AC 2012-3368: STUDENT-LED DEVELOPMENT OF A FUEL CELL EXPERIMENTATION SYSTEM FOR ALTERNATIVE ENERGY SYSTEMS LEARNING

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Student-led Development of a Fuel Cell Experimentation System for Alternative Energy Systems Learning

Abstract

This paper presents the student-led development and implementation of a new fuel cell experimentation system, part of a new course in energy conversion systems, created with extensive input and feedback from course-enrolled students and student volunteers.

The fuel cell experimentation system consists of the following primary components: photovoltaic cell, electrolyzer, hydrogen gas storage unit, PEM fuel cell Stack, various electrical loads, automated data acquisition system, and data display and analysis software. The equipment was purchased through partial support of an Electrical and Computer Engineering Department Heads Association Mini-Grant.

While the author designed a series of learning opportunities and experiments in fuel cell energy conversion systems, students and volunteers outlined their desired outcomes, completed the initial experiments, and provided significant feedback to improve the lab goals, procedures, and intended outcomes.

This paper describes the steps taken to design, troubleshoot, and develop the fuel cell systems learning opportunities and experiments, summaries of student outcomes and comments on the initial experiments, and the author's observations and recommendations for other instructors attempting student-led laboratory design. The results can help shorten the laboratory development learning curve and alert faculty to common early project errors and omissions to be avoided. More significantly, the results show the value of employing student feedback during the laboratory development phase.

Introduction and Lab Objectives

A new course in energy conversion systems was designed to meet several developing needs: the renewed or expanding government and private interest in support of alternative energy source research and applications, and the technology and society studies requirement in the university General Education program. The course includes extensive multi-discipline learning, with topics ranging from the physics and chemistry of energy conversion to the design and operation of major generation and transmission systems. All topics are presented in the context of environmental issues ranging from energy source availability, environmental pollution and degradation, and energy systems sustainability.

The labs for this course, which now include purchased fuel cell and wind energy experimentation systems, are intended to be introductory with an emphasis on first order design and operating principles. As most students registered in the course have been and are expected to be electrical engineering technology majors, the labs emphasize terminal (voltage, current, power) electrical characteristics and a practical rather than theoretical understanding of the behavior of the energy converter system to changes in its input energy or the load.

Given these course lab requirements, the design goal of the fuel cell experimentation lab was to include understanding and demonstration of the terminal characteristics under varying electrical load, i.e., current-voltage characteristics and voltage regulation, under constant input conditions, i.e., hydrogen generation and delivery to the fuel cell. Intentionally, fuel cell (and, in this lab system, electrolyzer) internal operating conditions, such as temperature, pressure, humidity, contamination, etc., were to be observed but not analyzed.

The fuel cell experimentation system included preliminary instructions to accomplish the current-voltage and voltage regulation tasks. The author used these, with minor changes, as the preliminary guide for the volunteer students. The experience and comments of the students as they followed the manufacturer's instructions provided much of the information incorporated in the student-led lab development.

Having students self-design or co-design experiments and laboratories has been reported in many education settings over many years[1, 2, 3, 4, 5, 6]. The author's approach differs from many of the published narratives in that, in this case, the students were deemed collaborators or "Co-PI's" on instructions sets for colleagues rather than for their own immediate experimentation. The benefits and advantages of this procedure, accruing to the students learning and the author's design philosophy and plans, are discussed below.

Fuel Cell Experimentation System

The fuel cell experimentation system used was manufactured by h-tec, Wasserstoff-Energie-Systems GmbH (see www.h-tec.com) and included the U102 Stack Experimentation Set Complete (Figure 1.). The system includes apparatus sufficient to complete experiments: a photovoltaic module (converting light energy to DC electric energy); an electrolyzer (using the photovoltaic module DC current output, or optional wall-plugged AC/DC power supply output, to separate hydrogen from oxygen in distilled water); a PEM (proton exchange membrane) fuel cell module (using atmospheric oxygen and electrolyzer-supplied hydrogen to create a DC current output); and simple electrical loads (lamp and DC motor). The unit included a data acquisition and display capabilities, including a custom measurement and data collection board and software. A wide range of experiments can be accomplished with this inclusive system including energy conversion efficiencies, load regulation, and other operating characteristics.

