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Designing Equitable STEM Education Modules with Renewable Energy Technologies

Dr. Matthew Aldeman, Illinois State University

Matthew Aldeman is an Associate Professor of Technology at Illinois State University, where he teaches in the Sustainable & Renewable Energy and Engineering Technology undergraduate programs.

Prof. James Mathias, Southern Illinois University, Carbondale
Daniel Austin Darcy, Illinois State University
Cheron James Elms
Kaitlyn Marie Quinn
Douglas Andracki

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Abstract

The DESSERT (Designing Equitable and Sustainable STEM Education with Renewable Technologies) project focuses on designing equitable STEM education modules centered on renewable energy technologies to engage middle and high school students from underrepresented groups in STEM fields. Led by an interdisciplinary team of faculty and undergraduate students from two universities, the project aims to inspire interest in sustainable energy-related careers among students from diverse backgrounds. The activities emphasize hands-on learning, empathy, and STEM literacy integration. Two sets of lab activities were developed. The first set of lab activities focuses on energy storage with a classroom set of pumped hydroelectricity kits. The second lab activity focuses on thermal energy, addressing energy efficiency and heat loss. The materials have been piloted with a high school environmental science class, and the activities showed promising results in enhancing students' understanding of energy concepts and promoting interest in STEM careers.

I. Introduction

An interdisciplinary team of two faculty and four undergraduate students at Illinois State University and Southern Illinois University recently completed a one-semester project called *Designing Equitable and Sustainable STEM Education with Renewable Technologies* (DESSERT). Funded by the Illinois Innovation Network, the focus of the project was to design renewable energy-focused STEM lesson and lab activities aimed at inspiring middle and high school students from underrepresented groups to pursue STEM and sustainable energy-related careers. The target audience of underrepresented students is a broad group including low-income students and members of racial and ethnic groups that are underrepresented in STEM fields. To develop the activity modules, the faculty member from each university led a team of two undergraduate students majoring in STEM disciplines at their universities. It is anticipated that this project will play a small part in making incremental progress toward the goal of increasing the number of underrepresented students who choose to study STEM subjects in college. While designing the project, team members placed an emphasis on incorporating materials that encourage students to gain confidence and understanding in sustainable energy-related topics. At the conclusion of the project, the materials that were developed were placed in STEM lending libraries maintained at the two universities so that the materials will be accessible to future generations of middle and high school students. Any educational organization in the state may borrow the classroom sets of lab activities at no cost.

The goals of the project were: 1) Through their engagement in the project, the four undergraduate students will gain an improved understanding of energy topics, allowing them to matriculate into STEM and sustainable energy-related career fields, as well as gaining an appreciation for how access to STEM materials constrains the STEM pathways available to students from under-resourced backgrounds. Simultaneously, 2) by engaging with the curricular materials, middle and high school students from underrepresented backgrounds will increase their knowledge and understanding of sustainable energy technologies, promoting their interest in pursuing related fields at the college level and beyond.

The materials developed in this project use several strategies to specifically target underrepresented groups. First, the curricular materials were developed by undergraduate students (under the guidance of faculty at the two universities) who are themselves from diverse backgrounds. Second, the materials have been designed using the latest educational methods for students of "non-dominant" groups [1] in mind. For example, the materials will be designed to break scientific misconceptions by stimulating the discovery of "discrepant events" during scientific discovery [2,3] and will utilize a range of real-world examples that will resonate with students from many different backgrounds. Third, the materials do not assume that students have a large amount of background knowledge regarding the topic because some students may not have had previous exposure to these topics. Fourth, the curricular materials have now been deposited into a "lending library" of school science materials. In this way the materials are available free of charge for widespread use in schools within the state.

II. Project Timeline

The DESSERT project spanned from November 2022 to June 2023, fully encompassing the spring semester of 2023. A Gantt chart showing significant project activities is provided in Table 1, and the activities are described in greater detail below.

Table 1. Project Gantt Chart

Tasks and Milestones	Nov '22	Dec '22	Jan '23	Feb '23	Mar '23	Apr '23	May '23	June '23
Hire undergraduate students	■	■						
In-person kickoff meeting			■					
Brainstorm ideas			■	■				
Purchase materials and prototype				■	■			
Pilot kit with other university						■		
Create description and instructions					■	■	■	
Deliver kits to lending libraries							■	
Inform local schools							■	■
Submit final report								■

The project began in November 2022 with the hiring of four undergraduate students to act as lesson activity developers. The faculty member at each university hired two students. These four students were third- or fourth-year students in STEM majors, and several of them identified as having backgrounds that are underrepresented in STEM fields. They were hired based on their interest and ability to develop learning modules involving renewable energy technologies built on an equity framework. During the spring semester, each undergraduate student was paid to complete up to ten hours of work per week on the project.

