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Implementation and Assessment of an Integrated Extended Reality Renewable Energy Laboratory for Enhanced Learning

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Abstract

The present educational research investigated the improvement, implementation, and initial assessment of a previously developed experiential Virtual Reality Renewable Energy Laboratory (VR-REL) and Virtual Reality Learning Environment (VRLE) module. The module enables students to explore fundamental concepts such as water electrolysis fundamentals, fuel cell characterization, solar power generation parameters and effects, and wind turbine parameters and operation. The developed learning framework and virtual reality experiential module targets students of different learning styles. Virtual Reality technology enables faculty to use multisensory teaching tools to enhance student comprehension and motivation to learn. The end-goal of these transformative immersive teaching instruments is to offer students improved means of exploration of fundamental notions of the topics studied, leading to a personalized and optimized learning in a subject matter [1], [2], [3], [4].

The paper is presenting the latest developments of the previously created Virtual Reality Learning Environment and its modules in Renewable Energy Sources laboratory, and the preliminary surveys of the impact and evaluation of the improved VR Learning Environment (VRLE). The main methods to achieve the goals of the investigation are questionnaire surveys conducted in various engineering courses both in our program and at the partner institution. The feedback received in this study is especially valuable concerning the students' opinion on the accessibility of the study material provided, the logical consistency between the topics, and the visual presentation of the knowledge. The questionnaires along with randomly selected interviews ask students to evaluate their overall experience about the Extended reality (XR) experiments, adequacy of virtual laboratory setups, and their suggestions for improvement. The results obtained from this survey are analyzed and summarized. Conclusions have been made about the importance of students' evaluation of the tutorials, and virtual experiments presentations and the perceived role of the platform in their knowledge retention and for the improvement of the quality of education.

Introduction

A critical role of any academic program is to explore pressing questions, identify new challenges, and to structure a framework for finding the answers to both. It is the mission of universities to prepare students to meet the needs of an increasingly complex global society: one of the present challenges is to demand governments, corporations, and other organizations to act in a sustainable manner. It is envisioned that sustainability can be achieved only through informed decisions, or a meta-disciplinary understanding of the issues relevant to a problem. Motivated by energy security requirements and the desire to create a sustainable and secure environment, there is a growing need to transition gradually from fossil fuels to emerging and renewable energy sources. The Energy Information Administration predicts that U.S. energy consumption will increase at a maximum rate of 0.8% annually (depending on the scenario approached), but that U.S. energy production will only increase at an average rate of 0.4% annually, until 2050, with a predicted growth of natural gas of 2.2% and a decline in coal production of 2.1% annually, and a slight decline in production of petroleum and other liquid fuels [5]. The renewable energy industry is the fastest growing sector, with a projected energy production growth of approx. 3.8%. Therefore, it will be imperative to create a workforce who can contribute to overcoming energy challenges [6, 7]. One method of supporting workforce development in future energy solutions is to incorporate new and emerging energy technologies directly into required undergraduate coursework, filling the gaps in existing coursework, and prepare the next generation of students to support renewable energy, energy efficiency and sustainability [8]. Despite the rapidly growing need for both renewable energy technology and trained engineers and technicians, the current undergraduate curricula of most of the engineering and engineering technology programs are not adequately prepared to meet these needs. A significant number of engineering and engineering technology programs still do not offer or offer a limited renewable energy education in their programs [9]. This is mainly due to (1) lack of faculty expertise, (2) lack of necessary laboratory facility, (3) the very tight curriculum occupied by traditional engineering subjects, (4) high cost and space requirements of laboratory equipment, and (5) lack of affordable and available educational materials and suitable textbooks [3, 7, 10, 11].

Teaching a renewable energy course is somewhat challenging since the field is quite broad and requires significant knowledge in multiple areas of electrical, mechanical, chemical, civil, and environmental engineering, and meteorology. These areas include turbine aerodynamics, power electronics, physics, controls theory, electric machines, or electrochemistry. The job of the course provider is often made more difficult because the theoretical analysis of the topics is particularly hard to understand without experimental observations. Thus, an effective renewable energy course should ideally contain hands-on design and laboratory in addition to the study of the theory [10, 12, 13].
However, while hands-on learning is crucial to deep understanding of topics and to knowledge retention, equipping such experiential laboratories is challenging. Development of a laboratory for the implementation of various aspects of the renewable energy sources is costly and requires a large space. Thus, as an alternative, simulations and virtual experiments and learning system are the choice. Computer applications in energy conversion and renewable energy laboratories have been used on an extended scale only in the last decade.
The establishment of the virtual reality renewable energy laboratory has been based on the following goal: creating a motivating environment for the practice of renewable energy and energy conversion systems.

