The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #43762

Virtual Reality Wind Turbine for Learning Green Energy Manufacturing

Dr. Richard Chiou, Drexel University
Isher Singh
Arjuna Karthikeyan Senthilvel Kavitha, Drexel University
Prof. Tzu-liang Bill Tseng, University of Texas at El Paso

Dr. Bill Tseng is a Professor and Chair of Department of Industrial, Manufacturing and Systems Engineering at the UTEP. He is also a Director of Research Institute for Manufacturing & Engineering Systems, the host institute of Texas Manufacturing Assistan

Dr. Md Fashiar Rahman, University of Texas at El Paso

Dr. Md Fashiar Rahman is an Assistant Professor of the Industrial, Manufacturing and Systems Engineering (IMSE) Department at The University of Texas at El Paso. He holds a Ph.D. degree in Computational Science Program. He has years of research experience in different projects in the field of image data mining, machine learning, deep learning, and computer simulation for industrial and healthcare applications. In addition, Dr. Rahman has taught various engineering courses in industrial and manufacturing engineering. His research area covers advanced quality technology, AI application in smart manufacturing, health care applications, computational intelligence/data analytics, and decision support systems.

Nijanthan Vasudevan, Drexel University

Virtual Reality Simulation of Wind Turbine

Abstract

This research study presents an innovative virtual reality (VR) laboratory module aimed at enhancing green manufacturing education, particularly focusing on the intricacies of wind turbine efficiency. This VR-based educational tool provides a hands-on learning experience that simulates the operation of a wind turbine, allowing students to explore the dynamics of wind energy conversion. Using VR controllers and headsets, participants can interact with a virtual environment that includes a vertical wind turbine and a fan blower, complete with start/stop buttons and controls for adjusting wind speed.

The virtual lab is built on the Unity 3D platform, incorporating meticulously designed 3D models of the wind turbine and fan blower created using AutoCAD and Blender. This immersive setup is further enhanced by the realistic visualization of wind effects on the turbine, achieved through a "smokey wind" effect. The integration of C# language scripts enables users to dynamically adjust the wind blower's speed, thus affecting the turbine's velocity and power output, and to observe the effects of these adjustments in real-time.

Through experimentation within this virtual environment, learners can witness the relationship between wind speed and power efficiency, which typically follows an upward curve to the Maximum Power Point (MPP) before declining due to mechanical and electrical losses. This decline beyond the MPP is indicative of real-world wind turbine behavior, where turbines are often deactivated to prevent damage. This VR module not only facilitates an understanding of wind turbine performance but also allows students to grasp the broader implications for sustainable energy systems.

The VR wind turbine laboratory stands as a dynamic educational platform that bridges theoretical knowledge with practical application. It underscores the role of innovative technology in fostering a deeper understanding of green manufacturing processes, highlighting the importance of efficiency and sustainability in energy systems. This immersive learning experience thus equips students with valuable insights into the complex factors influencing wind turbine efficiency, promoting a more informed approach to the design and operation of sustainable energy solutions.

Keywords: Virtual Reality (VR), Green Manufacturing Education, Wind Turbine Efficiency, Sustainable Energy Systems, Unity 3D Platform, AutoCAD and Blender, Wind Speed Control, Maximum Power Point (MPP), Innovative Educational Tools

1. Introduction

This paper outlines a green STEM (science, technology, engineering, mathematics) initiative centered around a renewable energy project where students are engaged in designing and constructing a wind turbine within a virtual reality (VR) environment and using Simulating software. The noticeable shift in educational settings, particularly the impact on hands-on lab experiences, prompted the exploration of VR technology to recreate and enhance the lab environment. Through immersive simulations, students can delve into the mechanics of wind turbines, ensuring continuity in experiential learning within engineering disciplines. The Virtual Wind Turbine Laboratory comprises modules aimed at elucidating key factors influencing the power efficiency of wind turbines. Variables such as wind speed, coefficient of power, resistance, voltage, and current collectively contribute to the rotational mechanical power, a critical factor in determining the wind turbine's maximum power point. The objective is to establish an online platform that not only replicates but also improves upon the traditional in-person laboratory experience, enabling students to conduct experiments, collect data, and collaborate on lab reports within a virtual setting. Testing emerging technologies in the physical world is costly and inefficient, with a high probability of errors. Virtual reality (VR) addresses this challenge by providing a simulated experience of the real or imaginary world for educational, technical, or training purposes. VR simulations can be coded based on the experiment or project objectives. Current VR technology utilizes headsets and software platforms for coding and testing simulations, with additional input devices like optical tracking sensors, motion controllers, 3D mice, and wired gloves. These devices allow users to navigate, create, stabilize, or build simulations in the virtual world. While VR is commonly associated with entertainment applications like video games or 3D movies, it also finds use in psychology, medicine, and as a workspace for testing and developing new technologies [1-4].

Incorporating wind energy technology learning into the education system can benefit from VR as a practical tool for understanding the design and development of wind energy technology. The paper presents the project's framework, reports, and student survey findings, along with conclusions and expectations for future success. The project report delves into the team structure, component selection, system design, and simulation results. The student survey indicates that the project enhances students' understanding of renewable energy prospects, providing them with the opportunity to play a significant role in the future development of wind energy technology using VR [5-8].

