Decarbonization of the Chemical Industry through Electrification: Barriers and Opportunities

Dharik S. Mallapragada1*, Yury Dvorkin2*, Miguel Modestino3*, Daniel V. Esposito4, Wilson Smith5,6,7, Bri-Mathias Hodges6,7,8, Michael P. Harold9, Vincent M. Donnelly9, Alice Nuz10, Casey Bloomquist11, Kyri Baker11, Lars C. Grabow9, Yushan Yan12, Nav Nidhi Rajput13, Ryan Hartman13, Elizabeth J. Biddinger14,15, Eray Aydil3, and Andre Taylor3

1. MIT Energy Initiative, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
2. Department of Electrical and Computer Engineering, Department of Civil and Systems Engineering, Ralph O’Connor Sustainable Energy Institute, Johns Hopkins University, Baltimore, MD 21210, USA
3. Department of Chemical and Biomolecular Engineering, New York University Tandon School of Engineering, Brooklyn, NY, 11201, USA
4. Columbia University in the City of New York, Department of Chemical Engineering, Columbia Electrochemical Energy Center, Lenfest Center for Sustainable Energy, 500 W. 120th Street, New York, NY 10027, USA
5. Department of Chemical and Biological Engineering University of Colorado Boulder, Boulder, CO, 80303, USA
6. National Renewable Energy Laboratory, 15013 Denver W Parkway, Golden, CO, USA
7. Renewable and Sustainable Energy Institute (RASEI) at the University of Colorado Boulder, 4001 Discovery Drive, Boulder, CO, 80303, USA
8. Electrical, Computer, and Energy Engineering (ECEE) Department at the University of Colorado Boulder, 425 UCB, Boulder, CO, 80309, USA
9. William A. Brookshire Department of Chemical and Biomolecular Engineering, University of Houston, Houston, TX, 77204, USA
10. Department of Electrical and Computer Engineering, Tandon School of Engineering, New York University, Brooklyn, NY, 11201, USA
11. Department of Civil, Architectural and Environmental Engineering, University of Colorado Boulder, USA
12. Department of Chemical and Biomolecular Engineering, Center for Catalytic Science and Technology, University of Delaware, Newark, DE, 19716, USA
13. Department of Materials Science and Chemical Engineering, Stony Brook University, Stony Brook, NY, USA
14. Department of Chemical Engineering, The City College of New York, CUNY, New York, USA

*Corresponding authors: dharik@mit.edu, ydvorki1@jhu.edu, modestino@nyu.edu

Abstract

The chemical industry is a major source of economic productivity and employment globally and among the top 3 industrial sources of greenhouse gas (GHG) emissions, along with steel and cement. As global demand for chemical products continues to grow, there is an urgency to develop and deploy sustainable chemical production pathways and re-consider continued investment in current emission-intensive production technologies. This Perspective describes the challenges and opportunities to decarbonize the chemical industry via electrification powered by the low-emission electric power sector, both in the near-term and long-term, and discusses four technological pathways ranging from the more mature direct substitution of heat with electricity and use of hydrogen to technologically less mature, yet potentially more selective approaches based on electrochemistry and plasma. Finally, we highlight the key elements of integrating an electrified industrial process with the power sector to leverage process flexibility to reduce energy costs of chemical production and provide valuable power grid support services. Unlocking
such plant-to-grid coordination and the four electrification pathways has significant potential to facilitate rapid and deep decarbonization of the chemical industry sector.

1. What is the problem?

The continued cost declines in the wind, solar, and energy storage technologies have expanded their role in deep decarbonization of the electric power sector (Figure 1) and economy-wide electrification of end-uses.¹⁻⁴ For example, in the net-zero by 2050 scenario of the International Energy Agency (IEA), wind and solar will provide 70% of the global electricity generation, while electricity is projected to increase from 20% of the global energy consumption (2020) to nearly 50%.³ In addition, electrification-based decarbonization or “electro-decarbonization” solutions in the transportation and building sectors (e.g., electric vehicles, heat pumps) are already commercially viable and deployed at scale. In contrast, decarbonization pathways for the industrial sector, which accounted for 24% of global greenhouse gas (GHG) emissions in 2019⁵, are less certain. Moreover, industrial sector emissions have grown faster over the past two decades than in any other sector, driven by demand growth for materials.⁶ As demand for industrial products is typically in lockstep with economic growth, there is an urgent need to develop and deploy scalable, sustainable production technologies so that economic growth can be decoupled from GHG emissions. This Perspective focuses on the opportunities and challenges for electro-decarbonization of the chemical industry, the third largest source of global industrial emissions in 2019⁶ and a major global source of direct and indirect economic productivity and employment.

