Electrochemical Manufacturing in the Chemical Industry

by Gerardine G. Botte

Chemical manufacturing creates products by transforming organic and inorganic raw materials using chemical processes. There are over 100,000 chemicals in the marketplace.[1] Chemicals can very broadly be classified into two groups: commodity chemicals and specialty chemicals. Commodity chemical manufacturers produce large quantities of basic and relatively inexpensive compounds (up to $1 per kg) in large plants, often built specifically to make one chemical. Commodity plants often run continuously, typically shutting down only a few weeks a year for maintenance. Specialty-batch or performance chemical manufacturers produce smaller quantities of more expensive chemicals ($1 to $1,000 per kg) on an "as needed" basis in plants that are used less frequently. Often there is only one or a limited number of suppliers producing a given product. In contrast to the production of commodity chemicals, batch manufacturing requires that the raw materials, processes, operating conditions, and equipment change on a regular basis to respond to the needs of customers.

Despite the large number of chemicals available in the market, electrochemical synthesis of chemicals has been limited to a narrow spectrum. The reasons for this have been previously attributed to a lag in the education of chemists and engineers in electrochemistry and electrochemical engineering, a lack of suitable resources for cell construction, and most importantly the prohibitive costs involved (in many cases) in electrochemical synthesis.[2] However, over the past 40 years, there have been significant developments in electrochemical synthesis and methods[3] due to the advances in materials science and nanotechnology,[4] the development of *in-situ* spectroscopy techniques,[5-7] and progress in multi-scale modeling.[8-10] As a result, it is timely to revisit some industrial electrochemical processes and to introduce examples of new economic opportunities for the electrochemical manufacturing of chemicals.

Chlor-Alkali

The Chlor-Alkali industry is one of the largest chemical processes worldwide. Its two main components – chlorine and caustic soda – are indispensable commodities that are used for a wide range of applications. Nearly 55 percent of all specialty chemical products manufactured require one of the chlor-alkali products as a precursor, with examples including: adhesives, plastics, pesticides, paints, disinfectants, water additives, rubbers, cosmetics, detergents, lubricants, vinyl and PVC, soaps, glass, cement, medical dressings, textiles, car, boat, and plane paneling, books, greases, and fuel additives.[18]

The chlor-alkali process dates back over 100 years, originating from the electrolysis of brine using mercury (Hg) as electrode. Building on these fundamentals, the chlor-alkali process has been improved through the development of diaphragm and ion exchange membrane cells. Recent improvements in membrane cell design, along with the introduction of oxygen-depolarized cathodes, have led to marked improvements in cell efficiency, reducing the overall process power requirements by nearly 30%. Table 1 summarizes the current state-of-the-art operating conditions of the chlor-alkali process.[12] The energy consumed has decreased from about 4,000 kWh/ton of caustic in the 1950s to about 2,500 kWh in ca. 1998 with the advent of the dimensionally stable anodes and optimal cell design/operation.

Despite the improvements in performance achieved in the last 50 years, there is room and need for optimization of the process to further reduce energy consumption. The thermodynamic voltage for the decomposition of brine is 2.2 V, however, the actual overall cell voltage applied to sustain electrolysis in most industrial processes is

Table I. Operating data of the Chlor-Alkali process using dimensionally stable anodes.[12]

Current Density	7 kA/m²
Cell Voltage	3.10
Power Consumption	2,130 kW-h per metric ton NaOH
Cell Temperature	88-90 °C
Service life	> 4 years (due to membranes and gaskets)
Active area	2.72 m²

in excess of 3.0 V, due to the accumulation of practical resistances encountered and the lack of uniform current distribution. The overall voltage of an operating electrolytic cell can, for the purpose of simple analysis, be represented by the following simple model:[13]

$$E_{cell} = \underbrace{E_{0,anode} - E_{0,cathode}}_{\substack{Thermodynamic \\ decomposition \\ voltage}} + \underbrace{\eta_{anode} - \eta_{cathode}}_{\substack{anode\ and \\ cathode \\ over\text{-}voltages}} + iR_{soln} + iR_{membrane} + \underbrace{iR_{hardware}}_{\substack{losses\ due\ to \\ practical \\ inefficiencies}}$$