The manufacturer's operating manual was comprehensive including some background theory of operation and commentary on practical applications of fuel cells. The students used the manual as a guide to ascend the learning curve of electrolyzer and fuel cell operations and, upon reflection of their experience, improve or modify the manual instructions to cooperate in the design of a lab for their future colleagues.

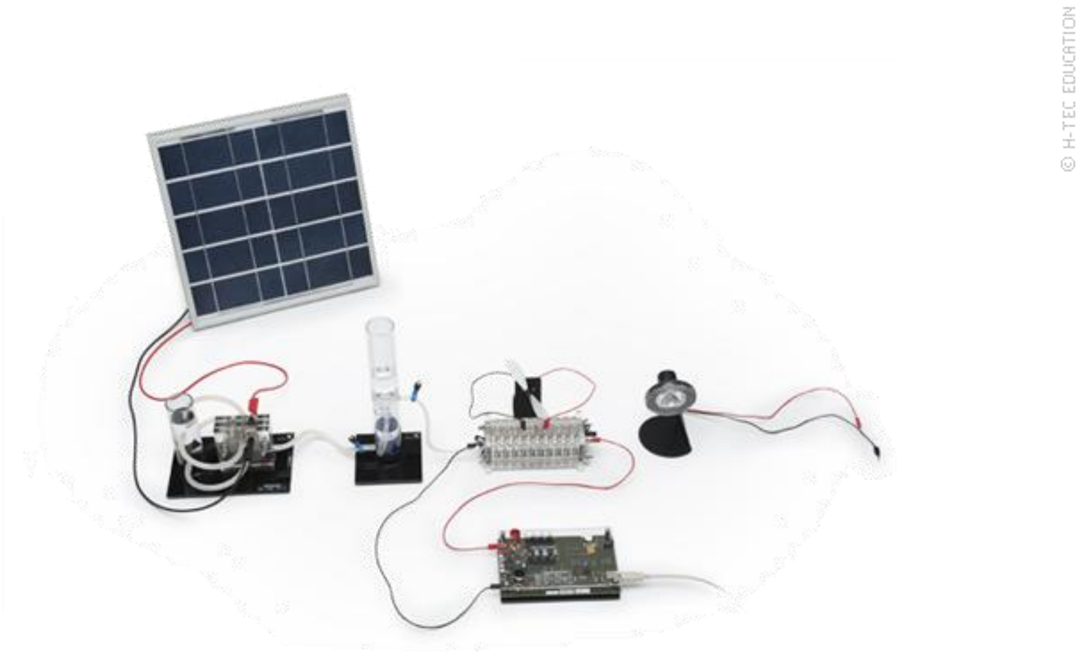

Figure 1. Wasserstoff-Energie-Systems GmbH U102 Stack Experimentation Set Complete

As the student volunteers had only varied and limited technical knowledge of fuel cell operation and performance, the author restricted the lab design experience to include only the monitoring of output characteristics of the fuel cell under constant 'fuel' (hydrogen) input and varying load. Constant fuel was accomplished using constant voltage applied to the electrolyzer to create continuous flow of hydrogen to the fuel cell, and varying load was provided by preprogrammed step changes in resistive load by the factory-provided data acquisition and display system.

Student Tasks

The author wanted the students to enter the lab experience as might any future student, i.e., with some theoretical knowledge and practical application awareness, but no other preparation. Student volunteers were encouraged to research fuel cell operation and applications to become familiar with the equipment and potential experiments. Student volunteers were asked to complete an initial knowledge and awareness survey, a three-hour lab experience, and a follow-up learning and lab design survey. Four students, three from the energy conversion course and one who had taken the course in the previous year, volunteered to help design and troubleshoot the fuel cell experimentation lab.

The three students from the class worked together and presented to the class the result of their experience, emphasizing the lessons learned and knowledge gained working with actual components and systems as compared to reading about them or being exposed to simulations, animations, and videos presented in lecture. The other student worked independently. The author was present for the lab experience to answer questions, provide procedural guidance and technical advice, to ask questions to explore and affirm student understanding and learning, and to record observations and comments to be used in the final lab design.