Virtual reality has been extensively explored, more widely over the past decade, as an important educational tool, with or without gamification of instruction's delivery [14]. Recently, an increased number of researchers are investigating the possibility of delivering real-time, virtual experiential learning using virtual or mixed reality (extended reality - XR) for enhancing understanding of studied topics and capturing a more diverse and inclusive student community. However, the issue of affordability is still an obstacle for implementation of immersive learning technologies [3]. Of particular interest is the assessment of the efficacy of such technologies, once implemented. Long term efficacy of learning using such technologies has been explored sporadically and the results are mixed. [1, 2]
Several tools and technologies are available to create virtual reality artifacts, UNREAL and UNITY engines being the most used ones, as they offer free development platforms. The standard algorithm is to generate assets (objects) using a variety of techniques, either by building them using CAD software or generating them using photogrammetry.

During past years, our team investigated the possibility of developing immersive learning artifacts to appeal to students having more diverse learning styles and generated several learning modules [15], [16]. As a result of these investigations, we generated a Virtual Reality Learning Environment (VRLE) and three virtual reality activity centers within this environment. The next step was the research of the possibility of creating a live wire link between numerical simulation of the experiential activity and the VR depicted artifact. Later, we generated a "learning room, which integrates a "VR lecture" and a "Self-assessment" activity. We described the development of our Virtual Reality Learning Environment (VRLE) and the VR Renewable Energy Virtual Lab in our previous published works [15, 16], including the virtual reality technology used.

In this paper we focus on describing the improvements and additions to the virtual laboratory and the preliminary assessment of the activities. In the sections below we are describing the academic context leading to the development of the VRLE.

Renewable Energy Course

EET 320 – Renewable Energy Technology: This is a core-curriculum course, with required laboratory activities and project-based learning, targeting sophomores and pre-juniors. It is offered twice per year at the Drexel University's Engineering Technology program (operating on a quarter system). Approximately 50 students annually take this course. The course's primary objective is to introduce the students to the principles, operation, performances, characteristics, and applications of the major renewable energy sources. Teams of students conduct experiments over the duration of the course, each laboratory activity culminating with a technical report of their findings. Their final summative assessment is based on a cumulative term project. Currently, we have an extremely limited experimental infrastructure for this course, relying on six DeLorenzo stations, relatively outdated, and some lab crafted small solar and wind modules. Therefore, there was a critical need for virtual experiments. Thus, the VR modules were generated based on the DeLorenzo laboratory manuals and activities, improved by the instructors of the course.

Laboratory Structure: *The on-site and virtual laboratory experiments are designed: 1) to reinforce and support the lecture-based courses; 2) to emphasize the importance of corroborating the results of experimentation, measurements, and data analysis; 3) to expose the students to renewable energy technologies, characteristics, performances, and principles of renewable energy systems. To achieve the above purpose, the virtual reality laboratory experiments, upon final implementation, will be divided into two levels: Level I: Virtual Laboratory of Renewable Energy Sources; and Level II; the e-Learning Support Platform (work-in-progress).* The virtual renewable energy laboratory consists of 3 emulators of renewable energy sources. They are developed to facilitate students' acquisition of deep insight into the complex and dynamic interactions of system parameters.

General Description of Virtual Reality Learning Environment (VRLE) and Renewable Energy Laboratory Modules (VR-REL)

The VRLE platform provides students with a high degree of interactivity, students having the possibility to investigate, to an extent, the causal relation between different states of the system under study. Each module is accessible, independent of time and place. ***Moreover, the models of renewable energy sources are posted within the app, with their simulation under different operating conditions.*** It is expected that students will be motivated to study and analyze these systems in more detail, to become skilled in designing and component layout of such systems. Thereby, the interactive applets show real time simulations for several basic topologies with the flexibility to change the input parameters and observe the output response correspondingly [8, 16, 17] The objectives of each lab unit are listed in Table 1, below. Course modules are divided into three parts: *basic principles, system technology, and the laboratory unit manual*. The imparted knowledge is divided into two parts: the first part is the basic knowledge constructed mainly during lecture.

Table 1 The objectives of the virtual laboratory units

Lab Unit	Lab Sub-unit	Objectives
Wind Turbines	Horizontal Axis Wind Turbine (HAWT)	Understand the principles and the operation of wind turbines, explain the parameters affecting the performances, control, and power electronics
	Vertical axis turbines Savonius/Darrieus Rotor System	Understand the principles and operation of vertical axis wind turbines, the differences with HAWT, control, and applications
Solar/PV	Solar-Thermal Systems	Understand operation and principles, system performances, thermal flow, collector efficiency, controls, and monitoring
	Photovoltaics	The performances, characteristics of solar cells, I-V curves of the PV modules, electronics, and controls
Fuel Cells	Water Electrolysis	Understand principles of water electrolysis: how change in potential affects electrolysis and the required energy to generate a predetermined amount of hydrogen.
	Fuel Cells	Principles of operations, power, and Coulomb efficiency, I-V characteristics

The second part is focused on depth of knowledge, additional contents of teaching, and experiential activities to enhance learning. The virtual reality laboratories are designed as complementary to the in-person experiential activities, as learning reinforcement rather than replacement of the in-situ part of the practicum.

