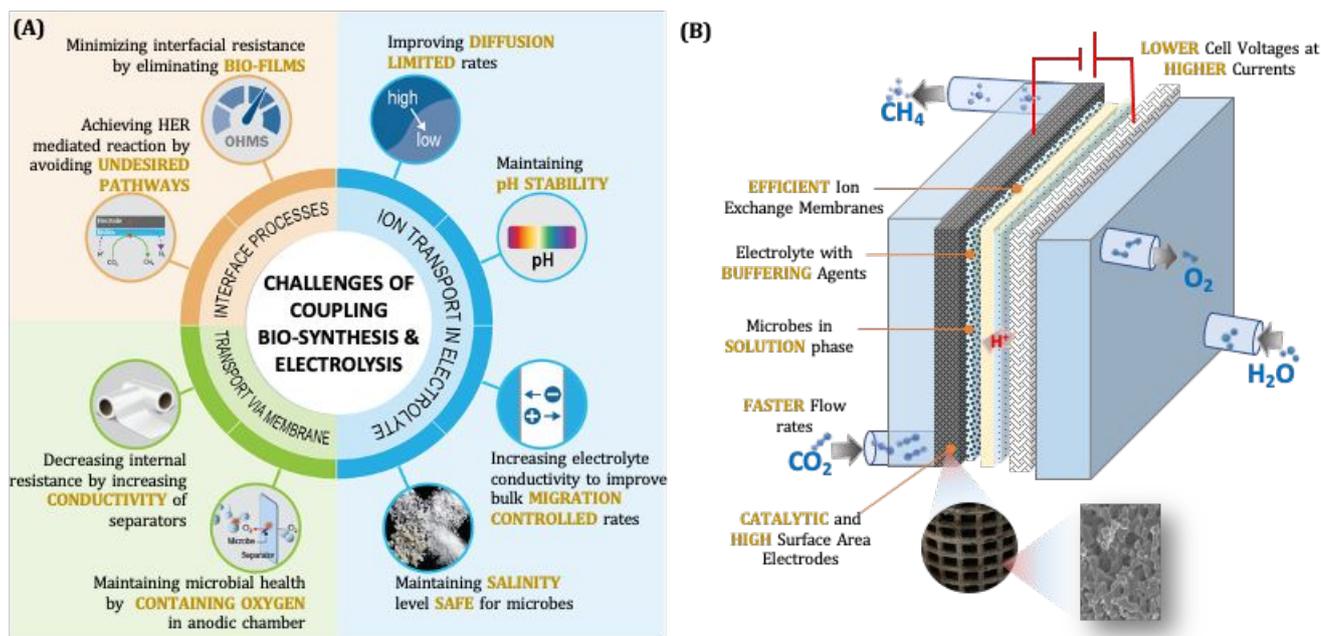
Figure 3. (A) Challenges of coupling electrolysis and microbial synthesis and (B) strategies for achieving biocompatible operation of hydrogen evolution in the presence of microbes. Strategies for reducing cell voltage to minimize the energy intensity and maximize reactor productivity include: selection of solution-phase biocatalysts to maximize utilization of reactor volume, development of high surface area cathodes and anodes composed of low cost and durable catalysts, use of flow reactors to facilitate turbulent mixing and improve mass transport, engineered electrolytes to reduce resistance and improve pH stability, and development of high ion conductivity membrane separators with low gas permeability.

biofilm formation also increases the interfacial resistance between electrolyte and electrodes leading to add higher ohmic resistance on the bio electrode and imposes diffusion barriers on reactants, such as $CO_2$ and protons, and products.[13,60] These effects can lower the energy efficiency of the system at a given reaction rate. In these systems, the use of additional conductive particles, molecules, or ions is necessary to improve the conductivity at the biofilm interface.[61,62] Additionally, biofilms may facilitate direct electron transfer for $CO_2$ conversion to methane per Reaction 2, which has a higher overpotential than that for HER.[27,33,61,63,64] Thus, design of reactors that use biofilms, while trying to achieve higher efficiency and productivity, is challenging.[50]

In contrast, hydrogen-mediated electro-bio-methanation reactors with solution phase microbes have attracted great commercial and research interest.[24] $H_2$ consuming methanogens are stable in long term performance even with fluctuations of electrochemical $H_2$ production, indicating their resilience in practical applications.[65,66] However, efficient delivery of the *in situ* generated hydrogen from the electrode surface to solution phase microbes is also very important to achieve high overall conversion kinetics.[67] This mediated process allows reduction in the kinetic barrier and removes the interfacial resistance associated with biofilms, as well as simplifies the scale-up process.[68] Thus, selecting microbes, cathode materials, and operating conditions to avoid biofilm formation is important for developing sustainable and large-scale systems. Regular monitoring and maintenance of the electrolyte with microbial media in this homogeneous bio-catalysis system is needed as suspension of microbes, their rapid growth, and dead cell mass may lower the ionic conductivity of the electrolyte and membrane.