In an analysis of the typical operating parameters during industrial operation, $iR_{hardware}$ values average 0.25 V and 0.37 V for the diaphragm and membrane varieties of chlor-alkali process cells, respectively, where the operating load is 2.32 kA m^{-2} and 3.5 kA m^{-2}, respectively.[13] This represents 7% and 12% of the total voltage applied across each cell, and is due entirely to inefficiencies that exist in the electrode material, contacts, electrode taps and interconnects. Additional improvements such as the incorporation of applicable advances in cell and stack design made in fuel cells and water electrolyzers, and electrocatalyst development could further reduce the energy consumption and hence, the cost for producing chlorine and caustic. The chlor-alkali process remains highly relevant and continues to offer challenges and opportunities for improvement in the context of electrochemical manufacturing.
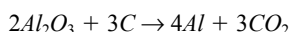
Aluminum

The electrochemical production of aluminum is one of the most successful examples of how electrochemical reactors can reduce the cost of commodities. Before the implementation of electrolysis, aluminum was as expensive as silver. Today, aluminum (average 2014 price $0.84 per lb[14]) is about 400 times cheaper than silver (average 2014 price $340 per lb[15]). However, primary aluminum production today is ranked among the most energy and CO_2 intensive industrial processes. Specifically, it is among the world's largest industrial consumers of energy, having an energy cost which accounts for approximately 30% of its total production cost.[16]

All of the primary aluminum production occurs through one industrial practice, which consists of three steps (a) mining of bauxite, (b) production of alumina (Al_2O_3) known as the Bayer process, and (c) reduction to Al metal known as the Hall–Héroult process *[Editor's note: Please see pages 36 and 37 of the summer 2014 issue of* Interface *for an ECS Classics article on the Hall-Héroult process by past ECS*

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president Theodore Beck]. Nearly all the electricity consumed in primary aluminum production (approximately two-thirds of the total energy input) is used in the Hall–Héroult process.[16] This process is also currently responsible for 2.5% of the world's anthropogenic CO_2-equivalent emissions.[17] The greenhouse gas (GHG) emissions of the Hall–Héroult process include a) direct emissions (from the reaction of oxygen with the carbon-based anodes) and indirect emissions (from the use of fossil fuel based electricity) of CO_2, and b) emissions of perfluorcarbons (PFCs) like CF_4 and C_2F_6, released due to the anode effect in the cryolite bath.

In the Hall–Héroult process alumina is reduced electrolytically to aluminium in a molten cryolite bath while carbon is consumed (oxidized) during the electrolytic process and supplies part of the energy necessary for the reduction of alumina, according to the following reaction:
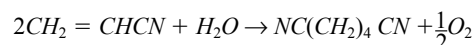
$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

The theoretical minimum energy requirement for the reduction of alumina in a carbon cell is 6.16 kWh/kg Al (with CO_2 emission at 960 °C). The theoretical decomposition voltage is 1.7 V; however, in practice the cell operates at about 4.7 V mainly because of ohmic losses throughout the components.[19] High-grade alumina is dissolved in a molten bath consisting mainly of cryolite (Na_3AlF_6) at a temperature of about 960 °C. Consumable carbon anodes are employed in the electrolytic cell to produce molten aluminum, which is periodically withdrawn from the cathode by vacuum siphoning. The electrolytic cells used in the process need to be periodically replaced, producing a carbon-based solid waste (0.02 kg/kg Al) known as Spent Pot Lining (SPL), which is classified as a hazardous waste due to its chemical content (12% F^- and 0.15% CN^-).[16]

The energy consumed by the Hall–Héroult process (processing energy) and the resultant GHG emissions are summarized in Table 2. The total energy consumption and the GHG emissions depend on the source of energy used. A significant increase in both is observed when electricity from coal is used vs. hydroelectric. Independently of the electricity source, the electrochemical reaction is the highest source of energy consumption, accounting for up to 75% of the energy consumed and for 50% of the GHG emissions generated.