2. Scope of the Project:

The primary objective of this project is to provide students with a comprehensive understanding of the factors influencing the energy production of wind turbines. Through the implementation of these factors within the Virtual Reality (VR) Wind Turbine Lab, students will engage in hands-on experimentation to grasp the intricacies of wind turbine efficiency. The project aims to create an immersive learning experience that closely mirrors real-world scenarios, allowing students to measure, analyze, and comprehend the impact of various elements on a wind turbine's performance.

EET 320 Renewable Energy Systems is an undergraduate engineering technology course on clean energy and energy efficiency taken by junior level students in the Engineering Technology

Department at Drexel University. It is a 3-credit laboratory course held each fall quarter. The students learn the basis of energy engineering, science and technology involves the relationship between the clean energy and the energy efficiency in manufacturing. It is necessary that the students learn and succeed in a multi-disciplinary environmentally conscious manufacturing that necessitates a sustainable system approach. Additionally, many colleges and universities are not providing all of their graduates with the critical thinking, problem-solving, and sustainable practices required to meet the needs of employers. In order for companies to compete in the global marketplace, employers in the 21st century will require that their engineers couple traditional engineering design skills with newer, modern skills in sustainability, and eco-design as well as the ability to function in multi-disciplinary teams

The first key factor explored in the VR Wind Turbine Lab is the influence of wind speed on the turbine. Students will actively measure wind speed while exposing wind turbine blades to a simulated fan. This data becomes pivotal for understanding the direct correlation between wind speed and turbine performance.

The second factor involves the wind turbine's rotor speed, where students have access to the bladed rotor. As wind interacts with the turbine blades, it induces rotation, resulting in a measurable rotor speed (in revolutions per minute). This data is essential for students to analyze and incorporate into their lab reports, providing insights into the output energy of the wind turbine.

The third factor, rotor torque, reveals the force exerted on the wind turbine's rotor blades. Understanding this force is crucial in calculating the wind turbine's rotational mechanical power, adding depth to the students' comprehension of the turbine's operational dynamics.

The fourth and final factor, Power Coefficient, measures the amount of wind energy retrieved by the rotor blades. Students gain insights into the disparity between theoretical power, calculated using formulas, and actual power produced by wind turbines. This factor, typically falling between 0.4 and 0.5, contributes to determining the Maximum Power Point (MPP) of the wind turbine.

Beyond the exploration of these factors, an additional project goal is to replicate the real lab environment as closely as possible in the virtual realm. This design approach aims to facilitate a seamless transition for students, ensuring that the virtual lab not only educates but also provides an authentic and intuitive learning experience.

The overall goal of this project is to develop an interactive VR framework where students can learn, apply, assess and create their own VR setups to understand working of wind power in different settings [2].

3. Building and Designing the VR Lab in Unity 3D

As shown in Figure 1, the development of the VR Wind Turbine Lab is executed on the Unity 3D platform, where the Scene, Hierarchy, Project, and Inspector tabs play pivotal roles in shaping the virtual environment.

Scene Tab Canvas for constructing game objects and visuals, facilitating real-time analysis with the Game tab.
Hierarchy Tab Organizes 2D and 3D objects, streamlining access and manipulation for efficient management.
Project Tab Core of Unity 3D, housing assets, scripts, and elements essential for building and designing the virtual lab.
Inspector Tab Provides detailed information about game objects, indispensable for fine-tuning characteristics within the virtual environment.
Project Objective Create an educational VR Wind Turbine Lab with a user-friendly interface for exploring scientific concepts.
Steam VR Plugin Kit Offers compatibility with diverse headsets and controllers, streamlined Unity integration, and a comprehensive feature set for immersive VR experiences. Accessible on the Unity Asset Store. Simplifies development with broad headset and controller support, ensuring a unified API.
Unity Integration: Valve's dedicated plugin streamlines workflow, enabling focus on immersive experiences.
Features: Enhances user experiences with Unity UI interaction, teleportation, and more.
Accessibility: Readily available on Unity Asset Store, saves time in project integration.