The semester started by establishing a common understanding of what equity looks like in educational coursework. To do so, the team started by conducting a literature review of STEM curriculum and educational frameworks that exemplified equity-focused approaches, and spent several weeks discussing the meaning of "equitable and sustainable STEM education." The group found that developing empathy for other communities is an important and recurring theme among curricula that are designed with equity in mind [4-6], and hands-on activities are widespread [6-8]. In addition, STEM literacy and the integration of multiple STEM areas were common themes [9-13]. Among all of the articles reviewed, the team found Jackson et al.'s "Equity-Oriented Conceptual Framework for K-12 STEM Literacy" [4] to be especially relevant and helpful in guiding the development of the lesson activities. Overarching themes that appeared repeatedly in the team's literature review and guided the subsequent work on the project include the following principles:

- Teach about success stories, not failures
- Curriculum should be personalized as much as possible to make it more relevant
- Activities should be designed to help students feel empathy and emotion toward the material
- The curriculum will be more impactful if it is easy for students to understand how it relates to *them*
- The material should help students develop a STEM Identity: a feeling that they can connect with STEM topics
- Students must first understand the sustainability problem. Why do we need renewable energy technologies? How are they useful? Students must understand that sustainability is a problem for *them*, in particular
- Address two or more areas of STEM
- The material should make the students feel like they have ownership of the sustainability problem (empowerment)

The teams from the two universities met twice at the beginning of the project: once on Zoom, and once in-person. The purpose of the first in-person meeting was to discuss the goals of the project and brainstorm ideas. Over the next several weeks the teams then continued independently brainstorming renewable energy-related activity ideas that could be performed by middle and high school students in a typical classroom environment. After brainstorming dozens of ideas and building functional prototypes of several, the groups settled on two platforms. The group at Illinois State University decided to build lab activities centered on energy storage with pumped hydroelectricity as the primary focus. The group at Southern Illinois University decided to build lab activities around thermal energy, with energy efficiency and heat loss as the primary focus.

After settling on a topic, the teams finalized the design of the classroom lab activities and built classroom sets of the lab activity kits. To determine the number of activity kits to build, the teams decided how many middle or high school students would be combined into one activity group in the classroom. This was dependent on the nature of the activity. The team at Illinois State University settled on an intended group size of three to five middle or high school students per group due to the low materials cost of the activity. This meant building eight kits per classroom set. The team at Southern Illinois University chose a group size of 5 middle or high school students per group due to the larger physical dimensions of their activity, which meant that 4 kits were constructed per classroom set with an expected enrollment of approximately 20 students per class. The size of the classroom set also reflected the need for the kits to be portable. Both sets of kits were sized to fit neatly into one or two large plastic totes.

Each team created two classroom sets of equipment necessary to perform the labs. In late April, three weeks before the end of the semester, the full group held a second in-person meeting. At this second in-person meeting the teams performed the lab activities that the team from the other university created, and provided feedback to improve the written instruction materials. Over the final weeks of the semester, the teams used the feedback from the other university to improve their written materials and instructions for the lab activities. The teams then exchanged one classroom set of equipment, so that each university has one classroom set of each lab activity. The materials were then placed into a STEM lending library maintained at each university.

III. Summary of Lab Activities

The project team at Illinois State University developed lab activities associated with energy storage and pumped hydroelectricity. The final set of activities includes two parts: a pre-lab activity that requires no equipment, and a hands-on lab activity that requires the classroom set of pumped hydroelectric lab materials created by the project team.

a. The first part of the activity is a pre-lab activity in which students visualize and “design” their own electric grid for their own fictional island nation. This pre-lab activity can be done by students in the class session before the hands-on lab activity, but it could also be used independently if there is not time to complete the lab activity. In this first activity, students are introduced to the advantages and disadvantages of each generation technology, and they must use critical thinking to select the generation technologies that they think will best meet the needs and constraints of their own island’s electric grid. Available generation technologies include natural gas, coal, nuclear, solar, and wind. In the second part of this first activity, students are introduced to the concept of energy storage, and they see the benefits that the inclusion of energy storage could have on the electric grid. Specifically, students see how the inclusion of energy storage could allow for increased renewable energy generation due to the variable nature of renewable energy generation.
b. The second part of the activity is a hands-on lab that utilizes the concept of energy storage. In groups of three to five, students are given the materials needed to complete the lab: two buckets with a valve in the upper bucket, a water turbine generator, a battery-powered pump, plastic hoses, a box with electric meters (voltage and current), and batteries. Students install the upper bucket (water reservoir) at three different heights, and observe the power that is produced by the water turbine generator at each height as the water flows from the upper reservoir to the lower reservoir. Students observe that a larger height difference between the upper and lower reservoir results in greater power produced by the water turbine generator, which reflects the greater energy storage as the height difference increases. Students also observe the power required to pump the water from the lower reservoir up to the upper reservoir, and calculate the efficiency of the closed-loop pumped hydroelectric energy storage system. A block diagram of the pumped hydroelectric system is shown in Figure 1.