Initial Knowledge and Awareness Survey

The Appendix includes a copy of the initial knowledge and awareness survey taken by the volunteer students. The purpose of the survey was to assess the student level of understanding and to identify their technical and practical interests.

Highlights of the Initial Survey

Students expressed only basic understanding, more descriptive than technically accurate, of the operation of the photovoltaic cell, the electrolyzer, and fuel cell. They described the fundamental energy conversion phenomena, but expressed little understanding of the basic physics of the energy conversion processes. Their interests, i.e., what they wanted to learn from the lab, were typical of the purposes of electrical engineering labs in general: they were interested in construction, operating efficiencies, and performance comparisons with other energy conversion processes.

The initial survey included a question requesting their scoring the importance of laboratory experience factors significant to their learning outcomes. Table 1 provides a comparative diagram of their opinions. Note the relative importance of the presence of the lab instructor, quality of the instruction set and lab construction, and data gathering/analysis factors.

Additional comments from the students added insight and details of student expectations and definition of the ‘quality’ of the rated significant experience factors. The author took note of the lab experience factors the students highly correlated with their positive learning outcomes to be sure they are included and of high quality in the final lab design.

Student-Assisted Lab Design Procedure

The students entered the laboratory setting having prepared themselves by reading introductory material about fuel cell theory and operating characteristics, from the course textbook and from their own research. No specific instruction was given concerning what they should read or where to retrieve the information outside of lecture material and the textbook. This behavior stipulation mimicked the likely or assumed typical preparation level of the future lab students. The intent was to be sure that the final lab design included technical background, lexicon, other style, and procedural detail appropriate for the future lab student.

