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Development of a Sociotechnical Module Exploring Electric Vehicle Batteries for a Circuits Course

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Abstract

This "Innovation in Engineering Teaching Practices" paper focuses on the development of a course module for an undergraduate introductory circuits course that highlights sustainability and life cycles of electric vehicle (EV) batteries. The EV battery module leverages circuits course concepts, introduces students to sociotechnical material, and emphasizes the circular economy in electrical engineering. We identify learning objectives for the module, provide pre-class activities and in-class teaching activities for circuits instructors, including discussion prompts and practice problems. We also offer samples of post-class assessments, including reflection and computation questions for homework and exams.

Introduction

Engineers are expected to solve grand challenges by applying math and science skills, but most undergraduate curricula teach these technical skills in isolation, without connecting them to the challenges facing society today. Research has shown that providing an applied sociotechnical context within the engineering disciplines can enhance learning [1], [2], [3] and increase students' satisfaction and interest - especially among marginalized groups in engineering [3]. Equations, free body diagrams, and textbook homework assignments dominate typical in-class engineering discussion, so students can lose sight of their field's significance. This disconnect can make it harder for students to understand the social responsibility that comes with engineering solutions.

It is critical that engineers understand the broader societal impacts of their proposed solutions and evaluate the tradeoffs between the value of technical work and the public good. However, many instructors find it difficult to effectively introduce sociotechnical concepts into foundational engineering science courses [4]. Engineering education should seek to teach beyond technical practicalities and offer the valuable contexts of engineering in society.

Core introductory courses in an engineering curriculum, including circuits, thermodynamics, and physics, address a wide range of technical topics that establish an important foundation for more advanced courses. Besides providing preparation for future classes, these courses must also prepare students for engineering projects that transcend limited course scopes. For example, electric circuits courses provide underlying conceptual and mathematical principles to model electronics. However, in practice, electrical projects can be interdisciplinary and go beyond the basic models introduced in class. Additionally, it is difficult to combine multifaceted sociotechnical concepts into entry level circuits classes. One method for developing course modules for electric circuits that explore technical content with a societal context is described by Lord, Przestrzelski and Reddy [1].

We offer a solution to better integrate the technical circuit concepts and societal principles in an undergraduate circuits course. Specifically, we describe a module designed to positively impact students' sociotechnical understanding. In this paper, we first provide a background for the project, and then we present specific details about the module – including learning objectives, pre-class activities, in-class teaching activities, and post-class assessments. We conclude by reflecting on the development process from a graduate student perspective, describing the anticipated next steps, and summarizing the work.

Background

Research in engineering education has explored the integration of sociotechnical concepts into engineering courses. Canney and Bielefeldt found that engineering students' sense of professional social responsibility varies across institutions, disciplines, religious backgrounds, and gender [5], [6]. They later created a framework for the development of social responsibility in engineers [7], [8]. More recently, findings in the literature have suggested a need for integrating sociotechnical concepts into core classes to retain socially motivated students [9], [10].

Various disciplines have integrated sociotechnical content into core classes. In a study by Gelles and Lord [10] of a materials science course, students considered the design needs of engineering solutions for people with disabilities by exploring the economic, environmental, and social impacts of materials. In an alternative class for thermodynamics, Hoople et al. presented a course to develop students' interdisciplinary understanding of energy topics, and society's energy problems [11], [12]. Polmear et al. proposed an in-class intervention they call a "micro-insertion" of ethics and societal impacts [13]. In this study, students explored a hydraulic fracturing micro-insertion in three different courses. They found that facilitating self-guided and/or collaborative learning, exploring engineering in the societal context, and creating a comfortable environment were important to students. Polmear et al. make a strong argument that including technical content in preexisting technical courses makes efficient use of available credit hours, while engaging students with engineering ethics [13].