During the pumped hydroelectric activity, students are introduced to mathematical equations relating to electrical power and energy. During the system “charging” process as the pump is used to pump water to the upper reservoir, students use Equation (1) to calculate the electrical power required to do so. Conversely, during the system “discharge” process as the water turbine generator is used to generate electricity as the water flows from the upper reservoir to the lower reservoir, students use Equation (1) to calculate the electrical power produced by the water turbine generator. Students measure the amount of time required to pump the water to the upper reservoir, and then measure the time for the water to flow through the water turbine to the lower reservoir. They then use Equation (2) to calculate the amount of energy required to pump the water from the lower reservoir to the upper reservoir, and the amount of electrical energy produced when the water flows through the water turbine generator as it flows back to the lower reservoir.

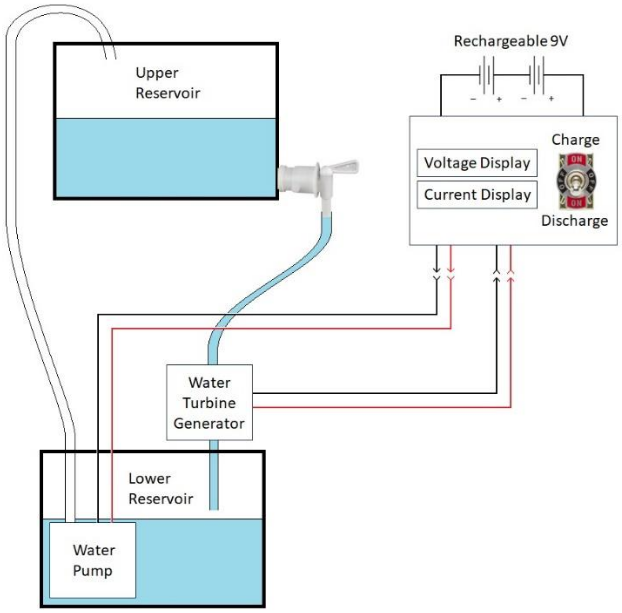

Figure 1. Block diagram of the pumped hydroelectric system

$$Power\ = (Voltage)(Current) \qquad \text{Eq. (1)}$$

$$Energy = (Power)(time) \qquad \text{Eq. (2)}$$

The lab instructions ask students to think about what parameters affect the amount of energy that can be stored by the pumped hydroelectric system. The lab manual also discusses the concept of efficiency: the fraction of energy input into the system that can be recovered as energy output from the system. Due to time constraints, the lab manual does not include calculations for these metrics. However, by answering the qualitative questions in the lab manual, students achieve an understanding of Equation (3) for power output, where Q is the flow rate, g is gravitational acceleration, h is the difference in height between the reservoirs, and η is the system efficiency. Similarly, by comparing the energy input and energy output from the system, students gain an understanding of Equation (4) for system efficiency, where energy output is the electrical energy output from the water turbine generator, and energy input is the electrical energy input to the pump to move the water from the lower reservoir to the upper reservoir and “charge” the system. The students are asked to consider why a system like a pumped hydroelectric system could still be beneficial for the electric grid, even though the system’s efficiency will always be less than 100%.

$$\text{Power} = \eta Q g h \qquad \text{Eq. (3)}$$

$$\eta = \frac{energy\ output}{energy\ input} \qquad \text{Eq. (4)}$$

The project team at Southern Illinois University developed lab activities associated with thermal energy, with energy efficiency and heat loss as the primary focus. This set of lab activities also contained two parts: a pre-lab activity and a hands-on lab activity.

a. The pre-laboratory activity discusses the history of insulation in buildings, such as using large stones to act as a thermal mass, building an air gap between walls, large tapestries over windows and doors, and finally modern insulation. The pre-lab activity also introduces the different fields of engineering that study these topics such as civil, environmental, and thermal (a subsection of mechanical) engineering.
b. The laboratory itself has the students measure the temperature difference across a wall with different insulations in the wall cavity. The different types of insulation tested are 1) air alone with no insulation, 2) polyethylene, 3) cotton, and 4) Styrofoam. The students plot the temperature differences versus time. The lab activity guides students through a procedure to determine the energy and the price of heating a typical 158 m^2 (1700 ft^2) house. The experiment ends with thought provoking extension questions such as “what would happen if the insulation was thicker?” and “what would happen if the heater’s thermal power output was doubled from 500 W to 1000 W?”