Despite the successful use of electrolysis for the production of aluminum, research efforts are still needed to improve energy efficiency, to minimize the use of consumable anodes, and to minimize waste generation. Recently, ARPA-E, under the modern electro/thermochemical advances in light-metal systems (METALS)[20] program, has sponsored research and development projects for the implementation of new technologies in the electrolysis of aluminum (e.g., advanced electrolytic cells with power modulation and heat recovery, dual electrolyte and electrolytic membrane extraction, and pure oxygen anode electrode). Hence, aluminum production offers another example of an established electrochemical manufacturing process that nevertheless offers challenges and opportunities for the future.

Electrochemical Synthesis of Organic Compounds

Traditionally, the synthesis of organic compounds has been accomplished via chemical routes. Alternatively, over the last century, the use of electrochemical methods for organic synthesis has been investigated at both the laboratory and industrial scale. Some of the benefits of electrochemical organic synthesis are (a) higher product selectivity and purity, (b) lower number of reaction steps, (c) inexpensive starting materials, (d) less polluting byproducts, and (e) lower consumption of energy.[21-22] However, these advantages have not translated to a widespread use of electrochemical synthesis and only a few processes have been commercialized from the laboratory scale. A list of organic compounds produced using electrochemical route and their proximity to industrial application is indicative of the current status of electrochemical synthesis (Table 3). The most successful organic electrosynthesis process that has been commercialized is the manufacture of adiponitrile from acrylonitrile:[3]

$$2CH_2 = CHCN + H_2O \rightarrow NC(CH_2)_4\,CN + \tfrac{1}{2}O_2$$

Adiponitrile (ADP) is a key intermediate for the production of nylon 6, 6 polymers. It is used for the synthesis of hexamethylenediamine (HMD), which along with adipic acid are the raw materials for the production of nylon 6, 6 fibers and resins. The electrochemical route for synthesizing adiponitrile is employed by Solutia in Decatur, Alabama in the U.S., Asahi Chemical in Nobeoka, Japan, and by BASF at Seal Sands, UK. Chemically ADP is produced by DuPont in Texas, U.S. and by Butachimie (joint venture between DuPont and Rhodia) in Chalampé, France.

According to the report from ICIS, a petrochemical market information provider, in 2000, world production for the adiponitrile was 1.375 million metric tons per year of which 32.8% was produced via an electrochemical route.[23] In a 2005 report, the global production increased to 1.564 million metric tons per year but the contribution from the electrochemical route dropped to 30.8% (0.481 million metric ton per year).[24] An assessment from PCI Nylon, a market research consultancy, is that 1.197 million metric tons of ADP was produced in 2010 and only 29% of the ADP produced was from acrylonitrile.[25] The demand for nylon 6, 6 is the driving force for the production of HMD and ADP, and this has remained fairly consistent over the past decade. However, the electrochemical synthesis of ADP has suffered slightly in its contribution towards global production mainly due to the reduced prices for the raw materials used in the butadiene (chemical) route of ADP production. Natural gas is used in the butadiene route to synthesize ADP and in recent years the price for natural gas has also come down.

New Vistas for Electrochemical Manufacturing of Organic Compounds

The ADP electrosynthesis process is a classical example of electrochemical manufacturing of organic compounds. Due to environmental regulations, combined with advances in materials,[3] the opportunity now exists to capitalize on the electrochemical synthesis of organic compounds from unconventional organic sources.

Table II. Processing energy and GHG emissions produced by the Hall–Héroult process.[16,18]			
Type of Energy	**Part of the process**	**Energy Consumption (kWh/kg Al)**	**CO_2 emissions (kg CO_2/kg Al)**
Hydroelectric	Reaction	14.50	3.82
	Carbon anode baking	6.01	3.83
	Total	**20.51**	**7.65**
Coal Based electricity (3 kWh for every 1 kWh required)	Reaction	46.86	13.50
	Carbon anode baking	6.51	4.30
	Total	**53.37**	**17.80**

Examples of this new avenue include the electrolysis of carbon dioxide[26-33] and the electrolysis of coal and solid fuels (e.g., petcoke, paper pulp, biomass).[34-40] These opportunities are briefly discussed below.