The most innovative feature of this project component is the three-dimensional virtual unit of either a part or the complete renewable energy source. The most important geometric features have been developed either using photogrammetry or CAD, to represent the renewable energy system. For example, in the 3-D fuel cells module each component is modeled separately, one accurate copy of each element and then integrated into a main file (as can be seen from the description of the modules in sections below). The textures, colors and illumination for each element are carefully chosen to create life-like textures for all elements in terms of form, bodywork, colors, and position. The system components can be observed from different visual points, which offer the best possibility to become familiar with the system assembly. ***The content of each module is always available to students through the developed app, which is an important aspect of effective teaching***. Moreover, the students will be able to measure and control the function of prescribed units and in this way to determine the system performances.

The virtual module (VRLE platform) is created to mimic the course structure to become a tutor agent for the student. The platform has a teaching part that ends with self-assessment and a virtual laboratory equipped with three activity centers. The self-assessment tests are realized as a set of multiple-choice questions and calculation tasks for evaluating the reached knowledge. After completing the learning and laboratory activities, students may continue to the self-test unit. At this point in our research model, there is no mechanism to prevent students from bypassing or skipping any of the modules in the VRLE platform. The VR platform begins with one specific start page in which all possible control commands are presented as a map of the entire platform Figure 1.) If any problems or questions arise, during the learning sessions, the students or TA may inform the instructor either in-person or via e-mail (for remote learning).

We generated the modules using the videogaming and VR gaming set-up, to make it student friendly. The graphical depiction of each experiential unit was generated using either UNITY or UNREAL engines, and the entire VR-REL is developed in UNITY development platform due to its versatility and accessibility to interactive features [16]. While most of the artifacts were generated using CAD modelling, some were imported assets from either UNITY or UNREAL. Initially, we generated each of the units, fuel cell, solar photovoltaic (PV) panel and wind turbines using basic geometry, focusing on live wire interaction of each experiment using MATLAB, SIMULINK, and C. Also, while we developed more realistic VR systems, we used realistic animations from both VR engine platforms to generate real-like motion of fluids and objects. To make the laboratory activities interactive we used numerical modelling [18] and tailored them to the intended laboratory exercises. We validated the generated numerical modelling by trial-and-error process using the results from in-situ physical experiment and those from VR one side-by-side. The connection between the numerical simulation of the experimental data and the VR module was realized using TCP/IP (Transmission Control Protocol/Internet Protocol)[15].

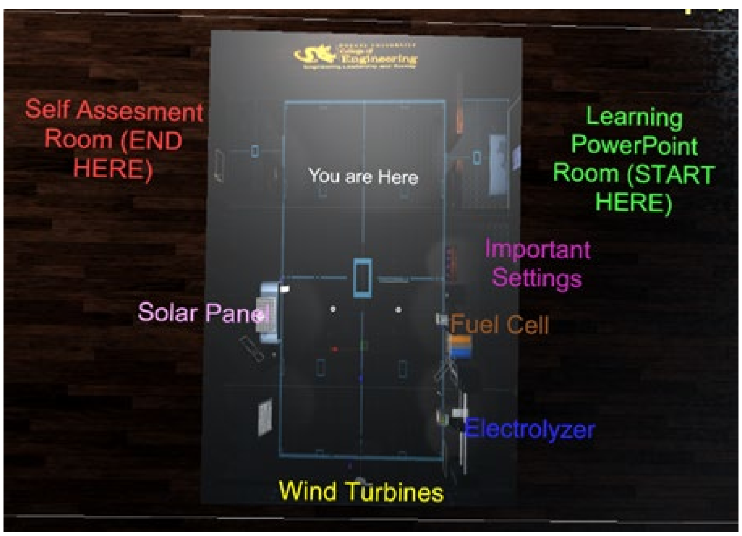


Figure 1 Map of the Virtual Reality Learning Environment

In addition to laboratory manuals, and the VR-REL app, we developed a detailed student-user manual. This manual will take them through every level of use of the virtual learning platform and hands-on virtual activity center. As can be seen from the map of the platform, each module is color coded for easiness of use (for example: Instructional room is green, Fuel Cell sub-module is orange, Wind Turbines module is yellow and Solar PV module is pink). As students/users enter the platform, they get to choose between the desktop 3D mode or the VR headset mode.