## Manufacturing of bio-compatible and efficient cathodes

The rate of the biocatalytic conversion in an electro-bioreactor is mainly characterized by the electron transfer rates in the system, which is controlled by physical and chemical properties and interactions between the biocatalyst and electrode surface.[69,70] Despite the high diffusion coefficient of protons in water ($10^{-4}$ cm$^2$/s, Grotthuss mechanism), their low concentration in neutral media ($10^{-10}$ mol/cm$^3$) causes water to become the dominant reactant for HER (Reaction 4), leading to local formation of hydroxide at the cathode and raising the local pH.

$$H_2O + e^- \leftrightarrow \tfrac{1}{2} H_2 + OH^- \qquad E^o = -410 \text{ mV vs NHE (at pH=7)}$$
(Reaction 4)
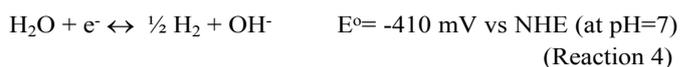
For an electrode performing HER, the electrode surface pH is related to the current density and diffusion layer thickness via Equation 1:

$$\text{Surface pH} = -\log [C^{*H+} - (I \delta / n F D)] \qquad \text{(Equation 1)}$$

where $\delta$ = diffusion layer thickness, D = diffusion coefficient of $H^+$, I = current density, F = Faraday constant and $C^{*H+}$ = bulk formal concentration of protons. During any electrochemical reaction, the concentration of the reactants at the electrode surface decreases compared to the bulk concentration.[71] The resulting concentration gradient is known as the diffusion layer, and is typically several micrometers for electrodes tested in standard electrochemical cells[72,73] Thus, rather than focusing on achieving high surface-area-normalized current densities, which is often the focus for non-biological electrocatalytic reactors, we propose focusing on reactor-volume-normalized metrics, such as the volumetric productivity to target higher conversion rates in neutral media.

One exemplary method to increase volumetric productivity of bio-methanation reactors without sacrificing energy efficiency is *fabrication of high surface area cathodes using 3D printing*, in tandem with solution-phase microbes (Figure 4).[74,75] Porous 3D electrodes, such as log-pile lattices, that allow solution-phase microbes to interact with hydrogen being produced throughout the structure can improve productivity at a given cell voltage by facilitating higher reactions rates. This means thinking beyond the commonly used graphite rods and planar electrodes, which do not optimize utilization of the reactor volume. 3D printed electrodes show the best reported volumetric productivity (2.2 $L_{CH_4} L^{-1}_{reactor} day^{-1}$) for electro-bio-methanation tested in H-cells, with stable biocompatible operation and near 100% utilization of *in situ* evolved hydrogen for methane production.[76] In this study, Kracke, et al. have studied a series of 3D electrodes and have demonstrated that at a fixed total current, 3D cathodes with larger surface area facilitate higher reactor productivity and minimize the outflow of unreacted $H_2$ from the electro-bioreactor.[76]

The ability to increase the volumetric productivity of the reactor relies on being able to increase the total current supplied to the reactor. Therefore, high surface area 3D electrodes enable high total currents to achieve high volumetric productivity by balancing the requirement of low current densities for maintaining biocompatibility and small pH gradients. Minimized pH gradients at the electrode surface enable higher volumetric productivity at a given voltaic efficiency. While increasing the geometric surface area can help maintain a low current density (1-5 mA/cm$^2$) and reduce the thickness of the diffusion layer, this alone is not currently a commercially feasible strategy. This is due to higher material cost for high surface area 3D electrodes compared to that used in typical MEA type reactors. Thus, innovating low-cost materials for 3D cathodes and identifying strategies for utilizing 3D cathodes effectively are also key to lower the production cost. Development of 3D electrodes allows the electrode geometry/topology to be optimized for a given



Figure 4: Strategic upgrading of performance in *in situ* hydrogen evolution based methanogenesis: improvements of both volumetric productivity and energy efficiency through cathode engineering allow higher rates of HER at lower cell voltages. Additive manufacturing of 3D porous electrodes helps achieve higher energy efficiency and productivity by directing the performance metrics to the top-left segment (crossed area) of the graph.

reactor volume, housing, and integration with fluid flow to promote turbulent mixing and reduce the thickness of the diffusion layer to push biocompatible current densities to relatively higher values.[77–83] Thus, manufacturing of 3D electrodes to improve reactor utilization is not an end in itself, but a means for reducing the diffusion layer thickness to enable larger current densities without impacting the biological performance.