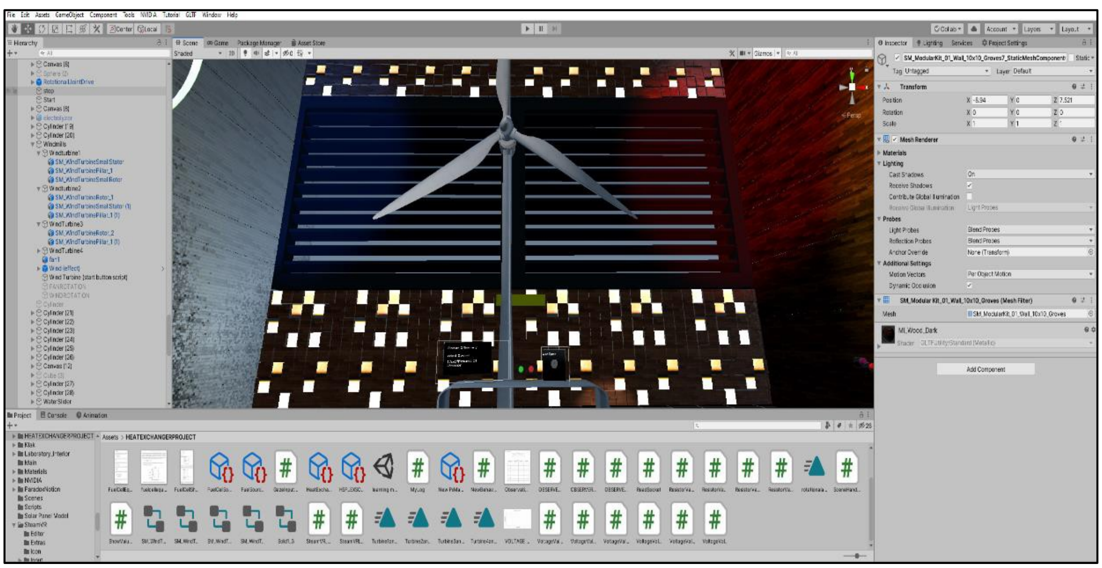


Figure 1. Unity VR experience showcasing wind turbine simulation.

4. Designing 3D Model with Blender, SolidWorks, and Unity 3D

The creation of 3D models for the wind turbine components involves strategic utilization of Blender and SolidWorks software. Blender's “. blend" file format seamlessly integrates into Unity's assets for designing the fan. SolidWorks-generated components are reimagined in Blender for compatibility with Unity as shown in Figure 2. The wind turbine model is sourced from the Unity 3D Asset Store, providing a pre-built foundation [3].

Within Unity 3D, the design process continues with the creation of essential elements, leveraging mesh colliders and scripting for user interaction as shown in Figures 3, 4, 5, and 6. The addition of reflections enhances visual appeal, contributing to a more immersive and realistic user experience. The design process seamlessly integrates Blender, SolidWorks, and Unity 3D, ensuring a cohesive and visually impactful representation of the wind turbine components for an interactive and immersive virtual laboratory environment [4].

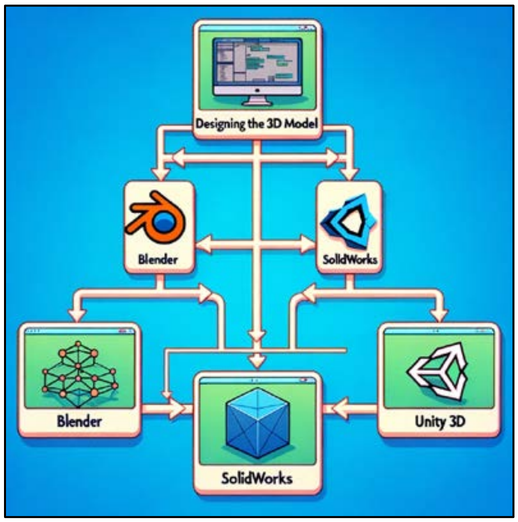


Figure 2. Visual representation of the collaborative workflow between SolidWorks, Blender, and Unity 3D, streamlining the creation of 3D assets for interactive projects.

Designed in SolidWorks to blender to Unity

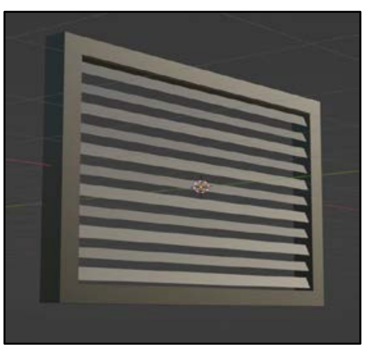


Figure 3. Grid designed in Blender

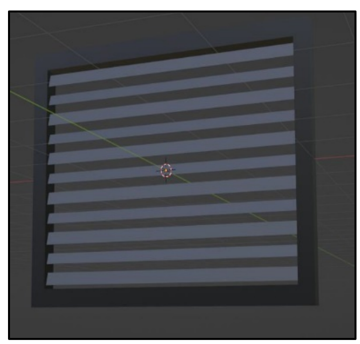
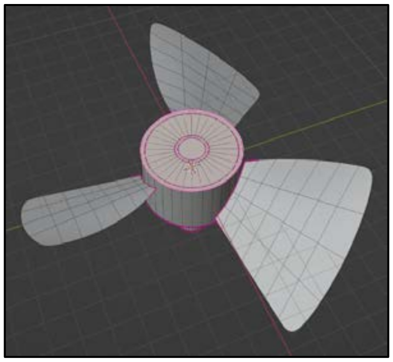
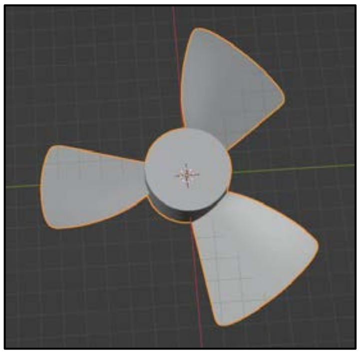


Figure 4. Grid designed Unity.