Electrolysis of carbon dioxide.—Carbon dioxide is currently generated at rates that far outweigh its removal/conversion to raw materials such as fuels and chemicals. The possibility of converting this abundant waste to useful products has created an avenue of interest from the perspectives of both sustainable energy and environmental decontamination.[3] Although several chemical and catalytic methods have been tested for converting carbon dioxide to fuels, including reaction with hydrogen, hydrocarbons and organic carbonates, the use of electricity provides a more sustainable approach, due to the possibility of renewable sources (solar PV, wind) being used as the source of electricity.[26] While alternative chemical routes for CO_2 reduction have shown disadvantages such as deactivation of catalysts due to the presence of water (methanol and ethanol formation) and high reaction temperatures (carbon monoxide formation from $C - O$ dissociation), electrochemical CO_2 reduction can be performed under ambient conditions.[27-28]
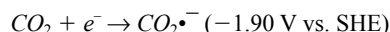
The electrochemical reduction of CO_2 has been investigated in aqueous and non-aqueous solutions. Various metal electrodes (Pb, Hg, Tl, In, Sn, Cd, Bi, Au, Ag, Zn, Pd, Ga, Cu, Ni, Fe, Pt, and Ti with CO_2 reduction potentials vs. SHE of -1.63 V, -1.51 V, -1.60 V, -1.55 V, -1.48 V, -1.63 V, -1.56 V, -1.14 V, -1.37 V, -1.54 V, -1.20 V, -1.24 V, -1.44 V, -1.48 V, -0.91 V, -1.07 V, and -1.60 V, respectively) have been explored for this reaction.[41,3]
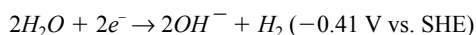
Table III. Examples of industrial organic electrosynthesis processes at commercial and pilot plant stages of operation. Adapted with permission from Table 2 in Sequeira, CAC and Santos DMF (2009) *Electrochemical Routes for Industrial Synthesis*. Place: Brazilian Chemical Society.[22]

Product	Starting Material	Company
Commercial Process		
Acetoin	Butanone	BASF
Acetylenedicarboxylic acid	1,4-Butynediol	BASF
Adipoin dimethyl acetal	Cyclohexanone	BASF
Adiponitrile	Acrylonitrile	Monsanto (Solutia), BASF, Asahi Chemical
4-Aminomethylpyridine	4-Cyanopyridine	Reilly Tar
Anthraquinone	Anthracene	L. B. Holliday, ECRC
Azobenzene	Nitrobenzene	Johnson Matthey Company
p-t-Butylbenzaldehyde	p-t-Butyltoluene	BASF, Givaudan
L-Cysteine	L-Cystine	Wacker Chemie AG
1,4-Dihydronaphthalene	Naphthalene	Clariant
2,5-Dimethoxy-2,5-dihydrofuran	Furan	BASF
Hexafluoropropyleneoxide	Hexafluoropropylene	Clariant
m-Hydroxybenzyl alcohol	m-Hydroxybenzoic acid	Otsuka
p-Methoxybenzaldehyde	p-Methoxytoluene	BASF
Perfluorinated hydrocarbons	Alkyl substrates	3M, Bayer, Clariant
Salicylic aldeyde	o-Hydroxybenzoic acid	India
Succinic acid	Maleic acid	CERCI, India
3,4,5-Trimethoxytolyl alcohol	3,4,5-Trimethoxytoluene	Otsuka Chemical
Pilot Process		
1-Acetoxynaphthalene	Naphthalene	BASF
2-Aminobenzyl alcohol	Anthranilic acid	BASF
Anthraquinone	Naphthalene, butadiene	Hydro Quebec
Arabinose	Gluconate	Electrosynthesis Co.
1,2,3,4-Butanetetracarboxylic acid	Dimethyl maleate	Monsanto
3,6-Dichloropicolinic acid	3,4,5,6-Tetrachloro-picolinic acid	Dow
Ethylene glycol	Formaldehyde	Electrosynthesis Co.
Glyoxylic acid	Oxalic acid	Rhone Poulenc, Steetley
Hydroxymethylbenzoic acid	Dimethyl terephthalate	Clariant
Monochloroacetic acid	tri- and di-Chloroacetic acid	Clariant
Nitrobenzene	p-Aminophenol	India, Monsanto
5-Nitronaphthoquinone	1-Nitronaphthalene	Hydro Quebec
Partially fluorinated hydrocarbons	Alkanes and alkenes	Phillips Petroleum
Propiolic acid	Propargyl alcohol	BASF
Propylene oxide	Propylene	Kellog, Shell
Substituted benzaldehydes	Substituted toluenes	Hydro Quebec, W.R. Grace