In addition to the lower cost, the materials that these 3D electrodes are fabricated out of must have high stability, conductivity, and catalytic activity. Commercially available carbon-based materials are typically used as cathodes in electro-bio-methanation as they meet these material criteria.[36,68,84,85] Since electrode resistance scales with the size of the reactor, improving conductivity of the electrode material is also a critical requirement. Doped carbons and graphene aerogels have improved performance compared to carbon black due to reduction in the internal resistance of the electrode.[76] 3D metallic electrodes formed by emerging additive manufacturing techniques also have promise, but the speed, cost, processing techniques and scalability of these materials must be improved. The direct printing of metallic materials is in development, e.g. via electrochemical 3D printing, a relatively new form of AM that creates metallic structures through electrochemical reduction of metal ions from solutions onto conductive substrates.[24] Electrode materials can also be modified with an overpotential-reducing catalytic layer, commonly formed through techniques such as electrodeposition. Platinum is the benchmark material, but not practical at large scale; more common and lower cost metals, like copper, nickel, and alloys such as nickel-molybdenum have been demonstrated to be effective for low overpotential HER in neutral media, suitable for use in electro-bioreactors.[32,34,86,87] Overall, future research should be focused on developing low-cost, biocompatible, catalytically active, and high surface area cathodes on conductive substrates.

Finally, if the reactants or products of the electrified bioreactors are gases, as is the case for electro-bio-methanation, bubbles must be managed so that they do not add extra resistance to the system by blocking the electrodes and membranes. Development of gas transport channels on the electrodes or flowing electrolyte through the electrodes are options to overcome bubble traffic in electrochemical reactors.[88] Here again, 3D printing offers a promising solution as the materials can be custom designed including channels at micro and macro scale, which can be prototyped, tested and optimized rapidly. 3D gas diffusion electrodes (GDE) improve the single pass reactant conversion efficiency in direct $CO_2$ reduction electrolyzers,[89] but their advantages need to be explored in hydrogen-mediated $CO_2$ conversion systems.

**Designing flow reactors to improve mass transport**

Flowing or stirring the electrolyte can enhance the volumetric productivity of the reactor by improving convective transport and eliminating ion concentration gradients, allowing biocompatible conditions to be maintained even when operating the electro-bioreactor at high productivity. In some cases,

microbial conversion efficiency can also be improved with the increased flow rate by improving the uniformity and gas-liquid mass transfer throughout the reactor: Kougias, et al. have demonstrated that increasing the biogas gas recirculation flow rate from 4 to 12 L/hr in a two stage bubble column bioreactor increased the average purity of methane from 66% to 98%.[58]

Typical H-cells are the basic membrane-separated electro-bioreactors used at lab scale in microbial electrolysis systems.[50] However, the mass transport kinetics of typical H-cell system are poor, leading to limits when exploring the performance and behavior of the system at higher reaction rates. The limitations due to low concentration of ionic species in the electrolyte are exacerbated in typical membrane-separated H-cell reactors due to the large distance between the anode and cathode, large electrolyte volume, and poor fluid dynamics.

Advanced membrane-separated cell reactor designs that facilitate the ability to circulate or mix the electrolyte (e.g., bubble column, flow cells) are commonly used in different electrolysis systems including $CO_2$ conversion. These types of reactor designs have not been extensively investigated for biological systems but have the potential to improve mass transport kinetics. Development of electrodes and reactor housings that can help reduce the thickness of the diffusion layer by inducing turbulent flow can enable higher current densities and volumetric productivities with smaller pH gradients (Equation 1), allowing microbial viability to be maintained. Optimization of gas and liquid flow paths, through design of flow plates, can also promotes turbulent mixing and maximizes reactor utilization. The components of the reactors can be designed with the aid of multi-physics models that simulate the fluid and reaction dynamics to improve ion transport and electrolyte mixing. Process modelling can help tune the maximum conversion in a single pass to optimize the performance of electrodes, electro-bioreactor volume, operation conditions, and gas separation and recycling systems.[58,59,90,91]

*Low-cost co-development of reactor designs and 3D electrodes composed of conductive materials to maximally utilize the cathode volume and supply molecular hydrogen to solution-phase microbes can lead to improvements in the productivity and energy efficiency of electro-bio-methanation reactors.*

### Completing the circuit: the anode half-cell reaction

To use renewable energy for electrifying bioreactors, cathodic hydrogen production must be paired with an oxidation reaction at the anode. At industrial scale, degradation of organic materials and water oxidation have been proposed.[61] The combination of organic digester and electrolyzer is widely studied for bio-methanation systems in wastewater based bio-reactors.[33,61,90,92] These reactors benefit from low cell voltage, reducing the energy intensity of bio-methanation, and ability to use inexpensive carbon electrodes for both anodic and cathodic reactions to reduce the capital cost of the system. Organic matter oxidation can non-selectively produce $CO_2$ at the anode, increasing the carbon intensity of the electro-bio-methanation process.

In contrast, the anodic oxygen evolution reaction (OER) from water (Reaction 5) is a sustainable and relatively robust counter-reaction for $CO_2$ reduction systems:

$$H_2O \rightarrow \tfrac{1}{2} O_2 + 2H^+ + 2e^- \qquad E^o = 1.23 \text{ V vs NHE (at pH=0)}$$
$$\text{Reaction 5}$$

One of the major limitations of the use of water as an electron donor in electro-bioreactors is the production of oxygen. Methanogens typically operate under anoxic conditions, and while further studies are desirable to investigate oxygen-tolerant methanogens, effectively preventing oxygen diffusion to the cathode is required.[13] This may be done through introduction of a membrane separator between the anode and cathode chambers or by engineering the reactor and electrode geometry to channel electrolyte flow in a way to prevent oxygen diffusion.

