Immersive Technologies for Renewable Energy Systems: Enhancing User Engagement and Understanding

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Abstract

Renewable energy, particularly solar energy, is a rapidly expanding field that is poised to address pressing global energy challenges. As energy demands rise, preparing future generations to leverage solar energy becomes important. However, traditional teaching methods in solar energy system design using simulations often offer limited practical interaction, poor integration of theoretical and practical learning and low learner engagement and motivation.

Virtual reality (VR) has emerged as a transformative technology for training and learning across various sectors due to its ability to replicate real-world scenarios and enhance user experience through immersive and interactive environments. This thesis investigates the application of VR in designing solar energy systems using computer based simulations, aiming to improve conventional methods by harnessing the "feeling of presence" unique to VR, which has been shown to promote high learner engagement. Therefore, the primary contributions of this research include:

- The development of innovative VR visualisations tailored for solar energy system design, enhancing the comprehension and interaction with complex solar configurations.
- A robust framework for evaluating VR applications in educational settings, focusing on engagement, enjoyment and technology acceptance.
- Guidance for developers and designers to optimise VR applications that aim to promote sustainability, thereby enriching the user experience and educational outcomes.

Methodologically, my thesis used a mixed-methods approach to evaluate the effectiveness of these VR environments. I incorporated qualitative data from surveys alongside quantitative physiological data gathered from wearable sensors and eye-tracking technology to assess user engagement and cognitive load. My findings show a strong user preference for integrating VR into solar energy system design, with significant improvements in understanding solar energy systems attributed to VR's interactive and visual capabilities. Participants reported higher levels of engagement and interest when using VR compared to traditional learning methods.

In conclusion, my thesis demonstrates the potential of VR as a pivotal educational tool in the renewable energy sector, offering an immersive alternative that could replace conventional teaching methods and substantially enhance learner engagement and comprehension.

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1 Journals

- Al-Qallaf, N., Elnagar, D. W., Aly, S. G., Elkhodary, K. and Ghannam, R. (2024) Empathy, education and awareness: A VR hackathon's approach to tackling climate change. Sustainability, 16(6), 2461. (doi: 10.3390/su16062461).

- AlQallaf, N. and Ghannam, R. (2024) Immersive learning in photovoltaic energy education: a comprehensive review of virtual reality applications. Solar, 4(1), pp. 136-161. (doi: 10.3390/solar4010006).

- AlQallaf, N., AlQallaf, A. and Ghannam, R. (2024) Solar energy systems design using immersive virtual reality: a multi-modal evaluation approach. Solar, 4(2), pp. 329-350. (doi: 10.3390/solar4020015).

2 Conference Proceedings

- AlQallaf, N., Chen, X., Hussain, S. and Ghannam, R. (2021) Learning Sustainable Development using Game Based Virtual Reality. 3rd IEEE UK&I YP Postgrad STEM Research Symposium, 10th November 2021.

- AlQallaf, N., Hussain, S. and Ghannam, R. (2021) Interactive Map for Visualising Electronic Engineering Curricula. ESLTIS21 Enhancing Student Learning Through Innovative Scholarship Conference, 10 Sep 2021.

- AlQallaf, N., Ayaz, F., Bhatti, S., Hussain, S., Zoha, A. and Ghannam, R. (2022) Solar Energy Systems Design in 2D and 3D: A Comparison of User Vital Signs. In: ICECS 2022: 29th IEEE International Conference on Electronics, Circuits & Systems, Glasgow, UK, 24-26 October 2022, ISBN 9781665488235 (doi: 10.1109/ICECS202256217.2022.9971065).

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- AlQallaf, N., Chen, X., Ge, Y., Khan, A., Zoha, A., Hussain, S. and Ghannam, R. (2022) Teaching Solar Energy Systems Design using Game-Based Virtual Reality. In: IEEE Global Engineering Education Conference (EDUCON2022), Tunis, Tunisia, 28-31 Mar 2022, pp. 956-960. ISBN 9781665444347 (doi: 10.1109/EDUCON52537.2022.9766460).

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Declaration

I hereby declare that this thesis, Immersive Technologies for Climate Change Education: Enhancing User Engagement and Understanding, is my original work and has been conducted independently unless otherwise stated. All sources of information, data, and references have been properly acknowledged and cited. This thesis has not been submitted, either in whole or in part, for any other degree or qualification at this or any other institution.

Chapter 1

Introduction

1.1 Renewable Energy: Sources and Sustainability

According to the United Nations (UN), more than 80% of the world's energy still comes from fossil fuels [1]. Burning these fuels greatly increases greenhouse gas emissions, raises global temperatures and leads to severe weather events like floods, heat waves and cyclones. This could raise global temperatures by more than 3.5 ° C by the end of this century [2]. Furthermore, about 1.1 billion people worldwide do not have access to electricity [3]. Therefore, a major challenge today is to effectively address the linked issues of population growth, energy scarcity, and global warming [4].

Renewable energy provides a sustainable solution to global energy concerns, as it is derived from continuously replenishing natural resources such as sunlight, wind, water, and biomass, and produces minimal or no greenhouse gas emissions or pollutants [1, 5]. The six primary renewable energy sources are illustrated in Figure 1.1. For instance, wind energy is a plentiful and clean source that harnesses the kinetic energy of wind to rotate turbines and generate electricity. Hydroelectric power uses the force of falling or fast-moving water to produce energy. Additionally, biomass energy converts organic matter into energy, while geothermal energy taps into the Earth's internal heat to generate electricity and heating [6]. Therefore, a fast conversion to renewable energy sources is essential for supporting population and consumption growth. Also, a transition to renewable energy sources could assist countries in reducing energy costs, mitigating the implications of climate change and strengthening their resistance to price volatility [7].

Using renewable energy is becoming more important in tackling global environmental issues such as climate change. One of the biggest benefits of renewable energy is that it produces little or no carbon dioxide, which helps reduce greenhouse gas emissions and improves air quality. In fact, transitioning towards greater use of renewable energy and aiming for net zero emissions can help create jobs globally, from manufacturing solar panels to operating wind turbines. This not only supports economic growth but also enhances stability [9]. Additionally, the cost of renewable energy has dropped significantly, making it a more affordable alternative to fossil

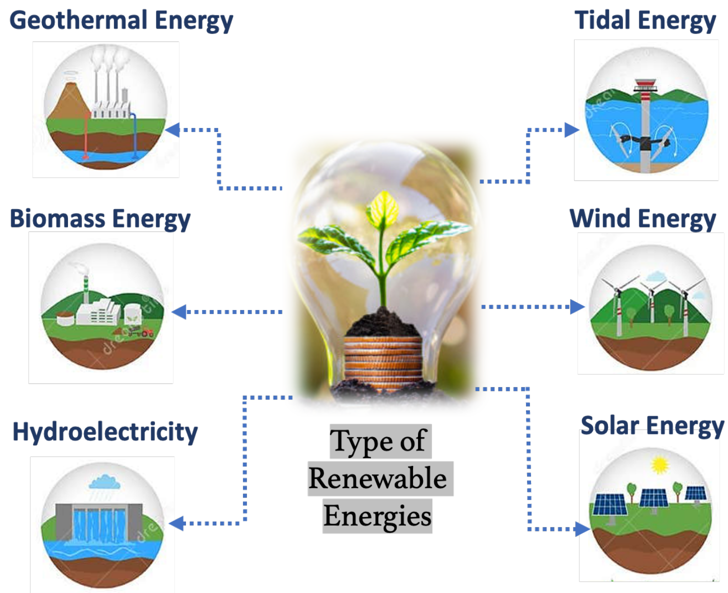

Figure 1.1: The six main sources of renewable energy are derived from natural sources and constantly replenished. These types of energy are clean energy and do not release pollutants like carbon dioxide [8].

fuels [10]. Moreover, renewable energy is plentiful. For example, the amount of solar energy reaching the earth's surface is far greater than energy produced from fossil fuels [11]. Therefore, the benefits of using renewable energy are environmental, economic and social, which makes it important for nurturing a sustainable future. In fact, the world is increasingly recognizing these benefits, leading to a steady rise in the adoption of renewable energies. This growth is clearly shown in Figure 1.2, which illustrates the trends in electricity generation worldwide from 1965 to 2023 from a variety of renewable energy sources, such as hydropower, wind, solar, and other renewables (including biofuels). Over time, hydropower has become the most popular renewable energy source. However, because of technological breakthroughs and growing popularity, wind and solar energy have grown rapidly in recent decades, especially since 2000.

Consequently, electricity prices generated from renewable energy resources have dropped significantly during the past decade. According to the International Renewable Energy Agency (IRENA) [13], solar energy costs have decreased the most during the last few years. In fact, the sharpest decline was seen with solar photovoltaics, which reached 82% between 2010 and 2024. Prices for concentrating solar power decreased by 47%, onshore wind by 40%, and offshore wind by 29%. Table 1.1 compares the prices of coal, solar photovoltaic and wind energy over this period from 2009 to 2024 [14, 15].

Among all the previously mentioned renewable energy sources, solar energy is the most plentiful source that provides clean and sustainable energy to help combat climate change. It is widely available for free and is capable of meeting global energy needs [16]. As the demand for energy rises and fossil fuels become more expensive and scarce, the solar energy industry is

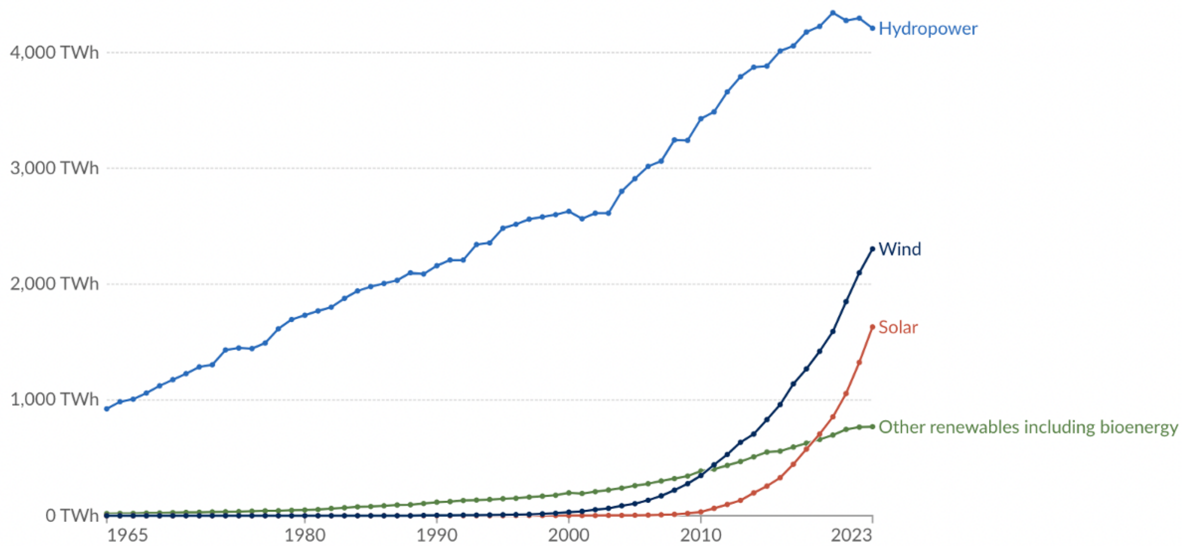

Figure 1.2: Renewable energy generation by source since 1965 [12]. The line chart demonstrates how each renewable energy source is changing over time. The data shows an increasing energy production in all types of renewable energy.

Table 1.1: Decline in electricity prices from coal, solar photovoltaic, wind and gas per MWh [14, 15].

Type/Year	**2009**	**2019**	**2024**
Coal	$111	$109	$ 69
Solar photovoltaic	$359	$40	$29
Wind	$135	$41	$27
Nuclear	$123	$155	$142
Gas	$83	$56	$45

expanding rapidly. This growth highlights the significant advantages of solar energy, making it an increasingly popular choice for clean and sustainable power.

1.2 Solar Energy Systems

Solar energy systems are mainly classified into two main types: photovoltaic (PV) [17] and solar thermal (ST) [18]. PV systems are the most widely used type for generating electricity, while solar thermal systems are primarily employed for heating water. There are also hybrid photovoltaic thermal (PVT) systems that combine both functions [19]. Given the global importance of electricity generation, this thesis concentrates on photovoltaic energy systems. These systems use PV cells to convert sunlight directly into electricity. A typical PV system includes PV panels that generate electricity, batteries that store this electricity, an inverter that converts direct current (DC) to alternating current (AC), and a charge controller that manages the flow of electric current to and from the batteries, as shown in Figure 1.3.

Despite the numerous advantages of harnessing the Sun's energy for electricity generation, the primary challenges include intermittency, cost and system efficiency, which often necessitates large installation areas [20]. Additionally, the complexity of solar energy systems often requires the expertise of dedicated professionals for their design and implementation.

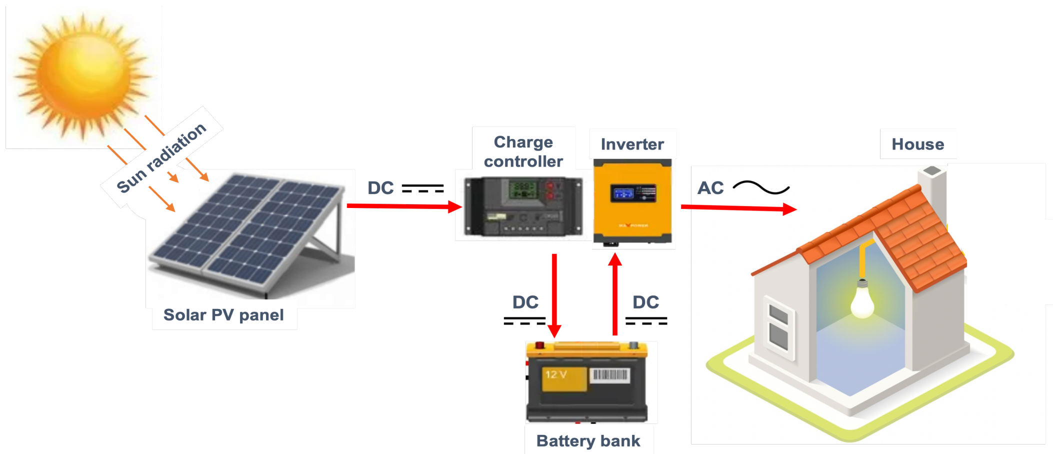

Figure 1.3: Schematic diagram of a typical PV system, which consists of PV panels, a charge controller and an inverter. Autonomous systems also often include a battery bank [8].

1.3 Simulating Solar PV Systems

As the demand for greener and more efficient energy solutions increases, education and training become crucial in promoting a workforce that drives innovation in the renewable energy sector, particularly in solar energy. Various PV device modeling tools, including 2D and 3D methods, have been explored in the literature, as highlighted in [21]. Commonly used 2D simulation software such as PVsyst, RETScreen, VelaSolaris, and Solar Pro allows users to analyze PV system performance under different conditions, including solar irradiance, shading, temperature, and system configurations, as shown in Figure 1.4 [22]. These tools also provide data on weather conditions worldwide. However, 2D simulations have limitations, such as oversimplified visualisations that may overlook critical system components like batteries and inverters, potentially limiting a thorough understanding of the systems. They also offer limited interactivity, which can affect user engagement and hinder learning [23, 24]. Moreover, the simplicity of 2D visualisations often fails to capture the dynamic and realistic aspects of PV systems, impacting the overall learning experience.

In contrast, 3D simulations offer a more comprehensive view of the system, considering important factors such as PV panel tilt angle, shading from surrounding objects and geographical changes in a more accurate representation of real-world conditions in comparison to 2D simulations. Some of these simulations can be performed using software tools such as Sketchup, Helioscope, PVSOL and Energy3D. For example, the Sketchup simulator enables users to visualise the exact location of the sun and shadows over objects during the day. Users are able to

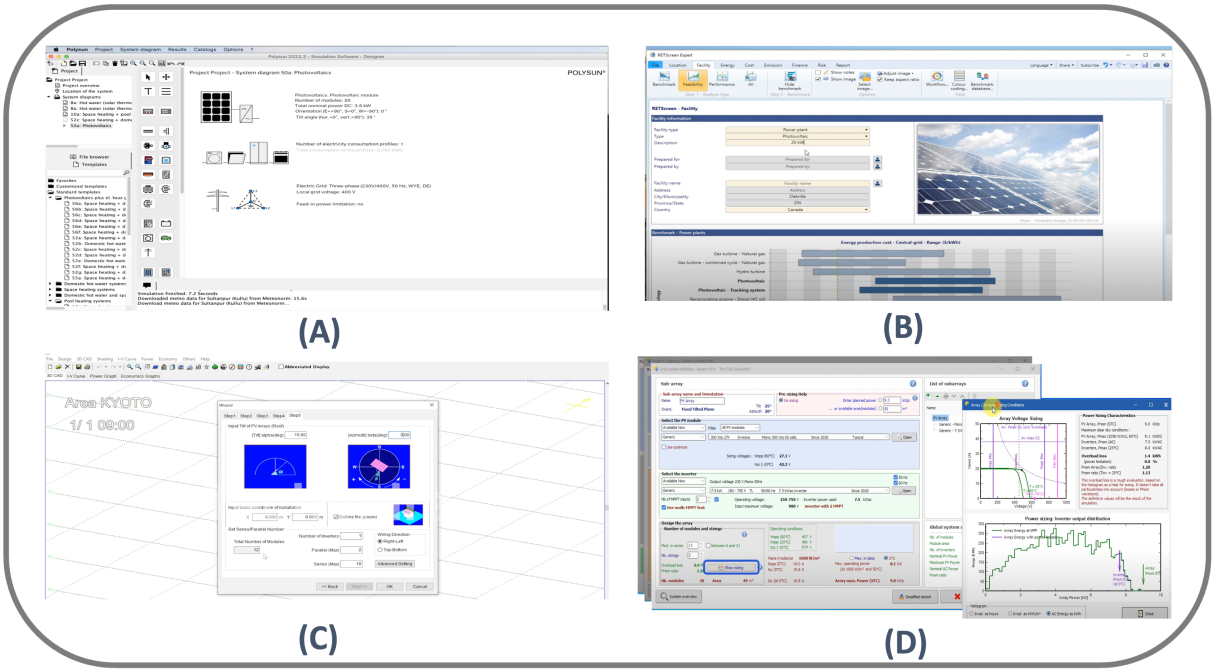

Figure 1.4: Screenshots of 2D simulations for PV systems design. (A) VelaSolaris (Polysun) [25], version 2022.4, users can select a template from the software and add more components to the system or create and design a PV system from scratch. (B) RETScreen [26], Expert version, where users can identify their location and the amount of sunshine in this location, and then calculate how much energy they can produce. (C) Solar Pro [27], version 2.4, users can specify the tilt and azimuth values for the PV arrays and electrical assembly that users prefer, and (D) PVsyst [28], version 7.4, users build an electrical organization of the system such as photovoltaic panels, inverters, batteries and others.

imagine the whole system in 3D images and how the solar installation will appear on their property [29]. In Helioscope, location address, array design and module and inverter specifications are the main inputs required. This software allows users to calculate energy efficiency while taking weather and climate losses into account. It offers a comprehensive diagram including wiring to show the proper locations for panels and other equipment [30]. The PVSOL software provides detailed shading analysis for PV systems with 2D or 3D visualisation. This simulator also offers PV systems' performance and evaluations of financial analysis [31]. Figure 1.5 demonstrates screenshots of PVSOL and Heliscope simulations.

Despite the benefits of 3D simulations, they also come with several limitations. Similar to 2D simulations, they lack immersion, realism and interactive features that enable users to manipulate PV systems in real time. Moreover, complex shading scenarios and terrain variations are challenging to accurately represent in these 3D simulations, leading to a limited ability to experience and understand PV system design.

To address the aforementioned limitation and enhance student learning experiences, 3D immersive simulations such as VR have been considered in the literature. VR technology offers novel immersive environments that enable users to interact with 3D PV systems and manipulate

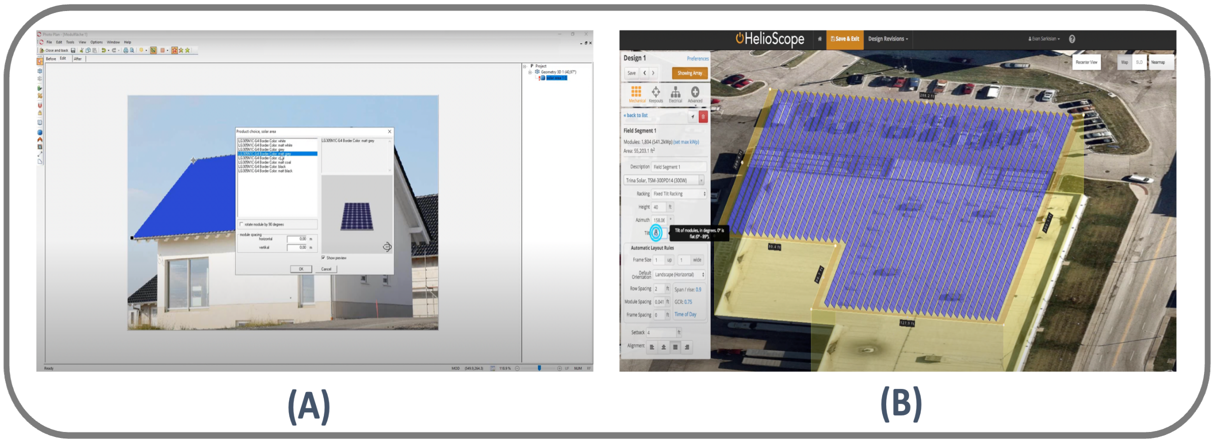

Figure 1.5: Screenshots of 3D simulations for PV systems design. (A) PVSOL [32], allows users to visualise and design the placement of PV panels for 3D models of buildings and then simulate the performance of the PV system under real-world conditions, and (B) Helioscope [33], enables users to visualise PV panels on rooftops or ground-mounted systems and provides advanced shading analysis.

their parts to comprehend their functionality. VR can help users visualise irradiance calculations on surfaces and simulate shadows. Additionally, VR offers a realistic feeling when users interact with, inspect and design a PV system.

In this context, VR technology has emerged as a valuable tool for education and training in the renewable energy industry. VR provides a unique method of enhancing the learning experience in the renewable energy domain by simulating an immersive and interactive 3D environment. According to the literature, VR has the potential to bridge the gap between theoretical knowledge and practical application by offering learners dynamic 3D representations of complex concepts and real-world scenarios [34]. It also offers real-life simulations and can be used for conducting risky experiments that would be dangerous to carry out in reality [35]. It can be used for distance learning and virtual laboratories [36] as students can access learning materials worldwide. As a new method, teaching with VR increases students' motivation, which is a primary key for specifying students' attitudes toward learning [37]. Also, VR provides game-based learning that increases the engagement and joy of the learning experience [38].