Students initially will be prompted by the app to decide what to activate, through detailed instructions that are described in the student user manual for the module. Statements such as: "When you first launch the VR-REL system on your computer, head over to the button panel designated by the purple box above it, corresponding to this is the directory you are facing when you first spawn the player-model" (see Figure 2).

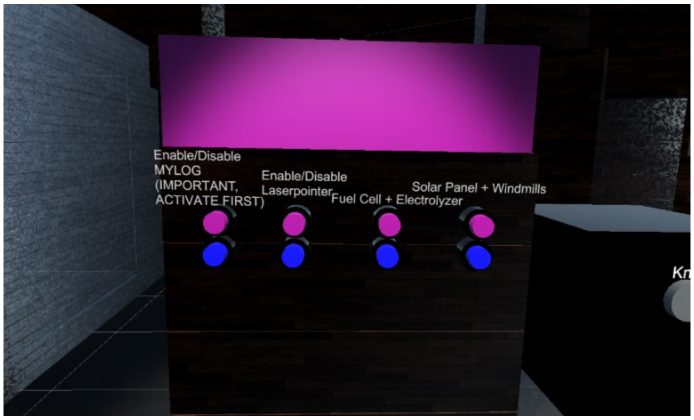


Figure 2 Selector for VR mode

The next step for the student is to select the “Instructional room" and choose the learning module that they wish to review. Every time they open the app, students are prompted to choose between desktop app and VR mode for their convenience and personalization to their learning style. As can be seen in below, in the Figure 3 and Figure 4 below, the modules are fully interactive.

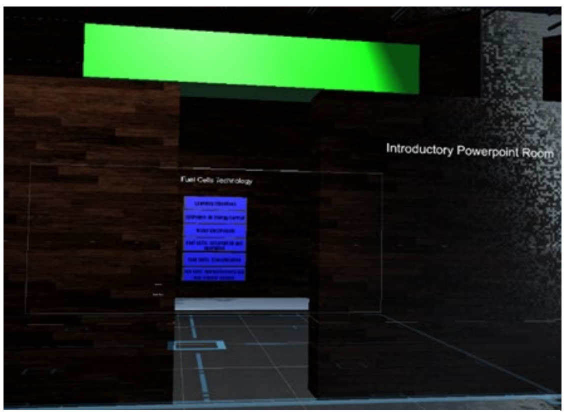


Figure 3 Instructional room (Introduction)

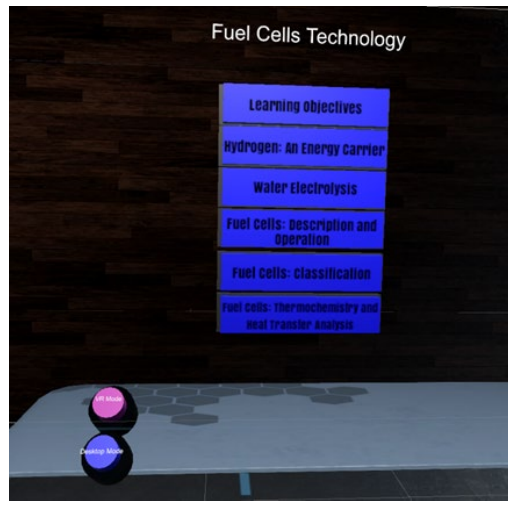


Figure 4 Instructional room with mode selector

Virtual Reality Experimental Units

Fuel Cell System

In the figures below (Figure 5 and Figure 6) we depict the fuel cell unit with the two subunits, the water electrolyzer and the hydrogen fuel cell, the solar – PV unit and the wind turbines.

The development of the water electrolysis and fuel cell subunits have been described in detail in our previous works [16]. To generate the real-time data that will drive the simulation of to be fed to the VR module for a similar learning experience as in a physical lab, we are using algorithms generated by MATLAB/SIMULINK, using Coleen Spiegel modelling [18]. Students can easily change block parameters to understand how different circumstances (e.g., temperature, pressure, nominal operating voltage/current) will change the efficiency and power of a fuel cell or a stack of fuel cells. Then the newest developments are more honing of the sub-modules, adding a game-friendly environment, more data stability and improved functionality in the back end. We also added features such as live plotting of the power curve and live data on-screen collection while the laboratory is performed (see Figure 5 and Figure 6 below). Resistance and potential may be varied according to laboratory manual requirements, and plots and tables are automatically filled with collected data as the lab progresses. Also, there is a built-in feature in the numerical simulation, where students receive the data measurement file for their future analysis and data reduction. The on-screen feature is helpful for live analysis of the system behavior, which in turn is an effective learning tool for knowledge retention.

