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by Christopher G. Arges

The Case for Making Electrochemical Science and Engineering Part of the Core Chemical Engineering Curriculum

I am currently writing this article for *ECS Interface* during back-to-back weeks with several days of 100°F weather in Chicago during the month of June. Unusual weather events seem to be the norm today and for the foreseeable future. However, the most concerning aspect of climate disruption is perhaps the unpredictable nature of a warming climate. I never imagined that San Francisco would be engulfed by a shroud of orange due to wildfire smoke. The Electric Reliability Council of Texas (ERCOT) did not think a winter storm in early 2021 could cover the whole state, making power unreliable for days and resulting in more than 240 deaths. In 2017, the temperatures in Phoenix got so high that planes could not take off from the airport as the density of the air was too low. Climate change, or what I like to call Climate Disruption[1]—a term I have adopted from my former colleague Seth Darling at Argonne National Laboratory because industrialization has changed Earth's climate in a fairly short time—is becoming front and center in our daily lives.

I suppose none of this information is new to the readers of *ECS Interface*. Many ECS members work on electrochemical science and technologies with a mission to develop and proliferate these technologies to electrify vehicle transportation, stationary power, and, more recently, industrial processes. It is halfway through 2022 and there is widespread consensus among many climate scientists that countries such as the United States need to reduce greenhouse gas (GHG) emissions by 50% by 2030 and achieve net zero emissions by 2050. There is much concern that as a society we are not moving fast enough to meet these goals. It is especially difficul to make a focused effort given all the other challenges of the day—such as high inflation and a war in Ukraine. However, it isn't all doom and gloom and there is progress to celebrate: several major automobile manufacturers have pledged to have all of their vehicles be electric within the next 10 to 20 years, the US government is investing in several regional hydrogen hubs to help accelerate adoption of carbon neutral hydrogen as an energy vector and feedstock for decarbonizing various sectors of the US economy (e.g., ammonia production and steel refining), and many global companies are looking at ways to reduce their GHG footprint. Given all these changes taking place, it is fair to ask educators if we are doing enough to prepare a future workforce that is adept in electrochemical technologies to meet this technological sea change.

I completed my Bachelor of Science in Chemical Engineering in 2005. During my undergraduate education, many of the practical examples conveyed to teach thermodynamics, reaction kinetics, and transport phenomena hailed from downstream processing of hydrocarbon feedstocks for the manufacture of commodity chemicals and fuels. It is almost unthinkable that graduating chemical engineers today (and in the past) would not be proficient in calculating the number of theoretical trays for distillation column using McCabe-Thiele analysis or sizing up a plug flow reactor to meet the production of a given chemical. Considering the pressing global challenges surrounding climate disruption, I often ask myself as an educator "is it better to teach students to size up a distillation column or an electrolyzer?"

A recent story in the *New York Times*[2] on batteries for the auto industry stated the following: "One thing is certain: It's a great time to have a degree in electrochemistry. Those who understand the properties of lithium, nickel, cobalt and other materials are to batteries what software coders are to computers." Given the role that electrochemistry will play in arriving at a more sustainable society, it seems justified to add a core electrochemistry (or electrochemical engineering) course to the undergraduate chemical engineering curriculum. However, adding any core course to a curriculum is a challenging proposition, as most programs run about 125 to 135 hours to earn a Bachelor of Science degree and any course addition is only possible by removing another course. Many chemical engineering departments were faced with a similar challenge in the past decade when it came to adding more process safety to the curriculum—which was advocated by many industrial companies. Several departments have added a process safety course or combined another core course with process safety. That said, sometimes it is argued that elements of process safety should be covered in all core courses so that the concepts of process safety can be reinforced multiple times over the years, rather than students getting a single dose of the concepts which are susceptible to fade from memory. I would contend that electrochemistry principles should follow the same playbook: being sprinkled across the curriculum in all core courses, starting from thermodynamics and ending in capstone courses in process design and in unit operations laboratory.

Figure 1 conveys a Greek temple structure that represents the chemical engineering undergraduate curriculum. The foundation to the structure is composed of math, chemistry, and physics. The floor on the top of the foundation is mass and energy balances and introduction to computational techniques. The foundation and floor support four columns in parallel that represent the heart of chemical engineering: thermodynamics, transport phenomena, reaction kinetics, and process control. The roof of the temple represents the capstone courses that bring it all together: unit operations laboratory and process design.

