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Work-in-Progress: Batteries, materials, and renewable energies to learn concepts, develop research skills, and connect knowledge to applications

Dr. Carlos Landaverde Alvarado, University of Texas at Austin

Carlos Landaverde-Alvarado is an Assistant Professor of Instruction in the McKetta Department of Chemical Engineering at the University of Texas at Austin. Carlos holds a PhD and MEng degree in Chemical Engineering from Virginia Tech, an MBA from Boston University, and a BS in Chemical Engineering from Universidad Centroamericana Jose Simeon Canas (UCA).

Carlos works with laboratory-based courses to promote the development of professional competencies in students through the active practice of engineering. Carlos integrates different learning approaches (active learning, experiential learning, project-based learning, etc.) to facilitate the professional development of students, close knowledge gaps, and incorporate innovative concepts into the engineering curriculum.

Kent J.X. Zheng, University of Texas at Austin
Evalyn Wilber, University of Texas at Austin
Irfan Arif, University of Texas at Austin

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Introduction

This work in progress describes the implementation of a newly created battery and renewable energy laboratory experiment (i.e., battery experiment) utilized to enhance concept learning in lecture-based courses and promote the development of research skills within laboratory courses in chemical engineering through project-based learning (PBL).

Gaining hands-on, interactive experience is invaluable for improving students' active learning and their understanding of complex engineering concepts, particularly those of an interdisciplinary nature. It has been proposed that the integration of practical learning experiences through the use of experimental equipment within engineering courses can enhance the understanding of concepts, challenge misconceptions, and increase student engagement [1], [2], [3], [4]. Learning in traditional lectured-based courses in engineering follows a typical step-by-step sequence [3]: (1) the introduction of new topics, (2) the learning of these concepts, (3) the application of theoretical deductions, and (4) the development of solutions that involve mathematical problems. However, while experimental demonstrations are increasingly recognized as a pedagogical strategy to promote conceptual understanding and facilitate connections between theory and applications, engineering lectures seldom dedicate extensive in-class time to the hands-on practice of real-world engineering applications [5], [6]. This final step in the lecture-based learning sequence linking the solution of problems to their real-world applications is often overlooked due to time limitations or lack of effective teaching tools.

In addition, to promote active learning, previous studies have suggested an approach that embraces experiment-based learning as an effective tool in the development of engineering skills and the solidification of concepts [3], [7]. The inclusion of laboratory work to complement theoretical work can be effective in the improvement of classroom learning and can help cement fundamental concepts in engineering students [3], [8]. However, it is often impractical to create a lab class for each core course in the engineering curriculum. In the particular case of chemical engineering programs, the undergraduate curriculum usually requires the completion of 1 to 3 lab courses to help solidify student knowledge, strengthen understanding of concepts, and facilitate the application of these concepts in the solution of practical problems [9].

Thus, we propose we can bridge this gap in practical learning using targeted demonstrations in lecture-based courses and the integration of experimental projects in lab courses. As an application example, we have developed an experiment focused on renewable energies, materials engineering, and sustainability. The developed experiment is a simple, cost-effective battery fabrication and testing module that can be configured for both lecture-length demonstrations in lecture-based courses and extended research-driven projects in laboratory-based courses.

In the case of lecture-based courses, we apply the Engineering for One Planet (EOP) Framework [10] as a practical implementation tool to focus our work on the development of technical skills (i.e., Design and Environmental Impact Assessment) to target the practice of new concepts and to help challenge student misconceptions in the engineering classroom. While, for lab courses, we focus on the development of technical skills (i.e., Design, Materials Selection, and Environmental Impact Assessment), and leadership skills (i.e., Critical Thinking and Communication and Teamwork, as defined by the EOP framework); in addition, we also target the creation of knowledge through the integration of Project-Based Learning (PBL). PBL is defined as an instructional method that engages students in the learning process through meaningful projects and the development of products created from these projects [11], [12], [13]. By taking this active approach, and by combining the EOP Framework and PBL, we hope to enable our students to enhance their technical and leadership skills as they create products and learn by solving complex open-ended problems.