OER in neutral to acidic media is generally hampered by high overpotentials and material instability. Furthermore, decreasing the pH in the anodic chamber to sustain the transport of protons through the membrane during electrolysis increases the energy required—one pH unit difference between anodic and cathodic chambers adds an extra 59 mV to the water splitting cell voltage.[93–95] Iridium- and ruthenium-based catalysts are the benchmark materials for OER in both alkaline and acidic media, but are prohibitively expensive at large scale.[67,96] Anodes based on platinum, nickel, or carbon suffer from degradation over relatively short periods of low pH electrolysis.[33,64,97–100] Cobalt, nickel, iron, or manganese oxide-based catalysts have been tested in neutral electrolytes, but often require high overpotentials (>400 mV at 10 mA/cm$^2$).[100,101] More exotic nanoparticle catalysts have also been developed, but are currently difficult to implement at large scale.[74,84] Strategic learnings from work by Bian, et al. are useful for fabricating and integrating efficient anodes using inexpensive substrates with a thin layer of catalysts in electro-bioreactors.[56] Development of low-cost, durable OER catalysts with low overpotentials in neutral to acidic environments is critical for improving the energy efficiency and productivity of electro-bio-methanation.

### Engineering electrolyte properties

In typical electrochemical systems, conductive supporting electrolytes are added to the electrolyte in large concentrations (10-100 times higher than the concentration of electroactive species) to reduce the ohmic resistance and migration effects in the solution. With these extra ions, the rate and energy efficiency of electrochemical reactions can be improved. Currently available commercialized electrolyzers usually operate at highly alkaline (20-30% KOH) or acidic conditions (0.5 M $H_2SO_4$) to benefit from the higher mobility and ionic conductivity in the electrolyte (>200 mS/cm) enabling current densities in the range from 0.2-1 A/cm$^2$ at <2 V of cell voltage.[30,48] However, the electrolyte properties that are optimal for water electrolysis are at odds with nutrient, ionic strength, and pH requirements for microbes.[32,34,48] For example, microbial media are typically buffered at circumneutral pH and have relatively low ionic conductivity.[97,98] Thus, bench scale electro-bioreactors typically operate at 1-20 mA/cm$^2$ current densities.[7,32,34,61,68] Verea, et al., have shown that the increase of the electrolyte conductivity from 7.5 to 15 mS/cm enhanced the productivity of hydrogen

producing electro-bioreactors by 60%.[102] Despite the fact that some studies show that introduction of sodium salts in micromolar concentrations can improve the growth of microbes and the biochemical properties of the biocatalyst (driven by sodium ion potential), the capabilities for improving the total salinity of the system to overcome the electromigration of the electroactive species is still limited due to the intolerance of microbes to high salinity.[27] Manon, et al. has described that addition of 100 mM KCl to an electrolyte composed of 50 mM phosphate buffer and 10 mM potassium acetate at pH 7.0, can enhance the conductivity by 15 mS/cm.[103] Research and development of biocompatible conductive electrolyte compositions and improving microbial tolerance to high ionic strengths (with conductivity >50 mS/cm) at neutral pH conditions is necessary for realizing competitive current densities to boost reactor productivity.

Furthermore, compared to proton or hydroxide ion-rich systems, the performance of HER in bio-compatible electrolyte is strongly limited by diffusion. When the rate of proton or hydroxide diffusion in the system is slow compared to the rate of water electrolysis, neutral pH may not be maintained in both anodic and cathodic compartments. Loss of the desired pH during electrolysis can cause some components of the microbial media to precipitate or decompose, or in some catastrophic cases, the microbes may be compromised and be unable to recover. To tolerate small pH fluctuations during electrolysis in microbial media, neutral pH buffer agents such as citrate, phosphate, Tris-HCl, MES, MOPS, and bicarbonate are added as supporting electrolytes. In some cases, the proton donation abilities of these buffers show catalytic effects for lowering the HER overpotential.[104] Buffer agents can minimize the pH increase at the electrode surface as well as in the bulk, since acid-base neutralization reactions are generally faster than electrolysis rates.[104] At high buffer concentrations, overpotential of the hydrogen evolution reaction is determined by the diffusion of both protons and buffering agents. However, the buffer capacity is limited by the electrolyte viscosity increase and solubility of buffer components at higher concentrations.[105]

### Facilitating ion transfer with gas impermeable separators

*We have identified that substantial efforts should be placed on innovating low-cost separators with rapid proton and/or hydroxide transfer, low internal resistance, and reduced gas permeability. An overall review and perspective on materials development to improve the energy efficiency and productivity of neutral media electro-bioreactors are described below.*

In water electrolysis, HER in the cathode is typically balanced with the oxygen evolution reaction OER in the anode. These two reactions are separated by a selective membrane or a porous separator (Figure 5(A-E)) to prevent unwanted mixing and gas transport between the two chambers, due oxygen's toxicity to the microbes and the potential for reduction in Faradaic efficiency at the cathode due oxygen reduction. Some membrane-less configurations (Figure 5(F)) have been studied but gas and liquid fluid flow need to be carefully regulated to minimize diffusion of oxygen towards the cathode and prevent diffusion of hydrogen, methane, and microbes to the anode. More commonly,

membrane properties are selected or tuned to facilitate efficient and selective ion transfer between cathode and anode while preventing gas crossover. In all these categories, there is still room for significant improvement in the materials.