Several factors make the decarbonization of chemicals uniquely challenging. First, chemical processes predominantly rely on fossil fuels as a feedstock and energy source (Figure 2). Second, demand for chemical commodities has historically grown with the gross domestic project (GDP), a trend that is expected to continue despite more aggressive levels of end-product recycling.⁷ For example, demand for primary chemicals (e.g., light olefins (ethylene, propylene), aromatics, methanol, and ammonia) is projected to increase 40-60% by 2050 from 2017 levels depending on the rates of plastic recycling⁷ (Figure 1). Third, existing chemical manufacturing involves processes interconnected through mass and energy flows, complicating production method changes for a single product in isolation. For example, using ethane from natural gas in steam cracking instead of naphtha from petroleum increases ethylene yields at the expense of lower propylene and aromatics yields,⁸,⁹ which drives the need for new propylene and aromatics units, as observed in the U.S. over the last decade.⁸ Fourth, the most carbon-intensive chemical products are commodities with large manufacturing volumes and relatively small profit margins, disincentivizing innovation investments. For example, ethylene, the largest chemical precursor to plastics, has a global annual production of over 150 MT/year and a similar scale of commensurate CO₂ emissions.⁷ Fifth, chemical processes are central to large economies (e.g., U.S., E.U., China), and regulators and policymakers have reluctantly proposed emission-reduction changes to manufacturing processes due to potentially negative economic impacts. Collectively, these factors mean that reducing the carbon footprint of the chemical industry requires a holistic and cross-disciplinary effort to overhaul the foundational principles underlying the production of chemical commodities and their interaction with economy-wide decarbonization efforts.
Figure 1. Projected global demand for key commodity chemicals across two alternative demand scenarios (Part A) and projected global electricity generation by source, with 2017 global chemicals sector energy consumption shown as a comparison. Data for electricity generation sourced from Stated Policy Scenario (SPS), Sustainable Development Scenarios (SDS), and Net Zero Emissions (NZE) by 2050 case of the 2020 World Energy Outlook report. Chemicals demand projections are taken from the Reference Technology Scenario (RTS) and Clean Technology Scenario (CTS) in the Future of Petrochemicals report. As described elsewhere, RTS represents a baseline scenario informed by “existing and announced policies and established behavioral and exogenous considerations. The CTS scenario, in contrast, models additional constraints such as direct sectoral CO₂ emissions to be reduced by 45% by 2050 vs. 2017 and other sustainability drivers such as increased plastic recycling.

2. Status quo of electricity use in the chemical industry and the case for electrification

In 2018, electricity accounted for only 20.4% of on-site energy use in the U.S. chemicals sector (Figure 2A), with the rest provided by combustion-derived heat. Energy efficiency trends in the industry have favored combined heat and power generation units, which generated 29% of electricity consumed by the U.S. chemical industry. The remaining electricity is purchased from the power grid (annual purchases of 147 TWh), a small footprint (~3% of the U.S. electricity demand) but will increase with industry electrification. Examining energy consumption in the U.S. chemicals industry reveals that electricity is used
primarily as **process energy** (89% of the electricity use, Figure 2B) for heating/cooling, electrochemical reactors, machine drive tools and other process-related uses, or as **non-process energy** (11% of the electricity use) to power HVAC, lighting, and transportation systems, among other uses. Notably, electrified reactors (e.g., in chloro-alkali process or adiponitrile electrosynthesis) account for a relatively small share of the total electricity use (40 TWh, Figure 2A) as compared to energy use for process heating for reactions and separation processes (500 TWh in 2018\(^{11}\)). This reliance on fossil-derived energy for chemical production also translates into a process carbon footprint — for example, for ethylene and propylene production, fuel gas combustion for process heat accounts for approximately 40% of the life cycle GHG emissions\(^{12}\).