In this manuscript, we detail the design and development of the experiment, its expected contribution to promote learning in chemical engineering courses, and its use as a tool to introduce students to the practical applications of engineering. We evaluate possible implementations of the experiment and we discuss possible avenues to explore students learning and perception. In addition, we share our early observations highlighting how the practical elements of this experiment can contribute to the overall educational experience.

Research Questions (RQ) and Intended Learning Outcomes (ILOs)

This work is implemented within the Chemical Engineering Department at the University of Texas at Austin, a large public research institution in Texas, USA. The experiment and demonstration are integrated to two required chemical engineering courses: (1) as a class demonstration in the course Chemical Engineering Materials (CHE-350, 3 credit hours, lecture-based course, referred as "Materials") and (2) as a PBL-type extended research-driven project in the senior year Chemical Engineering Process and Projects Laboratory course (CHE-264, 2 credit hours, laboratory-based course, referred as the "Senior Lab"). We define three research questions for this study:
RQ1: *To what extent does the integration of hands-on demonstrations in lecture-based engineering courses result in improved classroom learning?*
RQ2: *How are the learning perception and in-class engagement of students affected by the implementation of hands-on in-class demonstration in lecture-based engineering courses?*
RQ3: *How does the development of laboratory research projects focused on sustainable practices help engineering students conceptualize the links between their previous coursework and their future practice as engineers?*

Through their participation in the in-class demonstration students will be able to:
ILO1: Identify the main steps required in battery assembly (EOP Framework – Design).
ILO2: Apply engineering principles to design and test batteries (EOP Framework – Design).
ILO3: Analyze experimental data to assess how key design parameters affect battery properties (EOP Framework – Environmental Impact Assessment).

Through their participation in the laboratory project students will be able to:
ILO1: Identify the main steps required in battery assembly (EOP Framework – Design).
ILO2: Identify and explain the key parameters in battery material selection (EOP Framework – Materials Selection)

ILO3: Analyze experimental data to assess how key design parameters affect battery properties (EOP Framework – Design).
ILO4: Summarize experimental findings and propose effective engineering solutions (EOP Framework - Critical Thinking and Communication and Teamwork).
ILO5: Evaluate the application of engineering concepts in the solution of real-world problems (EOP Framework – Environmental Impact Assessment).
ILO6: Develop engineering knowledge by researching and experimenting (PBL – Creation of products and knowledge)

We propose these ILOs respond to a gap in practical application required by students to succeed in the engineering profession.

Experimental and Educational Development

The developed experiment leverages the practicality of aqueous Zn-ion batteries, which use a mildly acidic $ZnSO_4$ electrolyte that is air-stable and does not require a glove box, as well as the efficiency of coin-cell assembly to highlight state-of-the-art battery technology [14]. The battery experiment is developed as a two parts experience: 1) Battery fabrication and testing station (i.e., using a coin-cell assembly and a potentiostat) and 2) phase modification of as-synthesized battery materials via pyrolysis using a tube furnace with an inert gas supply. Figure 1 depicts the equipment and experimental workflow followed in the experiment.