Figures 5 and 6. Modelling and Layout view of fan designed in Blender.

Basic Interactable Property

Figure 7 shows the VR Wind Turbine Lab incorporating a fundamental feature — Interactable Property. This feature, applied to most module objects, enables users to touch, hold, rotate, and interact with various items. Leveraging the capabilities of the SteamVR plugin, this feature enhances user engagement and adds versatility to the virtual environment.

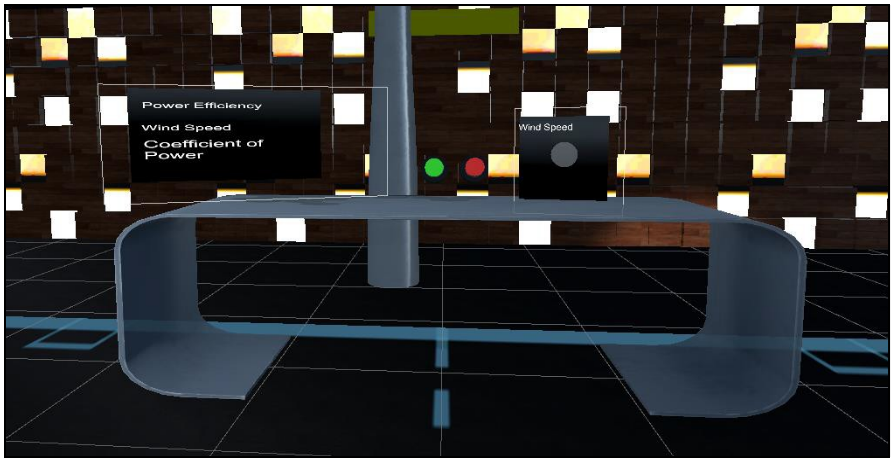


Figure 7. Basic Interactable for control rotor speed, blade pitch, and observe power generation.

Basic Wind Flow: Connection between Fan and Wind Turbine

The virtual reality wind turbine lab provides a realistic experience akin to physical presence. The fan, creating turbulence, simulates wind at different speeds. A C# programming script, developed in Visual Studio, enables fan rotation, mimicking the interaction between the fan and the wind turbine.

Wind Feature

Unity 3D tools illustrate wind speed through the WIND ZONE function and PARTICLE FLOW feature. The particle flow feature emits particles at specific speeds and directions, simulating wind movement. The hover button controls the enabling and disabling of the particle flow feature, ensuring a realistic representation of wind in the wind turbine lab.

Rotation of Fan at Different Speed with Knob

The wind turbine virtual laboratory maximizes power efficiency by varying wind speeds. The interactive Knob, featuring programmed wind speeds at different rotational angles, allows users to adjust the fan's rotation. The knob communicates with the turbine controller script, displaying results in a cube for a tangible representation of the wind turbine's performance.

Start and Stop Button

The start and stop buttons incorporate a box collider feature, enabling the button to initiate specific effects. This programmed functionality, triggered by the hover button, allows users to start or stop the wind turbine experiment seamlessly. Figure 8 show the C# code for the basic Interactable.

```
public class R1 : MonoBehaviour
{
    public GameObject TurbineRotation;
    public GameObject FanRotation;
    // Start is called before the first frame update
    public GameObject knob;
    private float speed = 1.0f;


    void Start()
    {

    }

    // Update is called once per frame
    void Update()
    {
        float knobValue = knob.transform.rotation.y;
        speed = knobValue * 100f;
        TurbineRotation.transform.Rotate(0, 0, speed * Time.deltaTime);
        FanRotation.transform.Rotate(0, 0, speed * Time.deltaTime);

    }


}
```

Figure 8. C# Basic Speed Controller script.

Circuit Diagram

The presented schematic depicts the circuit diagram and power flow of a wind turbine, illustrating the intricate process involved in converting wind energy into electrical power as shown in Figure 9. The sequence begins with the rotation of turbine blades, responding to the passing wind. The rotational movement is transmitted through a gearbox, causing the rotor to rotate. The generator, connected to the rotor and equipped with a pitch drive and brake, adjusts its speed accordingly. The brake serves as a safety measure to slow down or stop the generator in emergencies. The asynchronous generator plays a crucial role in converting mechanical energy into electrical power, forming a vital link in the power generation process as shown in Figure 10.

The efficiency of the wind turbine is intricately linked to the effectiveness of the blade's rotation. Mechanical efficiency covers the rotor, bearings, and mechanical generator, while electrical efficiency relates to the electrical generator post-brake and pitch drive operations.

$$P_{OUT} = \eta_t \times \eta_m \times \eta_e \times P_{IN} \quad \text{and}$$

$$C_p = \eta_t \times \eta_m \times \eta_e$$

$where: (\eta_t) is the Turbine Efficiency, (\eta_m) is the Mechanical Efficiency,$
$and (\eta_e) is the Electrical Efficiency.$