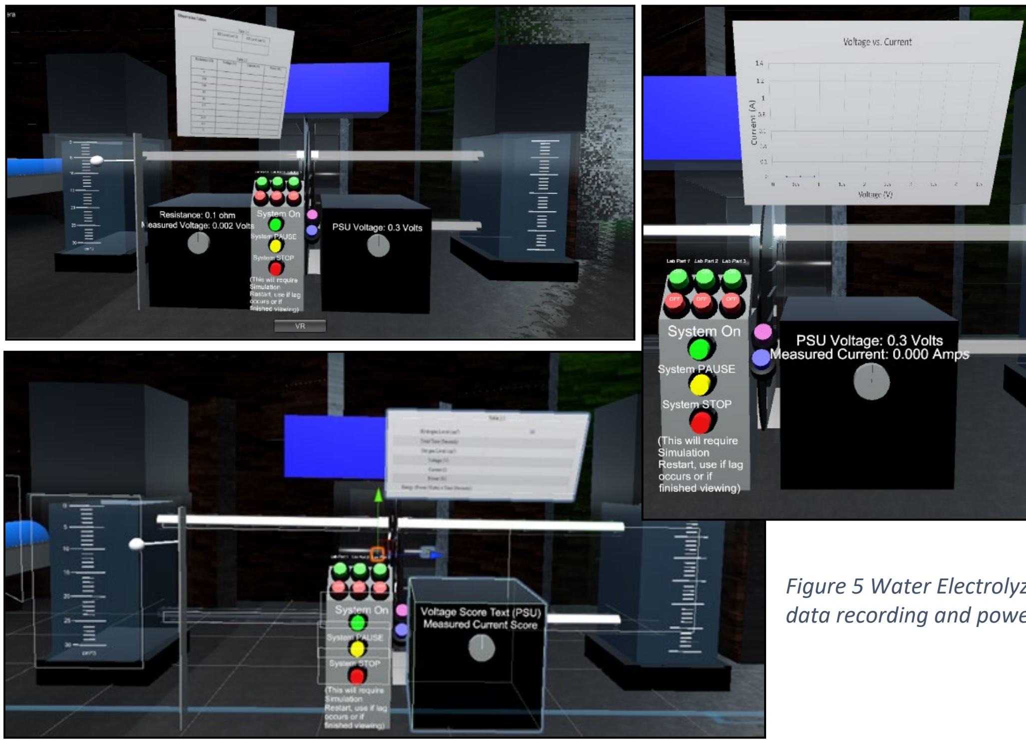


Figure 5 Water Electrolyzer with data recording and power curve

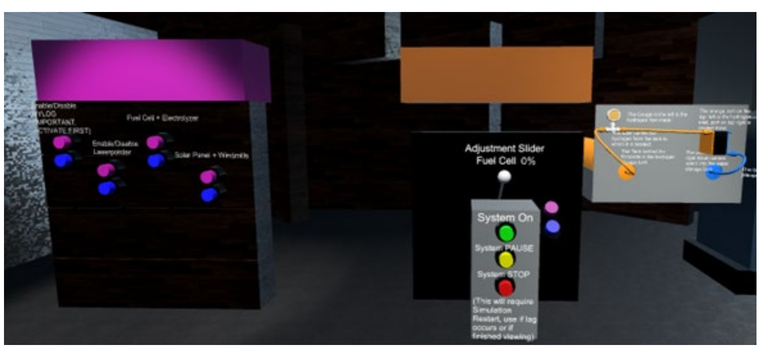


Figure 6: Fuel Cell Unit

Solar / Photovoltaic Energy Source Unit

The PV/solar cell system in our VR-REL is enabling students to study the effect of varying different parameters such input resistances (from low decimal values (e.g., 0.1 ohm to 1k ohm), or the panel angle. In Figure 7, it shows the instruments available for students to make the needed adjustments and the output data display. Students will be able to adjust the panel angle, the light angle and the system will accurately calculate the kWh/day based on input data. This set-up mimics very well the physical experiment, producing the same values as the one in the physical renewable energy lab. The numerical simulation of this unit is built in C# code in UNITY engine.