![Figure 2](image-url)  
*Figure 2. Overview of annual electricity use in the U.S. chemical industry in 2018. Part (A) compares the use of electricity vs fossil-derived heat. Part (B) itemizes the energy supply and consumption per use case. Data sourced from ref 7.*

With this heavy reliance on fossil fuels as the primary energy, it is more economical to use heat than electricity because fossil-based electricity generation causes additional efficiency losses. As a result, there is growing industry interest in powering chemical processes with cost-competitive, variable renewable electricity (VRE) to leverage decarbonization efforts in the electric power sector, as exemplified by recent announcements related to the exploration of electrified steam crackers\(^{13}\) and electricity use for process heat for hydrogen production from steam methane reforming (SMR).\(^{14}\) Both approaches focus on directly substituting heat with electricity without changing the process chemistry, as in option A in Figure 3. Other pathways for electrified chemical processes (Figure 3) include electrochemical production of hydrogen for process heat generation (option B), direct use of electricity for manufacturing of chemical products via electrochemistry (option C), and electricity-powered plasma reactors (option D).

Option A is appealing for earlier deployment in existing manufacturing facilities but lacks improvements in process energy and/or material efficiency and associated benefits to the power sector. For example, these processes operate at steady-state, and replacing fossil fuel heat with electricity (Option A) could create a large inflexible electricity demand in the power grid, rendering techno-economic barriers to the integration of variable renewable energy. Partial electro-decarbonization enabled by electrochemically generated hydrogen (Option B) as a fuel for heating or as a reactant in synthesizing chemical energy carriers...
will allow for greater flexibility due to the ability to store hydrogen or hydrogen-derived carriers. However, energy losses in the electrolysis imply that option B will have a much larger electricity consumption than direct electrification\textsuperscript{7,15} (Section 5). Unlike Options A and B, Options C and D have lower technology readiness levels (TRL) but are potent to facilitate chemical transformations at mild temperatures and pressures, unlike their thermochemical counterparts, thus enabling previously limited reaction paths\textsuperscript{16}. Operation at lower pressure and temperature can be beneficial for enabling flexible, grid-responsive chemical plants that adjust their electricity consumption similarly to the demand response provided by some current electrochemical industrial processes (e.g., aluminum\textsuperscript{17}). Also, electrochemical production pathways offer the prospect of modular intensified processes with simultaneous reaction and separation.\textsuperscript{18} This factor, along with the distributed nature of renewable energy and feedstocks, makes distributed manufacturing a feasible alternative. Supply chains based on decentralized manufacturing could also be more resilient to various disruptions, provided a reliable and cost-effective power supply is available. This latter condition highlights the importance of coordination of the electrification strategies for the chemical industry with electric power sector to achieve synergistic outcomes.
3. Direct electrification

Resistive heating

Many commodity chemicals produced today are based on endothermic reactions that operate at high temperatures (400-1000 °C) with fossil-derived heat. Examples include H₂ SMR, ethylene from ethane cracking, and HCN from methane and ammonia, among others. One approach to replacing fossil-derived heat is direct resistive heating, which involves passing high-power electrical current through a material resulting in heat generation from resistance to current flow. The attainable temperature of heat supply depends on the reactor’s heat transport characteristics and the material’s resistivity, with lower resistivity (high conductivity) materials enabling higher temperatures. While resistive heating is ubiquitous in everyday life, it is less prevalent in the chemical process industry because of the relatively inexpensive cost of heat supply from fossil fuels to date. However, despite historic cost disadvantages, resistive heating has many advantages, as highlighted by studies on developing electrically-heated reactors for methane steam and dry reforming for hydrogen production. Resitive heating can provide heat over a wide range of temperatures and affords faster and more uniform heating, resulting in more compact, scalable, and dynamically responsive reactors. Resitive heating can also displace fossil-fuel combustion in low-temperature separation processes such as distillation. Some examples include p-xylene and o-xylene separation (reboiler temperature near 150 °C), propylene and propane separation (reboiler temperature close to ambient), and alcohol-water separations (e.g., ethanol-water, methanol-water, with reboiler temperatures near 100 °C).