The text boxes adjacent to right of the temple in Fig. 1 present some electrochemistry concepts that are suitable for a core chemical engineering curriculum. I suggest that thermodynamics should be the first course in the curriculum to introduce electrochemistry concepts, as it is often taken by most students in the second semester of their second year or first semester of the third year. In thermodynamics, and in other core theory courses, basic electrochemistry material can be covered in one to two weeks' worth of class time. A thermodynamics course can introduce the relationship between potential and the change in Gibbs free energy, calculating cell voltages, activity coefficient for electrolytes, and Pourbaix diagrams. The latter is a good example for teaching students about corrosion and material selection to potentially prevent corrosion. It is important to note that Pourbaix diagrams are another type of phase diagram that can complement conventional phase diagrams based upon pressure and temperature that are taught in thermodynamics. A mass transfer course, which is part of the transport phenomena sequence, should

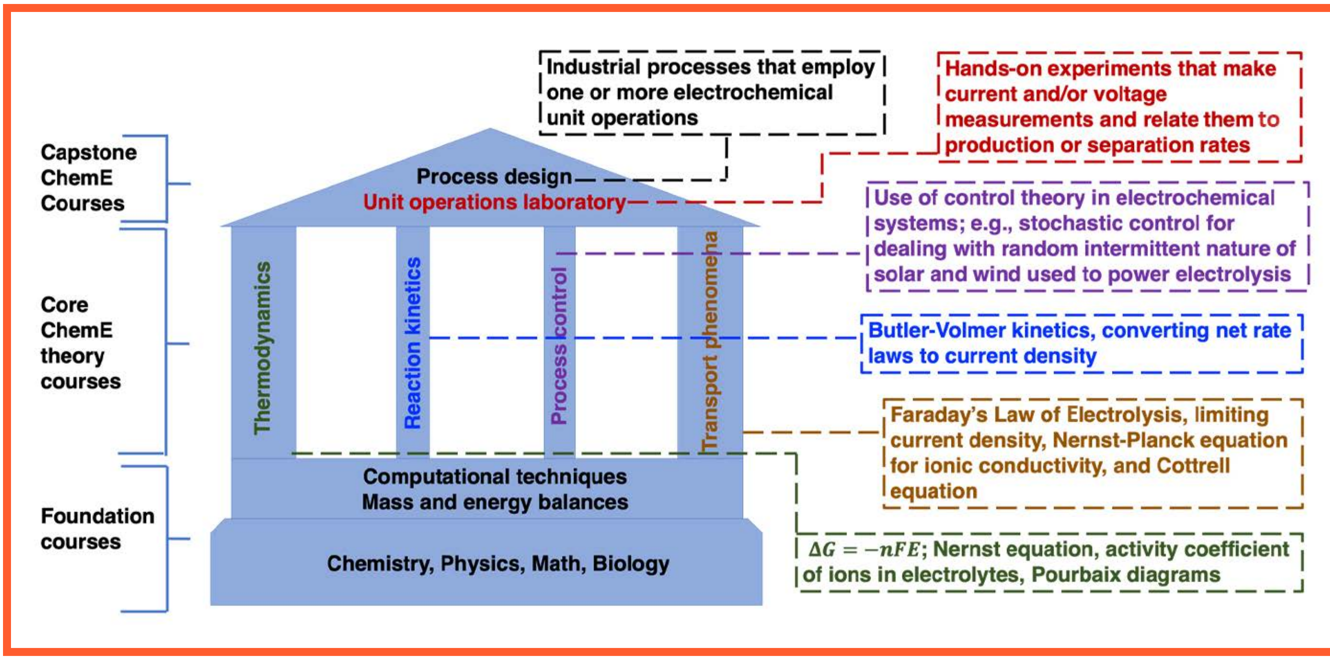

Fig. 1. *A generalized Chemical Engineering curriculum in the United States of America conveyed as a "Greek Temple." Adjacent to the temple are some electrochemistry topics to be introduced in core chemical engineering courses.*