1.4 Virtual Reality for Training and Education

It is commonly known that using information technologies is the main key to enhancing and refinement students' attitudes towards learning [39]. According to Vince, Virtual reality is a technology that creates computer-generated environments and simulations that transport users from the physical to the virtual world enabling them to engage and manipulate their virtual surroundings [40]. Also, in the online Oxford dictionary, Virtual Reality is defined as "Images and sounds created by a computer that seem almost real to the user, who can interact with them by using sensors".

VR is not a recent technology; in 1968, Ivan Sutherland created the first head-mounted display (HMD) called the 'Sword of Damocles' [41]. The headset was too heavy to head-mount and had to be suspended from the ceiling by a mechanical arm, figure 1.6.

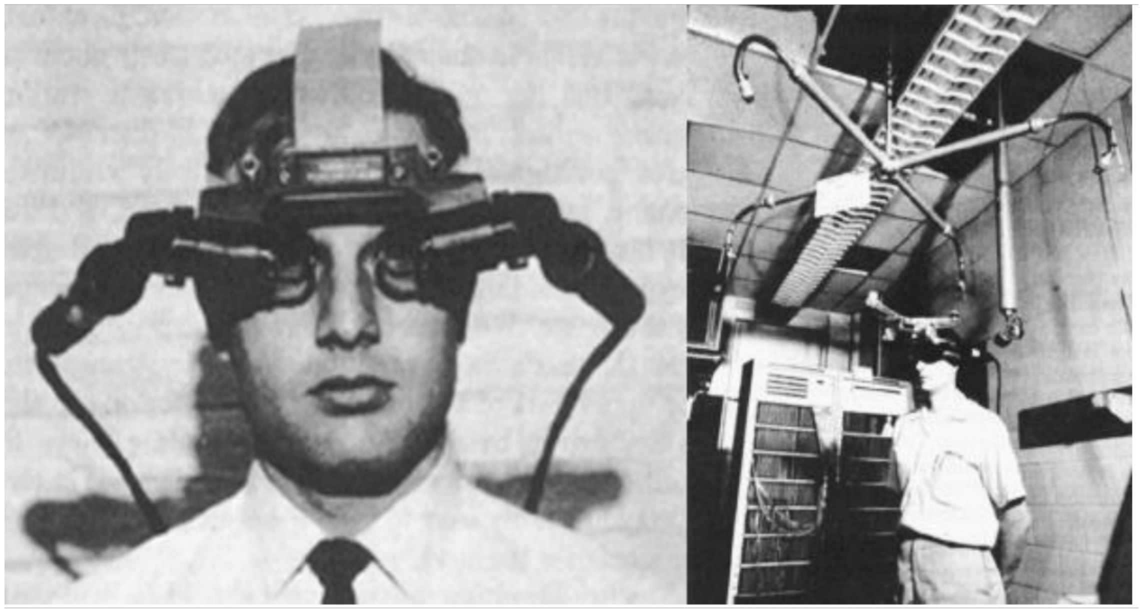

Figure 1.6: The first virtual reality head-mounted display created by Ivan Sutherland [42]. The HMD was so heavy and the system was primitive in terms of user interface and realism.

Virtual reality is a transformative technology that offers a new way to interact with digital information and immerse in a virtual environment. VR is a powerful tool for simulating aspects of the real world. This innovative technology has created new prospects across various sectors, from gaming and entertainment to education, healthcare, and business [43].

In contrast, augmented reality (AR) is an interactive experience that is created by overlaying the physical world with computer-generated perceptual information [44]. AR technology typically uses devices like smartphones, tablets or smart glasses, including cameras and sensors, to detect and enhance the user's environment in real-time.

In addition, mixed reality (MR), a more expanded form of VR, merges computer-generated content with the real world. This technology supports face-to-face and distributed communication [45].

The words "virtual reality," "augmented reality," and "mixed reality" (VR, AR, MR) relate to technologies and theoretical concepts of spatial interfaces that have been investigated by researchers in engineering, computer science, and human-computer interaction (HCI) for a number of decades. Extended Reality (XR) is a term that encompasses VR, MR, and AR technologies. The degree of mixing between actual and virtual items is expressed by the seminal continuum developed by Milgram and Kishino in 1994 [46]. They describe an immersive continuum spanning from the real environment (RE) end, where there is no digital immersion in

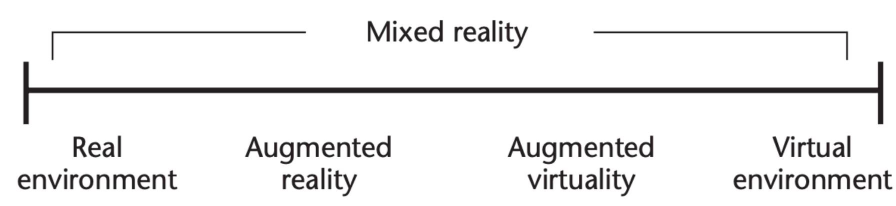

Figure 1.7: Milgram's reality-virtuality continuum [46] which is a scale ranging from a real environment which is the reality that we can see when watching the real world to a virtual environment which is virtuality.

the outside world, to the completely immersive VR end, where digital immersion is at its most intense - figure 1.7.

In addition, Schnabel *et al.* in [45] demonstrated a classification that shows the differences in the different types of AR and VR, figure - 1.8. The degree of realism decreases from left to right.

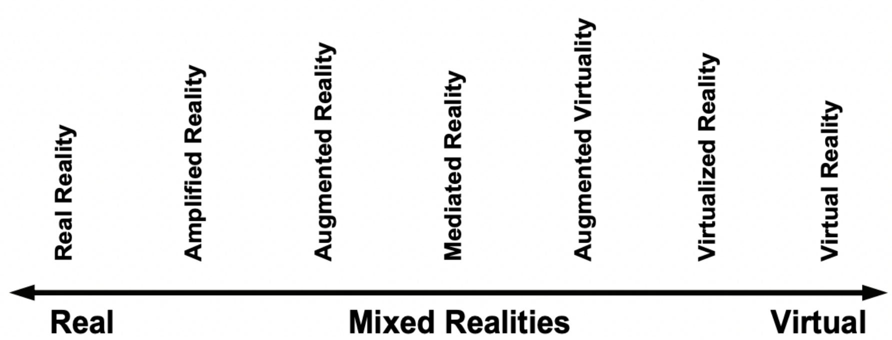

Figure 1.8: A classification for different types of AR and VR technology ranging from real to virtual environment [45].

Balleck in [47], raised the fact that active learning in the form of simulations, increases the quality of learning and students' retention of the material they learn between 75% to 90%.

When referring to VR, several terms are used interchangeably. These terms may include cyberspace, virtual environments, artificial reality, virtual worlds, and artificial worlds [48].

Several types of VR have been used in education including cave automatic virtual environment (CAVE), desktop VR and head-mounted devices (HMD), figure 1.9. The least immersive type is Desktop VR where a 3D virtual environment is displayed on a computer monitor. This type is not an immersive environment but can serve as a window into a 3D virtual world. Desktop VR is more affordable and accessible than the other types of immersive VR. The 3D virtual worlds of Second Life are a common example of desktop VR, where users can access them through the Internet as avatars [49]. CAVE is considered a semi-immersive type of virtual reality where projectors are used to show a virtual environment on walls surrounding users. Users should wear stereoscopic glasses to see the 3D virtual world. One major benefit of CAVE VR is that several users can easily share the same VR experience and interact face-to-face with each other. The most immersive type of VR uses a head-mounted display (HMD) that users wear to cover their field of view and provide stereoscopic 3D visuals. These HMDs also incorporate motion tracking technology to determine where the user is looking [50]. This type of VR supports the sense of presence which provides users the impression that are actually in the virtual environment.

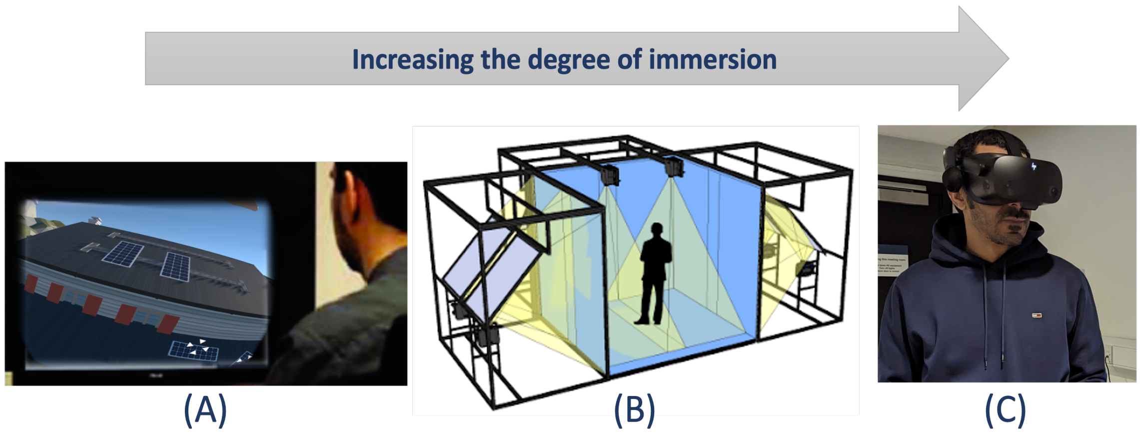

Figure 1.9: The three types of virtual reality: (A) a non-immersive Desktop VR, where users use a computer to control activity within the experience (B) a semi-immersive CAVE, which consists of a cube-shaped VR room in which the walls, ceiling and floor are projection screen and (C) fully-immersive HMD that provides the most realistic simulation experience by wearing a VR head-mounted display.

The success of the potential virtual reality application is highly dependent on the level of the user experience. User experience is gaining notable importance in the field of interactive product design.

The three key concepts commonly used to describe engaging experiences are flow, cognitive absorption and presence [51]. Csikszentmihalyi in [52] describes flow as the process of optimal experience where individuals are deeply involved in an activity that they do not seem to care about anything else. Agarwal and Karahanna in [53] define cognitive absorption as a state of deep involvement with software. Presence can be known as the subject experience of momentarily losing awareness of actions that are connected to the real world while simultaneously acknowledging oneself as a part of a virtual environment [54]. Burdea and Coiffet in [55], determined the 3 Is of virtual reality which are immersion, interaction and imagination 1.10.

Researchers have investigated the advantages and applications of VR in various contexts. Virtual reality has a potential in education which attracted researchers' interest in using it in the classroom. Nevertheless, VR technologies have not been adopted in education yet despite the positive feedback with VR applications.

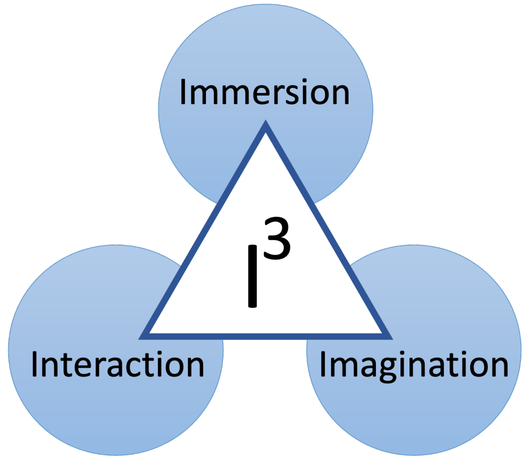

Figure 1.10: Virtual reality triangle that represents the three Is in VR, immersion, interaction and imagination [55]

1.4.1 VR headsets

Virtual reality headsets have witnessed incredible improvements that provide users with immersive realistic experiences across various domains, from gaming and entertainment to education and professional applications. Virtual reality technology has a wide range of headsets with different features and capabilities figure 1.11.

Figure 1.11: Overview of various models of VR head-mounted displays with different designs and features that cater to satisfy users' needs and requirements within the VR experience.

Among the prominent VR headsets in the market, the Meta Quest 2 is unique as it is a standalone headset that offers convenience and accessibility to a wider range of users, and operates independently without requiring a PC. The headset does not need any external sensors, because it has six degrees of freedom (6DOF) that allow the headset to track the movement of the user's body and head, and then accurately translate them into VR. [56]. In the high-end models, the HTC Vive Pro Eye and HP Omnicept offer cutting-edge capabilities including eye-tracking technology, extended field-of-view (FoV) and enhanced resolution [57, 58]. Also, the HP Omnicept has a state-of-the-art sensor system that measures muscle movement, gaze, pupil size and pulse. In addition, the Pico Neo 2 Eye headset is a standalone VR with native eye-tracking [59]. Varjo Aero is the lightest and brightest VR headset for professional and entertaining purposes [60]. The Google Cardboard is a low-cost head-mounted display (HMD) developed by Google [61]. In this type of VR headset, a smartphone is inserted into the back of the lenses. A software development kit (SDK) that offers a platform for creating VR content for iOS and Android is connected to this cardboard. Several factors should be considered when choosing a headset for student use such as price, quality and user-friendly. Table - 1.2, presents the specifications of some of the popular VR headsets.

Table 1.2: The specifications of popular VR HMDs [62].

VR headset	Price ($)	Weight (gr)	Type	Platform	OS	Field of View	Resolution
Meta Quest 2	249	503	Standalone VR	Oculus Home	Android	97°horizontal 93°vertical	1832 x 1920
Meta Quest 3	499	515	Standalone VR	Meta Quest	Android	110°horizontal 96°vertical	2064x2208
Oculus Rift	599	470	Tethered	SteamVR Oculus Home	Android	87°horizontal 88°vertical	1080x1200
HTC Vive Pro 2	1399	850	Tethered	SteamVR	Windows	116°horizontal 96°vertical	2448x2448
Pico Neo 2 Eye	899	690	Standalone VR	Pico Store Viveport	Android	101°horizontal 101°vertical	2048x2160
HP Reverb G2	599	186	Tethered	SteamVR Windows Mixed Reality	Windows	98°horizontal 90°vertical	2160x2160
Varjo Aero	990	717	Tethered	SteamVR	Windows	102°horizontal 73°vertical	2880x2720
HP Reverb G2 Omnicept Edition	1249	727	Tethered	SteamVR Windows Mixed Reality	Windows	98°horizontal 90°vertical	2160x2160
Google Cardboard	5 and up	110	Mobile	iOS, Android	-	360	-

1.4.2 Applications for VR in Education and Training

Virtual reality headsets are more affordable and widely available, enabling VR technology to be employed in several disciplines effectively. Numerous studies have shown the strengths of virtual reality use in the classroom. The strength of VR technology is to enhance understanding and learning of abstract concepts because students can experience and visualise these concepts in a virtual environment. VR technology can potentially overcome the associated problems related to traditional teaching methods and improve students' comprehension of a subject. Also, VR offers a dynamic and immersive environment that enables students to engage with the materials in a novel way. This virtual environment fosters experiential and hands-on learning which leads to a deeper understanding of the subjects and information retention. By cultivating a sense of presence, promoting critical thinking, problem-solving and collaboration, VR technology enriches education and prepares students to face any challenges within the training and learning process. Also, VR provides a safe environment to practice in lifelike simulations that would be too dangerous to perform in reality and can be used to simulate access to limited resources [34].

VR technology has a wide range of applications across various domains. Lampathaki *et al.* in [63] conducted a literature review to provide comprehensive information about using VR technology in many fields of psychology such as developmental, clinical, social, sports, organizational psychology and neuropsychology. In this literature review, VR has been found to promote children's socialisation and self-control in Developmental Psychology, contribute to phobia treatment reduce prejudice and enhance prosocial behaviour in Social Psychology, and facilitate early diagnosis and rehabilitation of neuropsychological complications in Neuropsychology. In addition, VR technology has been used in various areas of healthcare, including patient education, medical training, and telemedicine [64]. This technology can be used in professional and vocational training [65–67]. Also, VR is being increasingly explored and implemented in the field of the tourism industry [68, 69].

1.5 Research Motivation

The research covered in this thesis builds upon studies that were established to study the effectiveness of using virtual reality technology in education and training and whether we can use XR technologies for solar energy system design training.

The transition to renewable energy globally requires appropriate education resources that prepare future engineers and scientists. Solar energy is a key contributor to this transition due to its potential and declining costs. However, the conventional ways of teaching solar energy system design fail to fully engage students and offer a hands-on experience. This gap in teaching can be effectively addressed by incorporating cutting-edge technology such as Virtual Reality (VR). VR provides a unique immersive environment where students can interact with solar energy systems which hardly be achieved with traditional 2D or 3D simulations. Such an approach makes the learning process engaging and helps in developing practical skills that are necessary to design efficient solar energy systems. In addition, evaluating the effectiveness of VR technology in education requires employing comprehensive methods to measure users' engagement and learning outcomes. Therefore, this study focuses on evaluating a VR application of solar energy system design by incorporating advanced sensors for monitoring vital signs and eye movement data to gain deeper insights into the users' engagement levels. Integrating these biometric sensors with VR experience allows researchers and designers to determine which parts of the VR experience had the greatest educational value, or where adjustments should be made.

In the literature, no study has comprehensively explored the use of virtual reality technology for solar energy system design, incorporating all system components such as batteries, charge controllers, inverters, and solar panels. Also, no study evaluated the VR application by using sensors or monitoring eye-tracking data to estimate users' engagement levels.

This thesis aims to bridge the gap in the literature by addressing how virtual reality technology might be used for solar energy system design and fosters democratic access to renewable energy solutions. Solar energy system design training provides individuals with the necessary knowledge and skills to meet renewable energy demands and to be an effective contributor in the transition to clean and renewable energy.

In summary, the motivation behind this study lies in the potential of using virtual reality technology in solar energy system design by making this experience more immersive, engaging and effective. Also, improving the learning experience and promoting education technologies that can help in increasing the awareness and usage of renewable energy sources. This research involves designing and testing different interventions using immersive technologies and evaluating their effectiveness in improving learner engagement.

1.6 Research Questions

- What strategies can be used to make learning about solar energy system design more engaging for students by using immersive technologies?
- What specific technical skills can students gain by using VR technology in the design of solar energy systems?
- How do physiological responses, such as heart rate and eye-tracking data, correlate with students' engagement and focus when using VR technology in solar energy system design?

1.7 Thesis Outline

The thesis is structured as follows:

Chapter 2 presents a literature review of what has been done in solar energy system design, providing details on the VR applications, evaluation methods, the advantages and disadvantages of using VR technology in solar energy system design, VR contribution to enhancing users' engagement and participation in solar energy-related fields, and the innovative approaches exist for integrating real-time data from solar PV energy systems into virtual reality environments and how can this integration lead to better decision-making and performance optimisation.

Chapter 3 presents a novel approach to climate change education through a three-day Virtual Reality (VR) Hackathon. The hackathon focused on four United Nations Sustainable Development Goals (SDGs) - Quality Education, Affordable and Clean Energy, Sustainable Cities and Communities, and Climate Action. Engineering students worked in teams and competed against each other in designing immersive environments that demonstrated their understanding of these SDGs and climate change. The goal was to encourage the development of empathy, education, and awareness around these critical global issues. The hackathon also integrated authentic assessments, mirroring real-world engineering tasks and providing a more practical and relevant learning experience. Next, the chapter presents a study that showcases the approach for teaching solar energy systems design to higher education students using a game-based virtual reality approach. This approach enables students to immerse themselves in a virtual environment, which is safe for both students and their teachers. The game consists of two levels, where students are invited to solve an energy-related task in two different homes. Also, this chapter presents the development process and design of the VR application for solar energy systems. The VR application was created based on a learning theory called Dale's cone. The blender software was used for the 3D modelling of some 3D objects and the Unity3D game engine was utilised to create the scenes of the VR environment.

Chapter 4 presents a study that measures user engagement in both a 2D and 3D immersive virtual reality environment during a solar energy systems design task. User engagement was measured by estimating a user's vital signs using a non-invasive FMCW radar and medical grade belt. Then a deeper evaluation of the VR application for a solar energy system design was conducted using a multi-module approach and a detailed analysis of user engagement. This experiment was divided into several scenes and employed a range of sensors, including eye tracking and wire-less wearable sensors, to accurately assess users' engagement and performance in each scene.

Chapter 5 concludes the thesis with a summary of contribution, implications, general guidelines for developing VR applications and future work.

Chapter 2

Systematic Literature Review

2.1 Introduction

This chapter discusses the literature review of using virtual reality technology in solar energy system design. This literature review presents a comprehensive and systematic review of virtual reality (VR) as an innovative educational tool specifically for solar photovoltaic energy systems. VR technology, with its immersive and interactive capabilities, offers a unique platform for in-depth learning and practical training in the field of solar energy. The use of VR in this context not only enhances the understanding of solar photovoltaic (PV) systems but also provides a hands-on experience that is crucial for developing the necessary skills in this rapidly evolving field. Among the 6814 articles initially identified, this systematic review specifically examined 15 articles that focused on the application of VR in PV education. These selected articles demonstrate VR's ability to accurately simulate real-world environments and scenarios related to solar energy, providing an in-depth exploration of its practical applications in this field. By offering a realistic and detailed exploration of PV systems, VR enables learners to gain a deeper understanding of harnessing, managing and using such a vast energy resource. The review further discusses the implications of employing VR in educational settings, highlighting its potential to change the way solar energy professionals are trained, thereby contributing significantly to the acceleration of photovoltaic technology adoption and its integration into sustainable energy solutions.

2.2 Methodology

This section defines the research methodology in collecting and synthesising the literature on virtual reality for solar PV education using clearly defined criteria. Only academic journal articles and conference papers were chosen for review, considering their relatively high impact. Books, chapters, conference papers and academic articles unrelated to engineering education at the undergraduate level were not considered.

The review considered related publications from major search engines such as IEEE Explore, Web of Science and Google Scholar, using certain keywords to confine the results. IEEE Explore was used since it holds a comprehensive digital library for studies in the fields of computer science, electrical engineering and electronics. Moreover, the Web of Science has tools for data analysis. Google Scholar has a vast database that contains a broader range of academic sources and enables interdisciplinary search experience. In addition, the keywords used for the search query are shown in Table 2.1. These were: virtual reality, renewable energy, photovoltaic (PV) and education. The (AND) Boolean operator was used to connect these descriptors. All papers that contain the keywords above were included in the review. Publications were scanned within three stages based on their title, abstract and full text after removing duplications, Figure 2.1.