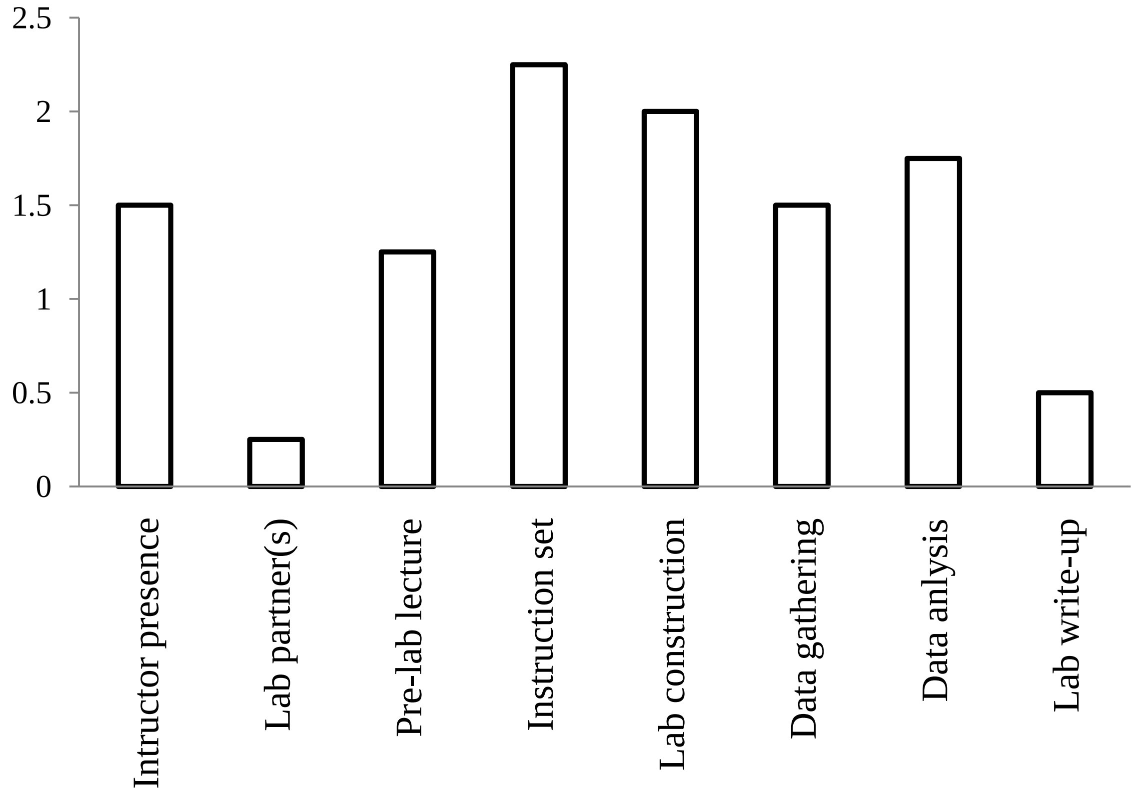

Table 1 Student Reported Relative Significance on Learning Outcomes of Lab Experience Factors (Average responses, 4-point scale)

The students were given the experimentation system with the manufacturer's manual. The author reminded them of the goals and objectives of the session: to identify and record comments and suggestions based on their own learning goals, objectives and outcomes, later to be incorporated in the final design of the course lab for future students,.

The author referred them to the background information in the manual, and guided them through the identification of components using the pictorials in the manual. Special handling instructions were reviewed, e.g., being careful not to allow undue contamination of the insides of gas tubing. The students were shown in the text the two experiments they would perform, and were then 'released' to attempt the experiments and record their observations and recommendations.

The students, one group of three, and one in a separate session, proceeded to follow the manual directions. They paused often to suggest clarifications in the instructions, to point out omissions of details in the procedures, to recommend additional steps, include extra information, and to suggest modifications to manual diagrams.

The author interrupted routinely to be sure the students understood and could explain each procedure result or consequence. If the experimental outcomes deviated from the displays and plots of the manual, I challenged the students to determine the cause of the deviation and to consider how the lab might be designed to be sure such knowledge is encountered and tested.

The following list provides a sample of the student comments and recommendations expressed during and after the lab experience.

- All apparatus connections (gas lines, voltage measurement points, etc.) should be shown clearly and in detail, perhaps using photographs of equipment under test.
- The manual did not provide specific periods of what constituted short- or long-term operation (important to assembly options).
- The power supply should be switchable.
- List of required but not supplied monitoring equipment (pressure, flow, voltage current, power) should be provided.
- The affects of observable changing pressures, temperatures, humidity (wetting) and other performance variables, while not the object of study in this current-voltage characteristics experiment, should be described.

Follow-up Learning and Lab Design Survey

The same survey as the initial knowledge and awareness survey was used in the follow-up survey after the lab experience to assess student learning outcomes and last design comments. Results of the follow-up survey and its use in considering final lab design are discussed below.

Highlights of the Follow-up Survey

We did not use the photovoltaic unit to power the electrolyzer as the lab was an interior room and had no lamps or other light sources capable of generating sufficient voltage and power from the included photovoltaic units. Therefore, the students could not comment on the operation of these units.

Students did report satisfaction in observing the construction and operation of the electrolyzer. they learned that the electrolyzer is in effect the reverse of a fuel cell, similar to the relationship between a photovoltaic unit and a light emitting diode (LED), i.e., they operate in essence in reverse of each other. As the students were electrical majors, they showed little interest in the chemistry of physics of electrolysis; they were pleased to observe and measure/monitor 'terminal' electrical characteristics, and to observe the collection of hydrogen. In addition, as this was not a chemical lab, pressure and volume of hydrogen were not quantified, though these parameters are measurable with the experimentation system and instructions (experiements0 are outlined in the manual for such investigation.

One student remarked he had not considered how little water volume would be consumed, having overlooked the difference in density of the hydrogen as 'fuel' and as raw material bound in a water molecule.

One student remarked he would like to have experimented also with a model of the system. By model, he meant a simulation, as electrical students are quite familiar using simulation software packages to preview system operation and performance. The author believes this would be a helpful supplement to the lab learning experience.

Two students asked that they be invited to participate further in the lab development beyond these initial experiments. Their enthusiasm stemmed from their enhanced learning experience and encouragement to think and ‘color outside the lines’, and their interest in the technologies involved from a career perspective.