There are numerous products that arise during CO_2 electrochemical reduction based on the number of electrons transferred over the course of the reaction. In fact, one study has shown as many as 16 products in varying amounts (formate, carbon monoxide, methanol, glyoxal, methane, acetate, glycoaldehyde, ethylene glycol, acetaldehyde, ethanol, ethylene, hydroxyacetone, acetone, allyl alcohol, propionaldehyde, and 1-propanol).[29] However, while the reduction potentials for the respective reactions indicate mostly favorable thermodynamics, the poor kinetics necessitate overpotentials upwards of 1.0 V to yield these products.[41] In most instances, multiple products are formed leading to poor selectivity. The bottleneck in CO_2 reduction has been postulated to be due to the formation of a radical anion:[30]

$$CO_2 + e^- \rightarrow CO_2\bullet^- \ (-1.90 \text{ V vs. SHE})$$

In addition to this limiting step, a competing reaction is hydrogen evolution reaction in aqueous environments[30-31]

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \ (-0.41 \text{ V vs. SHE})$$

These issues with electrode kinetics and the nature of the chemical environment as well as the issues associated with poor selectivity indicate that further fundamental understanding of CO_2 electroreduction is required before viable electrochemical manufacturing of useful products from CO_2 can be realized at a commercial scale. However, this is undoubtedly an area with immense potential and opportunity for further exploration at the laboratory and perhaps pilot scales.
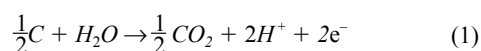
Electrolysis of coal and solid fuels.—The controlled manipulation of complex hydrocarbon sources (e.g., coal, pet-coke, lignin, pulp paper, biomass) to high value products with minimum carbon dioxide emissions is a tantalizing prospect and presents an excellent opportunity for electrochemical manufacturing of chemicals from complex and messy feedstocks. One example is the electrolysis of coal, wherein researchers have demonstrated that through the implementation of advanced materials, nanotechnology, and appropriate cell design, significant improvements in process performance can be achieved. A case in point is the nearly 2 order of magnitude improvement observed over the past several decades from current densities of 4 mA/cm^2 in the late 1970s[42-46] to up to 250 mA/cm^2 today.[34-40,47-49]

The efficient production of hydrogen (22 kWh/kg of hydrogen[34] electrical energy with 100% faradic efficiency), liquid fuels,[40,50] and graphene[51] enabled by the electrolysis of coal with minimum carbon dioxide emissions (15-25% faradaic efficiency[40,50]) has been demonstrated recently. A schematic representation of the process for the electrochemical manufacturing of high value chemicals from coal is shown in Fig. 1. The process consists of three main steps: 1. Electro-hydrogenation of the coal (or coal electrolysis),[34-37] 2. Extraction of liquid fuels,[40,50] and 3. Synthesis of graphene films.[38,39,51]
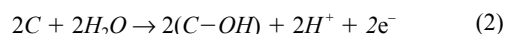
In the first stage (step 1),[34-37] coal slurries (coal particles/electrolyte) are electrochemically oxidized in the presence of water in the anode compartment of the electrochemical cell (producing carbon dioxide and hydrogen rich films on the surface of the coal), while hydrogen is produced in the cathode compartment of the cell. 4 M sulfuric acid, with a small concentration of Fe^{+2}/Fe^{+3} (ca. 40 mM) is used as the electrolyte. This electrolyte is not consumed during the reaction and can be reused and/or recycled during the process.[40,50] The anode and cathode compartments are electrically separated. Nafion® membranes and polyethylene separators have both been used successfully. Protons are transported from the anode to the cathode. The electrochemical cell operates at relatively low cell voltages (0.7-1.0 V) and intermediate temperatures (25-110ºC). Figure 1b shows the galvanostatic performance of the coal electrolytic cell at 100 mA/cm^2 operating at 104 ºC. Wyodak coal (sub-bituminous coal) DECS-26 was used with a particle size between 210-250 microns. The concentration of the coal slurry (coal in electrolyte) was kept at 0.04 g/ml. As shown, the voltage of the cell increased as the coal was