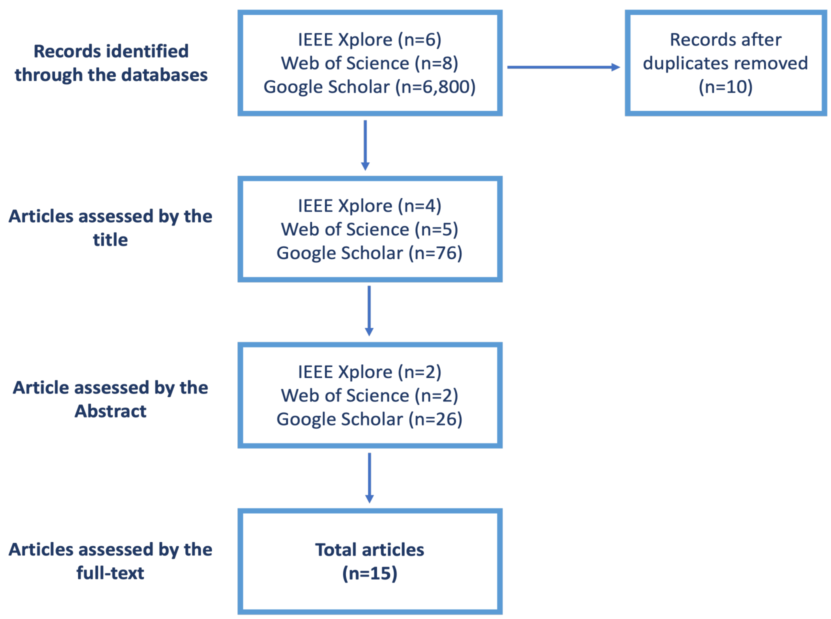

Figure 2.1: The process of scanning articles from three search engines: IEEE Xplore, Web of Science and Google Scholar. The first filter was removing the duplication. Then, the articles were manually scanned based on reading the title, abstract and full text, respectively. The process resulted in a total of 15 articles.

To ensure a rigorous literature review, the first step was to establish clear research questions and inclusion criteria. Next, select manuscripts adhering to these criteria. Finally, analyse and interpret the search results. In this study, the following research questions (RQs) were posed:

1. RQ1: In what solar energy aspects are VR applications used?

2. RQ2: What are the benefits and limitations of using immersive VR applications for PV systems design?

3. RQ3: How can virtual reality contribute to enhancing the engagement and participation of students and learners in solar PV energy?

Table 2.1: Descriptors and synonyms used for the search query.

Descriptor	Definition	Synonyms	Ref
Virtual reality	An interactive technology that enables users to be engaged with a computer-simulated environment, either a real or imaginary world.	A simulated 3D environment	[70]
Renewable Energy	Energy that derived from natural resources that are continuously replenished and never run out.	Sustainable energy green energy	[1]
Photovoltaic	“Photovoltaics involves the direct conversion of sunlight into electricity in thin layers of material known as semiconductors with properties intermediate between those of metals and insulators”	PV, Solar panels	[71]
Education	“A process of teaching, training, and learning, especially in schools or colleges, to improve knowledge and develop skills”	Learning, teaching, and training.	[72]

4. RQ4: What innovative approaches exist for integrating real-time data from solar PV energy systems into virtual reality environments, and how can this integration lead to better decision-making and performance optimisation?

Investigating these questions provides a comprehensive understanding of the current landscape and helps showcase the capability of virtual reality as a tool for improving solar energy education. By examining the VR applications in solar energy education and knowing their benefits and their impact on increasing the engagement level, we can provide insights into potential future directions for research in order to integrate virtual reality technology into educational practice.

Based on the above questions, the following inclusion criteria (InC) were defined as:

1. InC 1: Articles written in English.
2. InC 2: Articles matching the definitions and descriptors mentioned in Table 2.1.
3. InC 3: Publications between 2011 and 2023.

The exclusion criteria (ExC) were:

1. ExC1: Articles from studies written in languages other than English.
2. ExC2: Presentations or abstracts or reviews.
3. ExC3: Publication before 2011.

2.3 Results

The development of virtual reality head-mounted displays (HMDs) can be traced back to 1968, which were pioneered by Ivan Sutherland and Robert (Bob) Sproull [73]. However, based on publications retrieved from the Web of Science, no research related to using virtual reality in renewable energy was published until 2005. In contrast, research publications on the use of virtual reality in renewable energy education emerged in 2011, as shown in Figure 2.2. The number of publications has increased gradually over the years, indicating interest in this field. The growing interest can be attributed to many reasons, especially the rapid advancement of virtual reality technology, which makes it more accessible and affordable [74, 75]. Additionally, this advancement has led to virtual reality being widely used in various industries including renewable energy. The capabilities of virtual reality technology have encouraged researchers to develop novel applications specifically for improving solar energy education and training, while providing practical experiences without the need for real-world installations or equipment.

Figure 2.3 illustrates the distribution of publications focusing on virtual reality across different research areas. Based on data retrieved from the Web of Science, most of the research is in computer science, representing 65% of the publications, followed by engineering with 60%. A significant portion of the research cuts across multiple areas, with computer science often serving as the primary or complementary field.

Figure 2.4 demonstrates that the majority of publications came from China, followed by the UK and USA. This notable growth in China is mainly attributed to its increasing economic expansion and its leading role in producing photovoltaic (PV) energy [76].

2.4 Discussion of the Results

In the following section, the results of the systematic study are explained according to the selected research questions. A total of 15 papers matched the InC and ExC criteria; 10 were conference papers and 5 were published in journals.

2.4.1 RQ1: In What Solar Energy Aspects Are VR Applications Used?

Virtual reality applications are being used in the solar energy industry to improve comprehension, training and students' engagement. According to the literature, the following are some of the key domains where VR applications are currently being used.

Grivokostopoulou *et al.* in [77] developed a virtual reality application that has been used in energy generation from renewable energy sources (RES). This application provided an immersive and interactive learning experience. Various power plants, such as hydroelectric plants, factories and constructions, such as wind turbines, photovoltaic panels and hydropower turbines,

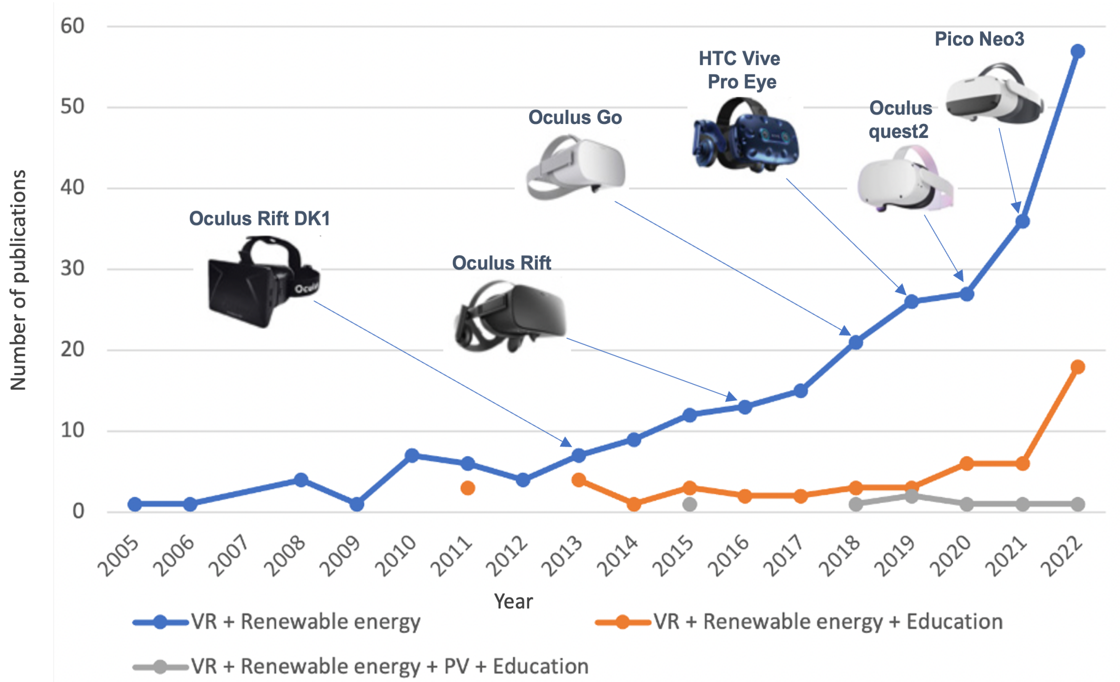

Figure 2.2: Number of publications on using virtual reality for renewable energy (the keywords are virtual reality OR VR AND renewable energy OR sustainable) and using virtual reality in renewable energy education (The keywords are virtual reality OR VR AND renewable energy OR sustainable AND education OR learn* OR teach* OR train*). The grey line shows using virtual reality for PV energy education. In addition, the figure demonstrates the development of the VR headset over the years. The number of publications was extracted from the Web of Science search engine.

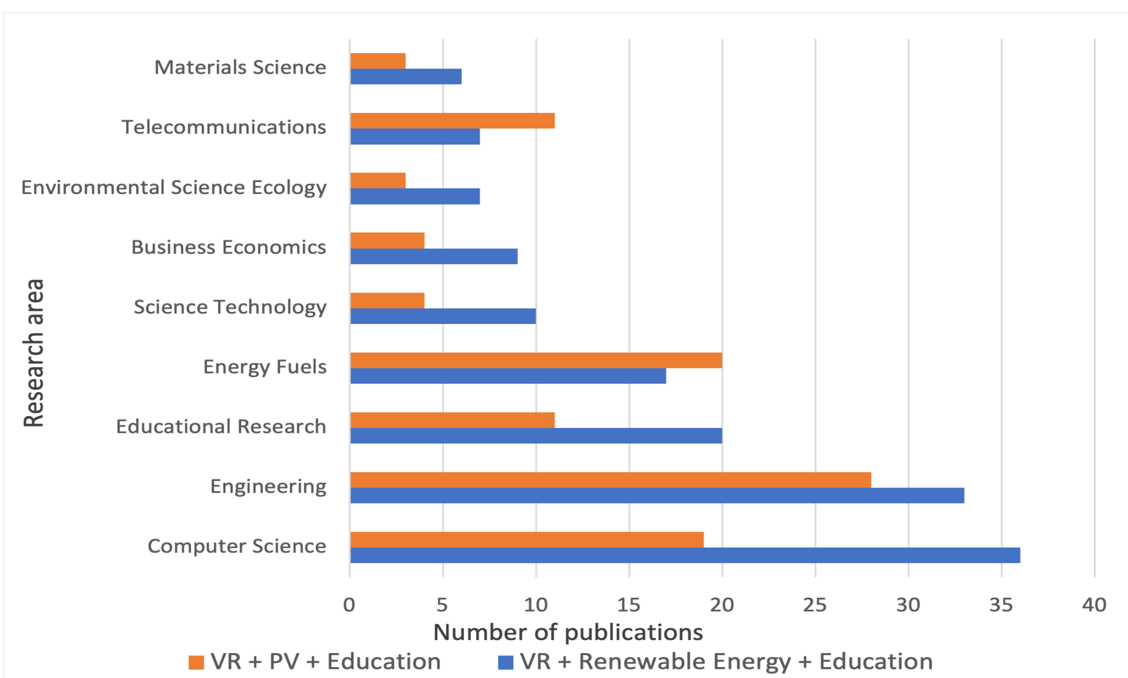

Figure 2.3: Distribution of publications on VR in Renewable Energy Education vs. PV Education by research area.

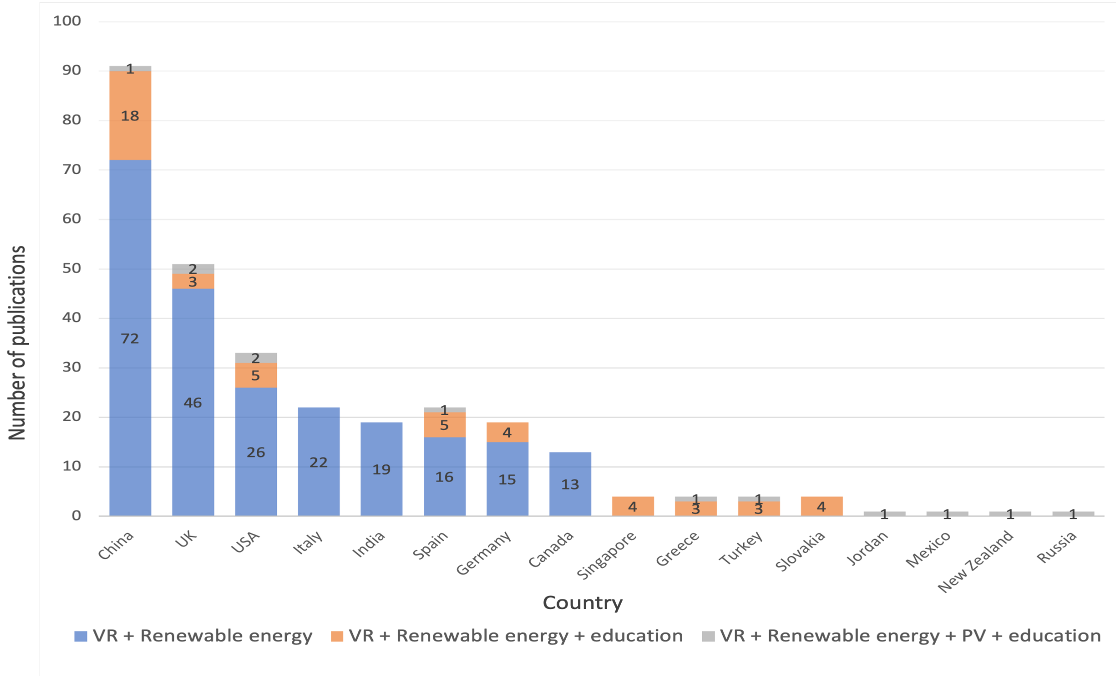

Figure 2.4: Number of publications by country on the use of virtual reality in renewable energy, virtual reality in renewable energy education and virtual reality in photovoltaic (PV) energy education.

have been created in the VR environment, mimicking how they operate in real life and allowing learners to understand their functionality. The 3D virtual environment enabled students and tutors to interact with and inspect individual parts of the construction, observing how they function and interact with other components. When a student manipulates any piece of an object, information appears explaining how it functions and how to connect it to other components of the machine.

In [78], a VR learning platform was developed, and the framework was modelled and used with a number of experimental modules, including solar PV generation parameters and effects. Learners can explore the system's parametric and thermochemical characterisations in this VR application. The learning module was created based on current laboratory physical experiments on renewable energy and the need for remote laboratory exercises. In general, in this platform, students were introduced to the learning scenarios and modules, that have specific learning objectives. Then, theoretical concepts were demonstrated to students and instructors regarding the performance of the module. Next, students were able to explore interactive artefacts or the XR multisensory laboratory platform, depending on the kind of platform developed for a specific topic. One of the learning modules was the VR PV module. In this module, users were able to adjust the tilt of the PV panels and the angle of solar irradiation. Moreover, live data could be plotted in an interactive and dynamic user interface power curve. Students were able to gather data as stated by the lab manual and try different input parameters that can be visualised on the PV power curve. They were able to use their hands or a lever in the VR environment to try different situations with the solar panels. In addition, students were able to investigate the impact of shade on solar panels and analyse the maximum power point (MPP). According to the authors, students had a chance to gain insights into the effect of load resistance on a solar panel.

Moreover, in [79], the researchers developed a virtual reality environment for the purpose of teaching and training students to install a photovoltaic power plant. According to the authors, this VR application helped students better comprehend and visualise the technical aspects of the installation, as it supports teachers in visual laboratory practice. Their VR application enabled users to interact with activities including reading boards and vocal explanations and inspecting the photovoltaic system installation. This training tool aimed to improve students' abilities to design and build a solar power plant appropriately, providing technical assistance with the specific equipment in the project.

AlQallaf et al. in [38], chapter 3, developed a virtual reality application for teaching solar energy system design using a game-based approach. The application comprised modalities including text, audio, quizzes, interaction with 3D objects and animations. This application aimed to recognise the modularity of photovoltaic systems, the difference between direct current (DC) and alternating current (AC) and show the importance of using photovoltaic panels to meet their household energy need. The application contained two levels presented in virtual houses where users have to solve an energy-related task. In the first level, users learn the importance of using PV panels to generate energy and reduce their high electricity bills. An animation was displayed to illustrate the process of generating electricity from producing direct current from solar panels to supply a house with electricity explaining the role of using an inverter to convert DC to AC. In level 2, users measured the power consumption of electrical appliances in a home to determine the required number of PV panels to meet the power needs. Users were then expected to install the required number of solar panels on the house's rooftop.

Moreover, a Virtual Ecological Laboratory was developed at Saint Petersburg State Electrotechnical University [80]. This application contained various elements that included teaching materials, quizzes and lab work using virtual reality technology. It consisted of laboratory work that supported students in becoming experts in dismantling solar panels. The main goal of this VR application was to develop a set of laboratory work on PV module recycling as part of ecological sustainability efforts.

Ritter and Chambers in [81] developed a PV VR application that used a scale model of the Photovoltaic Applied Research and Testing (PART) Lab to provide interactive virtual reality tours. Users of PV-VR were taken on an interactive educational tour where they can interact with a variety of technologies to support virtual hands-on learning. A teacher avatar led the virtual tour while explaining each technology and presenting educational animations and interactive games. According to the authors, the VR application helped users gain knowledge of solar power technologies and power generation, conversion and transmission. PV-VR is composed of various interactive teaching sections that provide students with an introduction to solar resources, PV panels, converting DC to AC and PV technologies. Additionally, it allowed the investigation of different PV technologies such as polycrystalline, monocrystalline and thin-film simultaneously. An animation was presented on how photons displace electrons to generate direct current (DC). After that, students can take part in a photon shooter exercise where they shoot photons at negatively doped silicon to liberate electrons to produce direct current and supply electricity for a light bulb. In addition, students had a chance to learn about the role of an inverter in converting DC to AC to supply electricity to the home via an animation. The authors also used this VR application in another study to compare a 3D-modelled environment with a 360° panorama environment for an interactive educational virtual reality tour, at the PART Lab located near the University of Louisiana at Lafayette to learn about PV solar power [82].

Hatzilygeroudis et al. in [83] demonstrated a hybrid platform that helped teach solar energy concepts. The platform combined a traditional virtual learning environment (VLE) via Moodle with a 3D virtual environment. The Moodle VLE provided students with theoretical solar energy concepts, while the VR world enabled them to interact with many virtual devices and constructions. Students were able to understand the functionality of solar collectors, energy machines and transmitters. The VR application included three elements, which were Solar Energy Island, 3D Auditorium and Classrooms or Meeting Rooms, where students were able to learn about solar energy and renewable energy sources (RES). In Solar Energy Island, there were many learning materials such as presentations, flash animations and 3D objects where students could read basic information about photovoltaic cells, learn how photovoltaic panels work and discover the main components and their functionality. In this application, students were able to learn how to produce solar energy and use photovoltaics and other technologies to harness heat from the sun to generate electricity. Moreover, students were encouraged to discover and investigate the devices up close and view their components and functions. Thus, students gained a deeper understanding of how these devices work.

Similarly, Arntz et al. in [84] developed a VR application based on a real PV array. The idea was to use the full capabilities of virtual reality technology to replicate every characteristic of the real PV array and then add extra features to enhance the experience, for instance, visualising power couplings and how they fit into the grid. Learners interacted and engaged with the PV system in a game-based manner by exploring, adjusting and connecting individual PV modules. In the VR application, students were required to complete three tasks. The initial task was to install the virtual panels most effectively and then connect these panels to the power grid. After that, depending on the panels' type, students have to connect the panels with their dedicated power couplings.

Moreover, Arntz et al. [85] developed an immersive VR environment with a virtual photovoltaics array. This VR application enabled users to investigate the PV array components, like the corresponding circuits and the power inverter. Users were able to gain information about the PV modules' characteristics and specifications. The user interface (UI) overlay demonstrated information about any specific PV panel, including the present and previous performance or power feed that can be presented in numbers or a line chart. The application also visualised the current flows through a pulsating shader that was applied to the PV array cables, explaining to users the outcomes of their actions when they connected or disconnected a panel into the power grid. The application provided different weather scenarios like rain, cloud coverage, temperature change, fog and time of day, where students can learn the PV array performance in different weather conditions. To achieve this, a dynamic weather system was integrated into the virtual environment. Based on data gained from OpenWeatherMap API, users were able to opt for the current weather or historical information dating back to 2015. The chosen option was synchronised with the corresponding merit obtained from a network interface, which confirmed the matching PV array output with the displayed weather conditions.

Alqallaf et al. in [86], chapter 4, developed an immersive VR application for a solar energy system design task and measured user engagement via physiological signs. The VR application mimics the steps of a 2D commercial application for teaching solar energy system design. This VR application contained four scenes showing Earth, a house, a power room and a roof. Users were able to select the location from the map, which then presented the location information. In the power room scene, users have to install the system components on a stand, such as the battery, charge controller, and inverter. Then, users were able to access the house roof to install solar panels on a stand. In this scene, there was a gauge chart that showed the amount of electricity generated by the current system. Users were able to add and remove solar panels and change the tilt of the stand to test the power generated from different scenarios.

In [87], a 3D virtual environment was developed to simulate the operation of many kinds of power plants and devices in renewable energy sources, including photovoltaic panels. The application enabled learners to interact with 3D objects and structures to manipulate their components and comprehend their functionality. In the VR environment, users were depicted as avatars to visit constructions and explore and investigate 3D objects. Moreover, there was a virtual library that contained many books as educational materials. Users were able to choose a virtual book and study the corresponding theoretical content in the textual format. This offered a diverse range of educational materials. For instance, to examine the electricity generated from photovoltaic cells in the virtual environment, users can first start with text-based presentations and learn the theoretical concepts, as well as interact with the corresponding 3D object. The layers of a photovoltaic cell were represented in 3D objects and the process of electron release was visualised. Users can click on any layer to display a dialogue message that describes the features of the layer and its functionalities.

The study in [88] presented a cloud-based virtual reality application for the purpose of providing learning modules on solar energy, such as virtual solar PV, solar PV modules and solar PV arrays through a game-based approach. The VR application comprised self-guided laboratory modules that explain the fundamental principles of PV cells' output power losses by exploring the relation between finger length, width, depth and spacing. Moreover, the application addressed the configuration of PV cell connections in series and parallel to achieve the desired voltage and current output. Moreover, the VR application covered the consideration of solar PV array tilt.

Asghar et al. in [89] demonstrated a VR application called SolarPro. This application offered various training scenarios to enhance solar farm engineers' training. SolarPro integrated three training scenarios and assigned distinct priority levels to each scenario: visual inspection, module exchange and string testing. In the visual inspection scenario, users explored the solar farm and reported any visual errors, such as a disconnected DC cable, dirt, broken panels or corrosion. In the module exchange scenario, there was a smashed panel where a user used the readout SMS to determine the location of the faulted panel and then went to the site to replace the module. The string testing scenario was specific for well-trained users. In this scenario, there were multiple poor-performing strings, and users had to determine the string combiner box attached to the strings and then follow the required instructions to fix this issue.

Chiou et al. in [90] presented a VR-based laboratory module in green manufacturing education. This application aimed to provide students with comprehensive knowledge about the efficiency of solar energy. This solar lab comprised four different modules that enabled users to appreciate four factors that impact the efficiency of solar PV performance, which were the effects of heat, tilt angle, shade and the maximum power point of solar panels. In the first module, students were able to measure the PV output when exposing the solar panel to a heat lamp. In the second module, students were able to interact with the solar panels and the light source. Students can try different angles of the solar panels and alter the light source's angle. The third module allowed students to learn about the influence of the setup configuration of the PV on the energy output. This setup encompassed parallel and series setups. Students were also able to learn about the effect of shade on the PV output. Finally, students were allowed to see the impact of resistance on the output energy. This enabled them to calculate the maximum power point of the PV system, which represents the point with the highest amount of power.