Electric circuits is typically the first course electrical engineering (EE) students take in their major, and they typically enroll as sophomore undergraduates. It is also often a required course for students pursuing other engineering majors. As an introduction to EE, its primary objective is to introduce fundamental concepts. However, the course could also expose students to engineers' potential impact on society, thereby introducing sociotechnical concepts for engineers to consider beyond the classroom. Researchers have suggested ways to introduce sociotechnical concepts specifically in EE related courses [1], [14], [15], [16].

Lord, Przestrzelski and Reddy [1] describe a course module for circuits that addresses the impact of conflict minerals used in electrical components. Their module resulted in greater student engagement with the material and enhanced learning of technical circuits concepts (i.e., students thought critically about the impacts of using these materials in circuits). The researchers found that many students were not only receptive to the integration of sociotechnical content, but they also wanted more modules included in class.

A separate study by Leydens, Johnson, and Moskal [14] spanned multiple semesters and explored incorporating social justice into a higher-level EE course by applying the Social Justice for Engineering Framework. In this study, students were taught social justice principles through lectures in a controls course. As a result, some students identified social justice considerations as potentially transformative to technical fields. This study highlighted the need for curricular integration of social justice in an engineering problem-solving context.

Courses outside of the traditional EE curriculum also have the potential to introduce sociotechnical content [15], [16]. In a study of interdisciplinary engineering education, Hoople and Choi-Fitzpatrick [15] developed course materials for faculty to explore the intersection of drones and society. Similarly, Huang and Reddy [16] designed a robotics course module for an elective robotics course to promote critical thinking about the ethics and social implications of robotics [16].

Module Description

Inspired by Lord, Przestrzelski and Reddy's [1] module about conflict minerals and Polmear et al.'s [13] ethics and societal impacts micro-insertion about fracking, we developed a circuits module that explores the technical considerations for, and sustainability of, EV batteries. We choose EV batteries to highlight the importance of circular economies, defined by the Environmental Protection Agency as "… *an economy that uses a systems-focused approach and involves industrial processes and economic activities that are restorative or regenerative by design, enable resources used in such processes and activities to maintain their highest value for as long as possible, and aim for the elimination of waste*" [17]. Our EV battery module emphasizes the importance of engineering for sustainable economies in the realm of EE.

Our EV battery module comprises one 50-minute class session in an Introduction to Electric Circuits course. The module is designed to be implemented at a point in the semester after students have already been introduced to several fundamental circuits concepts (i.e., Kirchhoff's Voltage Law (KVL), Kirchhoff's Current Law (KCL), Direct Current (DC) circuits, and voltage dividers). These fundamental concepts, which serve as the backbone for the sociotechnical exploration, are typically covered early in the course. As such, this positions our module for deployment after teaching the first third of the circuits course.

In designing the module, we relied on the extensive experience of two senior EE instructors (the second and third authors of this paper) from two different institutions, each of whom has more than 20 years of experience teaching circuits. This expertise ensured the module fits within the original course framework and aligns with technical course objectives.

We structured our EV battery module in a comparable manner to Lord, Przestrzelski and Reddy [1], with pre-class and in-class teaching activities and with post-class assessments. And as we developed the EV battery module, we applied the principles of backwards course design [18]. Specifically, we defined the learning objectives for the module, the pre-class and in-class teaching activities, and the post-class assessments so that all three elements aligned (Fig. 1).

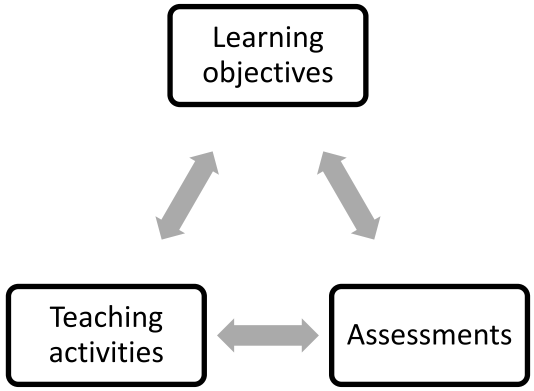


Fig. 1 Backwards Design Principles [18]

Learning objectives

In keeping with the process of backwards course design [18], we began by defining the learning objectives for the module. The learning objectives for the module leverage preexisting technical knowledge to introduce sociotechnical concepts (Table 1). The outlined objectives build on students' prior technical knowledge to introduce circular economy concepts for EV batteries.