During the thermal energy activity, students perform calculations to determine the rate of heat transfer through the walls of the simulated home. Students learn about conduction heat transfer and convection heat transfer, and how the two modes combine to draw heat away from the interior of the home. Students use Equations (5) and (6) for conduction heat transfer, where L is the wall thickness, k is the thermal conductivity of the wall material, A is the heat transfer area, and T_2 and T_1 are the interior and exterior wall temperatures, respectively.

$$R_{conduction} = \frac{L}{kA} \qquad \text{Eq. (5)}$$

$$\dot{Q}_{conduction} = \frac{T_2 - T_1}{R_{conduction}} \qquad \text{Eq. (6)}$$

Students then use Equations (7) and (8) for convection heat transfer, where h is the convection heat transfer coefficient and A is the heat transfer area.

$$R_{convection} = \frac{1}{hA} \qquad \text{Eq. (7)}$$

$$\dot{Q}_{convection} = \frac{T_2 - T_1}{R_{convection}} \qquad \text{Eq. (8)}$$

Finally, students use Equations (9) and (10) to evaluate the combined effects of conduction and convection heat transfer on the heat lost from the home.

$$R_{total} = R_{conduction} + R_{convection} \qquad \text{Eq. (9)}$$

$$\dot{Q}_{total} = \frac{T_2 - T_1}{R_{total}} \qquad \text{Eq. (10)}$$

IV. Implementation and Results

Several of the lab activities have been piloted with one high school science class thus far. The high school class was an environmental science class with 14 students. The students performed the pre-lab activity to design their own electric grid, evaluating the pros and cons of each generation technology and the potential benefit of adding energy storage to their electric grid. Students completed the pre-lab activity in groups during normally scheduled class time. Several days later, the high school class visited the campus of Illinois State University to complete the pumped hydroelectric lab activity. In groups of four to five students, the groups of high school students completed the lab activity in approximately 90 minutes. Images of the class completing the activity are shown in Figures 2 and 3. In Figure 2, the students are shown setting up the pumped hydroelectric system. The upper reservoir is suspended from a high-strength suction cup. The upper and lower reservoirs are installed with a penstock (vinyl tube) connecting them. A water turbine generator is connected to the lower end of the vinyl tube from the upper reservoir to the lower reservoir, and a small battery-powered pump is attached to the lower end of the tube connecting the lower reservoir to the upper reservoir. In many real-world pumped hydroelectric systems, the turbine and pump are often the same piece of equipment. In the classroom activity, we found that we could achieve better results by having separate pump and turbine devices. Both the pump and the turbine are connected to a box with meters to measure the voltage and current of the pump and turbine. A toggle switch selects whether the parameters are measured for the pump or the turbine. In Figure 3, the students are shown using the box to take measurements of the voltage and current from the pump during the charge cycle, and from the turbine during the discharge cycle.

Following the lab activity, the students were asked to complete a brief survey about their experiences with the lab activities. The survey included the following questions:

> On a scale of 1 (strongly agree) to 5 (strongly disagree), how would you rate the following statements:
>
> 1. Before this lab activity, I had a good understanding of the meaning of “energy efficiency.”

2. Before this lab activity, I had a good understanding of the meaning of “energy storage.”
3. Compared to before this lab activity, I now have a better understanding of energy efficiency.
4. Compared to before this lab activity, I now have a better understanding of energy storage.
5. Compared to before this lab activity, I now have a better understanding of how energy storage could allow for an increased amount of renewable energy.
6. The lab activity was fun.
7. Compared to before performing the lab activity, I am more interested in learning about careers in related fields (like science and engineering).
8. Do you have any other comments?

a. b. c.

Figure 2. Pumped hydroelectric system and power meter shown with intermediate penstock height (a); lab groups installing pumped hydroelectric systems with short (b) and intermediate (c) penstock height.

a. b. c.

Figure 3. Lab groups taking measurements with the pumped hydroelectric voltage and current meters. The same meters are used for charging and discharging the system.

The students' responses to the survey are shown in Table 2 for Questions #1-7, and in Table 3 for the open-ended Question #8.