introduce Faraday's law of electrolysis, ionic conductivity of an ideal electrolyte from a Nernst-Planck framework, limiting currents, and potentially the Cottrell equation. Mathias and co-workers illustrated nicely how the low limiting current density of lithium-air batteries (<10 mA cm^{-2}) makes them prohibitive to be used in a vehicle application, as over 1000 square meters need to be packed into a module conducive for a vehicle.[3] So although lithium-air can achieve energy density values that are much higher than today's lithium-ion batteries, their limiting current needs substantial improvement to make them practical. Educating chemical engineers who are capable of these types of "back of the envelope" calculations is part of the goal of introducing electrochemical science and engineering into the chemical engineering curriculum. A reaction kinetics course would present Butler-Volmer kinetics, and its simplified version, the Tafel equation, and Tafel plots. Students should feel confident in converting net rate laws to current density expressions. Prescribing fundamental electrochemistry content for the final theory course, process control, is difficult but the course is amenable for showing how process control strategies can benefit electrochemical processes integrated with intermittent energy sources. For example, energy extracted from solar and wind can rapidly diminish if a passing storm blocks sunlight or the wind dials down. The drop in these renewable energy sources can be problematic for meeting energy demand. Control systems that deal with these random events and rapidly ramp up electrochemical energy conversion technologies to satisfy energy demands is vital for further penetration of solar and wind as our society's energy sources. Process control also could benefit electrosynthesis processes that may have varying feedstock compositions or environmental factors (e.g., outside temperature).

With respect to the capstone courses in chemical engineering, the unit operations laboratory affords undergraduate chemical engineering students hands-on experience collecting current and/or voltage data points of operating electrochemical cells and relating these values to the production rate or separation rate of chemicals and expended energy for making the chemicals or performing the separation. It is important in engineering education to balance theory courses with hands-on, experiential learning. The electrochemical engineering elective I have taught over the past six years to senior undergraduate and graduate students has included an experimental project. Students are assigned into teams of three to four people and perform experiments over two to three class periods. Previous experimental modules include a low-temperature proton exchange membrane (PEM) fuel cell, an ammonia-copper redox flow battery, a membrane capacitive deionization unit, and a rotating disk electrode for the oxygen reduction reaction. These experimental modules also ask the students to use electrochemical impedance spectroscopy to diagnose ohmic, charge-transfer, and diffusion-related resistance values within the cell. The laboratory assignment requires a written report and oral presentation and requires students to apply electrochemistry theory to interpret and analyze experimental results. As part of my NSF CAREER project, I plan to develop an electrochemical hydrogen pump for the unit operations laboratory so that a large contingent of graduating chemical engineering seniors can experience working with an electrochemical system. Electrochemical hydrogen pumps are captivating because they perform gas compression without any moving parts.[4] They are also effective for purifying hydrogen from steam–methane reforming (SMR) effluent and could be a key technology in deriving blue hydrogen.[5] Finally, a senior process design course should task students to realize a chemical process that integrates more than one electrochemical unit. One example could entail the use of electrodialysis for deionizing brackish water to be fed into a PEM water electrolyzer for green hydrogen production. This hydrogen can then be used in downstream processes to produce ammonia via Haber-Bosch or steel manufacturing. A technoeconomic analysis assignment can be devised to compare that process against a chloro-alkali electrolyzer that produces a caustic solution stream (e.g., $NaOH_{aq}$) that is subsequently fed into an alkaline water electrolyzer for green hydrogen production.

One problem with integrating electrochemical processes in senior design courses is the lack of standard electrochemical units in process simulators such as Aspen HYSYS. The Aspen Custom Modeler can allow more advanced users to develop electrolysis units to be deployed in process flows[6] Making electrolyzers (e.g., water, carbon dioxide, carbon monoxide, and chlor-alkali), electrochemical pumps (hydrogen and CO_2), and electrodialysis units standard modules in commercial process simulator software packages will help produce the next generation of graduates who are adept in designing more sustainable chemical processes that use electrochemical units.

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In closing, The Electrochemical Society is at the forefront of the science and technology that is critical to addressing climate disruption. The race to decarbonize requires an army of college graduates with a basic proficiency in electrochemistry. In 2018, there were fewer than 1,100 doctoral degrees awarded in chemical engineering in the United States while there were over 11,000 degrees conferred for a bachelor's degree in chemical engineering in the United States. Of the individuals with an advanced degree in chemical engineering, a small subset of them have been exposed to electrochemical science and engineering. Imagine if we could increase the number of chemical engineering graduates who are knowledgeable about electrochemistry by 10x. Such a substantial change is possible by adopting the core tenets of electrochemical science and engineering in the chemical engineering curriculum.

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