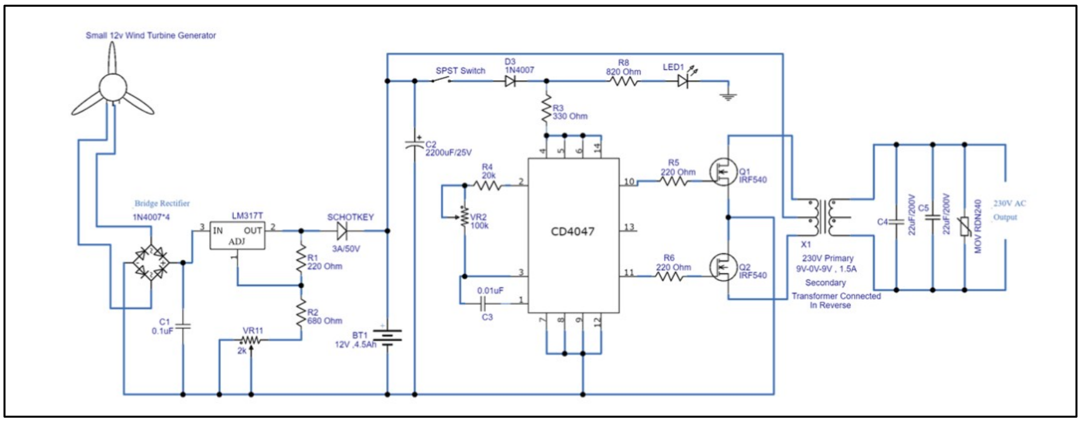


Figure 9. Circuit Diagram of Wind Turbine [7]

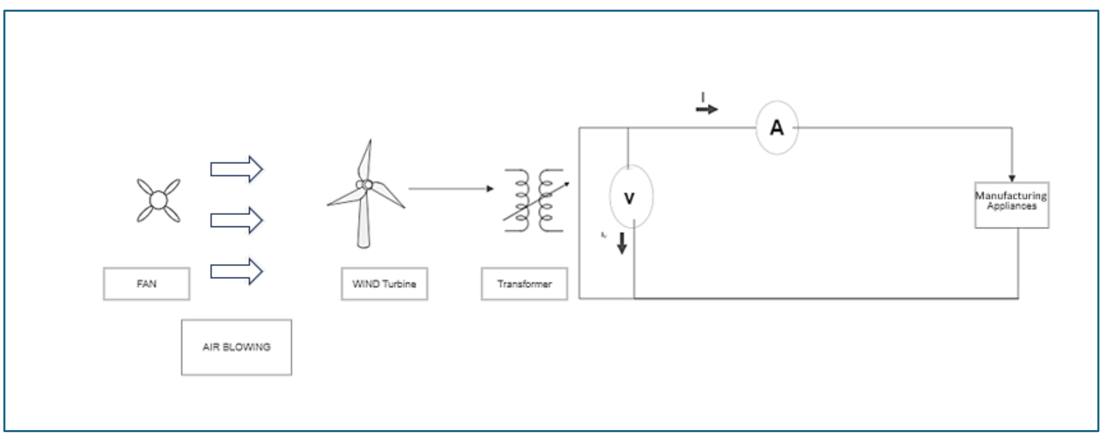


Figure 10. Basic Circuit Diagram of Wind Turbine

This comprehensive implementation and programming approach ensures an immersive and educational experience within the VR Wind Turbine Lab, seamlessly integrating real-world physics with interactive virtual elements.

4. Wind Turbine Performance Analysis for Manufacturing

A comparative analysis of wind turbine performance, the outcomes derived from traditional land-based assessments with those obtained from cutting-edge Virtual Reality (VR) simulations is shown in Figure 11. Our focus is to scrutinize the disparities and congruencies in performance metrics, operational efficiencies, and diagnostic capabilities between the physical and virtual environments. This comparison not only highlights the potential of VR in replicating and enhancing real-world testing conditions but also explores its role in revolutionizing the field of wind turbine performance analysis.

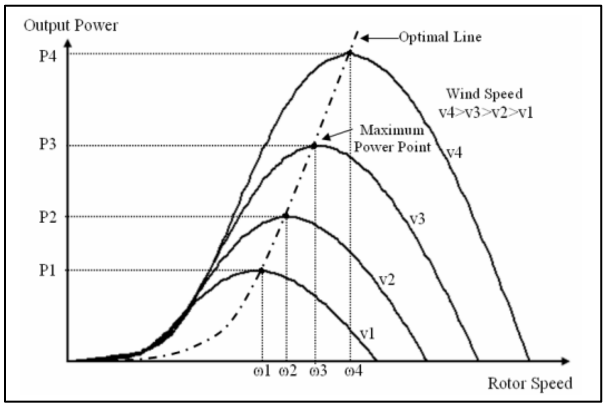


Figure 11. Output power versus rotor speed at various wind speeds [8].

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) V^3$$

$$\lambda = \frac{\omega R}{V}$$

$$\omega_{\text{opt}} = \frac{\lambda_{\text{opt}} V}{R}$$

4.1. Wind Turbine Performance Analysis in Lab Environment

The purpose of this laboratory is to analyze the power generation of wind turbines. Multiple variables are tested in the wind turbine energy efficiency experiments. Experiments include analyzing the effects of the angle at which the wind strikes the turbine blades and changing the load resistor values to maximize power. To properly implement wind power, these variables should be analyzed, and solutions designed to maximize efficiency.