**Ion selective membranes.** Electrolysis systems use proton exchange membranes (PEMs) or anion exchange membranes (AEMs), depending on the operating pH of the system, to facilitate proton or hydroxide transport, respectively. However, at neutral pH, the poor activity of protons or hydroxides limits their rate of transport, particularly when supporting cation or anion concentrations are 4-5 orders of magnitude larger.[93,106] Thus these systems suffer from two serious problems with the sluggish ion conductivity across the membrane in bio-compatible electrolytes: (1) pH increase in the cathode chamber due to water splitting (Reaction 4) and (2) high internal resistance and voltage drop between the anode and cathode in neutral media applications, reducing energy efficiency. Membrane fouling, bubble trapping, and interaction between functional groups in the membranes and microbial media components are also known key issues linked to membrane failure.[107] Because ion selective membranes contribute significantly to the overall capital cost of any electrochemical system, they must be as efficient and robust as possible. Development of conductive and robust ion selective membranes for neutral media applications is urgently needed. With the rapid growth in diverse applications of ion selective membranes in non pH extreme, mild operation conditions, mass manufacturing cost of these expensive materials could be lowered in the future.

PEMs (Figure 5(A)), specifically Nafion™, transport protons generated at the anode to the cathode chamber and generally have low permeability to oxygen when the membrane thickness is high (e.g.: Nafion 117), making them the typically studied ion selective membrane in electro-bio-methanation reactors.[32,34,36] The proton conductivity of PEMs is highly dependent on the hydration and the temperature, but can be up to 0.2 S/cm for Nafion™.[108] Development of cross linked PEMs, such as Ultrex CMI-7000,[109] has shown a path for lowering the cost by varying the composition, thickness and manufacturing method. In parallel to synthesizing inexpensive membranes, increased proton conductivity in neutral media, and higher oxygen rejection can also significantly benefit the commercial development of efficient electrified bioreactors.

AEMs (Figure 5(B)) are used in alkaline electrolyzers to transport hydroxide ions generated at the cathode to the anode chamber. Their use in electro-bio-methanation systems has been demonstrated by Logan et al., despite the poor ion conductivity in neutral media.[98] In bio-catalytic $CO_2$ conversion systems, they can non-selectively transport bicarbonate, carbonate, and anionic liquid products from the cathode to the anode.[45,107,110] Therefore, for AEMs to supplant PEMs in electro-bio-methanation reactors, improvements in selective hydroxide transport must be made.