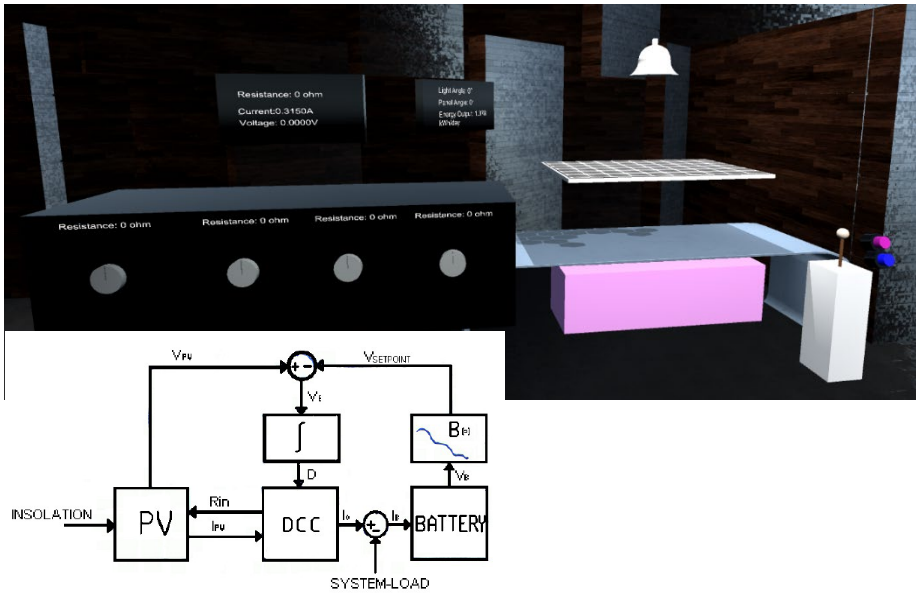


Figure 7 VR Photovoltaic Unit

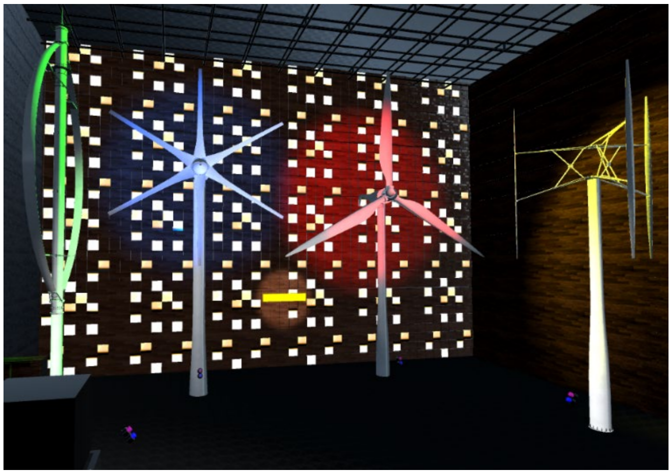
PV Emulator: The model of the photovoltaic (PV) array uses basic circuit equations of the solar cells including the effects of solar irradiation and temperature changes. PV arrays are built up with combined series-parallel combinations of the solar cells, scaling up the output of a limited number of PV actual solar cells. The PV emulator is tested and operated using a directly coupled DC load as well as AC load via an inverter. The experiment involves: *I-V characteristics of PV, open-circuit voltage, short-circuit current, power output vs. solar irradiation, and meteorological parameters, and tracking system performances*.

Wind Turbines Module

The wind turbines functionality is still a work in progress. Currently in the VR simulation, these are just animations that play on a loop until you turn said animation off (via button press in VR). For the future of these modules, the controls and emulators will include as follows:

Savonius Rotor Emulator: The wind turbine simulation system is designed to include ***wind speed simulation, turbine model, rotor blade characteristics, modeling of tower effect and emulation of rotor inertia.*** Wind speed is programmed based regression model, or actual wind speed data. The algorithms would be implemented by a low-cost, digital signal controller and will be tested using a 1 kW DC generator, typically used for vertical axis wind turbines. The experiment involves: **the *output torque and power, drag coefficient and efficiency estimates.***

The Emulator of Horizontal Axis Wind Turbine (e-HAWT): We are designing the horizontal axis wind turbine emulator (e-HAWT) considering a variety of requirements based on the basic parameters of study. The HAWT is based on a DSP system and a DC motor. e-HAWT may accurately reproduce the characteristics and performances of the actual wind turbine and simulated data will be compared with experimentally collected data. The experiment involves: the output torque and power, lift coefficient and efficiency estimates, optimum operation under varying wind conditions, generator power output.