Resistively heated reactors and unit operations represent a new paradigm in chemical processing that require a redesign of established processes to maximize benefits. For example, endothermic catalytic reactors utilizing large furnaces could be replaced by units containing resistively-heated catalyst supports. Such new designs and operational schemes have started to be explored, including, Ni-based catalyst supported on structured SiC or coated metal tube reactor operated under unsteady power input. A notable advantage of the layered catalyst approach is the intimate contact of the catalyst with the heated substrate, which allows precise temperature control and reduces diffusional limitations. Alternatively, new materials that combine catalytic activity with superior electrical conductivity (e.g., FeCrAl alloy) would circumvent the need for electrically-conductive supports and benefit from efficiency gains and facile reactor integration.

Inductive and microwave heating

Inductive heating applies a magnetic field to a material to convert induced radio frequency (RF) electrical currents into heat, and the temperature rise depends on the material’s magnetic susceptibility. A typical approach involves the placement of a solid bed of magnetically susceptible particles within the RF field. The appeal of inductive heating includes a) potential for localized heating of catalytic substrates with higher reaction rates and smaller reactors, b) the ability to generate heat more uniformly, shortening start-
up times and thus facilitating more flexible operation. Despite successful medical and cooktops applications, it has only recently been investigated for chemical reaction systems. For example, inductive heating has been applied to steam reforming systems for hydrogen production, using magnetic, catalytic particles with the potential to achieve similar energy efficiency as fossil-fuel-based steam reforming for large-scale systems by proper coil geometry design.26

Similarly, microwave heating of catalysts applies radiation to a susceptible solid within the microwave cavity. Like inductive heating, microwaves lead to focused, localized heating of catalysts. This can target desired reactions at a catalytic site, supported on the microwave-susceptible material, with a very fast response time relative to conventional heating.27 This poses interesting opportunities to explore forced thermal cycling or short-lived production campaigns in response to demand and availability/pricing of electricity supply. However, current megawatt-scale applications of microwave-enabled reactions and processes are scarce, with examples including the production of esters from waste oils and alcohols and the microwave-assisted synthesis of HCN for small-scale distributed applications to avoid potential hazards of shipping and handling large quantities of this toxic material.25,28,29

While the methods mentioned above have many advantages, some barriers remain to be addressed for their commercial adoption. Barriers include reactor scalability and materials compatibility. For example, whether uniform heating can be achieved in larger diameter reactors remains to be determined, and materials and designs that enable higher temperature heat supply relevant for chemical processes will need to be identified. Also, the approaches described above do not enable significant levels of process flexibility or improvements in process energy efficiency, both of which imply that the power grid impacts of large-scale deployment of these electrification strategies could potentially pose barriers to the integration of VRE electricity.

4. Hydrogen as a vector for electrodecarbonization

Hydrogen is a versatile energy vector that can enable emission reductions in hard-to-decarbonize industrial sectors. Electrolytic hydrogen can provide low- or zero-carbon heat via its combustion for applications where direct electrification is challenging, as well as serve to displace fossil hydrogen use as a feedstock in industry,30,31 e.g., production of chemicals, steel, cement, lime (CaO), metals, and glass32–34. The chemical and refining industry is already the largest consumer of hydrogen8,33,35, primarily as a critical feedstock in oil refining and production of commodity chemicals like ammonia and methanol16. However, these processes produce hydrogen from natural gas reforming without carbon capture and storage (CCS). Alternatively, water electrolysis can produce hydrogen with a lower carbon footprint. Because of its potential for decarbonization, more than 80 electrolytic hydrogen projects with capacities over 100 MW and more than 10 projects over 1 GW were under development worldwide in 2021.37