Bipolar membranes (BPMs, Figure 5(C)) are composed of a PEM laminated with an AEM layer. Water dissociation occurs at the center of the BPM, allowing the cathode and anode chambers to maintain a pH difference. Wang, et al. has demonstrated use of a BPM with acidic catholyte is more effective than an AEM
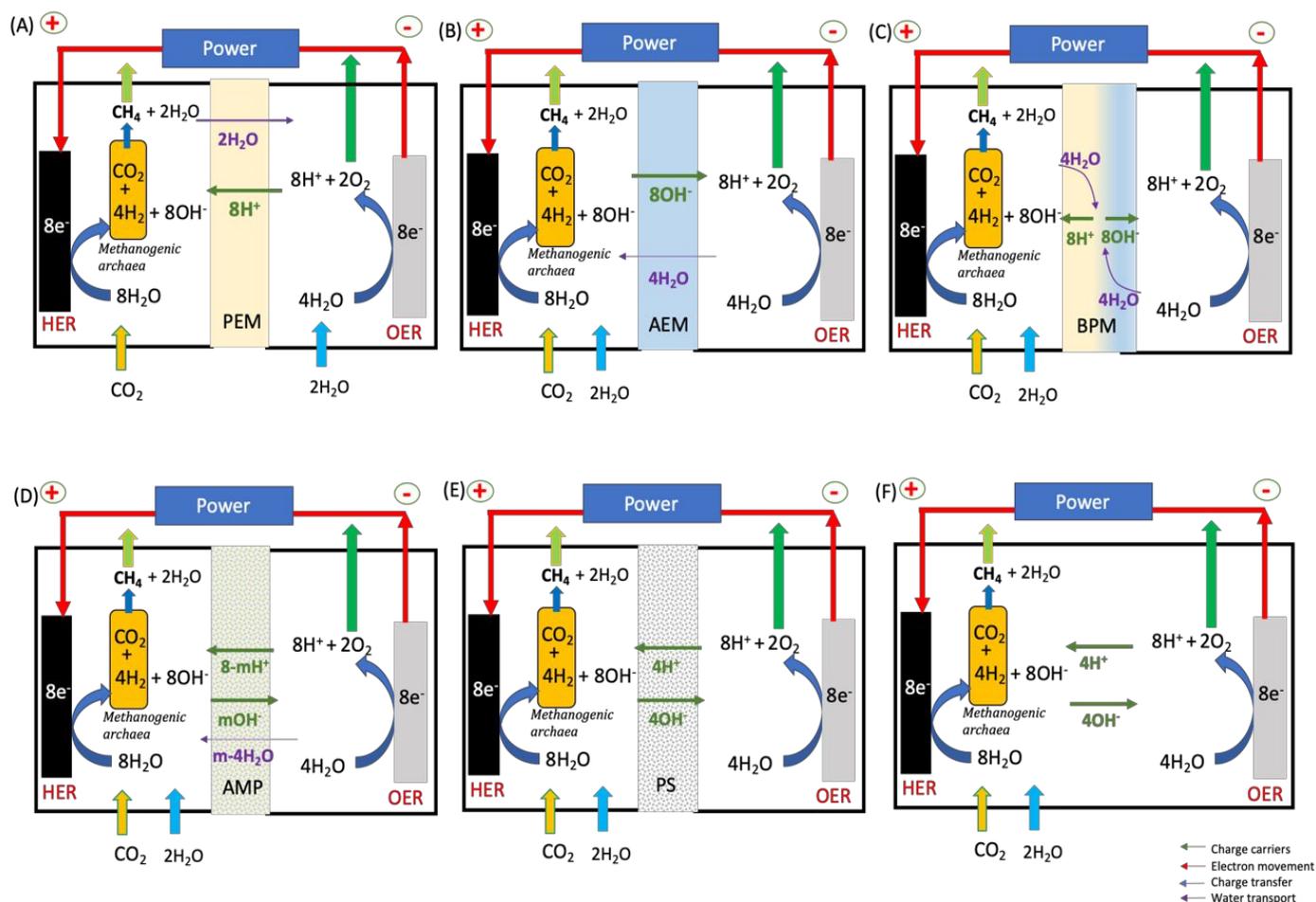
Figure 5. Schemes of electro-bio-methanation with different separators (not to scale): (A) proton exchange membrane (PEM), (B) anion exchange membrane (AEM), (C) bipolar membrane (BPM), (D) amphoteric membrane (AMP), (E) porous separator (PS), and (F) membrane-less system. Fast ion transport and impermeability to oxygen are the key criteria of membrane selection and design. Managing water input and engineering water movement across ion selective membranes are important for sustainable operation. The gap between electrodes and separator are shown in the schemes to clearly illustrate chemical and electrochemical conversions and transport of ions or molecules compared to real systems where zero or minimal gap is present.

with neutral catholyte in microbial electrolysis cells.[111] However, due to the extra energy requirement for water dissociation at the middle of the BPM, the internal resistance of BPM is higher than that of monopolar membranes. Additionally, the long-term durability of BPMs has not been proven, and delamination of the layers can cause irreversible performance degradation. Though promising for being able to maintain the required physiological conditions within the cathode chamber, the conductivity and durability of BPMs must be improved to become viable for application in electro-bioreactors.

Amphoteric membranes (AMPs, Figure 5(D)) contain both cation and anion exchange groups in a single material. These membranes demonstrate high proton conductivity and superior ionic selectivity in redox flow battery applications, but have not been tested with bioreactors.[112,113] Additional fundamental studies on the polymer morphology and distribution of cationic and anionic groups in AMPs is still needed. However they may be a better alternative for neutral media electrolysis applications due to their ability to conduct both cations and anions to replace single type ion selective membranes and should be tested.[114]

**Porous separators.** Instead of selective transport of ions regulated by charge, porous separators, such as nylon or poly(propylene), achieve selective transport through control of pore size in the separator. They have been implemented in many electrochemical systems including solid-state aqueous batteries and alkaline electrolyzers. These separators typically have low internal resistance, improving the voltaic efficiency of the system and can be a cost-effective substitute for ion selective membranes. They may provide faster ion transport than ion selective membranes, facilitating pH maintenance during electrolysis in neutral conditions.[97] However, the porous nature of the membrane can allow dissolved oxygen and charge-neutral molecules to cross over. Pore size engineering and surface modification have been proposed to minimize permeation of gases, prevent non-selective crossover, and reduce biofilm growth on the membrane.

**Water management.** In addition to managing the transport direction and magnitude of ion flow between the two electrodes, managing the generation, consumption, and transport of water between the two chambers is an important consideration for electro-bio-methanation systems and is highly dependent on the

choice of separator, as depicted in Figure 5. Changing water concentration during operation affects the concentrations of supporting ions and buffer, affecting the solubility of gases, creating osmotic imbalance between chambers, and causing dehydration near the electrodes, affecting both microbial and electrochemical performance. In addition to the previously discussed requirements, the separators should facilitate effective water transport to match water electrolysis rates.