Table 2. Survey results for Likert-scale questions #1-7

n=14	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
1. Before this lab activity, I had a good understanding of the meaning of "energy efficiency."	1	9	0	4	0
2. Before this lab activity, I had a good understanding of the meaning of "energy storage."	3	7	2	2	0
3. Compared to before this lab activity, I now have a better understanding of energy efficiency.	3	8	3	0	0
4. Compared to before this lab activity, I now have a better understanding of energy storage.	3	9	2	0	0
5. Compared to before this lab activity, I now have a better understanding of how energy storage could allow for an increased amount of renewable energy.	4	10	0	0	0
6. The lab activity was fun.	8	5	1	0	0
7. Compared to before performing the lab activity, I am more interested in learning about careers in related fields (like science and engineering).	2	5	5	1	1

Table 3. Survey results for open-ended question #8

8. Do you have any other comments?
I really enjoyed this lab :) !
no sir
no can I get a scholarship?
No
thank you for the trip
No, thank you
Towel for leaks, step ladders?
Yeah this was cool and pretty interesting. I liked putting it together instead of being handed it and just getting numbers.
This lab is not for people who are shorter than 6 ft. - need stools

The results in Table 2 show that most of the students felt they had some understanding of energy efficiency and energy storage before completing the activity. For both Question 1 about energy efficiency and Question 2 about energy storage, 10 of 14 students selected "Agree" or "Strongly Agree." However, in Question 3, 11 of 14 students either "Agreed" or "Strongly Agreed" that they now have a better understanding of energy efficiency compared to before the lab activity. In Question 4, 12 of 14 students either "Agreed" or "Strongly Agreed" that they now have a better understanding of energy storage compared to before the activity. More impressively, in Question 5, all 14 students either "Agreed" or "Strongly Agreed" that they now have a better understanding of how energy storage could allow for an increased amount of renewable energy generation on the electric grid. In Question 6, 13 of 14 students "Agreed" or "Strongly Agreed" that the activity was fun. In Question 7, half of the students (7 of 14)

"Agreed" or "Strongly Agreed" that they are now more interested in learning about careers in related fields like science and engineering.

Most of the comments in Question 8 were neutral to positive, but two students provided constructive suggestions to improve the lab. One student noted that the height of the upper reservoir became difficult to manage when the penstock height was at its maximum height of six feet. This student suggested including stools as part of the lab equipment. Another student suggested including step ladders as well as a towel for leaks. The addition of stools or step-ladders would significantly reduce the portability of the classroom kits, so we plan to revise the directions in the lab manual for the third and highest penstock height. We will revise the directions to instruct students to raise the upper reservoir height to six feet "or as high as you can comfortably reach." The exact height is not critical; we simply want students to observe the greater turbine power output and energy storage at higher reservoir heights.

V. Conclusions

The DESSERT project involved the creation of two new sets of classroom lab activity kits relating to renewable energy and focusing on underrepresented groups as the target audience, including diverse populations such as low-income students and members of racial and ethnic groups that are underrepresented in STEM fields. By definition, diverse students come from a diverse range of backgrounds. Some students in these groups may not have had the same educational opportunities and resources that have been afforded to other groups. Without an intervention, the feedback loop will continue: groups of students that receive less exposure to STEM learning activities at the middle and high school levels will have less confidence and knowledge in these areas compared to other students, leading them away from STEM fields of study and STEM careers. Therefore, it is necessary to break the cycle by targeting these underrepresented groups for intervention at a young age. To better tailor the design of the activities to underrepresented groups, the team relied on a literature review of previous work. The framework of Jackson et al.'s "Equity-Oriented Conceptual Framework for K-12 STEM Literacy" [4] was particularly helpful in designing the curriculum, and it recommended focusing on themes of empathy, empowerment, hands-on learning, and including multiple areas of STEM learning.

It is our hope that the outcomes of this project will be an incremental step toward a more educated and equitable workforce, and a workforce that is better prepared to meet the technology- and energy-related challenges of the 21st century. The authors hope that this project will have benefits for numerous participant groups over many years. Through their participation in the project, the undergraduate students have gained experience in sustainable energy-related fields and an increased understanding of the societal and contextual factors that constrain STEM opportunities for students from underrepresented groups. These students are well-prepared to enter career fields in sustainable energy and related STEM fields. Meanwhile, the middle and high school students who have completed or will complete the lab activities will gain an increased understanding of and interest in sustainable energy-related STEM fields, which may lead them to pursue these fields at the post-secondary level, enter energy- and STEM career pathways, and eventually reduce the underrepresentation of some demographic groups that is currently endemic in STEM and energy-related fields.

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