This laboratory utilizes DELORENZO Green kit, a program that measures the voltage, current, and power of different renewable energy power supplies. The maximum power point (MPP) of the wind turbines was determined in the experiment. The MPP of the wind turbine is a function of both voltage and current, according to Watts' Law: P = IV, where P is power in Watts, I is current in amps, and V is voltage in volts. According to the maximum power transfer theorem, maximum power output is achieved when the resistor setting of the multi-decade resistor (the load resistance in this case) matches the internal resistance of the wind turbine. One wind turbine was configured for this experiment, as shown in Figures 12 and 13. The wind was directed at the turbine blades at the optimal angle and the steps were repeated, results are shown in Table 1. The wind was directed optimally at the wind turbine and the multi-decade resistor was initially set to the ∞ (infinity) position to simulate an open circuit (maximum resistance). The voltage and current output of the turbine was recorded. The multi-decade resistor was then cycled through each resistance setting (allowing time for the output to settle) and the data was recorded for each position, results are shown in Tables 2-3. Figures 14 and 15 show the experimental results on current-voltage (IV) curve and (b) power-voltage (PV) for maximum power point (MPP).

The maximum power point (MPP) occurs when the resistance of the wind turbine is equal to the resistance of the load. The current and voltage are used to measure the power instead of measuring the power with the Delorenzo Green kit.

Figures 12 and13. Students Working on Delorenzo Kit

Speed	Measured Speed	Calculated Power	Measure Power	Coefficient of Power
Low speed	5.6	1.1746	0.3876	0.33
Low Medium speed	6.6	1.9229	0.7883	0.41
Medium speed	6.9	2.1972	0.9667	0.44
Medium high speed	7.1	2.3938	1.1011	0.46
High speed	7.6	2.936	1.3799	0.47
Very high speed	7.8	3.174	1.5235	0.48
Extreme high speed	8.3	3.8243	1.4914	0.39
Very extreme high speed	8.5	4.1075	1.4787	0.36

Table 1. Performance of a wind turbine with varying wind speed data.

Resistor	Voltage	Current	Power
0.1	0.059	1.342	0.0792
0.33	0.073	1.269	0.0926
1	0.273	1.069	0.292
3.3	0.835	1.245	1.039
10	1.936	0.845	1.636
33	3.403	0.527	1.793
100	4.321	0.215	0.929
330	5.454	0.093	0.507
infinity	6.548	0	0

Table. 2. Medium Wind Speed

Resistor (Ohm)	Voltage (Volt)	Current (Ampere)	Power (Watt)
0.1	0.044	0.879	0.0387
0.33	0.078	0.791	0.0617
1	0.234	0.698	0.163
3.3	0.489	0.542	0.265
10	1.304	0.605	0.789
33	2.759	0.351	0.968
100	3.148	0.151	0.475
330	3.775	0.063	0.238
Infinity	4.653	0	0