The mentioned studies for the VR applications in PV systems education focused on certain learning theories that explain the process of learning and the acquisition and retention of knowledge. Most of the studies, 47%, did not determine the learning theories that have been used in their experiments. However, 35% of the studies selected game-based learning for the VR application, figure 2.5.

The studies in solar PV education showcase the promising potential of using virtual reality technology as a learning method that offers an immersive and interactive environment, enhancing users' comprehension of solar energy systems and their functionality. Most of the studies offer practical training environments for students, enabling hands-on experience. Only two studies [84, 85] from this review explained on-grid PV systems that connected the solar systems to the utility grid, while two studies [38, 86] focused on the off-grid PV systems. The rest of the

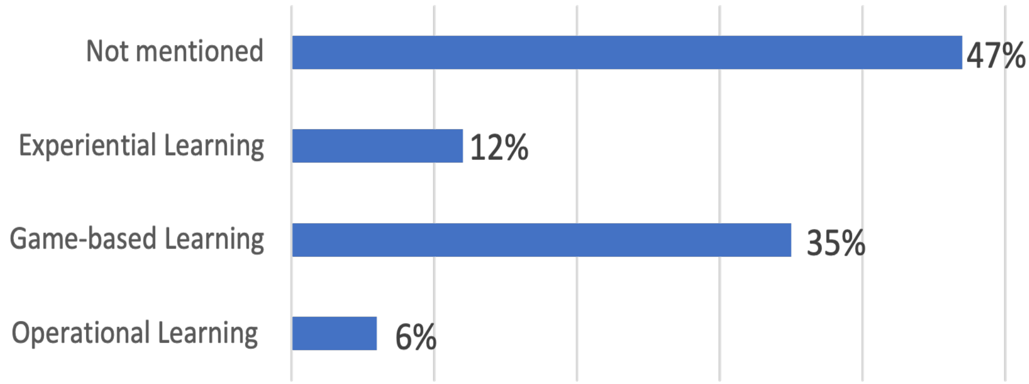

Figure 2.5: Applied learning theories in the mentioned studies using VR applications in PV systems education. The majority of the studies did not mention a specific learning theory, while 35% of the studies applied game-based learning.

studies did not clarify the type of system used in the virtual reality application. The majority of the studies that explained the PV system installation highlighted the power generation from the system and how to connect the PV system components together with their functionality. In addition, the main area that the researchers focused on with the PV system installation is how to set up the PV panels and the effect of changing the tilt of PV panels on electricity production. Only one study [86] explained clearly all of the components of the solar PV system and their functionality, such as PV panels, a battery, a charge controller and an inverter. In addition, only one paper explained the maintenance of PV systems and how to fix PV problems and errors [89]. In addition, many papers mentioned the importance of an inverter's role in converting DC to AC in producing electricity. Figure 2.6 demonstrates screenshots from some of the studies in this review that used virtual reality in solar PV education.

In addition, several facets within the PV system can be integrated into virtual reality, such as energy storage systems. Users can interact in a VR environment to understand the principle of storing surplus solar energy for later use by exploring the dynamics of charge and discharge cycles. Moreover, a solar tracking system can be used where users can learn how PV panels dynamically follow the sun throughout the day to absorb energy.

Integrating virtual reality seamlessly into PV system education involves many considerations to achieve an effective learning experience. Learning goals and objectives that can be achieved with VR should be determined within the curriculum as well as an understanding of how this VR technology supplements and aids the current learning methods. In addition, high-quality VR applications should be developed to align with the curriculum in order to increase students' understanding and engagement. Students should also be trained to effectively use VR as a learning tool.

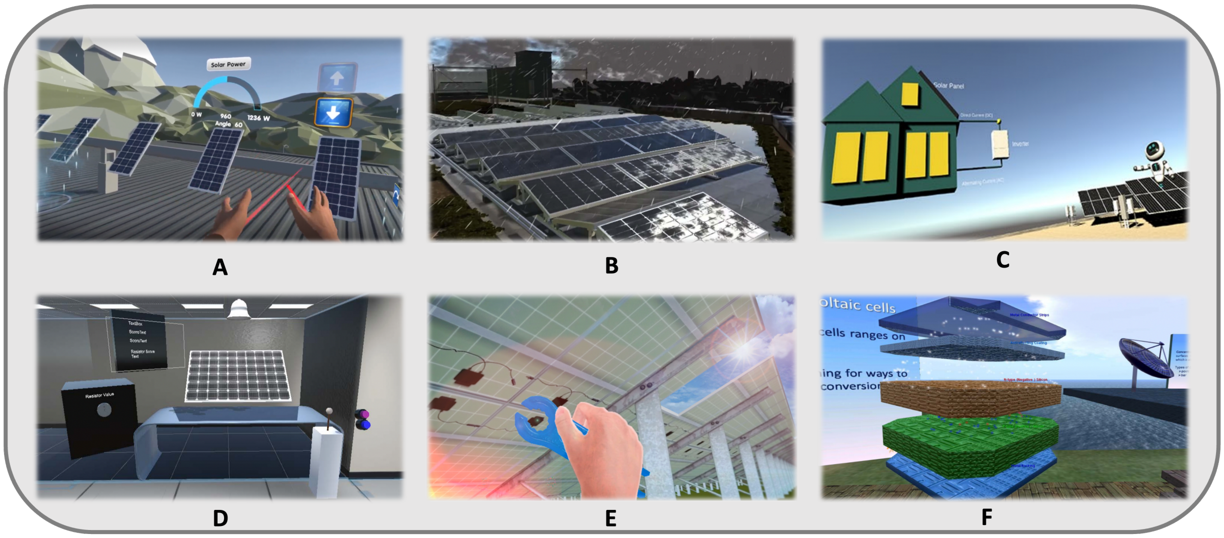

Figure 2.6: Screenshots for using virtual reality in PV solar education taken from the literature. (**A**) Users can install solar panels on a stand and try different scenarios: add, remove or change the tilt of the solar panels. A gauge chart appears in front of users to display the power generated from the system [86]. (**B**) Weather states are displayed based on actual weather conditions in order to promote a more comprehensive understanding [85]. (**C**) Instructor robot in a PART Lab explains DC to AC inverter [82]. (**D**) Solar lab modules [90]. (**E**) Module exchange scenario, where users have to replace a smashed panel in the solar farm [89]. (**F**) Visualising the layers of the PV cell and the release of electrons [87].

2.4.2 RQ2: What are the benefits and limitations of using immersive VR applications for PV systems design?

Using virtual reality applications in solar energy education provides many benefits. However, there are also some limitations to the use of this technology. The following is an overview of the advantages and drawbacks:

The researchers used different methodologies to evaluate their VR application in PV solar education, while 22% of the studies did not evaluate their VR application, figure2.7.

The researchers in [77] discussed many benefits of using 3D immersive VR applications in renewable energy development, as they claimed that the field of energy generation from renewable energy sources was regarded as challenging for learners to fully comprehend. The VR environment offered students the chance to interact with several 3D power plants, including photovoltaic panels, in order to better understand how they work. Their virtual reality application replicated the real environment, allowed students to learn in a setting that was as real as possible and developed adequate mental models of the relevant concepts by visualising them and interacting with the virtual phenomena and processes. It gave students the ability to make connections between abstract concepts and procedures to actual experiences. The VR environment in this study grabbed students' attention, enhanced their performance and supported peer collaboration. A pre-test and post-test approach was applied for 105 students to evaluate the effectiveness of

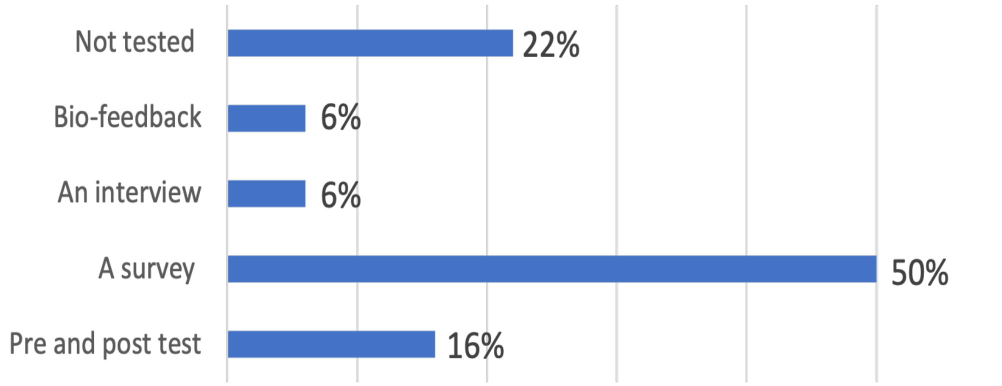

Figure 2.7: The evaluation methods that have been used in the mentioned studies. Most of the VR studies in PV system education focused on using surveys as a tool to assess using VR applications in solar PV education.

the virtual reality application. The students were divided into three groups to study in different learning conditions. The first group was chosen to study using traditional educational materials like textual presentations. The second group used the virtual application without any learning scenarios. The last group was selected to learn with learning scenarios and the virtual world. The post-test result showed a significant difference between the three groups as the performance of the third group was the best with a mean score of 8.514 out of 10, while the means of the first and the second groups were 4.987 and 6.971, respectively. The second and third groups had to fill out a questionnaire based on a Likert scale (strongly agree, neutral, disagree) to evaluate their feelings and opinions regarding the VR application. Nearly 85% of the second group showed enjoyment in learning in contrast to 94% of the third group. Moreover, the VR experience increased students' motivation and interest as indicated by 81% of the second group and 87% of the third group. In addition, most of the students in the third group, 97%, rated that they found learning to be effective, in contrast to 89% of the second group. The 3D objects in the virtual world had the role of enriching the student's knowledge, as stated by 87% of the second group and 91% of the third group. The majority of the students in both groups agreed with the usability of the virtual world according to 83% of the second group and 86% of the third group. Moreover, in [78], it was stated that VR learning provided students with a more integrative learning approach instead of using animations or conducting simple experiments, which improved students' motivation and enhanced their understanding of the concepts. VR also contributed to filling the gap between the theoretical approach and experimental activities in face-to-face education.

The VR application presented by Frank et al. made it possible to explore virtual engagements that would otherwise be challenging or impossible to complete due to financial or lab space limitations [78]. VR technology in this study allowed students to try new ways to apply their knowledge practically, strengthen information retention and encourage critical thinking. The VR application provided learning-by-doing experiences that met the needs of all types of students in one group.

In the study in [79], it was described that VR assisted teachers in conducting laboratory practice where no physical equipment was available. Additionally, this VR environment offered a realistic experience of a photovoltaic system, shortened the learning period and increased the amount of acquired information as students conduct an experiment in real laboratories. VR integration into photovoltaic projects gave users a realistic impression that they could explore and interact with the facilities. The application enabled users to walk between facilities in the virtual environment and participate in learning activities like inspecting solar panels, wire gauges and input variables for inverters. In addition, this virtual environment allowed students to check what was being learned in their training lectures. The purpose of this training tool was to improve the users' skills in designing and installing a solar power plant by providing technical assistance and details of equipment selection for such projects. To evaluate the VR application, 28 students were divided into two groups, traditional training (TT) and virtual-reality-assisted training (VRAT). During the first two weeks, both groups learned about designing PV systems, learning theory, concepts and selecting equipment through presentations. Then, the activities were evaluated in the third week by testing students in designing a solar plant considering all the required details. In the fourth week, the TT group was required to design a solar plant, while VRAT used a VR application to explore the facilities. During the fifth week, both groups were tested by designing a PV solar plant to evaluate the VR application. The results from the tests during the third and the fifth week showed an increase in average grades from 6.74 to 7.43, out of 10, for the TT group and from 6.34 to 8.7, out of 10, for the VRAT group. These results indicated the effectiveness of using virtual reality as a tool for teaching solar PV system design. Moreover, a satisfaction survey was applied to evaluate the students' satisfaction with using virtual reality. Students rated 4.83 out of 5 that the virtual environment was similar to the facilities at the faculty and 4.91 that the virtual objects looked like real equipment. They rated 4.75 that the virtual labs enhanced the theory classes' comprehension. In this study, learners felt dizzy after using the headset.

Alqallaf et al. in [38] mentioned that VR technology helped reinforce knowledge learned through conventional methods. Their VR application had positive feedback in terms of teaching the basics of solar energy system design as VR provides ease of interaction with 3D objects like real items. The gaming features in the VR application promoted active learning and motivated students in the learning process. In addition, the VR application had a proven ability to raise users' awareness and comprehension of solar energy systems and provided laboratory work for students in a safe environment to practice risky activities without worrying about the students' health. To evaluate the effectiveness of the virtual reality application, the students had to answer an online questionnaire, which measured the students' understanding of the main solar energy concepts. Students rated 3.58 out of 5 in their understanding that PV systems are modular, 3.42

in terms of their understanding of the difference between DC and AC in solar energy systems and 4.42 in terms of their appreciation that PV panels can be used to satisfy a home's energy needs. However, some users asked for assistance with grabbing and installing 3D objects. Moreover, dizziness, tiredness and cases of headaches were reported after using the VR application.

As a further example, in [80], a VR application was developed to help master the dismantling of silicon solar panels. In this process, the panels must be heated several times, which could result in burns. Additionally, toxic substances can be discharged into the air students breathe when heating many organic compounds. Moreover, grinding silicon and removing glass can hurt students. Silicon dust also affects students' respiratory systems. For these reasons, using this VR application in laboratory work helped to avoid any injury and harm to students while practising dangerous activities. Moreover, developing a VR lab is a cheaper option for preparing an ideal learning setting rather than providing costly equipment for training purposes. The VR environment enhanced the training quality in the PV module recycling alternative energy field through active learning that reinforces theoretical knowledge. One of the limitations of this study was that the creation of a simulated laboratory and a program using a lot of equipment was challenging. Based on Ritter and Chambers's study in [81], immersive virtual field trips provided many advantages such as cost-effectiveness, flexibility in conducting experiments, access by many users, overcoming weather issues, ability to work with inaccessible or risky places and damage resistance. Students were also eager to learn about photovoltaic power and took an educational tour using virtual reality, showing their acceptance of VR training in their curriculum. In total, 84% of students commented positively on the VR experience and 48% commented that the VR application was fun. However, some students, 18%, mentioned that the application was blurry, and they were scared of adjusting the headset because they might break it. Moreover, 7% felt that the application was confusing and 7% stated that the headset was heavy.

In another study, VR was shown to be a useful method for remote learning as it engaged students in interactions with each other and with their instructor in a class or with their environment. Students interacted with 3D devices and constructions such as solar collectors, energy machines and transmitters, which provided a deeper understanding of the devices' functionality. According to their study, VR technology helped shift the learning process to a more interactive and attractive way of learning, as students were able to learn by experimentation and interaction in the virtual environment. Out of the 18 students, 78% of them thought the textual learning materials were high quality and 56% mentioned that the 3D application helped them understand the system functionality and learn better about solar energy fields [83].

The virtual reality application in [84] provided close-to-reality learning scenarios. Students were fully immersed in a customised virtual simulation of a photovoltaic array. In contrast to a real installation, a supplementary benefit when installing PV panels in this virtual reality environment was the ability to manage failures. This feature encourages investigating and testing various contextual settings and improves the learning process regarding the corresponding topics. The VR application improved students' competencies in PV modules as students were willing to learn about photovoltaic systems with a new immersive learning method. In addition, the interest in the PV array features increased after using the VR application. The study also indicated that experimenting with the PV array in a non-hazardous and 'safe' environment using VR technology was more favourably received. Using VR technology in solar energy education increased student engagement and knowledge retention. The VR environment enabled learners to investigate and interact with PV solar systems in a virtual environment, offering a hands-on learning experience that could be challenging to simulate in a conventional classroom setting.

Research has also demonstrated that VR labs are cost-efficient solutions for universities to offer high-quality laboratory work for their students [82]. In their study, students who tried the 360° panorama environment gave a rating of 5.53 out of 7 for the sense of being in the application, while this was rated at 5.85 by students who tried the 3D-modelled virtual environment. As well as that, a few users had motion sickness after using the virtual reality headset. The authors mentioned that 3D-modelled applications employ an unrealistic virtual environment and do not accurately represent the real-world environment, which affects the quality of the virtual training experience. In addition, the process of developing a virtual environment that is close to real life is time-consuming and it is expensive to create every component in the scene. Using VR in solar energy offered the ability to visualize the consequences of students' actions. Moreover, it allowed students to explore and learn about the performance of the PV modules with different weather statues [85].

In addition, virtual reality offered a hands-on learning experience in solar energy system design that increased the engagement of users in an immersive virtual environment. Moreover, when evaluating the engagement levels between 2D simulation and 3D immersive virtual reality among students, the authors in [86] demonstrated a high average engagement rating for the 3D virtual reality application (4.5 out of 5) according to student responses. Also, a virtual reality environment was examined and compared with the classroom learning way in [87]. A total of 88 students were divided into experimental and control groups. In total, 70% of the participants agreed with the usability of the VR application and 85% enjoyed learning in the virtual world. Moreover, 68.5% indicated that the virtual world enhanced their engagement and for 60%, it increased their motivation. Additionally, 87.5% rated that the virtual world made them better comprehend the course and for 85%, it helped them learn more effectively. A total of 75% mentioned that the 3D objects enriched their knowledge and 90%, stated that 3D objects assisted them in understanding their operational process.

In [88], the VR application was evaluated using a survey of 48 students at the beginning and the end of each laboratory session to check whether the learning objectives were met. The results of this study showed that the students' knowledge increased significantly after they tried the laboratory modules. For instance, the mean students' score was 3.41 out of 5 on in the first survey when asking them to rate their understanding of the fundamentals of solar PV cells, modules and arrays. After finishing the laboratory modules, the mean rate for the question became 4.7 out of 5. In addition, the mean rate was 3.19 for understanding series and parallel solar (PV) cell connections initially, and it increased to 4.87 after trying the application. Students were also asked to provide their comments about the course and the current tool. In total, 82.7% connected this experience to gaming, 76.9% mentioned the effectiveness and the usability of the VR, and 89.1% indicated their increased knowledge and practical skills in solar (PV) cells, modules and arrays. In addition, the authors mentioned that the limitation of using VR applications in solar energy is the requirement for head-mounted displays, which can be costly and not readily adaptable to the general educational content.

A virtual reality environment had the ability to integrate PV plant technology, providing users with a deeper understanding of the design and construction of solar farms. Moreover, it enabled users to learn about solar energy in realistic scenarios, reducing the cost and risk associated with real-life training [89]. Also, a VR solar panel lab allowed students to work remotely on solar energy experiments and acquire knowledge with hands-on experience without having any physical equipment. In addition, a PV lab allowed students to learn about solar energy efficiency issues to reduce the industry's environmental impact [90].

The main limitation of the above studies was the experience of motion sickness associated with using VR headsets. The common symptoms were headache, nausea, sweating, tiredness, vomiting and dizziness [91, 92]. Many studies have investigated the factors that cause VR sickness and approaches to reduce it. Reducing the headset field of view (FOV) was found to be an effective solution to reduce users' discomfort that can happen especially during accelerating and rotating [93]. In addition, many IT solutions aim to address the limitation of heavy VR headsets, enhancing the learning experience and comfort for users. Manufacturers are constantly producing more lightweight materials, including lightweight plastic, to construct virtual reality devices as users feel better when using a VR headset that has a low weight [94]. This helps researchers maintain focus and cognitive performance in learning activities. The other solution to overcome the limitation of using heavy headsets is to use a wireless or standalone VR device, which helps reduce the weight of additional components such as cables and connectors. Moreover, to address the limitation of a blurry display in virtual reality, researchers can use a virtual reality headset with a high-resolution display to provide sharper and clearer images. In [80], the authors mentioned that modelling and simulating a large amount of laboratory equipment is challenging. This challenge can be addressed by using ready-made assets for the VR applications that are available in the game engines' stores such as Unity and Unreal. Additionally, artificial intelligence (AI) technology can help in 3D model generation from 2D images, reducing the time and effort in creating 3D objects [95].

Among all the studies in the review, four studies did not evaluate the effectiveness of using virtual reality technology in solar PV education [78, 80, 85, 90]. In addition, only five studies used a mixed methods approach that combined quantitative and qualitative methods to evaluate the use of virtual reality [79, 82, 84, 86, 88]. This approach helps strengthen the validity of evaluating virtual reality in solar PV education. Additionally, this approach improves the interpretation of the users' outputs. Only one study considered measuring users' vital signs to estimate the users' engagement level and validated these data with a self-reported questionnaire [86]. Biofeedback can provide and monitor the users' physiological processes in real time while using a virtual reality application. Using this method can overcome the limitation of using only a self-reported questionnaire, which can be subjective and influenced by biases. Moreover, the small sample size of some studies might hinder the ability to generalise the reliability of the findings. Therefore, expanding sample sizes would enhance the validity and credibility of the research results.

In fact, it is noteworthy to mention that none of the studies examined the integration of digital twin technology into VR applications for PV system education. This technology offers the promise of significantly improving the learning experience by accurately mirroring physical PV systems within a digital space.

2.4.3 RQ3: How Can Virtual Reality Contribute to Enhancing the Engagement and Participation of Students and Learners in PV-Energy-Related Fields?

Virtual reality can be considered a significant tool to enhance the engagement and participation of students. For example, VR enables students to interact with various components in a PV system. According to the literature, this hands-on experience increases learners' engagement and deepens comprehension.

Generally, incorporating interactive elements and gamification scenarios in VR applications in line with students' active learning enhances students' engagement and achieves a deeper comprehension of the topics, especially when using a variety of modalities such as text, audio, animations and quizzes [38]. In [77], it was shown that 3D constructions and visualizations can enhance students' understanding and make learning more efficient. Constructionism learning approaches were adapted into the virtual reality application, which engaged students with effective learning activities. Approximately 91% of the students who participated in this study (using VR and learning scenarios) indicated that the virtual application enhanced their engagement. In addition, providing an interactive and immersive learning experience and simulating the real world in the VR application enhance students' engagement and participation. Implementing virtual objects in the VR application that are very close to real equipment improved the sense of presence, which correlates with cognitive abilities [80]. The motivational features in the VR application, such as interactions and collaboration, significantly increased students' engagement and they gained higher grades in exams.

A VR application that was designed without external guidance enabled students to remain immersed and engaged until the task was completed [81]. In addition, in order to reinforce learning and increase the students' engagement, VR applications should include audio instructions, educational animations and game-like interaction. Students can receive personalised instructional procedures in VR environments, where they can explore and learn at their own pace and schedule. This can improve students' participation in the educational materials. For example, the renewable energy sources (RES) topic was considered a difficult domain for learners to comprehend. Therefore, virtual reality learning approaches were combined with conventional learning to teach the RES subject more effectively. This was suggested to enhance students' and learners' engagement and participation in renewable-energy-related fields [83].