Besides its use as a chemical feedstock, hydrogen can also be combusted to produce process heat. Due to efficiency losses for hydrogen produced by electrolysis for process heat compared to other competing technologies, e.g., heat pumps and direct resistive heating (Section 3), the adoption of power-to-hydrogen for low-heat applications may not be cost-effective on a dollar-per-calorie basis. However, hydrogen combustion could provide high-temperature heat in decarbonizing industrial applications currently powered by natural gas combustion that cannot be electrified directly. Like direct heating, hydrogen-based heat can be deployed for existing chemical production facilities, though some material changes and retrofits are likely required to enable hydrogen combustion38. One impediment to using hydrogen for high-temperature heat applications has been the low average costs of fossil-derived heat.
Another potential adoption barrier is the infrastructure limitations on supplying and storing large quantities of electrolytic hydrogen. For instance, there is limited hydrogen transmission and storage infrastructure (e.g., ~1,600 miles of dedicated hydrogen pipelines vs. 300,000+ miles of natural gas transmission pipelines),\textsuperscript{39,40} and natural gas pipelines may need to be converted to be compatible with hydrogen.\textsuperscript{41} This barrier, however, could also motivate the development of decentralized chemical production concepts in the future that combine the modular nature of electrolytic hydrogen production with other emerging electrified chemical production routes (Section 5). Finally, the GHG emissions benefits of using electrolysis vs. SMR for hydrogen production are only realized if low-carbon electricity generation sources are adopted beyond current levels\textsuperscript{42}.

Using electrolytic hydrogen for heat supply would increase electricity demand more than direct electric heating methods due to inefficiencies across the hydrogen supply chain\textsuperscript{7,15}. For example, one estimate suggests that replacing natural gas with electrolytic hydrogen for industrial process heating in Texas would require ~5.8 MT/year of hydrogen supply, resulting in a >20 GW of electric power based on typical electrolyzer efficiencies\textsuperscript{15}. For context, the peak electric power demand in Texas was 72 GW in 2018, and U.S.-wide annual hydrogen consumption in 2015 was ~10 MT/year.\textsuperscript{35} While the electricity demand could be large, the potential for flexible operation, particularly for low-temperature electrolyzers,\textsuperscript{43} coupled with the relatively low capital cost of hydrogen storage vs. Li-ion energy storage,\textsuperscript{44} creates an opportunity to schedule electrolytic hydrogen production as a flexible load to balance fluctuations of renewables in future power grids. Importantly, flexible hydrogen production can still serve baseload hydrogen demand from industrial applications. While this flexibility in hydrogen production can bring substantial benefits, electrolyzers must be designed for dynamic operation to avoid unintended impacts on stability and efficiency\textsuperscript{45}. Figure 4 highlights potential power grid impacts of producing varying levels of hydrogen using flexible electrolyzers + hydrogen storage for a range of grid decarbonization scenarios in Texas.\textsuperscript{15} With increasing hydrogen demand, while the overall installed capacity of the power system increases, the analysis reveals that the system-average cost of electricity declines due to improved asset utilization for both the electricity generation assets (i.e., VRE) and electrolyzers.\textsuperscript{15} This example illustrates the importance of close coordination between electricity-consuming processes and the grid to maximize the benefits of electrification (Section 7).
Figure 4. Power system impacts of providing hydrogen use for industrial processes considering flexible electrolyzer operation and range of grid decarbonization scenarios. The decarbonization scenarios are defined in the model on a CO$_2$ emissions intensity basis, either 1 g CO$_2$/kWh or 5 g CO$_2$/kWh. Results based on Texas case study described elsewhere\textsuperscript{15}. Here, the 100% hydrogen demand represents the case where all natural gas used for process heat in the Texas industry in 2016 is replaced with H$_2$ (5.8 MT/year). System-average cost of electricity is defined as the ratio of total annualized system costs (investment and operating) to the total annual electricity consumption (including electricity used for hydrogen production). VRE curtailment refers to the fraction of available VRE generation that was not dispatched.