oxidized. The experiment was stopped when the cell voltage reached 1.17 V to avoid water electrolysis. The voltage of the cell increases due to the formation of films (caused by the oxidation of coal) on the surface of the coal particles.[49,35] Jin and Botte have presented a discussion on the mechanism of the electro-oxidation of coal.[35] The authors demonstrated that the coal is directly oxidized at the anode of the cell and proposed that the iron ions (additive to electrolyte) serve as a bridge that enables the instantaneous adsorption/binding of the coal particles on the electrode surface as they flow through the three dimensional electrode. As the films grow on the surface of the coal particles, this adsorption/binding is inhibited and the voltage of the cell increases.

Even though the electrochemical oxidation of coal is a complex process due to the heterogeneity of the material, it has been hypothesized that the anodic current is used for the direct oxidation of coal to carbon dioxide and for the formation of the films.[35] Assuming that coal can be represented as carbon, the electrochemical oxidation of coal to carbon dioxide takes place according to:

$$\frac{1}{2}C + H_2O \rightarrow \frac{1}{2}CO_2 + 2H^+ + 2e^- \qquad (1)$$

The formation of the films can involve multiple complex reactions due to the heterogeneity of the coal. A simple mechanism has been hypothesized:[40]

$$2C + 2H_2O \rightarrow 2(C-OH) + 2H^+ + 2e^- \qquad (2)$$

The majority of the current in the process (75-85% depending on the type of coal) is used for the oxidation of coal into hydrogen rich films that grow on the surface of the coal particles (for example, simplified reaction 2), while the electrochemical oxidation of coal to carbon dioxide (according to simplified reaction 1) is low. When Wyodak coal is used for the process, 75% of the coal is oxidized according to reaction 2, while 25% of the coal yields CO_2. On the other hand, at the cathode the evolution of hydrogen occurs with 100% faradaic efficiency.[34-37]

Step 2 of the process, extraction of liquid fuels, capitalizes on the formation of the films on the surface of the coal to yield chemicals and fuels. It has been demonstrated that liquid fuels can be obtained through extraction using ethanol at 78 ºC and ambient pressure with a yield of 0.2 g per g of coal.[40,50] The extraction yields obtained could compete with the yields reported using supercritical conditions (197 atm, 380°C), 0.5 g per g of coal.[52] Using the combined electrolysis/liquid extraction process presents an opportunity to reduce costs for the production of liquid fuels and chemicals from coal. Another application for the use of the electrolyzed coal is the synthesis of carbon nanostructures, nanotubes, and graphene – step 3 of the process. For example, Vijapur *et al.* have demonstrated the synthesis of graphene films from coal using chemical vapor deposition.[51]

The electrochemical manufacture of high value chemicals from coal is another electrochemical manufacturing technology that is in a nascent stage and, like CO_2 electro-reduction, will benefit greatly from further research and development efforts.
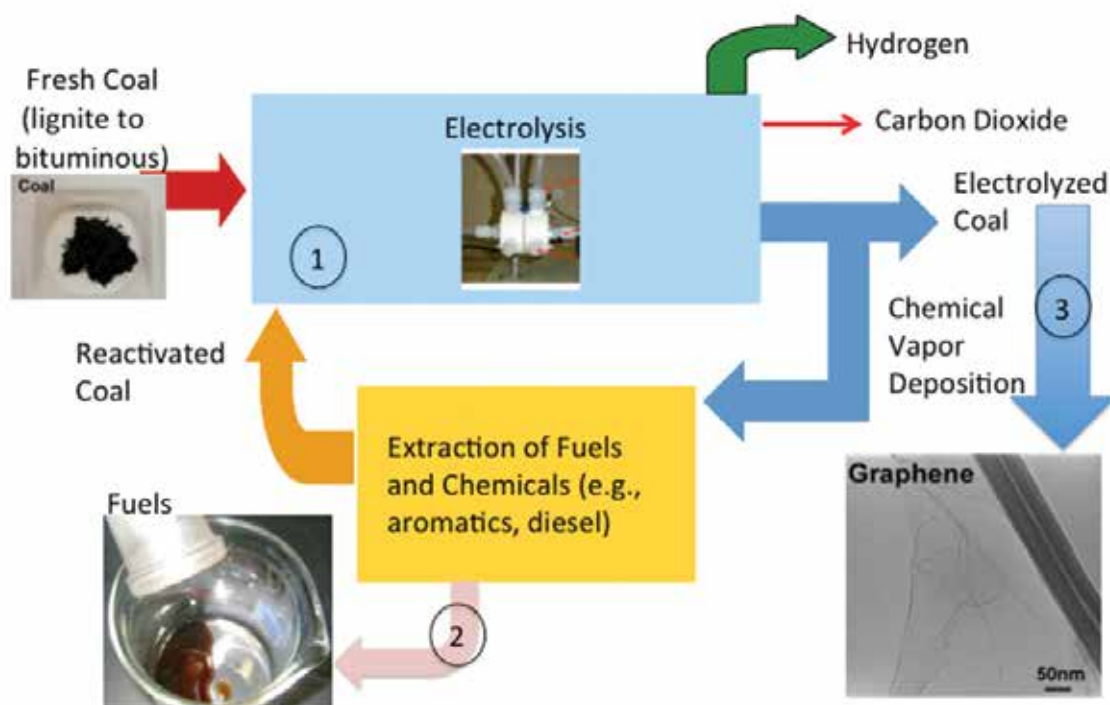
Outlook