TABLE 1
LEARNING OBJECTIVES OF THE EV BATTERY MODULE

Upon completion of the EV battery module, students should be able to: • (LEARN OBJ 1): design a voltage divider for a DC voltage source to illustrate reusing second life EV battery packs • (LEARN OBJ 2): interpret the estimated capacity of end-of-life EV batteries regarding circular economy potential • (LEARN OBJ 3): describe and categorize sociotechnical problems introduced by EV batteries that could be alleviated by circular economy principles

Teaching activities

Like Lord, Przestrzelski and Reddy's [1] conflict mineral module, the teaching activities for our EV battery module include both pre-class and in-class activities. These activities are aligned with the learning objectives of the module and are described below.

Pre-class Activities:

The pre-class activities, outlined in Table 2, consist of two parts. First, students listen to a podcast exploring the circular economy of EV batteries and answer a series of related questions (PRE-CLASS 1). Then, students make two estimates: the capacity of existing batteries (PRE-CLASS 2) and the amount of voltage that remains on EV batteries at their "end of life" as primary EV battery packs (PRE-CLASS 3).

TABLE 2
PRE-CLASS ACTIVITIES

1) Listen to the podcast: Is There Enough Cobalt for Electric Cars and Can Circular Economy Help? with Katherine Whalen and answer the following questions: a) Which of the following is the top global producer of Cobalt? i) Australia ii) Chile iii) China iv) Democratic Republic of the Congo b) Which of the following is the top global producer of Lithium? i) Australia ii) Chile iii) China iv) Democratic Republic of the Congo c) What is the biggest feasibility concern for a circular economy for EV batteries? i) The quality of urban minded Cobalt ii) Battery degradation over time iii) There are fewer current EVs than future demand iv) Fair trade certifications
2) Answer the following question about recycled battery capacity: Battery packs need to be replaced after about 10 years of on-road use. By the year 2030, we could assume that 70% of battery packs from 2020 would be recycled. In the year 2020, there were about 10.1 million cars on the road, and the batteries would have approximately 75% capacity when removed (assume a 500 Volt charge per battery pack at initial sale). Based on these assumptions, how many Volts are there available in recycled car batteries from 2020?
3) Answer the following question about the circular economy: Based on current policies, there are 25.8 million sales predicted for 2030. If we recycled 70 percent of degraded batteries from 2020, what percentage of future battery demand (in Volts) could be supplied using repurposed batteries? What does this imply about the feasibility of the circular economy for EVs?

In-Class Activities:

The module is designed for a 50-minute class session. Class begins with an in-class discussion (DISCUSSION 1) in which students meet in small groups to discuss the pre-class assignment and compare their estimates of end-of-life EV battery capacity. Students also discuss: What mathematical assumptions were made in the estimation done for the pre-class assignment? How would you attempt to connect multiple batteries to increase voltage using circuit concepts? How would you limit voltage to achieve desired output? And what types of sociotechnical factors might complicate the process of using second life batteries?

After the discussion, the instructor gives a brief presentation (PRESENTATION) about the circular economy of EV batteries. This presentation addresses electrical concepts that influence the methods of recycling/repurposing, the current shortcomings of battery recycling, battery innovations, and the influence that material costs have on EV markets. Finally, the instructor relates technical concepts of voltage division and KCL to the application of repurposing EV batteries. The instructor reviews the concept of voltage dividers with an example problem.

Class ends with a second in-class discussion (DISCUSSION 2) in which students work in small groups to discuss technical innovations for EV batteries that would be useful for a circular economy. Such innovations include having more efficient recycling done on a larger scale, changes in battery electrochemistry, alternate transportation options, etc.