5. Electrochemical pathways

Electrochemical processes have been successfully commercialized at scale for select products, including chlorine and aluminum, with total primary energy consumptions of 55 TWh/year and 31.5 TWh/year, respectively, based on 2010 US production estimates. In addition, smaller-scale processes such as adiponitrile production, electrowinning, perchlorate production, ozone production, HCl recycling, and water electrolysis have also found commercial success. Yet, these electrochemical processes are a small fraction of the total energy consumption footprint of the chemical industry. Thus, there remains tremendous potential for electrochemical processes to replace energy- and carbon-intensive thermochemical processes, thus enabling broader electrification of the chemical industry.

There are potential competitive advantages for electrochemical processes versus thermal processes. First, the main driving force for electrochemical reactions is electrochemical potential (i.e., electrical voltage) rather than temperature, giving electrochemical unit operations the ability to operate at very low temperatures (< 100 °C), where they can avoid high thermal losses and materials stability issues like catalyst sintering. Operating at low temperature gives electrochemical reactors an extra advantage over exothermic thermocatalytic processes such as ammonia or methanol synthesis, for which conversion is typically limited.
by chemical equilibrium constraints encountered at the elevated temperatures required to drive reaction kinetics at appreciable rates. By being able to operate at lower temperature where equilibrium conversion for many exothermic reactions is very high, electrochemical processes present opportunities to reduce costs associated with downstream separation units compared to their thermocatalytic counterparts. Third, by using a membrane or diaphragm divider to separate the anode and cathode, electrochemical reactors simultaneously carry out conversion and separation of oxidation and reduction products, reducing the need for downstream separation processes. Fourth, the potential operational flexibility to dynamically change output as electricity prices change and modularity of electrochemical systems could make it possible to design flexible and grid-interactive chemical plants. Finally, the ability to scale down provides opportunities to realize smaller-scale chemical plants with lower financial risk and easier integration into distributed power grids to minimize electric power transmission losses and transportation needs for reactants and products.

Accelerated adoption of electrochemical processes requires additional R&D to address several key barriers. First, electrochemical systems must be capable of operating for long periods (>10 years) without significant degradation in key performance metrics. Degradation of an electrode, membrane, device, or system can be expressed in terms of two related but different metrics: (i) long-term stability at constant conditions (i.e., constant applied potential and/or current), and (ii) durability under dynamic operating conditions. The dynamic operation could entail step changes or ramp up/down of input power, changes in temperature, pressure, and composition of chemical streams entering each unit operation. Based on these considerations, it is important to study degradation phenomena under industrially relevant dynamic operating conditions to inform operational limits and electrode/reactor design strategies to minimize degradation issues.

Other major barriers are related to the development of electrocatalyst materials and reactor designs that are as selective to desired products as their thermocatalytic counterparts. For example, very few electrochemical demonstrations of high selectivity and/or yield for industrially relevant organic reactions are currently carried out at volumes relevant to chemical commodities. These multi-step reactions are often carried out over complex multi-component catalysts in porous scaffolds that allow large surface-to-volume ratios for high volume production of chemicals. However, many of the major products made through thermal catalytic processes have yet to find electrochemical analogs. It is imperative to discover new catalysts for selective electrochemical transformations and develop novel reactor configurations that allow higher throughput of reactants and products without compromising selectivity or yield. For complex reaction networks involving multiple competing reaction pathways characterized by small differences in energy barriers, scaling up electrochemical reactors to sizes necessary for industrial chemical plants becomes especially daunting due to the effects of concentration, temperature, and/or pressure gradients that naturally develop as scale increases.