Impact on Final Lab Design

Active Learning, Learning-by-Teaching, Discovery-based learning and the Lab Co-design Experience

The pedagogy of active learning has received significant interest for many years[7]. The author obtained further insight into the importance of active learning on the part of the students. The role of lab co-designer motivated students to pay close attention to the quality of the instructions sets and the various lab apparatus in operation.

The author suggests that involvement in lab design, for those students who can or choose to participate, can be an excellent learning experience. The author’s experience, and the experience shared by many colleagues, is that one learns the most when one has to teach a subject. This has been recognized formally and subject to much research under the pedagogy called Learning-by-Teaching (LdL, in the original German)[8]. The advantages to students who teach to learn include:

- Student work is more motivated, efficient, active and intensive due to lowered inhibitions and an increased sense of purpose
- By eliminating the class division of authoritative teacher and passive audience, an emotive solidarity is obtained.
- Students may perform and learn from many routine tasks, otherwise unnecessarily carried out by the instructor
- Students gain important key qualifications such as
    - teamwork
    - planning abilities
    - reliability
    - presentation and moderation skills
    - self-confidence

The author observed many of these benefits accruing to the volunteer students who were focused on the learning of their future colleagues in their role as co-designers of the future lab. The author planned to consider including some LdL procedures could be carried over to the future lab design.

The author was reminded that professionals often forget their own state of mind and preparedness in their first learning experiences. These experiences occurred during the rapid, early rise of skills development, a relatively short time compared to, often, years of professional practice. In addition, learning skills and procedures required in professional practice can be very different from those in the original, primary learning environment of a university lab. Observing and listening to the student volunteers, the author’s memory was refreshed of his own early learning experiences in electrical engineering labs. The author's design of the final lab based on his own insight and hindsight of the learning process was reinforced with the foresight provided by observation of the students' behavior and listening to their comments and recommendations.

Savery and Duffey[9] suggest eight instructional principals to guide the teaching in and design of a learning environment for discovery-based learning, as follows:

1. Anchor all learning activities to a larger task or problem. That is, learning must have a purpose beyond, "It is assigned".
2. Support the learner in developing ownership for the overall problem or task.
3. Design an authentic task.
4. Design the task and the learning environment to reflect the complexity of the environment they should be able to function in at the end of learning.
5. Give the learner ownership of the process used to develop a solution.
6. Design the learning environment to support and challenge the learner's thinking.
7. Encourage testing ideas against alternative views and alternative contexts.
8. Provide opportunity

In having students participate in the lab design, the author observed many of these elements of discovery-based learning in the volunteer students' approach and behavior. While this certainly enhanced their learning (as compared to a traditional passive, step-by-step procedural lab experience introducing fuel cell operation), it also reminded the author to consider seriously the improved outcomes of a discovery-based learning opportunities, and to incorporate such activity in the final lab.

Author's Learning

The author learned from the students important features to include in the final design of the lab that were not considered before this trial in student-led development. The following is a list of sample features to be included in the final lab design that the author would not have considered without the input from the volunteer students.

- Students reported that the presence of the lab instructor, quality of the instruction set and lab construction, and data gathering/analysis were the most significant experiment factors affecting their learning outcomes, and require special attention compared to other factors.
- Students preferred that the instruction set include actual equipment photographs rather than schematic or illustrated connection diagrams.
- The observable effects of variations in pressure, temperature, etc. in the fuel cell should be included in the 'lecture' (introduction part of the lab. While these parameters are not studied nor measured, their impacts need be described and anticipated by the students, especially as they attempt manual load measurements, where under high load conditions, regulation of load conditions varies significantly with time.
- The author will consider seriously the opportunities for enhanced learning by including, where possible, the elements of active learning, learning by teaching, and discovery-based earning that active student design of experiments affords.

The author will observe closely the experience and outcomes of students using the student-designed lab procedures. The hope is that the intuition of the volunteers and their procedure recommendations provide what the majority of their colleagues 'need' from a lab learning experience, and provide learning opportunities the author design alone might not have provided.

Comments to Faculty

The author offers the following comments to faculty who would attempt involving students in lab design.