Post-Class Assessments:

Post-class assessments for the EV battery module include reflection and computation questions for both homework and exams. Each question addresses the learning objectives of the module and relies on the concepts covered before and during class. Including such content on course assessments is important for increasing students' understanding [18].

Table 3 shows examples of post-class assessment questions. The first question (ASSESS 1) asks students to discuss different sociotechnical factors that impact EV battery development and/or second life for several sociotechnical contexts. These categories were selected to reflect sustainable sociotechnical concepts centered around environmental, social, and economic considerations [19]. The second question (ASSESS 2) asks students to reflect on the circular economy. The third question (ASSESS 3) applies a voltage divider within a social context of the circular economy.

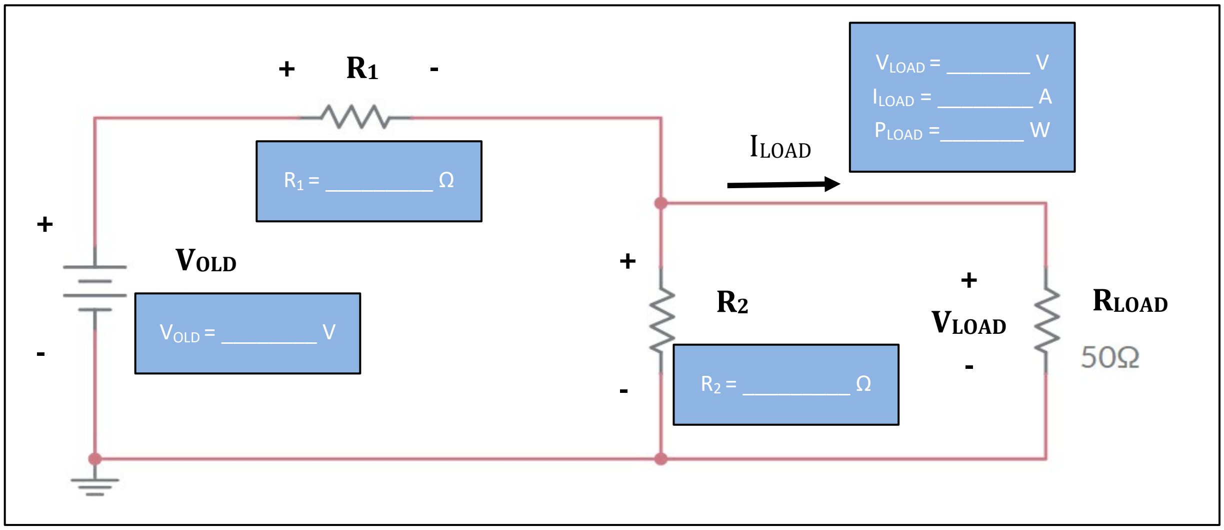
TABLE 3

SAMPLE POST-CLASS ASSESSMENT QUESTIONS (FOR HOMEWORK AND/OR EXAMS)

1) Describe an example of challenges or solutions for each of the following sociotechnical factors in the manufacturing and repurposing of EV batteries
   - Technical example: ____________________
   - Environmental example: ____________________
   - Health and safety example: ____________________
   - Economic example: ____________________

2) In your own words describe the purpose and benefits of a circular economy.

3) Complete the following problem about EV battery recycling:



A repurposed battery (represented by V_{OLD} in the above schematic diagram) is connected to power a mobile home. The load requires 240 V and 30 A to charge, the load resister (represented as R_{LOAD}) is included to draw current from the battery. The repurposed battery is a 600 V pack at 76% capacity, and R_{LOAD} is 50 Ω

In the answer boxes provided on the schematic, enter the following values:

a. The effective voltage of the entire second-life battery pack, V_{OLD}. (You may assume that all the current can be delivered from battery)

b. The value of R_1 and R_2 required to set the output voltage and current to 240 V and 30 A.

c. The total power supplied by repurposed EV battery.

d. Suppose the battery degrades over 2 years to 65%, recalculate a-c.