6. Plasma Pathways

Plasma-driven reactions are an alternative to using electricity to break chemical bonds and generate useful products with less or no conventional heating. The electricity delivered to a reactor energizes electrons, which ionize the gas, generating more electrons that absorb power. The electrons collide with the gas, generating a distribution of electron energies while heating the gas. A steady-state is quickly established, where the electron “temperature” can range from much greater than the gas temperature (non-equilibrium plasmas) to nearly equal to the gas temperature (equilibrium plasmas). The electron energy
distribution can be characterized as having a temperature of typically 10,000 to 20,000 K (1 eV = 11,606 K) with a very small population of a high-energy tail that exceeds the average ionization potential of the gas (typically 10 to 15 eV). The gas temperature ranges from moderately above the reactor wall temperature (could be anywhere from ambient to higher temperatures) to the electron temperature, depending on power density, pressure, and reactor configuration. Although no commercial deployments of plasma-based chemical production facilities exist today, they have shown promise for several valuable processes, including production of NH₃ from N₂ and H₂, CO₂ reforming of methane, decomposition of methane to form H₂ and carbon, and synthesis of larger hydrocarbons. For these reactions, the primary appeal of plasma-based approaches is the role of electrons in promoting gas-phase reactions that would not occur in a conventionally heated gas under mild temperature and pressure conditions. This can occur by the excitation of an electron to a dissociative state or a vibrational excitation. Electronic excitation requires plasma electrons with minimum energies in excess of the bond energy (typically 3 to 10 eV for species of interest). Realizing substantial excitation rates often require relative dense plasmas (electron densities >10¹² cm⁻³) where the high collision frequency of these high-energy electrons results in a substantial rate of excitation of the feed gas. Additionally, placing a catalyst in the reactor allows for the possibility of radicals adsorbing on the catalyst as opposed to the parent molecule (e.g., N atoms instead of N₂), which could increase the rates of reactions to generate products.

For plasmas, barriers to overcome to achieve wide-scale applicability include a) fundamental characterization of technology performance, including materials integrity and durability under sustained plasma exposure and overall energy efficiency, and b) developing principles for reactor design and scale-up for these systems that accounts for intimate coupling of catalysts with conductive substrates and electrodes. For instance, in the case of plasmas, dissociation and recombination rates are comparable at atmospheric pressure, which necessitates the need to place the catalyst as close as possible to the plasma to capture significant fluxes of radicals as well as rapid transport of products out of the reactor before they are decomposed.

7. Grid integration challenges and opportunities

Successful implementation of electrified technologies envisioned in Sections 3-6 hinges on the ability to coordinate their operation with the power grid. From the viewpoint of an electrified chemical producer, this coordination will allow for valorizing the flexibility of the electrified chemical production by providing various power grid services, thus yielding an additional revenue source. The power grid will also benefit from this coordination to minimize the economic and operational impacts of increased electricity demand from the chemical industry and achieve decarbonization goals (Figure 5).
Figure 5. Vision for coordination between electrified chemical plant and electric grid, where emissions burden of the energy use at the chemical facility is shifted to the grid in return for low-cost energy supply and revenues from the flexible operation of the plant in response to grid conditions.

Due to the lack of widespread deployment of electrified chemical production technologies, there are limited means for chemical plant owners to realistically evaluate the flexibility and revenue potential of the electrified processes beyond lab-scale prototypes. Thus, it is important to develop high-fidelity yet computationally tractable simulation tools to study plant-to-grid coordination under various technological and regional contexts. In addition, while tools have been developed for select electricity-intensive industrial processes, such as air separations, they have not been generalized to consider a diverse set of unit operations with different functions (e.g., reactions, separations), complex topologies, and multiple products, all of which are features of existing chemical production facilities.

A key input parameter influencing the economics of chemical process electrification is the electricity cost and procurement mechanism. Electricity can be procured in advance via long-term bilateral contracts between the chemical plant and independent power producers and utilities with fixed contract terms (e.g., electricity price and quantity with conditions on emissions intensity). This strategy partially de-risks chemical plants from the uncertainty and volatility of electricity prices at the expense of forgoing revenues from potential power grid services. Alternatively, electricity can be procured via a spot wholesale market, where prices can range from as low as negative to as high as thousands of dollars per MWh, depending on grid conditions. Volatility in spot electricity prices is expected to grow with increasing supply from variable renewable generation and demand-side participation from newly electrified loads in transportation and building sectors. These factors could increase the cost of contracting baseload power and
enhance the economic value of flexible chemical plant operations. Furthermore, if chemical plants become large and flexible electricity consumers, they can participate strategically in a wholesale market to affect market prices in their favor. However, trading-off between the electricity procument mechanisms is challenging because of the inherent uncertainty arising from complex correlations between terms of the bilateral contracts, highly volatile spot electricity prices, regulatory and policy ambiguity, as well as the uncertain intra- and inter-annual demand for chemicals. An additional source of uncertainty is the effect of large-scale power outages, which may interrupt or limit electricity supply from several hours to several weeks and have profound revenue and wear-and-tear impacts on chemical manufacturing. Additionally, interfacing a large-scale consumer such as a chemical plant with the power grid may impose additional charges unique to their operation (e.g., interconnection costs and peak/duration demand charges).