In [84], the building structure and the environment were designed using Google map terrain meshes and photogrammetry data, which guaranteed the virtual environment matched reality as much as possible. This approach increased the immersion in the virtual environment as students interacted with the PV modules as real objects. In addition, VR technology allowed learners to explore and interact with solar energy technologies and offered hands-on experience, which increased students' engagement and motivation [82]. VR technology can simulate real-life scenarios and allow students to explore and comprehend the consequences of their actions, increasing their engagement with the educational materials. Also, VR technology provides isolation from the external environment enabling the reduction in distraction and increasing the level of students' attention to the educational content [85]. Simulating the real world and interacting with 3D objects in the VR environment for solar energy system design keeps students engaged and immersed in the virtual environment. Moreover, providing immediate feedback on users' decisions, for example, adding or removing solar panels and displaying the outcomes of the system directly by the gauge chart, enhances engagement by enabling students to see the consequences of their actions in real time [86]. The study compared users' engagement levels in a 2D simulation and a 3D immersive VR application. The students gave a rating of 4.5 out of 5 in terms of their feelings of engagement with the VR application. This led students to focus and encouraged them to move to critical thinking and to be able to retain more information. Additionally, using avatars in the virtual world contributed to increasing the sense of presence and awareness and facilitated the way of interacting with the virtual constructions to learn about photovoltaic cells and their functionality, which in turn enhanced communication and cooperation among students and tutors [87].

Nevertheless, the integration of virtual reality technology in education faces several ethical and practical issues such as privacy, accessibility and cost. Sensitive data such as users' behaviour profiles and interactions within VR environments, raise privacy concerns about protecting data and the misuse or unauthorised access to personal information. This can lead to identity theft, which is a major concern for virtual societies [96], or the sharing of personal data with third parties [97]. Accessibility concerns can be noted in terms of the use VR headsets by people with disabilities [98] and socioeconomic accessibility that refers to the affordability of VR devices [99]. Moreover, the high cost of VR headsets represents an obstacle to its widespread adoption in educational institutes, restricting access for schools with limited resources.

2.4.4 RQ4: What Innovative Approaches Exist for Integrating Real-Time Data from Solar Energy Systems into Virtual Reality Environments, and How Can This Integration Lead to Better Decision Making and Performance Optimisation?

Integrating real-time data from renewable energy systems into virtual reality environments gives students a more realistic and engaging experience, allowing them to better understand the performance of renewable energy systems and investigate the effect of any modifications in the system simultaneously.

Frank et al. in [78] proposed a way to generate real-time data while interacting with a 3D renewable energy system in their VR application. To simulate the same data that students would have in a laboratory experience, MATLAB was connected to Unity using TCP/IP (Transmission Control Protocol/Internet Protocol), setting Unity as the server and MATLAB as the client. In this way, the researchers were able to send Unity the calculated parameters. Ultimately, they implemented the code into Unity by developing C# scripts. Therefore, integrating real-time data from solar energy systems into a virtual reality environment helped students experience a real-world laboratory setting. It also offered students an immersive and more realistic experience, enhancing their comprehension of the performance of the solar energy system.

To integrate live data in a virtual reality environment, the study in [84] explained that by using a web interpreter engine, the display of incoming data was expedited using full-spectrum responsive web technologies, offering a wider range of animations and UI capabilities than the Unity UI system. In addition, using the network-based approach made it possible to offer legacy data from a web-based database. This approach helped broaden the scope of educational content by enabling learners to customise and change the learning materials and experiment with different result states according to individually chosen criteria. The degree of immersion and direct presentation of the output of the PV systems in the VR application motivated students to comprehend and investigate all facets of the PV array.

A network interface, combined with a dynamic weather system, can be incorporated in order to transfer data from the real PV array into the virtual one [85]. Users could select the current weather or any historical data from any period back to 2015, based on the data gained from OpenWeatherMap API. The selected data was synced with the value obtained from a network interface, with a guarantee that the outputs from the actual PV array and weather display coincide. This approach ensured live data and allowed for the inclusion of any historical state to create great versatility in scenarios to experiment with. As a result, users were allowed to access any previous data of the PV array and tested different outcomes based on various parameters, i.e., weather conditions, allowing a broader range of educational materials to be explored, such as inspecting PV modules and exploring their characteristics in the VR environment.

Table 2.2 presents a summary of the review findings, including the learning theory applied in the study, evaluation methods of the VR application, the VR headset used as well as the advantages and disadvantages of using VR for solar PV education.

Table 2.2: Summarising the papers that met the review criteria in the review.

Ref	**Learning Theory**	**Method to Evaluate the Effectiveness**	**HMD**	**Pros and Cons**
[77]	Operational learning and game-based learning	Pre- and post-tests were taken by 105 students enrolled in the renewable energy course	-	Pros • Attracted student's interest. • Entertained and improved students' performance. • Facilitated collaborative learning. • Achieved efficient learning. • Increased motivation and engagement.

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Table 2.2 – continued from previous page

Ref	**Learning Theory**	**Method to Evaluate the Effectiveness**	**HMD**	**Pros and Cons**
[78]	Experiential learning	Not tested yet	-	Pros • Bridged the gap between theoretical approach and experimental activities. • Supported remote experiential and virtual laboratory learning. • Provided a replicable and scalable immersive educational model. • Improved students' understanding and gaining knowledge. • Developed a learning-by-doing environment. • Enhanced information retention. • Promoted critical thinking.

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Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[79]	-	A satisfaction survey and a test for 28 final year students in electrical engineering from the University of Colima on renewable energies course. The students were divided into a traditional training group and a virtual-reality-assisted training (VRAT) group.	Oculus Rift	Pros • Offered training in installing a photovoltaic farm. • Motivated self-learning. • Provided laboratory practices in case of lack of equipment. • Offered a realistic experience. • Provided effective teaching time. • Provided a platform to learn by interacting in a visual, auditory and kinaesthetic way. • Improved students' knowledge. • Visualised all the technical details of the PV installation. Cons • Dizzy after using the headset. • Uncomfortable using the headset for students with visual problems.

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Table 2.2 – continued from previous page

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[38]	Game-based learning	Survey for 12 students from the University of Glasgow	Oculus Quest2	Pros • Understanding of PV systems. • Raised student awareness for solar energy. • Reinforced and assisted learning. • Promoted learning in a fun and interactive way. Cons • Cybersickness after using the headset. • Students needed assistance in grabbing and installing solar panels.

Continued on next page

Table 2.2 – continued from previous page

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[80]	-	Not tested yet	-	Pros • Simulated complex processes. • Worked safely in dangerous situations. • Visualized the most complex and bulky real objects. • Provided accessible and fun learning. • Improved the quality of training in the PV field. Cons • Simulated a large amount of laboratory equipment.

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Table 2.2 – continued from previous page

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[81]	Game-based learning	A survey for 44 students after using the VR application.	Oculus CR1	Pros • Provided users with the knowledge and visual experience of a facility without physically visiting the location. • Provided remote access to disciplines. • A cost-efficient method for high-quality laboratory work. • The virtual lab allowed the sharing of costly equipment and resources. • Facilitated virtual hands-on learning. • Fun and informative. Cons • Blurry. • The audio was too low. • Confusing application. • Heavy headset.

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Table 2.2 – continued from previous page

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[83]	Experiential learning	A survey questionnaire for 18 students in Mechanical Engineering Section	-	Pros • Provided interaction with 3D devices and constructions. • Attractive and effective way of learning. • Visualized theoretical concepts. • Offered a sense of presence. • Enhanced communication and collaboration between students and tutors. • Assessed students' understanding of the functionality of solar energy systems. • Students could study anytime even without a tutor.

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Table 2.2 – continued from previous page

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[84]	Game-based learning	Pre- and post-test online questionnaires and semi-structured individual interviews for 7 students from Photovoltaics and Energy Systems course	Oculus Quest	Pros • Provided hands-on learning. • Visualised many components that were too abstract to imagine such as power couplings and their integration into the grid. • The representation of the PV array was similar to their real experiences . • Error tolerance. • Visualised a real PV array located in the faculty building of the University. • Felt safe using VR in the COVID-19 pandemic. • Usability. • Learning motivation using a new method of learning. Cons • Motion sickness. • Illegibility of the menu text.

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Table 2.2 – continued from previous page

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[82]	Experiential learning and game-based learning	pre-and post-tests and a presence questionnaire with 28 students who were divided into two groups to test 360° panorama VR training application and 3D-modelled virtual environment; then a comparison questionnaire	Oculus Go	Pros • Provided remote access. • Provided hands-on experience. • Cost savings. • Flexibility in experiments. • Multiple user access. • Damage resistance. • Avoided weather issues. • Access to online teaching environments. • Informative. • The 360° panorama application was more realistic than the 3D-modelled VE. Cons • Low-quality pictures for the 360° panorama application. • Experienced a blurry display.
[85]	-	Not tested yet	-	Pros • Provided cooperation and group work. • Changed properties of the solar PV.

Continued on next page

Table 2.2 – continued from previous page

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[86]	-	Measuring users' vital signs using two biosensors (FMCW radar and a medical grade belt) and self-reported questionnaires for 4 students	Oculus Quest2	Pros • Offered a higher user engagement level than a 2D simulation. • Provided interaction with the solar energy system components. • Enabled users to notice the amount of electricity generated in different scenarios. • Participants enjoyed the immersive learning experience.
[87]	-	Pre- and post-test for 80 students enrolled in the RES course. Students were divided into two groups (experimental and control group)	-	Pros • Offered a sense of presence. • Provided collaboration between students and their tutor. • Developed virtual library. • Enhanced students' engagement and motivation. • Enriched knowledge. • Offered a better understanding of the operational processes. • Effective learning.

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Table 2.2 – continued from previous page

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[88]	Game-based learning	Pre- and post-test surveys for 48 students and formative assessment approach (testing students while using the VR application by a series of questions with feedback based on students' responses)	-	Pros • Growth in student engagement. • Increased students' knowledge and hands-on skills regarding solar (PV) cells, modules and arrays. • Enjoyable learning experience. Cons • Costly headset.
[89]	-	The System Usability Scale (SUS) questionnaires for 30 participants	-	Pros • Enhanced users' skills in solar farm training. • Risk-free training environment. • Reduced requirement for specialised training facilities. • Learning from mistakes. Cons • Feeling dizzy.

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Table 2.2 – continued from previous page

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[90]	-	Not tested yet	-	Pros • Replaced the physical solar energy lab. • Provided in-depth learning about solar energy. • Worked remotely in a solar experiment. • Provided hands-on experience without physical equipment.

2.5 Recommendations for Developing Future VR Applications in Solar PV Energy Education

According to the systematic review, it was found that there is a need to improve curricula in line with recent technology in solar PV energy education. Virtual reality simulations should be considered in the curricula for educational institutions that focus on PV energy, where students can receive practical insights into renewable energy systems and enhance their understanding through hands-on experiences in a virtual laboratory. Virtual reality in solar energy education should place a higher priority on intuitive interactivity and immersion to prepare engaging and memorable learning experiences.

The systematic review highlights the urgent need to enhance our curricula to keep pace with constant advancements in photovoltaic (PV) systems and meet our net-zero climate change targets. It indicates that incorporating virtual reality (VR) simulations into educational programs could benefit student learning. VR simulations allow students to gain practical insights into PV systems and deepen their understanding through interactive experiences in a simulated laboratory environment. Notably, interactivity and immersive experiences provided by VR can create engaging and memorable learning opportunities. Moreover, the review showed that many VR applications promote collaborative learning by allowing multiple users to interact with each other in the same VR environment. This encourages teamwork, problem-solving and simulates collaboration on actual solar energy projects.

To further deepen the impact of VR, VR simulations should strive to provide highly realistic representations of solar PV systems. This includes incorporating accurate physics modeling, authentic weather scenarios and dynamic systems that adjust based on user inputs. Additionally, integrating real-time data from actual solar energy systems into VR applications could offer students genuine experiences. This allows them to analyze and improve system performance using data derived from real solar panels.

Considering these recommendations, VR can enhance solar PV teaching, since it provides learners with immersive, engaging and effective learning experiences that enable them to face the challenges of the solar PV industry. In addition, using VR for designing a solar energy system has the potential to democratise the design process, ensuring that is not limited to a select few experts.

To address limitations in VR technology, 360-degree panoramic virtual environments offer a cost-effective alternative. These environments use real-world footage, which eliminates the need for computer-generated graphics and enables accurate representation as well as a high level of immersion and sense of presence [82]. Moreover, to overcome the high cost of Head-Mounted Displays (HMDs), academic institutions might consider using low-budget mobile VR sets, such as Google Cardboard and Samsung Gear VR. This approach would facilitate wider access and enable everyone to experience immersive virtual reality learning [100].

2.6 Summary

A growing focus on photovoltaic (PV) energy education is being driven by the urgent need for sustainable energy alternatives to combat the effects of climate change. Therefore, the use of virtual reality (VR) technology in solar PV education was reviewed. The review demonstrates a strong interest among most studies in using VR as a key tool for providing an interactive and immersive learning experience, thereby enhancing users' understanding of PV energy systems.

The majority of the literature focused on PV system installation, explaining the function of each component and electricity generation. It also explored the relationship between changes in parameters and their impact on energy production. Additionally, the literature demonstrated how VR can simulate real-world scenarios, allowing users to visualise, interact with and manipulate PV systems in dynamic environments.

In summary, virtual reality technology effectively enhances experiential learning, fostering deeper engagement and improved knowledge retention through hands-on simulations. However, despite its potential, several limitations have been identified in using VR for PV system education. For example, motion sickness is a common side effect that can significantly impact the learning experience. Additionally, hardware and software issues can arise, which potentially hinder the overall effectiveness of VR-based PV education. To address these limitations and pave the way for future VR advancements in the solar PV sector, several recommendations derived from the findings of this review were proposed.

Chapter 3

Student Perceptions of Renewable Energy Systems Design using VR

This chapter demonstrates the role of VR in renewable energy education by combining insights from student perceptions and innovative teaching approaches. First, it examines the use of a VR hackathon as an innovative teaching method, showing how collaborative problem-solving and practical VR development may improve students' learning, cooperation, and awareness of sustainability issues. The chapter then discusses the use of virtual reality (VR) in photovoltaic (PV) system design, evaluating how well it enhances user interaction and comprehension in comparison to traditional teaching approaches. The chapter concludes by discussing the development and improvement of a virtual reality application specifically suited for solar energy system design, incorporating feedback from the previous implementation to enhance usability, engagement, and educational impact.

3.1 Empathy, Education and Awareness: A VR Hackathon's Approach to Tackling Climate Change.

Tackling some of the world's toughest environmental challenges requires widening the scope of education and training to accelerate our energy transition to zero carbon by 2050 [101]. Moreover, reducing our carbon emissions will help limit the effects of climate change [102]. In fact, replacing fossil fuels with renewable energy can potentially achieve 90% of the required carbon reductions [103]. However, the traditional methods of teaching and training students in renewable energy system design have been significantly hampered by COVID-19 social distancing restrictions, which have made it challenging for students to gain practical, hands-on experience [104]. To address this challenge, this study explored the effectiveness of a constructionist-based learning approach [105, 106]. Students were encouraged to use virtual and augmented reality (VR/AR) technology to build their own immersive virtual environments. This facilitated easier, safer, and faster visualisation and understanding of climate change's impact and how renewable energy systems can mitigate it.

The preliminary findings using virtual reality (VR) for teaching solar energy system design have already shown a positive student experience [38]. The motivation was to develop a curricular innovation in teaching renewable energy technologies using modern technology tools as a compelling offering for tackling climate change issues.

The literature suggests that VR and augmented reality (AR) training enhances the user's intrinsic motivation, which improves their learning and performance when transferring skills from the virtual environment to the real world [107]. This risk-tolerant learning environment can be transformative for design learning [108]. Additionally, creating a learning space where students can transfer theoretical information to tackle real-world challenges enables educators to develop skills in teamwork, communication, and problem-solving among students. [109]. Moreover, the literature suggests that immersive environments create a much more stimulating learning experience since students become active participants, rather than bystanders in the learning process [110, 111]. Furthermore, VR/AR can expose students to new experiences that would otherwise be impossible, costly, or dangerous [112, 113]. For example, students would not be able to accelerate time to witness rising sea levels in coastal cities like Alexandria [114], a consequence of greenhouse gas (GHG) emissions linked to climate change [115], nor could they experience the heat-trapping effect of burning diesel fuel in the atmosphere [116]. Therefore, immersive VR and AR can deliver meaningful climate change content and test how students think and respond to these issues, particularly given the complexity and abstract nature of climate and environmental changes [117, 118]. One major barrier to tackling climate change is the perception that it is a distant threat, unconnected to people's daily lives. This psychological distance often leads to a sense of detachment [118, 119], whereas VR allows users to visualise information and future scenarios.

Therefore, this student-centred teaching intervention aimed to achieve its objectives by inviting penultimate-year engineering and computer science students to participate in a 3-day hackathon to raise empathy, education and awareness around four UN SDGs (depicted in the concept image shown in Figure 3.1. Evidence suggests that these programmes offer students an opportunity to forge relationships with new staff/students and to gain new skills [120]. The term "hackathon" combines the words "hack" and "marathon" and denotes an extended, focused time spent developing a project [121]. Hackathons have been used as an educational tool to help students learn social skills, such as teamwork and collaboration, or to raise students' curiosity about learning new things [122]. Educational hackathons provide an informal setting to enhance the learning experience. Depending on the learning objectives, these hackathons might provide varying formats and durations [123].

During the hackathon, participating students compete against each other in developing VR applications to help raise awareness, empathy, and education around climate change. This teach-

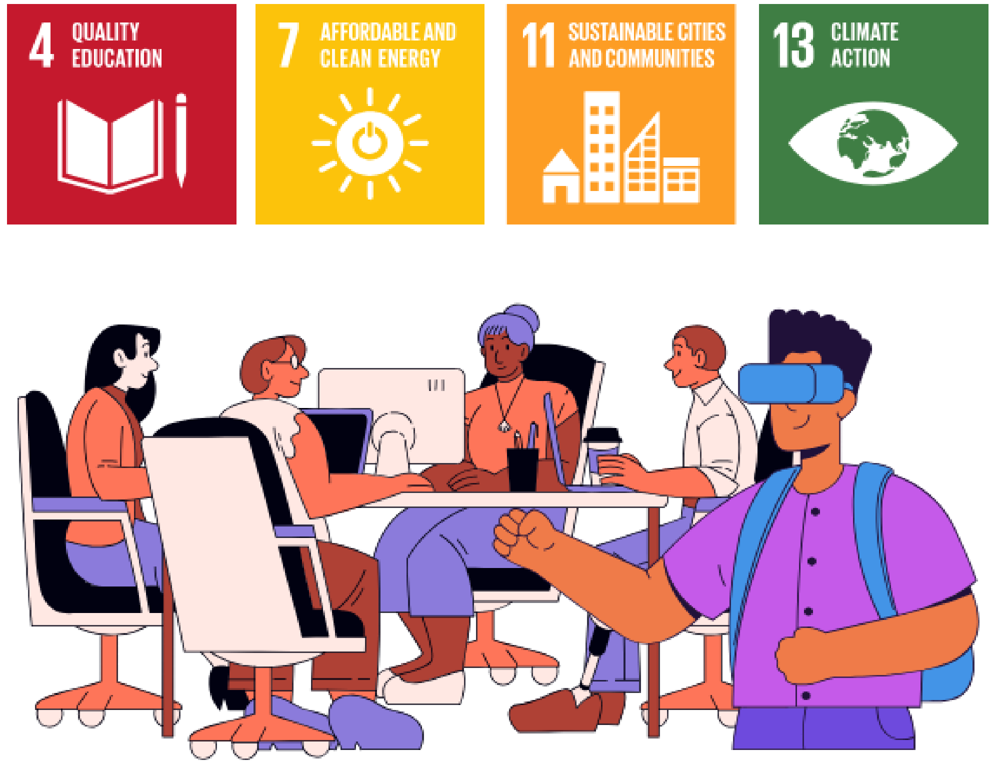


Figure 3.1: Conceptual illustration of virtual reality (VR) used in a collaborative environment for addressing real-world climate change challenges. Image generated using artificial intelligence-based image synthesis techniques.

ing intervention aimed to give students the opportunity to improve their technical understanding of renewable energy technologies that can effectively counterbalance the negative impact of climate change, as well as improve the sustainability of their local communities. Another motivation was to give students opportunities to develop their digital literacy skills, as well as critical soft skills that include teamwork and collaboration all of which will help prepare the next generation of students to tackle global climate change issues.

The intended learning outcomes (ILOs) of the teaching activity were twofold:

1. Understanding and application of the UN's Sustainable Development Goals (SDGs) [124]: By the end of the intervention, students will demonstrate a comprehensive understanding of the selected UN SDGs and the associated climate change issues. They will be able to apply these concepts to analyse real-world environmental problems and propose sustainable solutions, thereby showing their readiness to contribute meaningfully to the field of climate change and sustainability.

2. Proficiency in VR/AR technologies: Students will acquire proficiency in using VR/AR technologies as tools for learning and problem-solving. They will demonstrate the ability to effectively use these technologies to create immersive experiences, model complex systems, and visualise solutions. This proficiency will prepare them for future roles in technology-driven fields and give them a competitive edge in the job market.

3.1.1 Background and Motivation

Empirical evidence of the effectiveness of VR in changing environmental attitudes has been reported in the literature [125, 126]. For example, Markowitz et al. in [127] assessed the effectiveness of an immersive VR environment as a teaching tool to elucidate climate change effects, particularly ocean acidification. The findings of one experiment of this study confirmed the potential of immersive VR in fostering knowledge about important social issues and showed a positive environmental attitude of students. Fonseca and Kraus in [128] conducted a study to examine the effects on the environmental attitude and behaviour of the narrative content and immersion level. According to the findings, the degree of immersion raised the viewers' emotional response and pro-environmental attitude.

Therefore, below are the systematic research questions (RQs) and hypotheses (Hs) that were formulated to guide the study:

- Research Question 1 (learning effectiveness): How does the integration of VR/AR technology in a constructionist learning environment, specifically within the context of a VR hackathon, enhance students' comprehension and application of the selected UN SDGs? How does this innovative approach influence their capacity to address real-world climate change challenges?

  - **Hypothesis 1** (learning effectiveness)**.** *The immersive, hands-on approach of the VR hackathon will significantly improve participants' understanding and knowledge of the four selected UN SDGs and climate change issues compared to traditional classroom-based learning methods.*

- Research Question 2 (technology familiarity): How does the VR hackathon experience influence students' proficiency and comfort with VR/AR technologies? How does this immersive learning context impact their preparedness for future technologically oriented roles?

  - **Hypothesis 2** (technology familiarity)**.** *Participation in the VR hackathon will significantly increase students' familiarity and competence with VR/AR technologies, thereby enhancing their preparedness for future technological roles in their respective fields.*

- Research Question 3 (teamwork and collaboration): How does the team-based collaborative nature of the VR hackathon contribute to the development of students' teamwork and problem-solving skills, and how does this prepare them more effectively for real-world engineering scenarios? Does it enhance their ability to work collaboratively and effectively as a team?