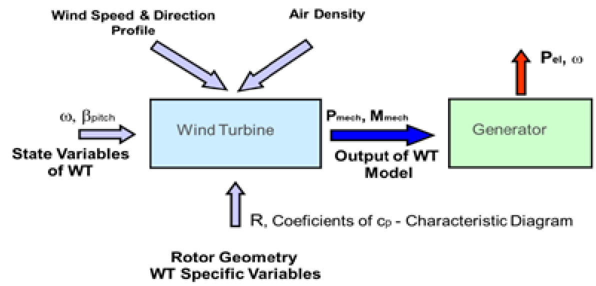


Figure 8: (a) Virtual Reality Wind Turbine Module *(b)Proposed data flow diagram for wind turbine simulations.*

Assessment of the VRLE platform

The preliminary assessment of the module was performed by our partner institution at University of Texas at El-Paso, on a sample of 31 graduate students with a diverse background and majors, from industrial engineering, mechanical and manufacturing engineering, and systems engineering according to Figure 9 below. However, only 15 students completed the entire trial and the survey, therefore all our results are presented based only on the limited number of surveys. It is to be noted that out of 15 students, the vast majority (89%) affirmed that they were novice in using VR technologies, having little to no experience with VR systems.

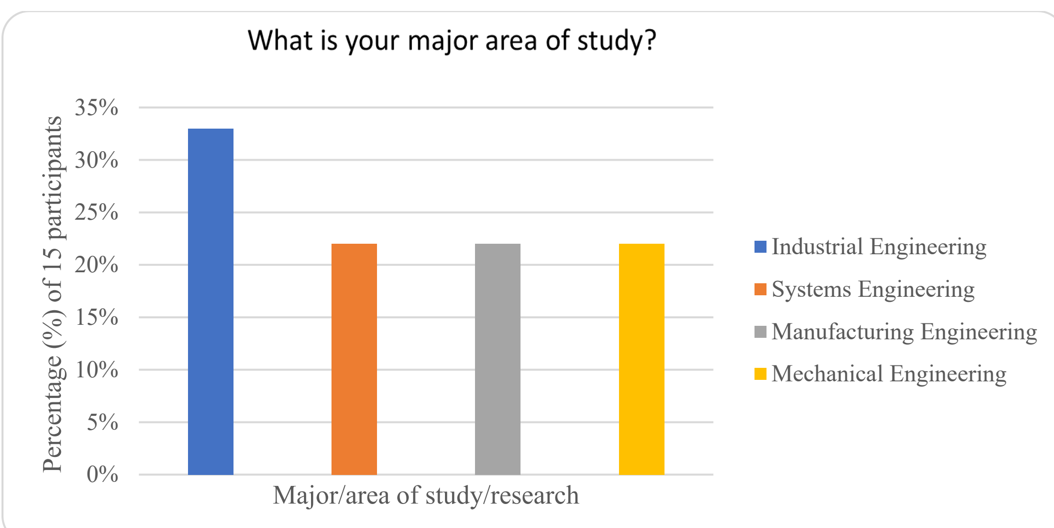


Figure 9 Distribution of the areas of study for respondents (in percentages)

Students were able to experiment with the VRLE platform on a VR headset and on the desktop app. They had available the laboratory manuals to perform the task for which the platform was evaluated.

The questionnaire administered to students explored the evaluation of several qualitative aspects of the platform and its modules. We assessed several factors: (1) easiness of operation, (2) interactivity level, (3) functionality of each module and its associated functions, (4) if it stimulates learning interest, (5) the extent of fulfilment of the learning objectives, (6) its suitability to promote learning in a remote environment, (7) overall rating of the platform. The scoring was based on a LIKERT scale from 1 to 5 where 1 was the lowest score (or strongly disagree) and 5 was the highest score (or strongly agree). Students spent playing with each module different time intervals, ranging from 7 to 35 minutes per module with an average of 10 min. Most of the time was spent on the fuel cell and electrolyzer module, followed by the PV/Solar module.

Based on the answers received to the questionnaire, we concluded that the VRLE is perceived as highly interactive as 78% of the respondents strongly agreed with the statement that VR Lab was highly interactive, while 22% agreed. Regarding functionality, most of the respondents were satisfied with the VR lab functionality, although improvements are needed. Easiness of operation was appreciated by 66% of the respondents (scoring 4 or above out of 5). The Learning aspects of the VR modules were assessed, and the results are presented below in Figure 10.