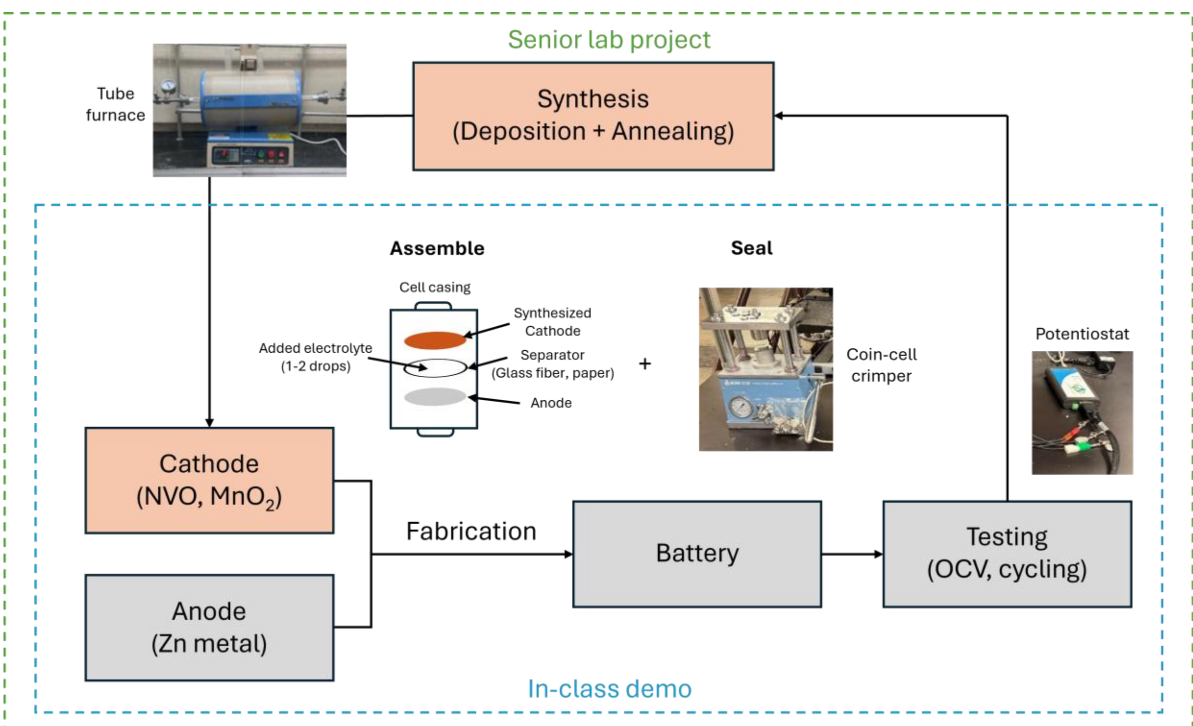

Figure 1. *Suggested workflow for Materials in-class demonstration and Senior Lab research project. Blue dotted line delimits experimental procedures covered during in-class demonstration. Green dotted line shows the expected workflow in the Senior Lab project.*

The experiment is integrated into the required courses Materials and the Senior Lab. We selected these courses because Materials covers all concepts related to batteries, energy storage, and materials selection; while the Senior Lab requires students to complete a self-directed research project that promotes learning through experimentation. Registration in Materials is approximately 50~70 students every semester and the course is offered twice a year. All students interact with the concepts discussed in the demonstration described in this paper. Registration in the Senior Lab is approximately 50~90 students every semester. The course is offered twice a year. More details on the courses are provided in the following sections.

Course Implementation

As depicted in Figure 1, in the lecture demonstration (Materials), students assemble a Zn||MnO_2 coin cell using pre-supplied electrode materials, power a small LED, and characterize current–voltage behavior with a potentiostat. For longer experimental projects (Senior Lab), students optimize the cathode synthesis process or modify the electrolyte, test their hypotheses, and evaluate cell performance. Overall, we believe this platform is highly configurable and offers an intuitive, engaging learning experience for engineering students. It provides not only insight into the science underlying battery technology but also valuable practice in critical reasoning and hypothesis-driven research. In the following sections, we present application examples conducted during the 2025 Fall semester:

Example A: Hands-on in-class demonstration in the Materials course.
Example B: Research project in the senior year laboratory.

Example A: Hands-on in-class demonstration

For the in-class demonstration, as part of the Materials course, students were offered a hands-on learning opportunity related to battery concepts covered in lecture. The in-class demo had a total of 20 student participants (~30% of the class) across two, 1 hr sessions. Participation was voluntary, registration in the demonstration was limited to 10 students per section since this was the first time we implemented this experience. During the demonstration, students worked in groups to assemble zinc-sodium vanadate oxide (Zn-NVO) split cells. During assembly of the cells, students were asked to describe the purpose of each part of the battery by connecting them to concepts described during lecture. Once assembly was completed, students were asked to predict the open circuit potential (OCV) of their cells based on learned concepts, before measuring it to confirm correct assembly. Finally, students were shown cycling data from the same type of cell and asked to describe conceptually which plots described charging and discharging of the cell, while also describing what is happening physically and chemically during each process. Anecdotally, we believe participation increased understanding and curiosity about the subject. Students asked thoughtful questions and actively engaged in discussions. This demonstration was also an opportunity for students to explain learned concepts from lecture in application to a physical example, which we believe solidified their understanding.