Due to recent technological advancements and a changing economic climate, electrochemical technologies and processes now represent a relatively untapped frontier of opportunity for unique, enabling, and translational solutions that can benefit the chemical industry. Electrochemical processes provide significant benefits including:[3,55]

- **Easy integration with renewable energy (electricity) sources**. The scalability of the technologies, as well as their ability to easily operate in an on-demand mode, facilitates the technologies' ability to interface with renewable, time-varying energy sources.
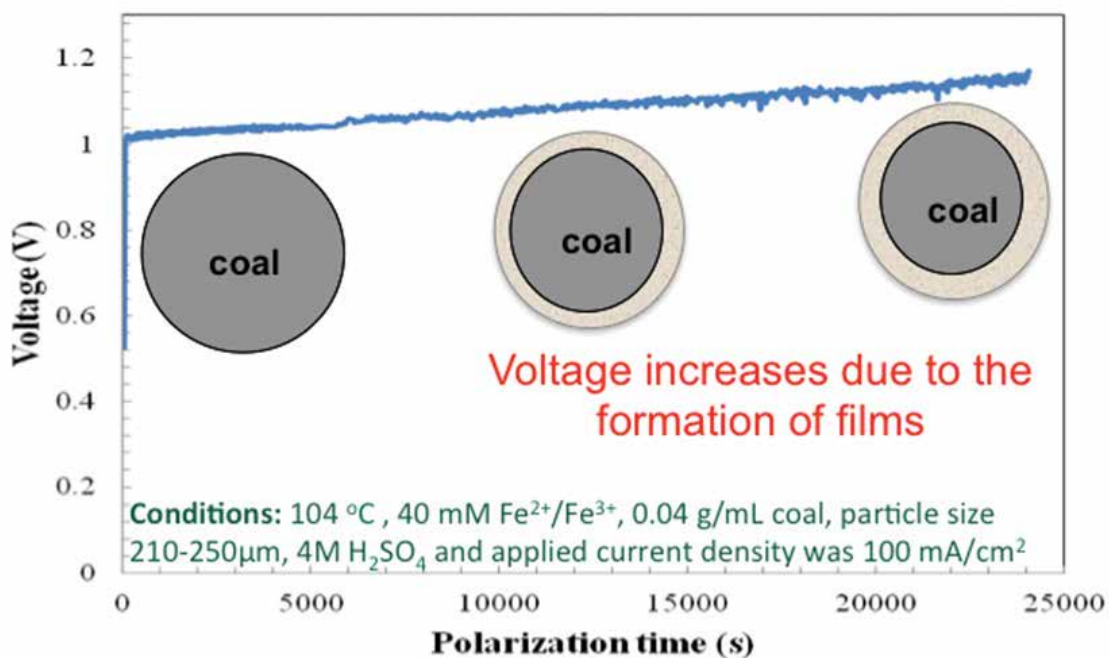
Fig. 1. *(a) Electrochemical manufacturing of high value chemicals (hydrogen,[34] liquid fuels,[40] graphene[51]) from coal. (b) Galvanostatic performance of the coal electrolytic cell at 100 mA/cm².[50]*

- **Minimization of purification and separation costs**. Electrochemical synthesis and/or electrolysis potentially allow the direct production of pure fuels and/or chemicals.