In general, there are several critical components of electro-bioreactors that require engineering and development of new materials. Some developments, such as scalable and durable OER catalysts for operation in neutral to acidic media or new separators with improved ion transport, will benefit multiple electrolysis applications as long as they are performed with scale up in mind.

Other developments, such as reactor and electrode geometry and flow engineering, may need to be co-developed with other aspects of the system, such as specialty electrolytes and the specific biocatalyst used in the reactor. Increasing the productivity of these reactors to commercially relevant values will require an understanding of the final scale and the path to scale-up and may require translation of novel designs for mass manufacturability.

## 5. Outlook for Scalability and Industrial Deployment

Development of novel designs and components for electro-bioreactors—cathode and anode geometries and electrocatalysts, flow reactor designs, electrolyte compositions, and selective separators—must be performed with manufacturability and the ultimate scale of the process in mind. For example, bubble column reactors have been successfully implemented in gas fermentation applications where long residence time for gas bubbles is desired to improve conversion.[115] Holtmann, et al. have demonstrated that the resistance of reactor components of an electro-bio-methanation reactor can be reduced by using an

bubble column reactor, rather than an H-cell reactor.[116] However, an electrified bubble column bioreactor requires electrodes and membranes that are specifically manufactured for use in a cylindrical geometry. This is not an inherent limitation of the reactor geometry but requires that components be manufactured in new ways compared to current practice.

To achieve high surface area to volume ratio and even distribution of current for high productivity, flow cell reactors (Figure 6) should be used in electro-bio-methanation.[117] Such
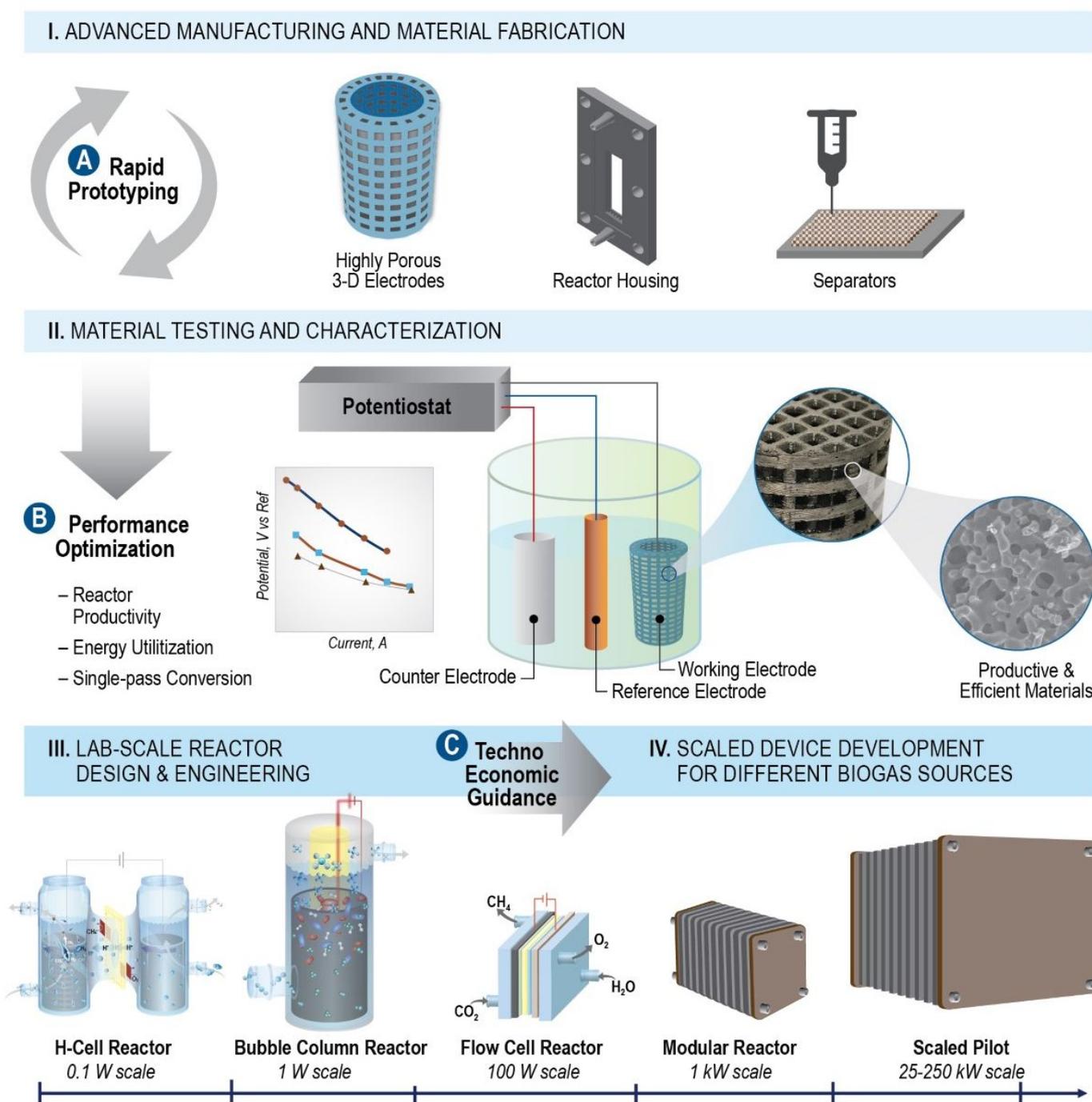