Appendix A shows the handouts used during this demonstration. In future iterations, we plan to increase the number of participants to at least 40 total students. In addition, we plan to implement an after-experience survey to explore student perception and a pre- and post-demonstration quiz (to address RQs 1 and 2). Appendix B shows the instruments we have developed to this end.

B. Chemical engineering laboratory project

The senior year laboratory is divided into two interdependent sections: a) students complete 3 – 4 pilot-plant-type lab experiments, and b) they simultaneously develop a research project that is self-directed as depicted in Figure 1b). The battery experiment is integrated as a research project (b) to maximize learning and pursue the development of knowledge through PBL.

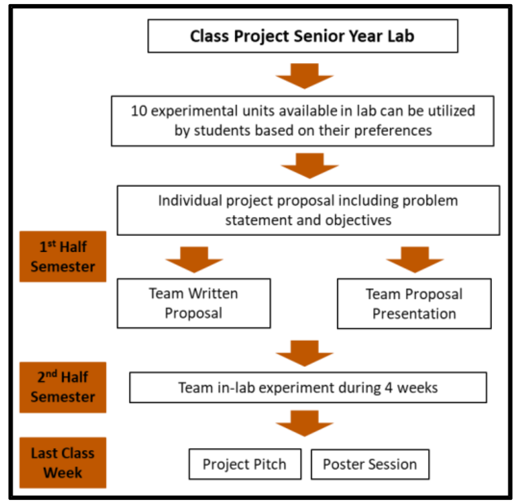

Figure 2. *Class projects structure in lab course. Adapted from [15].*

Details on the course structure and learning objectives have been described elsewhere [8]. Briefly, during the first week of classes, students decide on a project topic using any of the experiment stations available in lab. Subsequently, they complete an individual proposal; requiring each student to research the project topic and create a problem statement and a list of objectives. After receiving feedback and discussing in one-on-one meetings with the teaching team, student teams complete a written proposal and proposal presentation defining the problem to be solved, the relevance of the problem, their proposed experimental solution, a summary of relevant theory and methods, their management plan, a detail of supplies and equipment needed, and the calculations needed to complete the problem solution. Teams then complete their proposed experiments in-lab over a four-week period. This self-directed project culminates in a poster session and a project pitch which are the final products of the experience. During Fall 2025, one student team in the Senior Lab used the battery experiment as their class project. Participation in the project was requested by 3 teams of students; however, we limited participation to only one team in the class as this was the first time implementing the experiment. In total, we had 20 total student teams this semester, the other 19 teams were assigned to the other projects and experiments available in the lab (e.g., polymer processing, reverse osmosis, absorption, reaction engineering, etc.).

The student team working on the battery project submitted a research proposal titled "Effects of varying temperature during the annealing of MnO_2 doped carbon cloth on the performance of carbon electrodes for sustainable batteries". Their objective was to select a battery material and compare its performance with conventional Li-ion batteries to reduce costs, increase safety and promote a higher electrode potential. As part of this process, students collaborated with faculty to design their experiment. Once in lab, students performed an electrochemical synthesis of an oxide on a carbon cloth using aqueous solutions. The as-synthesized battery materials were added onto the carbon cloth and cut into smaller pieces before pyrolysis at different temperatures. During these temperature treatments, students observed as the deposited oxide was converted into an ordered crystalline phase to enhance electron mobility and improve the battery performance. Following pyrolysis in the tube furnace oven, students assembled coin-cells with a hydraulic crimper using foil, electrolytic solutions of metal salts soaked on fiber cloths, the pyrolyzed battery samples, and a spacer. Students then determined the performance of the created coin-cells by charge-discharge cycles using the system depicted in Figure 1. Data analysis included voltage vs. post pyrolysis capacity plots, comparisons with existing literature values, and plots of discharge capacity vs. cycle number and coulombic efficiency vs. cycle number. At the end of the semester, the student team presented their results to the class in a poster session to ensure they effectively synthesized information and created new knowledge as they developed and evaluated this research project.