Constructive Alignment

The activities and assessments developed for the module follow the backwards course design framework [18], as we presented in Figure 1. The learning objectives associated with each pre-class and in class teaching activity and with each post-class assessment are summarized in Table 4.

TABLE 4
SUMMARY OF CONSTRUCTIVE ALIGNMENT

Learning Objective	Teaching Activities	Post-class Assessments
LEARN OBJ 1	PRE-CLASS 2 and 3 DISCUSSION 1 and PRESENTATION	ASSESS 1 and 3
LEARN OBJ 2	PRE-CLASS 2 and 3 DISCUSSION 1 and 2	ASSESS 1, 2 and 3
LEARN OBJ 3	PRE-CLASS 1 and 3 DISCUSSION 1and 2 and PRESENTATION	ASSESS 1 and 2

Reflection on the Process by First Author

In this section, I (first author of this paper) reflect on this process as a first year EE graduate student. I led the iterative process of developing the module, in collaboration with two faculty members who both have many years' experience teaching circuits and doing engineering education research (EER) (the second and third authors of the paper). The process consisted of identifying learning objectives, conducting an EV literature review, refining technical and sociotechnical assessment questions, defining (and redefining) the scope of the module, considering evaluation criteria, and exploring the broader realm of EER.

I started by defining an initial set of learning objectives and reviewing the literature on EV batteries. However, as my research on EV battery technologies continued, the technical and sociotechnical complexity of the issue grew. It became clear that the initial scope of the module was too broad for one class period. As a result, I continuously narrowed the scope to present the information more concisely to second-year EE students. Notably, there were important points that I had to remove from the module including the effects of electrochemistry limits on the charging rates and capacity of the batteries, environmental implications of deep-sea mining for raw materials, and the current limitations of battery recycling.

In addition, I had limited prior experience with course development. The original goal was to leverage the work presented by Lord, Przestrzelski and Reddy [1] and to rely on previous EE experiences coupled with a review of EV battery literature. As a result, I needed to learn about course design. For instance, the process of defining learning objectives was new to me. It required learning about action verbs in education considering the audience of second-year EE students [20], while also understanding the principles of backwards course design [18]. The work in this paper also served as a more formal introduction to the field of EER. I was constantly learning about broader EER and education frameworks. Without formal exposure to education frameworks, developing these new skills was unexpected, but important to the module design.

As well, I did not initially appreciate the specific focus areas in EER that this project covered. This led to increasingly complex considerations when designing. For example, the question of evaluating students' response to an intervention is an entire focus area in EER. Validated instruments and assessment were a new research concept to me, a student coming from solely an EE focused background. Another issue was considering the teaching activities for a larger classroom setting. Coming from a smaller undergraduate program, I had difficulty conceptualizing such a large introduction class, let alone implementing a specific sociotechnical module at that larger scale.

Next Steps

We are continuing to refine the EV battery module by expanding the course materials to include a detailed lesson plan for instructors and ensuring that the additional post-class assessments will align with the learning objectives [18]. We plan to pilot test the module in both our own circuits courses as well as in those of our colleagues, which will require creating more example questions/activities from which instructors may choose.

Following our pilot tests, we plan to assess the impact of the EV battery module on students' learning and attitudes using a mixed methods approach. We will develop formal evaluation rubrics for both the pre-/in-class activities and the post-class assessments. Additionally, we will use adapted validated surveys before and after the course to determine students' sense of social responsibility or adherence to normative cultural beliefs [7], [8], [21]. We will also conduct semi-structured interviews following the module to gain a deeper understanding of the results.

Summary

We present an EV battery module for an introductory circuits course that integrates technical material with a societal context. The module aims to increase students' sociotechnical understanding and motivation for studying EE concepts. After defining learning objectives for the module, we developed pre-class and in-class teaching activities that offer a wide introduction of circular economies for EV batteries. Then we prepared post-class assessments that allow students to apply what they have learned. We hope this sociotechnical module can be implemented in other circuits courses and can serve as an example for how to integrate sociotechnical material into traditional engineering courses.

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