1. Choose volunteers who bring a range of skills levels, academic and career interests, and learning preferences.
2. Provide students a draft of general goals and objectives for the lab being designed. They will need some vision of the untended outcomes of the lab to frame their thinking and evaluate their original ideas and alternative procedures. Explain that the draft outcomes are preliminary, ideal as it were, and encourage them to consider new or supplemental goals and objectives as they work through the lab.
3. Prepare a draft lab procedures outline, some kind of guide, for the students to orient their own tasks and efforts. Challenge your own thinking so that the proc4dures you provide are not too 'leading', thereby missing an opportunity to observe volunteer thinking and learning dynamics. Explain that the procedures provided are only a guide and that the volunteers are encouraged and expected to modify procedures as they see fit.
4. Emphasize that the 'audience' for their work is not you, the instructor, but their colleagues and future students. Repeat that the overall effort is to provide an optimal learning experience for their fellow students. Repeat that you value only the usefulness and effectiveness to future students of the volunteers' suggestions, and that the volunteers should not feel that they are being evaluated by you on their knowledge, skills, or progress.
5. Your interaction during the lab design process should include only:
    a. teaching and/or correcting technical understanding of the lab subject matter
    b. providing comments on the relative learning effectiveness of volunteer-suggested procedures
    c. assuring that all lab equipment is functioning properly
6. Keep notes of observations and student suggestions during the design sessions. If students will allow, record the sessions on video. Review will capture nuances of communication, learning, interactivity, etc., that can prove helpful in your understanding of the learning dynamics in the particular lab.
7. To evaluate your own intuition and lab design skills, you might design and write a detailed lab on your own. Record comments of your logic or intent for the various procedures. Set this design aside to compare later your design results with the results of the students. Having your *written* design on hand will help you improve your own insight and skill in preparing lab procedures for students in your other labs.

Conclusion

This paper described the steps taken to design, troubleshoot, and develop the fuel cell lab systems learning opportunities and experiments, summaries of student outcomes and comments on the initial experiments, and the author's observations and recommendations for other instructors attempting student-led laboratory design. The results were of significant value to the author in completing the design of fuel cell lab experiments for a course in energy conversion systems.

Including students in lab design can help shorten the laboratory development learning curve, alert faculty to common early project errors and omissions to be avoided, and potentially improve learning outcomes. More significantly, the results show the value of employing student feedback during the laboratory development phase. And most significantly, for the students involved, lab design participation provides an enhanced active learning experience.

Acknowledgements

The author wishes to express his gratitude to the Electrical and Computer Engineering Department Heads Association, his department, and the Virginia Applied Technology and Professional Development Center at Old Dominion University for the grant funds to purchase the fuel cell experiment station used in the development of this paper. The author also expresses his gratitude and appreciation for the time and interest of all of the volunteer students.

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Appendix

Fuel Cell Experimentation System

Lab Development Questionnaire

Fall, 2011

Instructions: Please answer the following questions candidly, as your responses will be used to help optimize the design a Fuel Cell Experimentation System for successful learning outcomes. If you need more room, please continue your answer on the back of any page.

1. Explain briefly what you know about the theory or operation of each of the following:

    a. Photovoltaic cell

    ____

    ____

    ____

    ____

    b. Electrolysis

    ____

    ____

    ____

    ____

    c. Fuel cell

    ____

    ____

    ____

2. List what you would like to learn about each of the following in a laboratory setting.

    a. Photovoltaic cell

    b. Electrolysis

    c. Fuel cell

3. On a scale of 1 to 5, rate to what degree each of the following lab-related experiences, in the ideal, are significant factors in your <u>laboratory learning outcomes</u>. Use the following scale:

    1=Not significant
    2=Somewhat significant
    3=Significant
    4=Very significant
    5=Critically significant

a. _____ Instructor presence

b. _____ Lab partner(s)

c. _____ Pre-lab lecture

d. _____ Instruction set

e. _____ Lab assembly or construction

f. _____ Data gathering

g. _____ Data analysis

h. _____ Lab write-up or report

4. Please provide any additional comments that you think will help in the design of an effective Fuel Cell Experimentation System laboratory learning experience.