In the future, we will modify our laboratory rubric to evaluate the final product created by students (i.e., research poster), in particular, we plan to evaluate their approach to material selection following EOP framework principles and the development of an Environmental Impact Assessment of their final research work. In addition, we will implement a post-experience interview to understand the effects of the experience over perceived learning and skill development (to address RQ 3). Appendix C shows a draft of this planned interview.

Conclusions and Future Work

We believe the main educational benefits produced by this project are the opportunities students will have to work on projects directly related to sustainability (i.e., batteries), the implementation of the EOP framework in chemical engineering, the incorporation of hands-on classroom demonstrations in our program, and the creation of knowledge on the effective use of experiments in different settings to tailor the learning of engineering students.

In the long term, we expect this study will help us create a framework to identify best practices and benefits of implementing tailored hands-on experimental demonstrations to highlight real-world applications of concepts in lecture-based courses and laboratory courses. As discussed, to develop this study, we will conduct surveys of students participating in the Materials course, interviews with students participating in the laboratory projects, and pre- and post-demonstration quizzes to further assess whether these experiments enhance student learning effectively. We will also analyze final products from the research projects using grading rubrics created for this purpose. In addition, we will compare results between students in two course sections to evaluate student learning and gauge increase in engagement with the courses. We will also be able to evaluate whether participating in the lab projects results in better results in the Materials course for those students enrolling later in Materials (i.e., Materials is not a pre-requisite to the lab course). This can be implemented by keeping a year-by-year record of students participating in the class demonstration and the laboratory research project.

This demonstration will also benefit the teaching of Materials in several ways. First, it serves as a direct supplement that will help students connect electronic properties and electrochemical principles to real-world phenomena. In addition, it functions as a pilot program that allows us to critically evaluate how the design of a hands-on demonstration influences student learning outcomes. We hope the quantitative, evidence-based assessment will establish a foundation for developing additional instructional modules to support other challenging and highly abstract concepts in the course, such as electronic band structures and solar cells.

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Appendix A

In-class demonstration documents utilized in the Material course.