From the power grid perspective, rapid and uncoordinated growth of electricity demand from an electrified chemical industry may lead to insufficient generation capacity to serve all electricity demand in their service territory, which may, in turn, reduce power grid reliability, leading to electricity rationing, and delay the retirement of emission-intensive generation resources. Degradation of power grid reliability, reinforced by recent failures (e.g., 2021 Texas Power outages and 2021 California wildfire’s rolling blackouts), may also inadvertently disincentivize large-scale electrification. Therefore, it is important to implement plant-centric simulation capabilities to understand the power grid impacts of widespread electrification of the chemical industry. This would allow plant operators to estimate the amount and value of power grid support services that individual chemical plants provide. An important future risk and a present simulation capability gap is a lack of cross-sectoral emissions accounting that may lead to emissions leakage (e.g. when electrified plants are supplied from a partially decarbonized power grid, thus shifting emissions to the power sector).

Conclusion

Deep decarbonization of chemical manufacturing is a critical part of broader economy-wide decarbonization efforts but has received little attention compared to other energy-intensive sectors, presumably because of its complexity, multi-product nature, and pivotal role in regional economies and associated employment implications. In this article, we identify the key barriers and opportunities for leveraging emissions reduction efforts in the power sector to decarbonize chemical manufacturing via four alternative electrification strategies at varying technology readiness levels. These strategies range from commercially available (electrical heating and electrolytic hydrogen) solutions with large technical and cost uncertainties (electrochemical and plasma pathways). While R&D and deployment to advance these electrodecarbonization solutions must be actively pursued, other institutional barriers also need to be addressed to enable the adoption of these technologies at scale to reduce the industry’s emissions impact even as demand for chemical products continues to grow. First, a major barrier to implementing new processes in the industry is the inertia of the chemical industry to transform itself. The global chemical industry has been built up over the past century, accumulating a multi-trillion-dollar infrastructure that supports large chemical plants based on reliable and robust processes that have been scaled and de-risked over several decades. Companies may not abandon known technologies and large capital investments made in chemical plants, especially when they are early in their operational lifetime. Two related challenges are to (i) identify and deploy, in the short term, technical solutions, including some highlighted above, to mitigate emissions from existing chemical plants without sacrificing performance, and, in the intermediate term, (ii) develop a new generation of chemical plants powered entirely by electrical and renewable inputs.
and enable step-change benefits in cost and functionality compared to conventional plants. Second, the industry workforce, ranging from recent graduates, plant operators, and senior leaders, may not have the experience and knowledge of concepts related to power grids, electrochemistry, and plasma science, since, historically, these have not been part of the undergraduate level chemical engineering, materials science and engineering and chemistry curriculums. Therefore, workforce training at all levels of the industry is required hand-in-hand with technology development and de-risking to increase the chances that the industry adopts these processes. Overcoming these technical and workforce development barriers will require large, concerted efforts between government, industry, and academia and a clear legislative framework that establishes a path toward decarbonizing all industry sectors. Otherwise, emissions from the chemical industry will continue to grow, fueling more intense climate impacts in the decades to come.

Acknowledgement

We would like to thank the Alfred P. Sloan Foundation for supporting this work (Grant # 201-16807) that is part of the recently established Center for Decarbonizing Chemical Manufacturing Using Sustainable Electrification (DC-MUSE, https://www.dc-muse.org/). B-M. H. and W.S. acknowledge the Alliance for Sustainable Energy, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under contract DE-AC36-08GO28308. Funding was in part provided by the DOE Office of Energy Efficiency and Renewable Energy. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. government. The U.S. government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. government purposes.

References