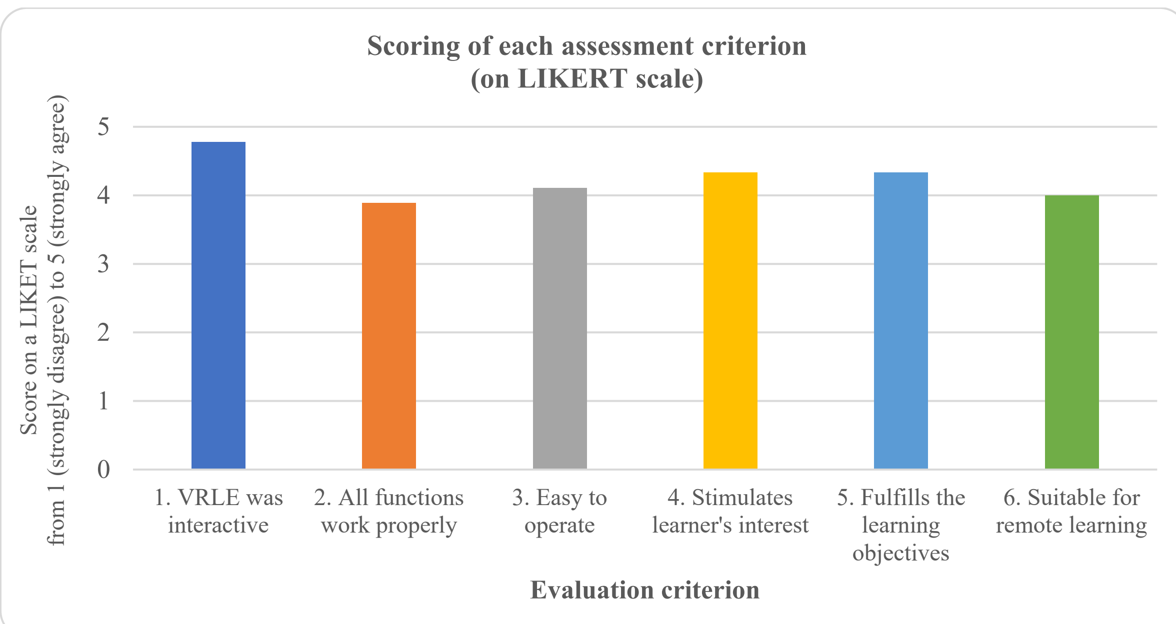


Figure 10 VRLE and its modules assessment - Scoring of the performance indicators on a LIKERT scale (1 to 5)

All respondents (100%) were satisfied with the VR Lab (4.57/5 satisfaction rating), 67% of them giving a maximum score of 5. Regarding the merit of the VRLE, 78% of the respondents scored the lab with a 5 out of 5 and 22% scored them with a 4/5, leading to an overall rating of 4.78 out of 5.

To the question: "How likely you want to learn using such kind of virtual laboratory?" the respondents scored an average rating of 4.44/5, with 56% giving a score of 5 and 33% a score of 4 out of 5 on a Likert scale.

Another important part of the overall qualitative and quantitative preliminary evaluation of the developed learning platform was the open-ended comments part of the questionnaire. Students reflected on a second set of questions, such as:

"1. Which part of the VRLE you liked most?

2. Which part of the VRLE lab seems uncomfortable to you?

3. According to your opinion, how this VRLE can be improved and more effective in remote learning? Please provide your insights."

Students commended the interactivity of the systems and their applicability in a remote environment. Also, data visualization in real time was highlighted as an important aspect of virtual laboratories. Real time animation of each activity center was another positive aspect emphasized by students:

"You can learn from home like it is really applicable now that the COVID19 happened."

"I liked how interactive the VR-REL is in every aspect".

"I like that part where graphs are interactive, and they change according [to how] you change the inputs with the bottoms included."

When asked about the disadvantages of the VRLE evaluated, students complained about "dizziness" due to the moving scenes either in VR mode (headset) or desktop app. Other aspects raised by students were related to the dark mode employed in the VRLE and some of the texture/lighting used. Most complaints were related to the number of computational resources needed to run the app.

Students provided us with a wealth of recommendations for platform and modules improvements. They would like to have recordings (video and audio) of the lectures within the platform. A more scaffolded approach of both learning and virtual experimental activities was recommended as well. On the technical aspects of the platform, students were interested in having an app with better mobility and compatibility, adding better resolution of each artifact, and generating more realistic models. Adjustments to the functionality of each radio button, slide and other interactive features of each sub-system were emphasized. All students recommended (wished) to have more time dedicated to exploring the VRLE platform and to have it available for them as learning enhancing tool.

Conclusion

The goal of this investigation was to develop a packaged cyber learning module using immersive Virtual Reality Learning Environment: a digital twin in virtual reality of a series of three physical laboratory activities based on simulation of renewable energy sources.

We developed a learning platform and a learning module that will enable students to experience hands-on learning even if they may not be in a physical laboratory. Our platform has proven to be useful for enhancing remote teaching. The VRLE developed will help students visualize and conceptualize various abstract topics, such as energy and mass conservation principles as renewable energy systems to engineering design.

These modules, once validated, may be shared among departments and colleges that are located in different regions. This is a way for colleges and universities to use more efficiently their lab resources, allowing students from disadvantaged minorities to benefit of state-of-the-art experiential education, on one hand and for the universities to acquire more units and expand their class seats, becoming more economically sound, while sharing resources.

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