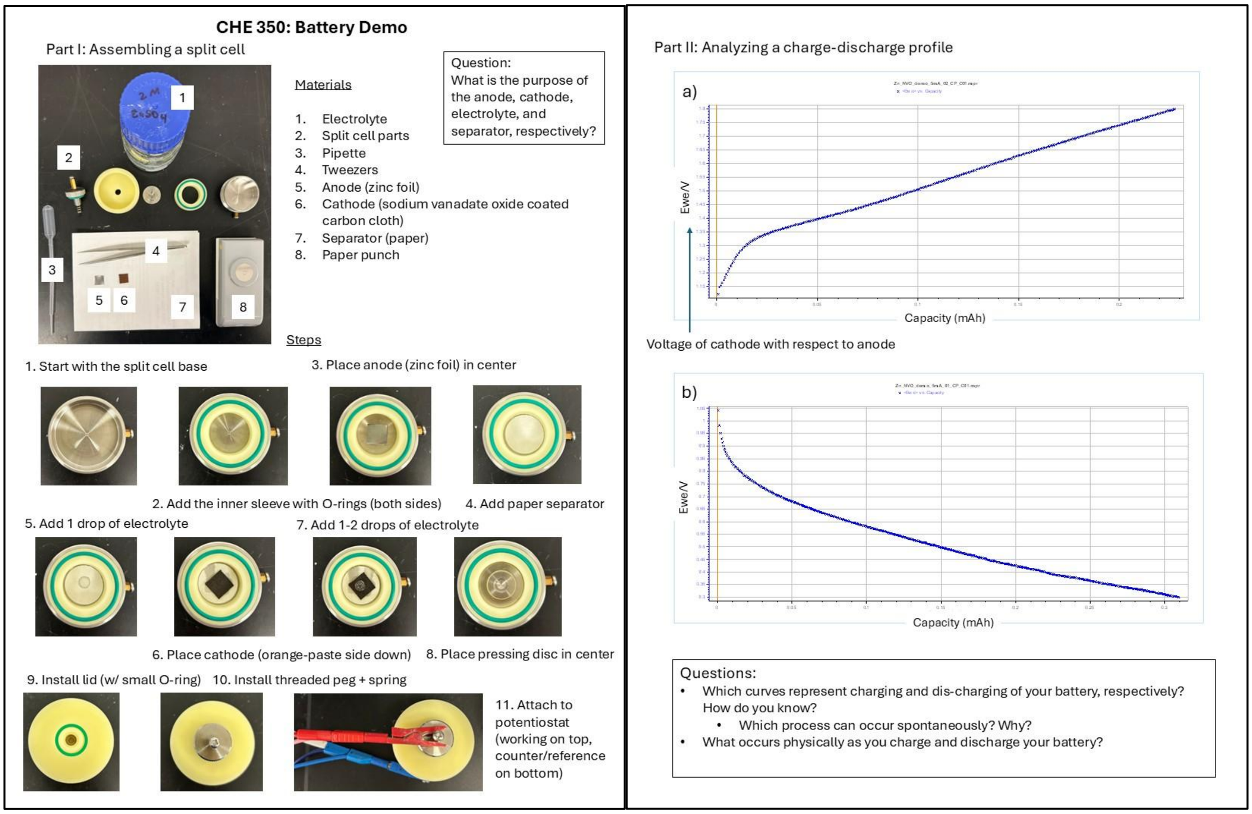

Figure A1. In-class demo handouts and integrated discussion questions.

Appendix B

Pre- and post- demonstration quiz (Materials).

This quiz on batteries is part of an engineering learning research project. It will not be counted towards your final grades. Thank you for your participation! :)

Name:____________________ EID: ____________________

1. During *recharge*, a battery converts ____ energy into ____ energy?

A. electrical, chemical B. chemical, mechanical

C. mechanical, electrical D. chemical, electrical

2. Which of following is/are correct about the *electrolyte* component in a battery? [select all that apply]

A. The electrolyte conducts electrons. B. The electrolyte conducts ions.

C. The electrolyte conducts electrons during discharge, and ions during recharge.

D. None of the above.

3. Knowing that the Fermi level (E_F) in Li metal is higher than that in O_2, which of following is/are correct about a battery made of a Li metal anode and a O_2 cathode? [select all that apply]

A. During discharge, electrons flow from the Li metal anode to the O_2 cathode.

B. During discharge, electrons flow from the O_2 cathode to the Li metal anode.

C. During discharge, the O_2 cathode gets reduced.

D. During discharge, the O_2 cathode gets oxidized.

4. Free response: In your own words, what is a battery, how does it work, and why batteries are important to our society? Please draw a schematic diagram of a battery to show the mechanism. [<60 words]

Page 1/1

Figure B1. *Proposed pre- post- demonstration quiz in Materials course. The same quiz is used for pre- and post- demonstrations.*

Survey instrument (Materials).

Q1: The experimental demonstration helped me identify the steps required in battery assembly

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q2: The demonstration helped me understand how to evaluate the performance of batteries

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q3: The experiment helped me connect class concepts to real-world applications in materials and energy storage

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q4: Overall, the class demonstration was engaging and relevant to my learning experience

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Q5: What part(s) (design, discussion, questions, etc.) or element(s) of the demonstration (visual, auditory, hands-on, etc.) was/were most helpful to your learning?

Please write in:

Q6: Additional Feedback: please use the text below to provide your comments and suggestions (positive or negative) about the battery experiment/demonstration

Please write in:

---End of survey---

Appendix C

Interview Instrument (Senior Lab).

Q1: Describe what you did in this most recent project. Write down steps.

Q2: What did you learn in the project? In each step?

Q3: Which parts were the most difficult? Why?

Q4: Which parts were the easiest? Why?

Q5: How much of this project feels directly applicable to your future practice as an engineer?

Q6: Describe what it was like collaborating with your classmates in this project.

Q7: What about this project has elements of doing things that an engineer does? Which parts don't?

---End of interview---