Table. 3. Low Wind Speed

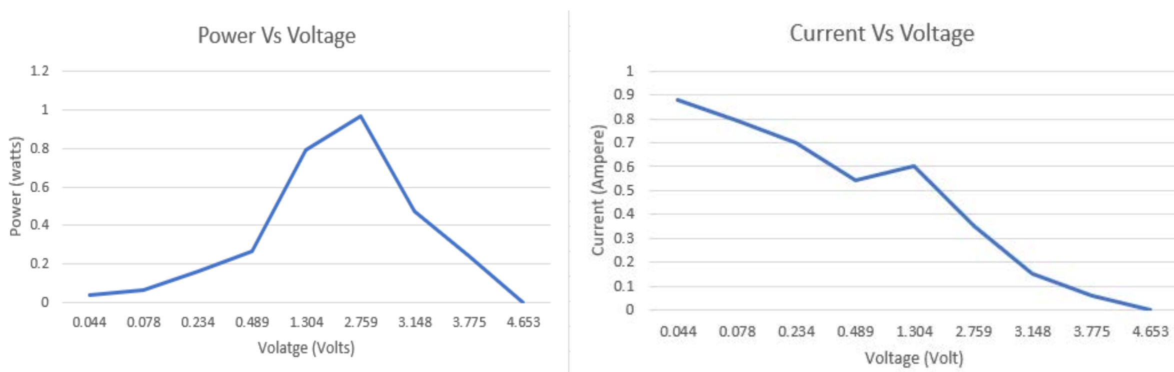


Figure 14. Low Wind Speed

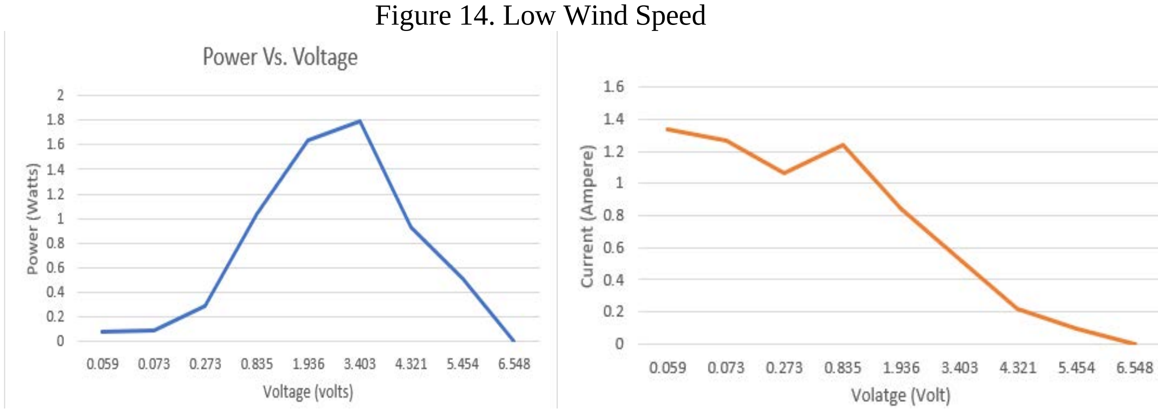


Figure 15. Medium Wind

The Power vs. Voltage graph vividly illustrates maximum power points for medium and low wind speeds. At a medium wind speed, the Maximum Power Point (MPP) occurred at 3.403 volts, yielding a power output of 1.793 watts. Conversely, for low wind speed, the MPP materialized at 2.759 volts, resulting in a power output of 0.968 watts.

4.2. Wind Turbine Performance Analysis in VR Environment

This project aims to implement a renewable energy virtual reality laboratory featuring a wind turbine module. The VR laboratory is designed to accurately simulate the physics and behavior of a wind turbine. The features of the wind turbine module developed for the simulation in this virtual renewable energy environment closely mirror those of a wind turbine module used in real-world laboratory settings. This ensures a highly realistic and educational simulation experience, effectively bridging the gap between virtual and physical renewable energy studies.

Students engaged in a comprehensive exploration of wind turbine design and performance standards using a virtual reality (VR) wind turbine. The experiment involved applying established equations governing wind power, with turbine blades set at a 45-degree angle and a resistance of 10 ohms. Simulating real-world conditions, a virtual fan was strategically placed 60 cm away from the wind turbine. the VR Wind Turbine Lab, effectively blending real-world physics with interactive virtual elements.

The gathered data, documented in the provided table, revealed diverse coefficients of power and observed power across a spectrum of wind speeds. The experiment aimed to pinpoint the wind turbine's maximum power point—the state of optimal efficiency. As wind speed increased, measured power ascended until reaching a threshold, followed by a gradual decrease. The graphical representation showcased a power vs. wind speed curve, emphasizing the significance of the maximum power point in wind turbine efficiency.

$$P_w = \frac{1}{2}\rho A v^3 \ and \ P_m = P_w \times C_p \times \frac{9.55}{T \times n}$$

$$Where\ T\ is\ Torque, n\ is\ Number\ of\ Revolutions\ Per\ Minute,$$

$$and\ C_p\ is\ CoefficientofPower\ (0.3\ to\ 0.5)$$

The decline post-peak in the curve indicated mechanical or electrical losses within the wind turbine system, affecting components like the rotor and transmission system. This experiment not only explored wind turbine performance dynamics but also highlighted the importance of optimizing operational conditions for maximum efficiency.

In the VR lab setup, determining the maximum power point involved dynamically adjusting resistance. The ripple effect on current and voltage values influenced the wind turbine's overall output. The power computation formula, which succinctly captures the interplay between current and voltage, serves as a fundamental equation for understanding and optimizing wind turbine performance [4-5].

The hands-on adjustment of resistance in the virtual environment enhances the learning experience, providing students with a tangible understanding of how changes in electrical characteristics impact overall wind turbine efficiency. This experimental approach deepens comprehension and instills a practical appreciation for the multifaceted considerations in renewable energy systems as shown in Figure 16.

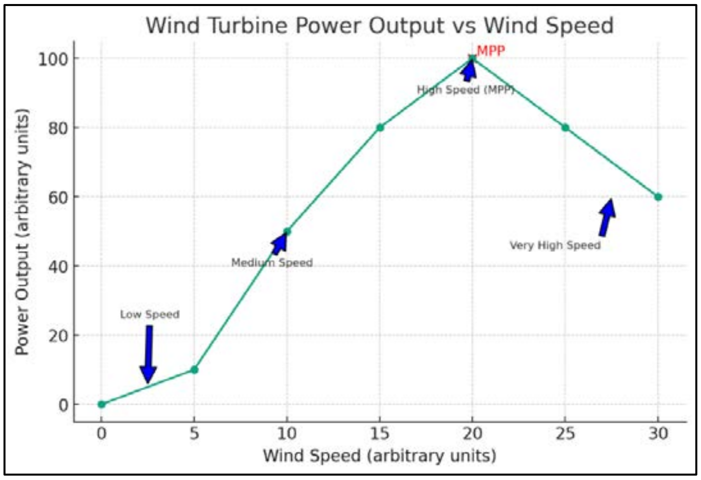


Figure 16. Power Output VS Wind Speed in VR

5. Student Learning Outcomes

Students were given a final project of coming up with an idea of how wind energy can find application in the scope of simulating panel behaviors in 3D for understanding and in virtual reality for the course EET 320 Renewable Energy Systems. A set of materials giving instruction were provided to students included a simple idea and few implementations, for instance, on energy power output. The course project flow was as shown below.