Figure 6. Electro-bio-methanation reactor development for commercial applications can benefit from an iterative design-manufacture-test cycle, enabled by 3D printing and other additive manufacturing technologies. This allows (A) rapid prototyping of components, (B) performance optimization in realistic reactor configurations, and (C) technoeconomic evaluation to identify the most promising areas for improvement. Technology maturation can be aided by (I) advanced manufacturing of materials, (II) bio-electrochemical performance testing and material characterization, (III) design and engineering of bench scale reactors to develop scalable, modular designs, and (IV) scaled device development that can operate on different biogas sources (e.g., dairy farms, crop residue and food waste anaerobic digestion, wastewater treatment plants).

reactors enable stacking multiple individual cells in parallel for designing modular reactors (Figure 6) and avoid some of the complexities associated with manufacturing column reactors. However, as discussed previously, directly integrating commercial flow cell electrolyzers with bioprocesses is not straightforward. Multi-physics models that comprise computational fluid dynamics simulations, coupled with mass transfer and reaction models, can help guide design of 3D electrodes and reactor flow paths to maximize reactor productivity and energy efficiency.[118]

Coupling reactor modeling and design with advanced manufacturing techniques such as 3D printing can help rapidly fabricate prototypes of more efficient reactor components (Figure 6).[117,119] We propose adopting an iterative feedback cycle between reactor/component design, manufacturing of custom components, and performance testing/validation to rapidly prototype new components and geometries for specific electro-bioreactor applications. This strategy has recently been demonstrated by Corral, et al. for development of electrocatalytic $CO_2$ reduction reactors.[20] Learning and understanding gained from rapid prototyping and performance optimization of reactor components should be used to aid in developing reactors from bench to pilot scale. In particular, integration of components, paying attention to electrolyte and gas distribution and transport, electrode area utilization, and ion transport through separators will allow efficient operation of electro-bioreactors at the full potential of the microbes at higher productivities. However, in addition to tuning the knobs for optimizing overall performance, deep analysis of limitations and potentials of each reactor component is also critical to guide technology maturation through novel materials and reactors. A powerful analytical tool in this regard, in addition to standard polarization studies, product analysis, and surface characterization, is electrochemical impedance spectroscopy, which evaluates the internal resistance of the full system and aids in deconvolution of contributions from electrodes, electrolytes, and membranes in electro-bioreactors.[120,121]

Along with developing components that make electro-bioreactors more efficient and productive, technoeconomic and lifecycle analysis should be performed and refined to quantify the economic and resource impact of manufacturing novel designs at scale. In this way, research into new materials and reactor designs and development of scalable reactor components can be targeted toward optimizing the electro-microbial performance and improving the productivity of the reactors to make these technologies more competitive.

## Conclusions

The field of electro-biotechnology has made significant gains over the last decade and has many promising advantages over standalone electrocatalytic or biological processes. However, there are still significant gaps in reactor design and engineering that must be closed to enable electrification of bioreactors at commercially relevant scales. Using electro-bio-methanation as a case study in developing electrified bioreactors for $CO_2$ conversion and energy storage, *we identify the need to increase*

*the productivity and energy efficiency of the reactor while maintaining biocompatible conditions as the central challenge facing the technology.* Standardization of testing conditions and metrics for reporting performance will help facilitate comparison between different systems and more accurate comparison. Developments such as favoring microbes that stay suspended in the electrolyte rather than forming biofilms and co-design of 3D electrodes and flow reactors will help to maximize the utilization and productivity of the reactor. Improvements in electrocatalysts for neutral-to-acidic pH hydrogen and oxygen evolution reactions, developing better electrolytes for electro-bioprocesses, and innovations in new separators with improved proton or hydroxide transport will help improve the energy efficiency.

Finally, we propose an iterative design-manufacture-test cycle, enabled by additive manufacturing technologies, to rapidly prototype and test reactor components. Component testing and reactor design and engineering should be performed with manufacturability and the ultimate scale of the process in mind, and development of novel components should be performed in conjunction with technoeconomic analysis to quantify the impact of these developments.

## Author Contributions

B.S.J., S.H.P. and S.E.B. conceptualized the scope of the manuscript; B.S.J. performed the literature analysis and wrote the original draft of the manuscript; Z.H and L.T. performed the technoeconomic analysis; B.S.J., S.C., M.C.F., F.K., J.S.D., A.S., Z.H., L.T., S.H.P. and S.E.B. participated in regular discussions, reviewed, edited, and approved the final draft of the manuscript.

## Conflicts of interest

There are no conflicts to declare.

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any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

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