  - **Hypothesis 3** (teamwork and collaboration)**.** *The collaborative nature of the VR hackathon will significantly enhance participants' teamwork and problem-solving skills, preparing them more effectively for real-world engineering scenarios. Moreover, the metaverse breaks down barriers and enables learners to work together in teams.*

- Research Question 4 (authentic assessments): How do students perceive the authentic assessments used in the VR hackathon in terms of reflecting real-world engineering scenarios and measuring understanding and skill application compared to traditional assessment methods?

  - **Hypothesis 4** (authentic assessments)**.** *The authentic assessments used in the VR hackathon (developing an app that raises empathy, education, and awareness around 1 of 4 SDGs) will be viewed as significantly more reflective of real-world engineering scenarios and effective in measuring understanding and skill application compared to traditional assessment methods.*

- Research Question 5 (overall experience): How do students rate their overall experience of participating in the VR hackathon compared to traditional classroom-based learning experiences, and what factors contribute to higher student engagement and motivation?

  - **Hypothesis 5** (overall experience)**.** *The overall experience of participating in the VR hackathon will be rated significantly higher by students compared to traditional classroom-based learning experiences, leading to higher student engagement and motivation.*

These questions were investigated using mixed research methods consisting of surveys and interviews. The research aimed to inform how the use of VR/AR technology in raising awareness around the UN's SDGs can be scaled up and integrated into broader educational programmes to enhance the impact of this innovative pedagogical approach.

3.1.2 Teaching Approach and Delivery

This innovative approach to teaching and delivery involved organising a three-day immersive hackathon in Cairo (as shown in Figure 3.2), incorporating team-based learning (TBL) [129] and authentic assessments to respond to demands from engineering accreditation bodies. This hackathon aimed to raise awareness around four key UN SDGs: SDG 4 (Quality Education), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

Assessing and evaluating the impact of VR/AR technology in climate change education has been explored through various techniques in the literature. For example, pre and post tests were used to measure students acquiring knowledge and information retention. Also, questionnaires can be used to gather students' feedback regarding their experience using VR/AR regarding their engagement, satisfaction, and effectiveness. Moreover, qualitative data from interviews or focus groups can provide rich insights into the impact of using these technologies towards climate change and renewable energy education. To comprehensively evaluate the effectiveness of integrating VR/AR, a combination of these methods was used.

For delivery, on the inaugural day, an opening ceremony began to introduce the purpose of the hackathon and keynote speeches by two renowned experts in Africa discussing the interplay of VR/AR and artificial intelligence (AI). Following these keynotes, participants engaged in workshops on various VR/AR tools and platforms to equip them with the necessary skills. The day continued with two lightning talks by industry professionals shedding light on the interconnection of the selected SDGs with VR/AR technologies. The afternoon was dedicated to team formations, where participants pitched their ideas and formed teams, later spending the remainder of the day refining their concepts and planning their projects. The second day was primarily dedicated to hacking and development. Check-in sessions each morning and evening were organised to monitor progress and address any challenges encountered by the teams. The third day followed a similar pattern, with the majority of the day spent on project development. The latter part of the day focused on prototype testing and iterative improvements.

The final day of the hackathon saw teams putting the finishing touches on their projects and rehearsing their presentations. After a networking lunch, teams presented their VR/AR experiences to the judges and audience, who evaluated projects based on innovation, impact, relevance to the selected SDGs, and technical achievement. The event concluded with an awards ceremony, where winning teams were recognised for their exceptional work. Figure 3.2 demonstrates the VR hackathon agenda during the three days.

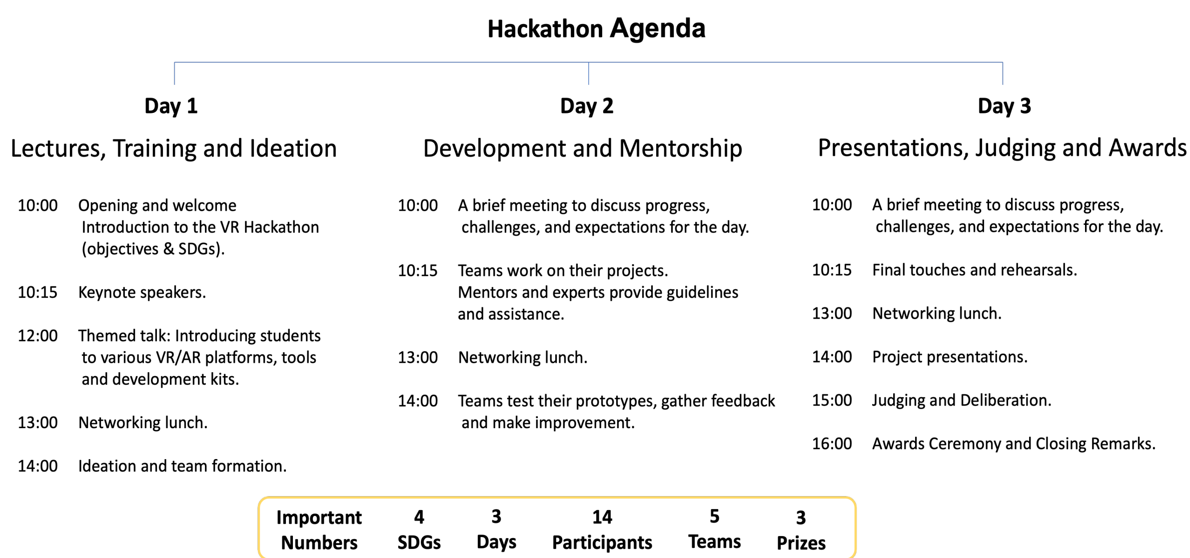


Figure 3.2: The 3-day schedule for the VR hackathon.

3.1.3 Methodology

Recruiting the right participants was crucial to the hackathon's success. Students from science and engineering disciplines were invited to apply through a form, providing their names, emails, and reasons for interest in the VR hackathon, followed by their CVs. A flyer was distributed to all undergraduate students through social media. Specifically, students from interdisciplinary backgrounds including computer science, computer engineering, information and computer systems, mechanical engineering, and renewable energy were targeted. The goal was to ensure that students with complementary backgrounds could team up to develop creative VR solutions. By inviting students from diverse areas with skills in programming, design, and engineering, the aim was to foster the creation of innovative VR projects.

Out of 36 interested students who submitted applications and motivation letters, 22 were shortlisted based on their technical skills for VR development, including proficiency in programming languages. Additionally, commitment to attending the entire duration of the hackathon was considered. Finally, the motivation letters helped identify participants with a genuine passion for VR technology and a strong interest in tackling climate change. This resulted in the selection of 14 participants.

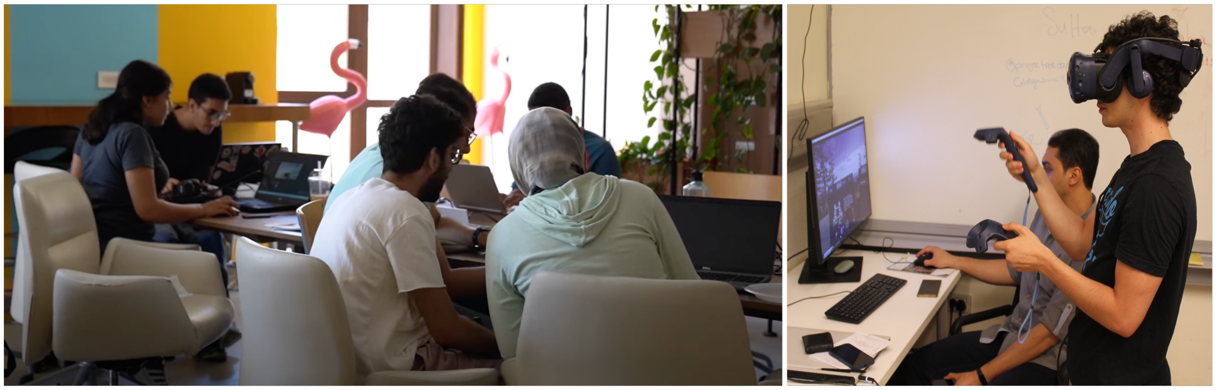
The selected students were divided into five groups, each advised by a senior graduate teaching assistant. Additionally, three academic staff members oversaw the project. To develop their applications during the 3-day hackathon, students were grouped into teams of 3 with complementary skills, except for one team with 2 members. Upon satisfactory completion of the hackathon, students received a certificate of completion.

In a boardroom format, a panel of staff members from AUC, UoG, and the British Council judged student presentations, evaluating team designs and awarding VR headsets to the winning application. Each group was also assigned a graduate student who acted as a mentor and provided technical troubleshooting, as well as domain-related content assistance in building their virtual worlds. On the last day of the hackathon, students showcased their designs via a 10-minute group oral presentation.

A series of questions were designed to assess each presentation based on three key criteria: clarity and organization, understanding and application of the SDGs, and use of VR/AR technology. The HTC Vive and Meta Quest 2 VR headsets were offered to students during the hackathon. Moreover, during the hackathon, game engines such as Unity and Unreal were used by the participants to develop and create their VR applications.

3.1.4 Survey Design

Based on the approach outlined in [109], the evaluation of this teaching activity involved securing participant consent beforehand. Students were assured of the voluntary nature of their involvement and the anonymity and confidentiality of the data collected. They were also advised



(A) (B)

Figure 3.3: (A) The students were divided into groups to work on developing and testing their VR applications. (B) One group was testing their VR application using the HTC Vive headset.

that their participation could be withdrawn whenever they wished.

An online survey with 23 questions was designed and distributed to gather student feedback regarding the effectiveness of this teaching approach, as shown in Table 3.1. These questions were divided into five Parts to measure the five research questions and hypotheses. The first five questions in Part 1 were designed to collect student opinions regarding their understanding of the UN's SDGs and their overall awareness of climate change issues (RQ1). Students were invited to indicate their learning experience via a 5-point Likert scale ranging from 1 (disagree entirely) to 5 (agree entirely). Moreover, while open-ended questions can yield rich, qualitative data, they can also be time-consuming for respondents to answer and for researchers to analyse [130, 131]. Therefore, I preferred a more structured response and gave students multiple options to choose from. Part 2 of the questionnaire consisted of structured questions asking students to rate the skills they developed throughout the hackathon (RQ2). Part 3 included three questions designed to collect responses about the assessment's quality (RQ3). Part 4 was focused on collecting insights into the students' experiences with teamwork (RQ4). Lastly, Part 5 of the survey contained questions aimed at capturing the students' overall experience during the hackathon (RQ5).

Table 3.1: Survey questions used to evaluate the effectiveness of the teaching approach.

Question	Description
Q1	Before the hackathon, how would you rate your understanding of the four SDGs (SDG 4, SDG 7, SDG 11, SDG 13) on a scale of 1-5?
Q2	On a scale of 1-5, how would you rate your understanding of these SDGs after the hackathon ?

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Table 3.1 – continued from previous page

Question	Description
Q3	How effectively do you feel the hackathon enhanced your understanding of climate change issues?
Q4	On a scale of 1-5, how confident do you feel in explaining these SDGs and their importance to others after participating in the hackathon?
Q5	Which of the following best describes how your understanding of the SDGs has improved as a result of the hackathon? (Choose all that apply)
Q6	Before the hackathon, how would you rate your familiarity with VR/AR technologies on a scale of 1-5?
Q7	After participating in the Hackathon, how would you rate your familiarity with VR/AR technologies?
Q8	To what extent do you agree with the following statement: "The Hackathon significantly improved my ability to use VR/AR technologies.
Q9	How useful do you think the skills you learned at the Hackathon (related to VR/AR technologies) will be in your future studies or career?
Q10	After participating in the hackathon, please rate your proficiency in the VR skills below on a scale from 1 to 10, with 1 indicating minimal proficiency and 10 indicating mastery.
Q11	On a scale from 1 to 5, to what extent did the practical assignments, such as project development and presentations, accurately represent scenarios you might encounter in real-world engineering contexts?
Q12	On a scale from 1 to 5, how effectively did the authentic assessments measure your understanding of the SDGs and your ability to apply VR/AR technologies?
Q13	On a scale of 1 to 5, to what extent do you agree with the statement: 'The assessments provided valuable feedback on my learning progress'?
Q14	Can you provide examples of how the authentic assessments enhanced your understanding of real-world applications of your learning? (Choose all that apply)
Q15	On a scale of 1 to 5, to what extent do you agree with the statement: 'The authentic assessments enhanced my learning experience during the hackathon'?
Q16	Reflect on your teamwork and problem-solving skills before and after the hackathon. On a scale of 1-5, to what extent do you agree with the following statements?
Q16a	I share positive opinions about the team's decision-making ability.
Q16b	I share positive opinions about the team's ability to achieve objectives.
Q16c	I share positive opinions about the team's ability to motivate each other to complete tasks.

Continued on next page

Table 3.1 – continued from previous page

Question	Description
Q16d	I give my colleagues feedback about their performance.
Q16e	I ask my colleagues for feedback about my performance.
Q16f	I ask my colleagues for help when I am unable to finish my part of the work.
Q16g	I provide solutions for the problems inherent in the task.
Q16h	I collaborate in order for us to coordinate our work.
Q17	After participating in the VR Hackathon, how confident are you in your ability to work as part of a team in real-world engineering scenarios?
Q18	To what extent do you agree with the following statement: "The collaborative nature of the VR Hackathon significantly enhanced my teamwork skills."
Q19	On a scale of 1-5, how would you rate your overall experience with the hackathon, where 1 is 'Very Poor' and 5 is 'Excellent'?
Q20	Would you recommend this hackathon to other students?
Q21	What aspects of the hackathon did you find most beneficial for your learning?
Q22	What improvements would you suggest for future versions of this hackathon?
Q23	Following your participation in the hackathon, how has your motivation to pursue further learning or career opportunities in the field of VR/AR technology changed? Please rate on a scale of 1-5.

3.1.5 Results

Throughout the hackathon, students were given the freedom to develop any kind of project they liked as long as it helped raise awareness regarding one of the stated SDGs. Examples of the student games are illustrated in Figure 3.4. For example, one of the VR projects was a multiplayer VR game that raised awareness of SDG 7, Affordable and Clean Energy. In each round of the game, players were given a certain budget to invest in any kind of energy: fossil fuel, solar energy, wind energy, etc. Their choices are reflected on the scoreboard, where their goal is to produce the biggest amount of energy while keeping the environmental damage at a minimum. In fact, AUC's Media Relations Unit helped compile a short video (https://www.youtube.com/watch?v=oByg9jLqu1U, (accessed on 14 March 2024)) demonstrating the teaching process.

According to the survey of participants during the registration, the majority, 40%, took part in the hackathon to learn about using VR technology and building an application. In addition, 20% of the students were interested in using virtual reality in solving global challenges, while 15% were interested in spreading awareness and environmental concerns to people. Figure 3.5 demonstrates students' approaches to participating in the hackathon.

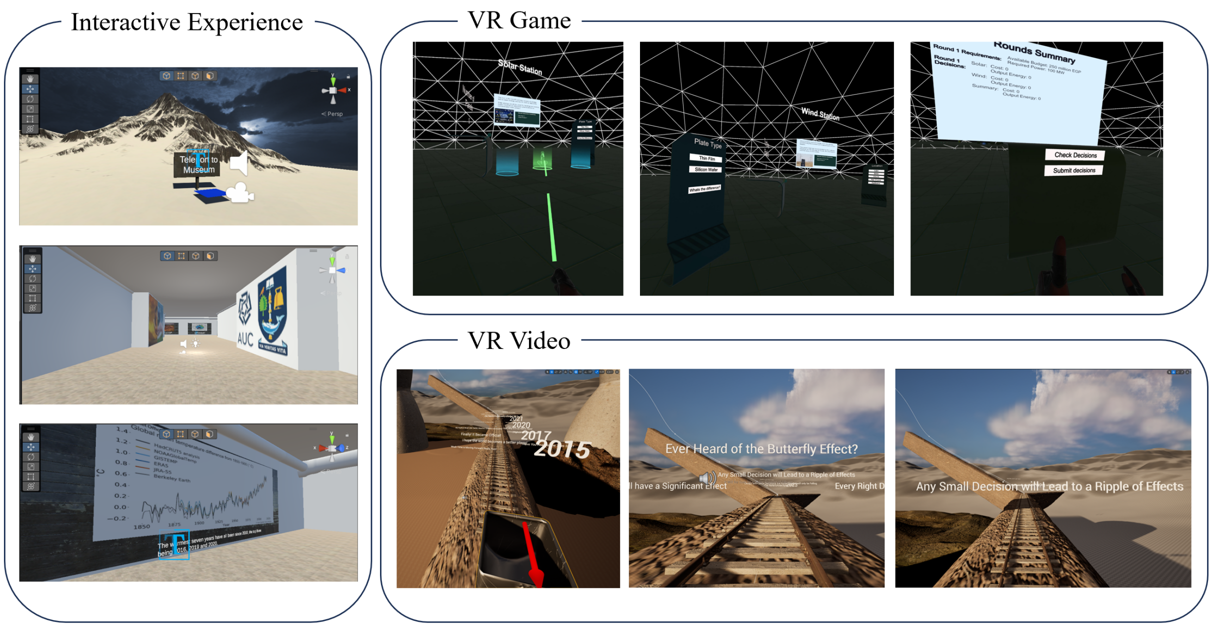


Figure 3.4: Snapshots from students' work during the hackathon. The projects that the students developed were diverse in regard to the output product; some created Interactive Experiences, some created VR games, and some created VR videos.

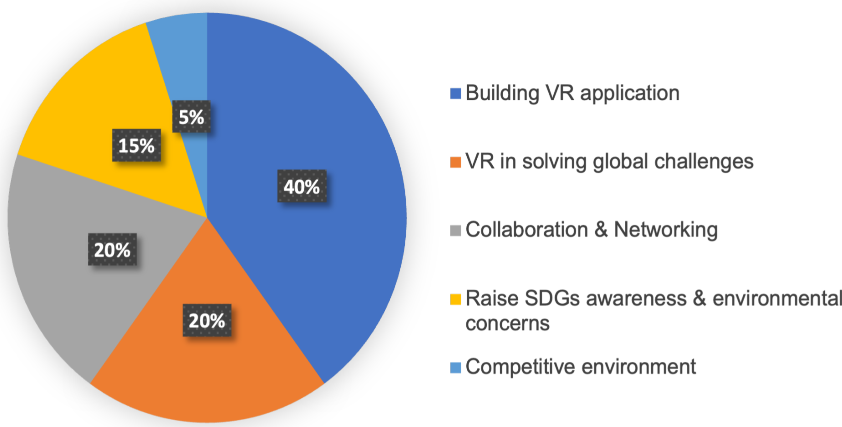


Figure 3.5: Distribution of students' motivations for participating in the Virtual Reality (VR) Hackathon. The chart highlights a range of incentives, with the majority (40%) of participants specifically citing their eagerness to develop a "VR application". Other reasons include using "VR for solving global challenges" and for networking opportunities.

3.1.5.1 RQ1: Learning Effectiveness

The first two questions in the survey were about rating the participants' understanding and comprehension of the four SDGs before and after the hackathon. The results showed a significant improvement in the SDGs' understanding after the hackathon as 63.6% of the students rated 5 "Excellent" and 27.3% rated 4 after the hackathon. Figure 3.6A demonstrates the notable improvement after participating in the VR hackathon.

Also, 45.5% of the students rated 5, as extremely effective, and 27.3% rated 4 on how effectively they believed the hackathon had enhanced their understanding of climate change issues. In addition, when asking the participants how confident they felt in explaining the significance of these SDGs to others, after participating in the hackathon, 27.3% rated 5 as extremely confident and 54.5% rated 4.

When asking the participants to select the best option that describes how their understanding of the SDGs has improved as a result of the hackathon, the majority of the students, 45.5%, selected that they had a better understanding of the role of technology (e.g., VR/AR) in advancing the SDGs. Figure 3.6B shows the results of the participants for this question.

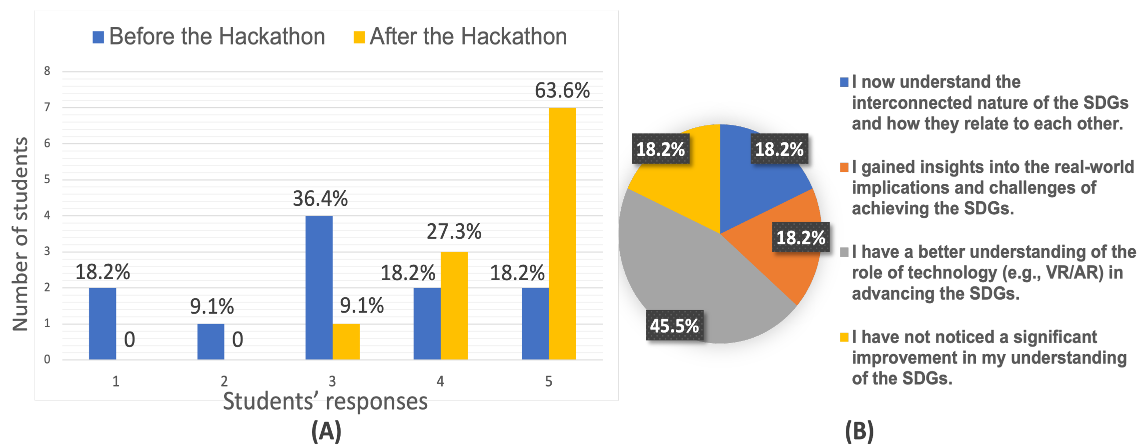


Figure 3.6: (A) Students' understanding of the SDGs, as measured on a scale of 1 (Very Poor) to 5 (Excellent) after taking part in the 3-day hackathon. The pie chart in (B) demonstrates which areas students saw the greatest improvement in as a result of participating in the hackathon.

3.1.5.2 RQ2: Technology Familiarity

Two questions in the survey were about rating the participants' familiarity with VR and AR technologies before and after participating in the hackathon. The results in Figure 3.7 show a noticeable development in how the participants got acquainted with the VR and AR technology in a short time, as the majority of the participants rated 4 (very familiar) and 5 (extremely familiar) for this question.

Also, most of the participants (72.7%) rated 5 as strongly agreeing with the statement: "The Hackathon significantly improved my ability to use VR/AR technologies". Interestingly, only one participant selected 1 as strongly disagreed with this statement.