1. Make a group of 3 or 4 students
2. Each group should come up with an idea and talk to TA or professor about it.
3. Once the group idea is approved, they can look for related work, background and other ground work research about the idea. Groups were advised to take on a part of work so that workload is equally divided between them.
4. Groups start to work with their 3D models using SolidWorks or any other CAD software with the help of teaching assistant. If they have time, it is advised to try simulation in Solidworks too. It is not mandatory.
5. Students use Blender or 3DS Max to convert .stil file to .obj or .max respectively making it ready for VR application.
6. Once models are ready, groups export them in UNITY as assets and they create a basic virtual environment.

7. Students add various factors such as effect of shadow on panel and effect of temperature with the help of scripts and try to simulate the expected behavior of system.
8. Groups present their final project presentation in class and is assessed by the professor and TA based on criteria like presentation skills, project idea, 3D modelling and applications, programming, understanding of the topic, etc.

Group 1 (Toroidal Wind Turbine)

Figure. 17 shows the team developing an innovative toroidal wind turbine design, leveraging aerodynamics for enhanced efficiency and power generation. Individuals engage in basic designing, VR development, Problem-solving, Collaboration, Innovation and C# programming to create immersive and interactive experiences.

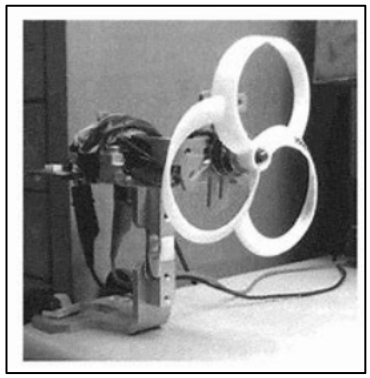


Figure. 17. Toroidal Wind turbine Project Presentation

Group 2 (Wake steering of Wind Turbine using VR and 3D printing)

Through teaching via VR, students develop an improved spatial understanding of complex engineering concepts simulations provide students with immersive, hands-on learning experiences. By executing 3D printing modern technologies, students learn to apply the iterative design process commonly used in engineering. They conceptualize designs, create virtual prototypes in VR, and then translate these designs into physical models using 3D printing technology as shown in Figures 18 and 19.

Figure. 18. Wake steering of Wind Turbine

Figure 19. 3d Printing for Final project

6. Conclusion

The renewable energy course focuses on imparting knowledge about alternative energy sources, with a specific emphasis on wind energy. Laboratory exercises concentrate on practical aspects of working with wind energy systems. In these experiments, students engage with wind turbines, exploring the impact of factors like wind speed, blade angle, and Number of blades. The incorporation of virtual reality into the course enhances the learning experience, providing students with a unique platform alongside traditional laboratory work. Through this approach, students not only gain insights into wind energy concepts but also acquire 3D modeling skills, learn the basics of virtual reality, and develop programming proficiency. The virtual implementation of wind turbine setups facilitates better understanding and visualization, and students also acquire essential skills such as SolidWorks designing, understanding the significance of virtual reality, working with UNITY 3D, programming, and creating simulations and interactive platforms. These hands-on, interdisciplinary efforts serve as both laboratory exercises and capstone projects, enabling students to integrate and apply their STEM skills and knowledge acquired from foundational coursework.

ACKNOWLEDGMENT

This work has been supported by the US Department of Education under the joint MSEIP Program with the University of Texas at El Paso, PR/Award No.: P120A180101. The authors wish to express sincere gratitude for their financial support.

Reference:

[1] Design and Development of an Immersive Virtual Reality Educational Game for Wind Power Education: https://peer.asee.org/measuring-individuals-systems-thinking-skills-through-the-development-of-an-immersive-virtual-reality-complex-system-scenarios
[2] https://www.futurevisual.com/blog/why-virtual-reality-is-the-future-of-wind-turbine-training/
[3] XR Labs: https://xrlabs.co/
[4] VR Lab (Nijmegen): https://www.vr-lab.nl/wind-turbine/
[5] https://nextgenamerica.org/press/nextgen-climate-expands-mission-relaunches-nextgen-america/
[6] https://www.neefusa.org/what-we-do/k-12-education/greening-stem-hub
[7] Source: https://www.circuits-diy.com/home-wind-turbine-circuit/
[8] L. Ni, D. J. Patterson and J. L. Hudgins, "Maximum power extraction from a small wind turbine using 4-phase interleaved boost converter," 2009 IEEE Power Electronics and Machines in Wind Applications, Lincoln, NE, USA, 2009, pp. 1-5, doi: 10.1109/PEMWA.2009.5208329. keywords: {Wind turbines;Control systems;Phased arrays;Field programmable gate arrays;Wind speed;Digital control;Mathematical model;Power system modeling;Analytical models;Hardware;wind turbine;interleaved boost converter;DCM;FPGA},