- **Ease of operation at low temperature and pressure**. Electrochemical synthesis and/or electrolysis typically takes place at low temperatures and pressures as compared to traditional heterogeneous catalytic synthesis. This could represent significant cost savings.

- **Mid-term impact**. The timeframe for implementation of these technologies could be mid-term to long-term (five to twenty years from now).

- **Ease of storage and transportation of feedstock and fuels**. Liquid fuels catalyzed through these processes can be transported, stored, and used using existing technology and infrastructure.

The chemical and allied industries (ChEAllieds) confront technology challenges – e.g., reliability of energy supply, lack of energy efficient/transformative manufacturing technologies, waste reduction, and water conservation – that hinder and jeopardize their growth and affect their competiveness worldwide.[54] Current chemical industry production methods have approached their practical performance limits, therefore, new disruptive, and enabling technologies are needed that will provide solutions to the ChEAllieds beyond incremental manufacturing improvements. Electrochemical manufacturing could provide opportunities for the ChEAllieds and, given the advantages and outlook discussed above, this is an emergent area for research and development. The Electrochemical Pathway for Sustainable Manufacturing (EPSuM) Consortium[56] funded by the National Institute of Standards and Technology (NIST) through the Advanced Manufacturing Technology Consortia (AMTech) Program is an example of an attractive collaborative model for pursuing translational advances in this sector. The overarching goal of this consortium is to develop a technology roadmap to support, sustain, and enhance U.S. manufacturing capacity in the nation's chemical industry and allied sectors through innovative processes that utilize electrochemical science and technology to address major technical barriers. Partners on the Phase I of the program are the Center for Electrochemical Engineering Research at Ohio University,[57] the National Science Foundation Industry University Cooperative Research: Center for Electrochemical Processes and Technology (CEProTECH),[58] PolymerOhio Inc.,[59] The Electrochemical Society,[60] and multiple companies. Similar government-university-industry partnerships would greatly advance the electrochemical manufacturing sector and should be actively pursued. ◼

About the Author

Gerardine (Gerri) Botte is the Russ Professor of Chemical and Biomolecular Engineering at Ohio University, the founder and director of Ohio University's Center for Electrochemical Engineering Research, and the founder and director of the National Science Foundation I/UCRC Center for Electrochemical Processes and Technology. Dr. Botte and members of her research group are working on projects in the areas of electrochemical engineering, electro-synthesis, batteries, electrolyzers, sensors, fuel cells, mathematical modeling, and electro-catalysis. Example projects include: hydrogen production from ammonia, biomass, urea, and coal, synthesis of carbon nanotubes and graphene, water remediation, selective catalytic reduction, ammonia synthesis, and electrochemical conversion of shale gas and CO_2 to high value products. She has 116 publications (peer-reviewed, book chapters, proceedings, and patents) and over 190 presentations in international conferences. She is the inventor of 18 U.S. patents and 29 pending applications. She is the Editor in Chief of the *Journal of Applied Electrochemistry*. In 2010, she was named a Fellow of the World Technology Network for her contributions on the development of sustainable and environmental technologies. In 2012 she was named a Chapter Fellow of the National Academy of Inventors. Dr. Botte served as past Chair, Vice-Chair, and Secretary/Treasurer of the ECS Industrial Electrochemistry and Electrochemical Engineering Division. She received her BS in Chemical Engineering from Universidad de Carabobo (Venezuela) in 1994. Prior to graduate school, Dr. Botte worked as a process engineer in a petrochemical plant (Petroquimica de Venezuela) where she was involved in the production of fertilizers and polymers. She received her PhD in 2000 (under the direction of Ralph E. White) and ME in 1998, both in Chemical Engineering, from the University of South Carolina. Prior to joining Ohio University as an assistant professor in 2002, Dr. Botte was an assistant professor at the University of Minnesota-Duluth. She may be reached at botte@ohio.edu.

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