When the participants were asked how useful they thought the skills they learned at the hackathon (related to VR/AR technologies) will be in their future studies or career, 54.4% of them rated 4, as it was very useful, while 23.3% rated 5 as extremely useful. No one selected 1 or

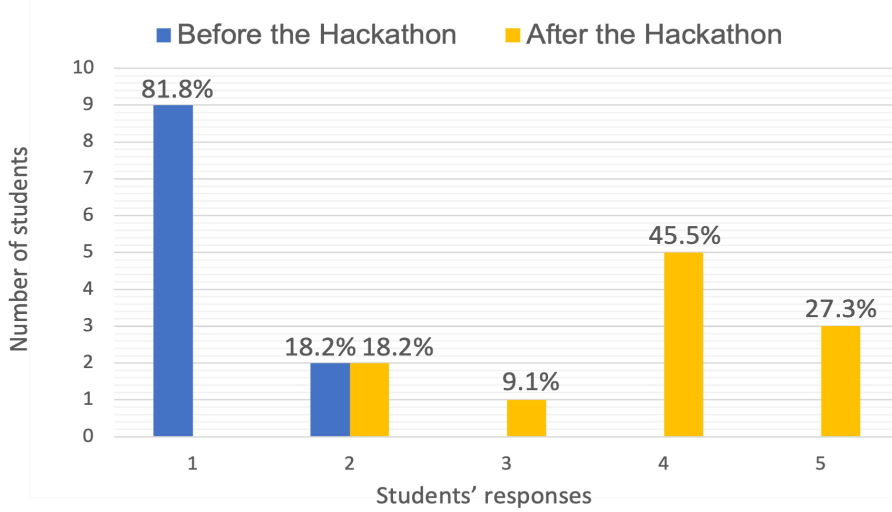


Figure 3.7: Students' rating their familiarity with VR/AR technologies on a scale of 1 (Not at all familiar) -5 (Extremely familiar) before and after participating in the VR hackathon.

2 as the skills they gained at the hackathon were "Not at all" or "Slightly" useful.

There were many questions aimed at measuring the VR skill proficiency rate after participating in the hackathon. The skills were related to the tools and the game engines that were needed for developing a VR application with its assets and animations, the capabilities and limitations of different VR systems, and problem-solving skills.

Table 3.2 summarises the VR skills gained during the hackathon. Students reported the highest proficiency in "Game Engine Proficiency", "Testing and Debugging", and "Problem-solving Skills", with 36.4% of participants rating themselves as "masters" in each of these skills. The majority (72.7%) rated their proficiency in "Understanding of VR Hardware" as 4 (proficient) or 5 (master). In contrast, 45% of students rated their "3D Modeling and Animation" skills as 1 (minimal proficiency) or 2 (less proficient). No participants mastered "Spatial Audio Design", while 72.8% rated themselves as 3 (less proficient) or 4 (proficient). Finally, only 36.4% of participants mastered "Programming and Scripting", with most rating their proficiency as lower.

According to students' responses, participants felt most confident in their "Problem-solving Skills" with the highest mean rating of 3.9, indicating a strong perceived improvement in this area. In contrast, "3D Modeling and Animation" received the lowest mean rating of 2.6, suggesting participants felt less proficient in this skill area. Moreover, "User Experience (UX) Design" and "Testing and Debugging" showed higher variability ($\sigma \geq 1.4$), indicating a wider spread in the participants' self-assessed skill levels. Conversely, "Spatial Audio Design" and "Problem-solving Skills" had lower variability, suggesting more agreement among participants about their skill levels in these areas.

Table 3.2: Participants' self-reported VR skills gained during the hackathon were measured on a scale of 1 (minimal proficiency) to 5 (mastery), including Mean (μ) and Standard Deviation (σ).

	Response Rate					**Analysis**	
VR Skills	**1**	**2**	**3**	**4**	**5**	μ	σ
3D Modeling and Animation	27.3%	18.2%	27.3%	18.2%	9.1%	2.6	1.3
Programming and Scripting	9.1%	27.3%	27.3%	18.2%	18.2%	3.1	1.2
Game Engine Proficiency	9.1%	9.1%	18.2%	27.3%	36.4%	3.7	1.3
User Experience (UX) Design	18.2%	9.1%	18.2%	27.3%	27.3%	3.4	1.4
Spatial Audio Design	18.2%	9.1%	36.4%	36.4%	0	2.9	1.1
Understanding of VR Hardware	9.1%	18.2%	0	63.6%	9.1%	3.5	1.2
Testing and Debugging	9.1%	18.2%	9.1%	27.3%	36.4%	3.6	1.4
Problem-solving Skills	0	18.2%	9.1%	36.4%	36.4%	3.9	1.1

3.1.5.3 RQ3: Teamwork and Collaboration

The VR hackathon brought together students from diverse backgrounds and skills to work on a VR project. The questionnaire results indicated that the VR hackathon enhanced the participants' teamwork and problem-solving skills. Figure 3.8 summarises the main questions used for evaluating the improvement of teamwork after participating in the hackathon.

Overall, participants reported positive improvements in teamwork and collaboration after the hackathon. When asked about their team's decision-making ability, 54.5% strongly agreed it was effective, while 27.3% agreed.

Regarding each team's ability to achieve objectives, 63.3% strongly agreed, while 18.2% remained neutral. Similar positive responses were found for the team's ability to motivate each other (54.5% strongly agreed, 27.3% agreed).

Providing feedback to colleagues was also seen as valuable: 63.3% strongly agreed they gave and received feedback, with 36.4% agreeing and 9.1% disagreeing. Integrating learnings from past performances was also positively viewed, with 54.5% strongly agreeing and 45.5% agreeing.

Collaboration in defining goals and coordinating work was also successful: 63.3% strongly agreed they collaborated on the desired results (27.3% agreed, 9.1% neutral), while 45.5% strongly agreed they collaborated on work coordination (36.4% agreed, 18.2% neutral). Recognising teammates' mistakes was reported positively, with 27.3% strongly agreeing and 45.5% agreeing.

Confidence in real-world teamwork scenarios was high: 54.5% rated themselves "extremely confident", 36.4% "very confident", and 9.1% "somewhat confident". Additionally, 45.4% strongly agreed that the hackathon "significantly enhanced their teamwork skills"; 27.3% agreed, while 18.2% disagreed, and only 9.1% strongly disagreed.

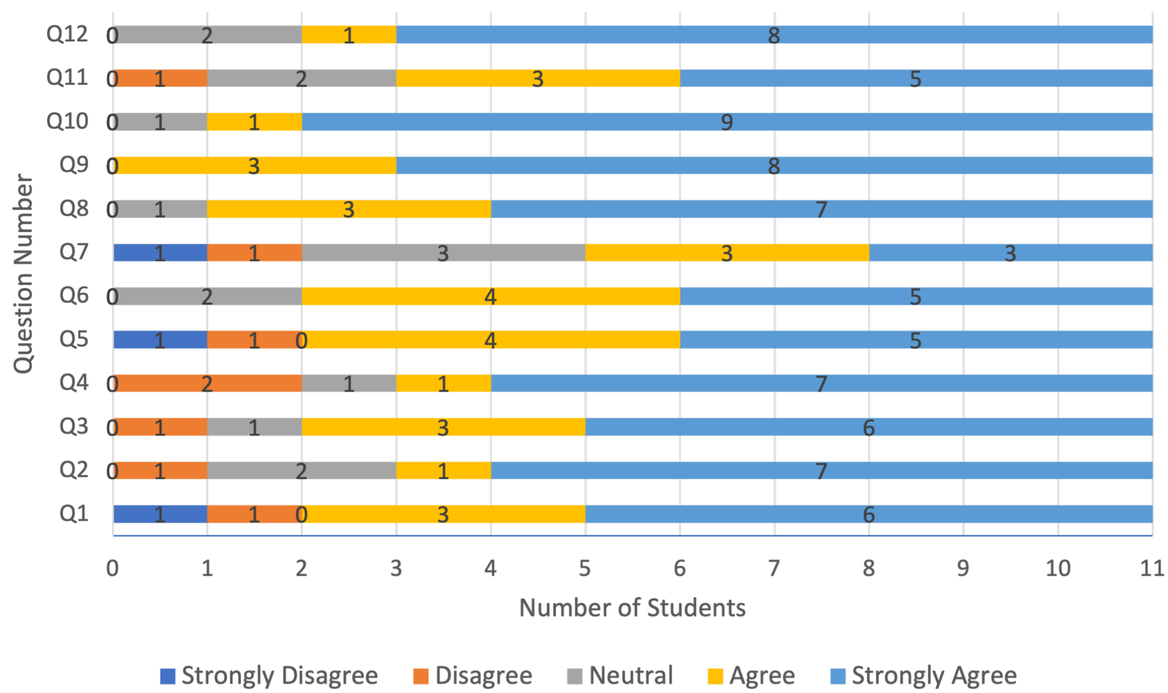


Figure 3.8: Students' responses to Section 3 survey questions for evaluating the improvement of teamwork and problem-solving skills. The 12 questions were about rating to what extent they agree with the following statements on a scale of 1 (Strongly disagree)-5 (Strongly agree). Q1: I share positive opinions about the team's decision-making ability. Q2: I share positive opinions about the team's ability to achieve objectives. Q3: I share positive opinions about the team's ability to motivate each other to complete tasks. Q4: I give my colleagues feedback about their performance. Q5: I ask my colleagues for feedback about my performance. Q6: I collaborate in order for us to coordinate our work. Q7: I ask my colleagues for help when I am unable to finish my part of the work. Q8: I collaborate in redistributing tasks. Q9: I talk to my colleagues in order to establish common objectives for all of us. Q10: I provide solutions for the problem inherent in the task. Q11: I speak openly with my colleagues about team conflicts. Q12: I make sure that what I communicate is understood.

3.1.5.4 RQ4: Authentic Assessments

When asking the participants to rate the extent to which the practical assignments, such as project development and presentations, accurately represent scenarios they might encounter in real-world engineering contexts, 27.3% rated 5 as an extremely accurate rate, while ratings 3 and 4 had the same percentage of participants (36.4%). The participants also were required to rate the effectiveness of the authentic assessments in measuring their understanding of the SDGs and their ability to apply VR/AR technologies: 54.4% of the participants rated 4 "Very Effective" and 45.5% rated 5 "Extremely Effective", while 45.5% strongly agreed with the statement: "The assessments provided valuable feedback on my learning progress", and 18.2% selected 4 as they agreed with the statement, while 27.3% rated 3 as neither agree nor disagree.

The participants provided examples of how the authentic assessments enhanced their understanding of real-world applications of their learning and were able to choose more than one option. Figure 3.9 shows the participants' responses to this question.

Also, 45.5% of the participants strongly agreed with the statement: "The authentic assessments enhanced my learning experience during the hackathon", while 27.3% agreed and 18.2% disagreed.

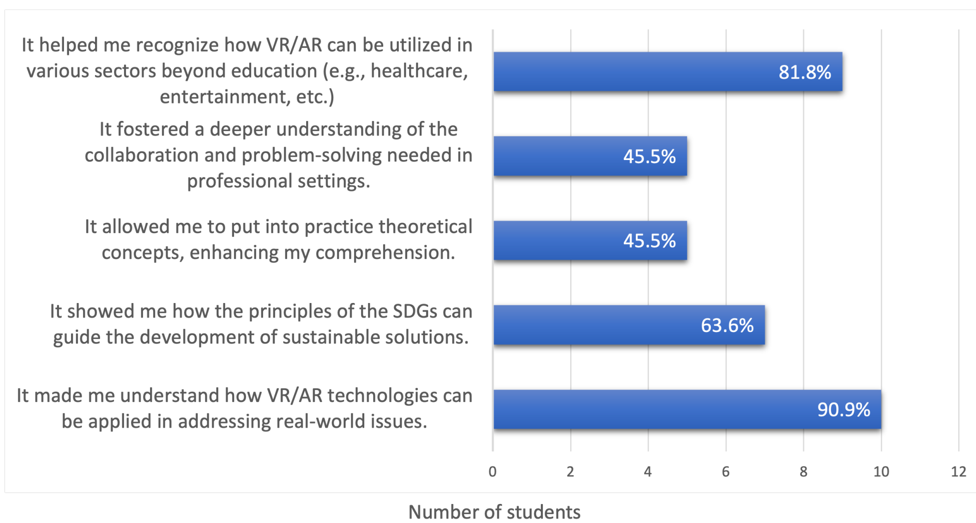


Figure 3.9: Examples of how the authentic assessments enhanced the participants' understanding of real-world applications of their learning.

3.1.5.5 RQ5: Overall Experience

When asked about their overall experience, most responses were positive, with 45.5% rating 5 and 36.4% rating 4, as shown in Figure 3.10A. This is further confirmed by Figure 3.10B, where 10 out of the 11 participants who filled out the survey would recommend this hackathon to other students.

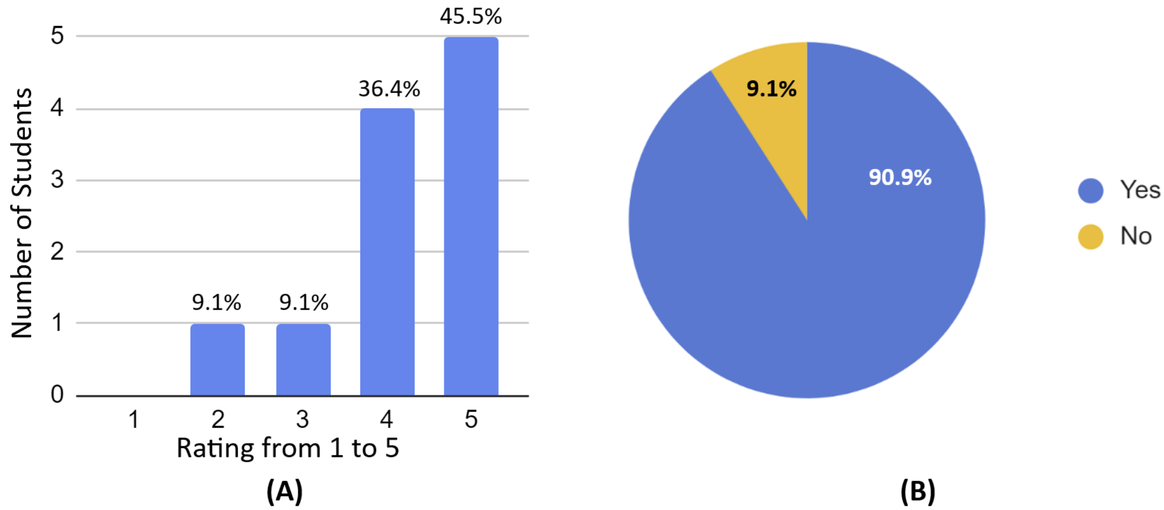


Figure 3.10: (A) Participants rating, on a scale of 1-5, their overall experience with the hackathon, where 1 is 'Very Poor' and 5 is 'Excellent'. (B) Whether they will recommend this hackathon to other students.

The participants also shared what they believed were the most beneficial aspects of the hackathon: the introduction to VR technology, hands-on work, the provision of equipment, the mentors' guidance, and the use of technology to solve real-life problems. However, they also believed that their experience would have been better if they had been provided more training on VR development, as well as more time to develop their projects.

Finally, when asked how their motivation to pursue further learning or career opportunities in the field of VR/AR technology changed, 54.5% stated that their motivation somewhat increased, while 18.2% declared that it significantly increased.

3.1.6 Discussions and Further Work

During this investigation, the aim was to understand how integrating virtual and augmented reality (VR/AR) technologies can foster the appreciation of the UN's Sustainable Development Goals (SDGs) through a hackathon. The findings offer perspectives on their effectiveness. Participants found the hackathon an engaging activity for collaborative innovation, aligning with research suggesting AR/VR can significantly enhance learning outcomes by reducing cognitive load, increasing engagement, and improving memory recall, especially for complex subjects such as engineering [132–134]. However, technical skill acquisition in "3D Modeling and Animation" was challenging within the event's timeframe, demonstrating the need for prolonged exposure, similar to traditional educational settings [135, 136]. Nevertheless, aspects such as "Understanding VR Hardware", "Game Engine Proficiency", and collaborative "Testing/Debugging" received satisfactory feedback, highlighting the value of immersive learning in fostering practical skills [137]. This suggests that, while VR/AR technologies hold promise for educational innovation, they require strategic integration into traditional teaching curricula to fully harness their potential.

VR hackathons have the potential to provide dynamic platforms encouraging creativity, collaboration, and problem-solving skills among participants, as well as increasing the students' comprehension of climate change issues and SDGs. The VR hackathon enabled students to immerse in a virtual environment that replicates the effects and consequences of climate change and simulates real-world scenarios related to the selected SDGs. This immersive experience allows users to engage with the objectives in a more tangible and meaningful way. The results of this innovative approach showed a notable improvement in the participants' technical understanding of VR/AR technologies, which can be seen from the questionnaire results. During the VR hackathon, participants typically worked on practical development tasks. They had the opportunity to improve their technical abilities while coding, troubleshooting, and designing 3D models, emphasising user experience (UX) design.

Also, the VR hackathon provided participants with an opportunity to cultivate and enhance a range of soft skills. For instance, the results showed how the VR hackathon enhanced teamwork and collaboration among participants, fostering the ability to convey ideas and achieve objectives. In fact, improving problem-solving skills leads to critical thinking and overcoming obstacles [138], which indicates that the VR hackathon encouraged creativity and positive thinking and motivated students to think outside traditional boundaries.

The VR hackathon posed challenges that closely resembled real-world engineering scenarios, making participants appreciate the authenticity of the issues they were solving. Participants rated their overall experience of the VR hackathon very positively compared to traditional classroom-based learning experiences as VR technology offers a unique learning environment. Users found themselves more engaged with the VR application with the ability to interact with 3D objects. This practical and hands-on approach offers a more dynamic and interactive learning experience [139].

In terms of instructor feedback and testimonials, the following was received:

Instructor 1—Mechanical Engineering Professor: "The VR hackathon provided a platform for our students to showcase their ability to engineer practical solutions for complex environmental challenges. Their ingenuity in creating immersive VR experiences was impressive. Their innovation and dedication exceeded all expectations".

Instructor 2—Computer Science Professor: "I was impressed by our students' proficiency in coding and software development for VR applications. Their innovative application of computer science principles to address climate change issues was remarkable. This event exemplified the value of experiential learning. Students not only honed their technical skills but also developed critical thinking and teamwork abilities. To further address the individual learning needs of each student, incorporating individual feedback sessions could be beneficial".

Instructor 3—Electronic Engineering Professor: "Student projects demonstrated a seamless synergy between electronics and virtual reality. The hackathon also effectively bridged the gap between theoretical knowledge and practical application. Students' projects offered insightful perspectives on climate change, showcasing a deep understanding of current issues. For future iterations, providing more structured preliminary workshops to better prepare students for advanced VR concepts could enhance their learning experience".

Funding Agency Representative: "Supporting this hackathon was an important decision to foster innovation at the intersection of technology and environmental awareness. The results surpassed our expectations and demonstrate the transformative benefits of interdisciplinary education".

Simultaneously, adapting VR/AR technologies in teaching climate change brings several challenges. For example, implementing VR/AR technologies in education requires devices and software that might be expensive and need continuous maintenance [140]. Also, developing high-quality VR/AR applications for renewable energy systems requires specialised skills and resources [141]. However, addressing these challenges can significantly improve and enhance the learning experience of renewable energy system design.

VR technology can be effectively integrated into existing curricula to enhance student learning outcomes as a supplementary tool to traditional teaching methods, creating an interactive environment that allows students to interact and manipulate renewable system components, fosters experiential learning, and increases active participation and engagement. This requires ensuring that VR/AR content directly corresponds to the learning objectives of the curriculum and that students are trained to use VR/AR effectively and supported all the time.

3.1.7 Summary

This study demonstrates a novel approach to climate change education through a VR hackathon. When compared to typical classroom-based learning approaches, the VR hackathon's immersive, hands-on approach boosted participants' understanding and knowledge of the four specified UN SDGs and climate change issues. Moreover, participation in the VR hackathon considerably improved the students' exposure and proficiency with VR technology, as demonstrated by over 90% of student responses. The participants believed that the hackathon's environment improved their teamwork and problem-solving skills and that, compared to standard assessment techniques, the authentic assessments employed in the VR hackathon were substantially more reflective of real-world engineering settings and effective in measuring understanding and skill application.

While the immersive VR experience significantly enhanced participants' understanding of specific UN SDGs and climate issues, it is also important to consider the limitations of the study, such as its scope and context. There were limitations related to the availability and accessibility of VR headsets, which affected and limited participation. Also, evaluating the effectiveness of VR applications is subjective, and it is challenging to develop standardised criteria for diverse projects within a hackathon. Future research could explore the long-term retention of knowledge and skills and the adaptability of VR-based learning for other renewable energy educational subjects. Additionally, examining the scalability and accessibility of this approach in diverse educational settings will be important. The hackathon's success in improving teamwork and problem-solving skills, as evidenced by over 90% of student responses, suggests that authentic assessments in such immersive environments are more effective than traditional methods. Nevertheless, the hackathon was overall successful in engaging and motivating students. The results indicate that the immersive hackathon effectively stimulated student interest in the chosen SDGs. The learning approach, designed to be both immersive and hands-on, fostered active engagement and collaboration among participants. This demonstrates the potential of such non-traditional classroom methods for educational and awareness-raising initiatives related to climate change and sustainable development.

3.2 VR application in solar energy systems design

3.2.1 Background

Our ability to effectively harness the Sun's vast energy has a profound impact on meeting the COP26 goals [142] and in the sustainable development of low-income countries [24]. Consequently, a general awareness of how solar energy systems are designed is required to ensure that these goals are met. Previous training methods relied on teacher-centred instruction using 2D software [143, 144]. However, evidence from the literature demonstrates that active learning as well as augmented and virtual reality (AR and VR) technology helps users gain a deeper sense of understanding due to improved concentration, interest and interaction with the learning materials [145–148]. Therefore, the integration of VR and AR methods in curricula is gaining greater interest from schools and higher education institutions (HEIs) [149].

The benefits of implementing VR in solar energy training and education have been reported in the literature. These previously mentioned projects assumed prior participant knowledge of solar energy systems and their constituent components. In contrast, the motivation was to provide students with a basic understanding of solar PV energy concepts, assuming no prior knowledge or skills in the field. Moreover, students were invited to evaluate the effectiveness of the pilot study, which aimed to investigate the benefits of VR on student learning and to collect preliminary results. In fact, the VR game combined many modalities such as text, audio, animations, interaction and quick quizzes to ensure direct feedback and to promote learning in a fun, immersive and interactive way. In summary, the main aims of the project were to:

1. Help students appreciate that PV systems are modular.
2. Appreciate the difference between Direct Current (DC) and Alternating Current (AC).

3. Demonstrate to students that PV panels can be used to satisfy their domestic energy needs.

3.2.2 Design and Methodology

This game-based VR application in solar energy systems design was developed using Unity3D game engine [150], blender [151] and VoiceMaker [152]. Unity3D was used for adding the 3D models and creating the scenes of the application. It was also used for developing the animations and scripts. All the scripts were developed using C# in Visual Studio within the game engine. Blender was used for the 3D modelling of some 3D objects with the texture and creating the animation as well. VoiceMaker was used to add audio for the animations in the game to explain how solar panels produce direct current (DC) and how this current has to be converted to alternating current (AC) to supply electricity for houses. A wireframe of the VR application design is shown in figure 3.11, explaining the stages of the game.

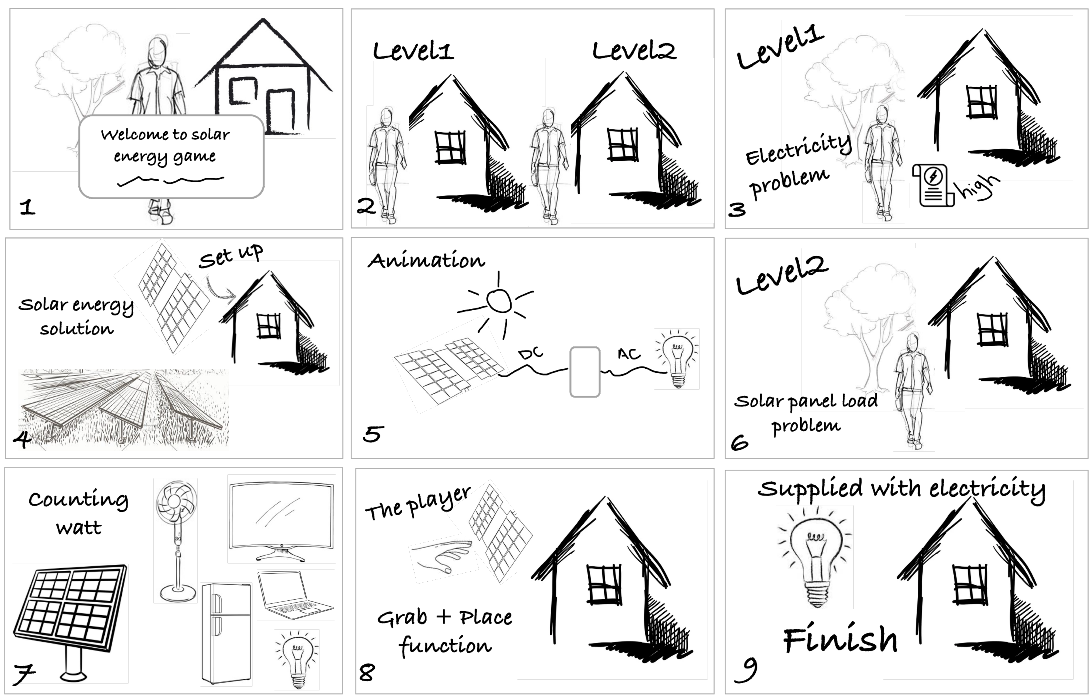


Figure 3.11: Wireframe of the solar energy systems design game. Users were invited to solve various energy-related tasks according to two difficulty levels. Tasks in level 1 tested students' understanding of key solar energy concepts. For example, animations were developed to explain the importance of conditioning electricity from solar panels to a form that can be used by electronic appliances in a home. Further animations were developed to show the impact of varying solar intensity on electricity generation. Upon completion of Level 1, participants transitioned to Level 2, where they were invited to navigate their way inside a home and identify all electrical appliances that draw power. Based on the total power consumption, they should then determine the required number of solar panels that satisfy the home's needs. The game allowed users to identify an appropriate location to pick and place the required solar panels to satisfy the energy needs of these appliances.

The solar energy game consisted of two gaming levels, which required participants to complete a set of tasks in two different 'virtual homes'. Instructions were provided to students to ensure satisfactory game completion. In the first level, users had to meet the power demands of a virtual home using a virtual PV system. In doing so, students would appreciate the modular nature of a PV system, in the sense that a greater output power can be achieved using more panels. Three animations were developed to explain the different processes of how to use sunlight to generate electricity. The first animation was supported by an audio that explains how a solar panel absorbs solar radiation to generate DC. The animation also explains the process when solar panels are exposed to photons from the sunlight and then release electrons to produce electricity 3.12 - A. Moreover, participants had to appreciate that the output power of PV panels is DC, which means that an inverter is required for AC conversion. Figure 3.12- B is a snapshot from the VR headset that explains the process of converting DC to AC by representing the current through the wires. An audio file was imported into the project explaining the steps. Further another animation was developed to help students appreciate how the output power of PV panels is dependent on sunlight intensity, as shown in figure 3.12- C. These animations were created using Blender software.

Following these animations, students were presented with a quiz that involved reordering technical sentences, which were used to evaluate their understanding of the provided animations. These animations and quizzes aimed to reinforce and assist in learning the basic solar energy concepts. Direct feedback was given to users in case an incorrect answer was chosen, prompting them to try again.

After completing Level 1, users were directed to Level 2 to learn about the solar panel load. In this stage, users were invited to identify and count the electrical appliances in a home. Based on the total power consumption, users then determined the required number of solar panels that satisfied the home's needs. After selecting the number of solar panels, users needed to grab and place the required number of solar panels on the house's roof-top, as shown in figure 3.13. The game would then inform users that the appropriate number of panels was chosen once a light bulb (representing the electrical loads in the virtual home) was switched on.

The game was designed without any external instructions, and the users can receive immediate and direct feedback that helps to ensure full immersion in the game.

3.2.3 Data Collection Process

A total of 12 students from the University of Glasgow volunteered to participate in the pilot study. The necessary ethical approvals were obtained from the University of Glasgow to conduct this experiment. Consent forms were distributed to participants before collecting data. Volunteered students were informed that their participation would not affect their grades and that all the information provided to them would be anonymous and confidential. Students were given brief instructions about the game, which took approximately 7 minutes to complete. A

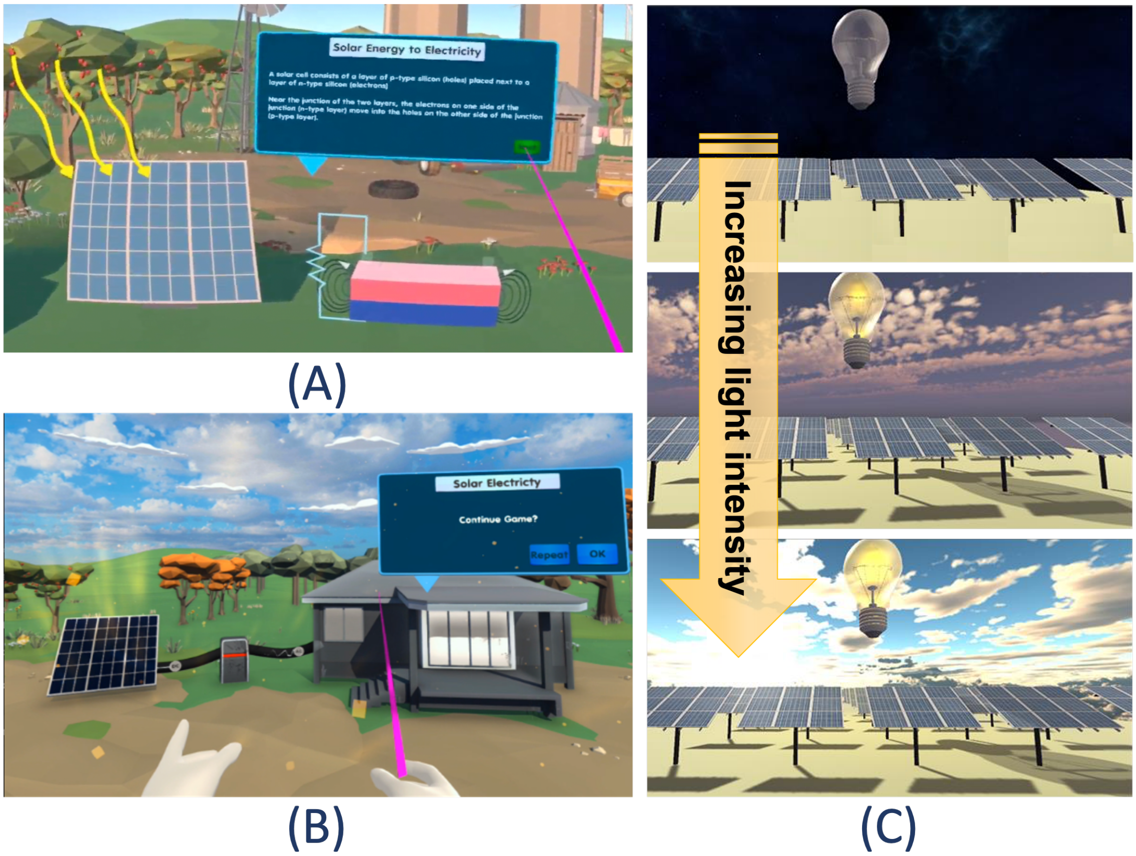


Figure 3.12: The animations in level 1 (A) the animation demonstrates the process of how the solar panels convert the sunlight into electricity (B) The animation shows the process in which solar panels produce direct current (DC) from the sunlight, and then this current is converted to alternating current that is used to supply a house with electricity. This animation is supported by audio and explains the converting process in detail and (C) The animation demonstrates the impact of the intensity of sunlight in producing electricity. Users notice the amount of electricity produced during the day and recognize the role of sunlight.

laptop was used to cast the students' game experience to assist them with any queries during the game. Figure 3.14 shows the working area and how to monitor participant progress during the game. Following the game, all participants were invited to complete an online questionnaire consisting of seven questions, which were designed to collect their feedback regarding future game improvements and to gauge their understanding of the basic solar energy concepts. The first question asked participants whether they had any previous experience using virtual reality. The next three questions invited students to rate their understanding (on a scale of 1 to 5, with 5 being the highest) of the key intended learning outcomes of the study. The fifth question asked students whether they experienced any cyber-sickness during the project. The sixth question asked students to rate their overall experience (on a scale from 1 to 5, with 5 being the highest) with the virtual reality game. The last question in the online survey invited students to provide any comments or recommendations for improving the game design.

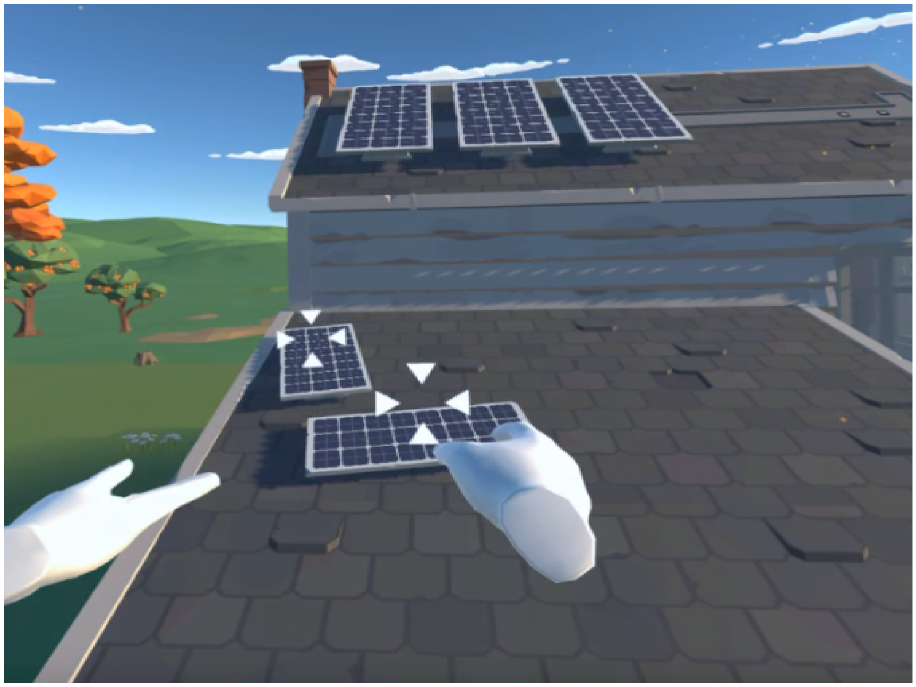


Figure 3.13: Level 2 task where users pick up a required number of solar panels and place them on the house's roof-top after counting devices watt inside the house. Users notice that the house is supplied with electricity after placing solar panels by lighting a light bulb in the house.

Table 3.3: The average score for each survey question. The maximum score is 5.

Intended Learning Outcome (ILO)	**Mean**	**SD**
Understand that PV systems are modular	3.58	0.92
Understand the difference between DC and AC electricity in solar energy systems	3.42	1.38
Appreciate that PV panels can be used to satisfy a home's energy needs	4.42	0.90

3.2.4 Results and Discussions

According to the survey results, 16% of participants had prior experience with VR headsets. Moreover, almost half the participants requested assistance during the project, especially with grabbing and placing the solar panels on the house's roof-top. Students were also asked to rate their understanding of the three main solar energy concepts that were introduced during the game. Table 3.3 summarises the mean and standard deviation (SD) of student responses, which were used to measure student understanding of the project's intended learning outcomes (ILOs).

All students rated their experience with the virtual reality game positively, giving an average score of 4.75. They described it as 'amazing', 'fun', 'cool', 'enjoyable' and 'interesting'. On the other hand, four participants experienced cyber-sickness (dizziness, tiredness, headache, etc.) after using the headset. This may be attributed to the headset not being worn properly. In future, therefore allocating more time for participants should be considered to adjust their headsets. Moreover, the participants provided many recommendations to improve the game. For example,

Figure 3.14: The data collection phase was associated with monitoring the participants' interaction by casting the application to the laptop for any assistance required by the students.

one of the participants requested including 'next' and 'back' buttons to make navigation easier, as mentioned in their comments:

Please include some commands to allow the participant to move/navigate the game in the VR project.

In addition, participants requested to make the process of grabbing and placing solar panels simpler. Furthermore, one of the participants praised the game and mentioned that it helped him understand basic solar energy concepts. The same participant also suggested changes to the way the questions were being presented in the game.

Despite the versatility of the tool, it is important not to set unrealistic expectations regarding what VR can achieve. Without a doubt, VR is a useful tool that can be used to assist in consolidating knowledge acquired during traditional teaching via lectures, workshops and tutorials. VR is not meant to replace these teaching activities, but rather provide instructors with additional means to complement teaching instruction, especially in a remote or online environment [153].

3.2.5 Summary

A VR game-based application was developed for teaching the basics of solar energy systems design. Results from this pilot student survey showed positive feedback, with the majority of students rating their experience as "excellent". Participants found it easy to interact with the VR application with little instructor assistance. Data collected from the surveys also showed that students were willing to learn using new teaching styles and methods in comparison to traditional lecture-based instruction. According to the survey results, students rated their understanding of modular PV systems with an average score of 3.58 out of 5. Moreover, on a scale of 1 to 5 they rated their satisfaction with using PV panels for meeting their energy needs with an average score of 4.42, which is a testament to the game's ability to raise student awareness and appreciation for solar energy systems.

Although VR offers advantages for designing PV systems, using surveys for evaluation purposes has its drawbacks. Surveys mainly rely on subjective self-reported data, which can be biased. Additionally, they do not capture the dynamic aspects of user interactions in real-time, such as cognitive load and engagement levels. In the upcoming chapters, I will introduce a modified VR environment for PV system design and an experimental setup designed to monitor physiological states using sensors, which aim to provide a deeper analysis of user behavior.

3.3 Design and Development of the PV System VR

3.3.1 Introduction

Based on the limitations and findings from the initial study highlighted in the previous section, a new application was developed to overcome these limitations by using multiple evaluation methods for solar energy system design tasks. Integrating qualitative and quantitative methods provides a more comprehensive evaluation of a VR application. Analysing real-time behavioral data can provide insights into how users navigate and engage in the VR environment. This can be achieved by using physiological sensors that collect real-time data from users during their VR experience in conjunction with surveys. Thus, a multi-modal assessment method is used for the next experiments in chapter 5.

Therefore, this section discusses the process of building and designing a virtual reality application. After the review of the VR technology in PV system design in Chapter 2, it was concluded that there is no study focused on solar energy system design with all the system components that enable users to deeply comprehend the system and get proper practice. Also, the review shows several learning theories that were proposed in using VR technology for solar energy system education. These theories provide different perspectives on learning objectives, consequences of teaching strategies, the process of information transfer and the crucial role of emotions. Also, it is essential that the development of VR applications be firmly based on existing learning theories to determine the guidelines for learners on the motivations, learning process and learning outcomes [100].

In this study, Dale's cone theory was chosen. It is a graphical model that shows various learning retention levels according to the used methods. Based on Dale's cone, when students are actively involved in the learning process, they retain more information, figure3.15.

In accordance with Dale's cone theory [154], which structures learning experiences, I chose to focus on active and passive learning through hands-on experiences, since these are situated at the base of the cone. This decision stems from the fact that teaching sustainable energy subjects

Figure 3.15: Developed by Edgar Dale, the cone of experience categorises learning experiences and suggests that learning by doing leads to better information retention compared to simply hearing, seeing or observing.

typically relies on a theoretical approach, which may not provide the most effective learning experience [155].

3.3.2 Experimental Design

3.3.2.1 VR application

Two versions of the VR application were developed using the Unity3D game engine. One version was for the Meta Quest 2 headset with the Android operating system, and the other one was for HP reverb G2 Omnicept which used the Windows platform. The main difference between these two versions is that hand tracking was used for the Meta Quest 2 and controllers were used in the HP Omnicept headset. For the Meta Quest version, the Oculus XR Plugin package was used for all the Oculus features. OVRCameraRig prefab is used in the app. The app uses Quest 2 hand tracking and interaction to interact with the 3D objects. User will use their hands and hand gestures to pick up objects and place them in appropriate positions. Users used their hands for the interface as well. The headset detects users' hand position, orientation and the configuration of users' fingers. After hands are identified, computer vision algorithms are used to track hands' movements and orientations. For interactions, the OVR Grabbable script was attached to the gameobjects with colliders & rigidbodies which have to be picked up. Also, OVRHandPrefab was used to enable interaction with Hands. The OVR Grab with Hands script

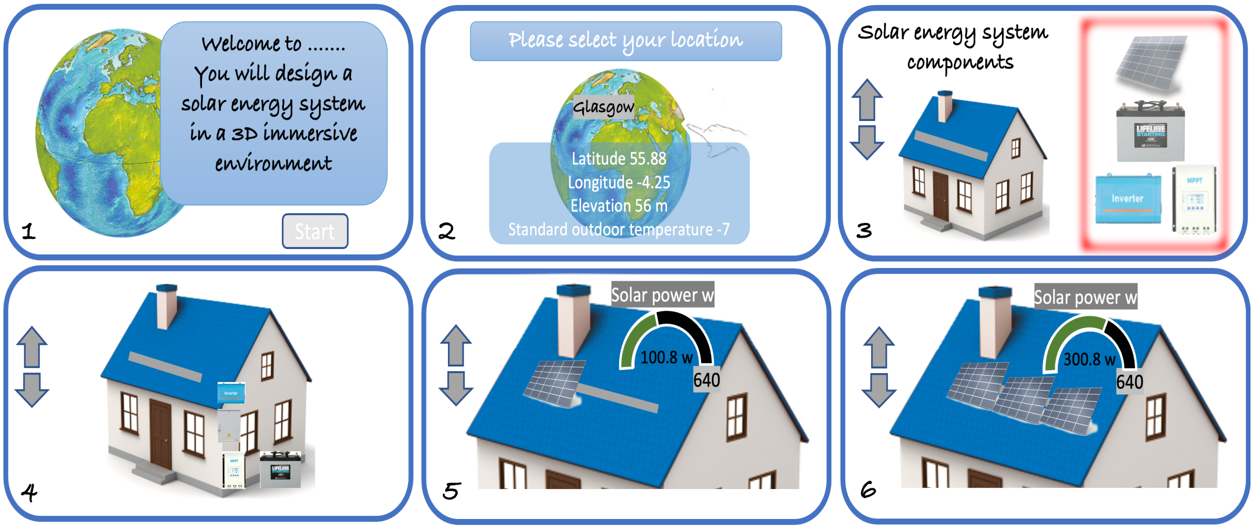


Figure 3.16: Wireframe of the solar energy systems design VR application. After the welcoming scene, users have to select the location from the 3D Earth to install a solar energy system. The location's details will appear to users such as latitude, longitude, elevation and standard outdoor temperature. Users will get familiar with the solar energy system components and read information about the role of each item. Then, system components should be installed in the power room and the solar panels should be placed in a stand on the rooftop. In the last scene, users can add, remove and change the tilt of the solar panels and try different scenarios to see the impact on electricity production.

has been attached to the OVRHandPrafab for the interactions. In addition, for the Windows version, Unity's Open XR Plugin package was used for all the VR features and OpenXRRig was used in the app. For interactions, XR Grabbable script was attached to the gameobjects with colliders and rigidbodies which have to be picked up. XR Interaction Manager was used to enable interactions.

First, a wireframe was created to plan the spatial layout of objects, interactions and the interface, and to determine the flow of the application 3.16.

Unity store was utilised for providing 3D assets and the environment for the VR application. Only the solar panels' stand was modelled using Blender software. The stand was designed to be adjustable and enabled users to rotate it to change the tilt of the solar panels, figure 3.17.

The application consists of four scenes: the earth, house, power room and roof. In the earth scene, the opening scene of the app, users choose the location on the map and then the location's details will appear, such as latitude, longitude, elevation and standard outdoor temperature, figure 3.18- A.

The scene will then be changed to a house where users have to design and install the components of the solar energy system. First, two buttons will appear for users to either learn and become familiar with the solar energy system components, figure 3.18- A, or to go to the power room to install a battery, charge controller and inverter. The system presented in the application is an off-grid system that contains a battery, inverter, charge controller and solar panels.

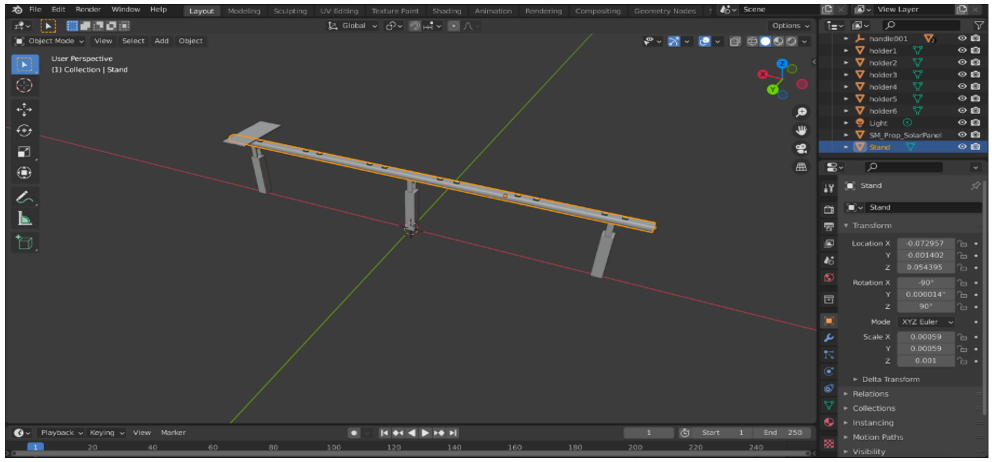


Figure 3.17: Designing a 3D adjustable stand for installing solar panels using Blender software Version 2.93.4. This stand is placed on the rooftop to enable users to add, remove and change the tilt of the solar panels in order to measure the electricity generation in different scenarios.

(A) (B)

Figure 3.18: (A) The first scene where users select a location from the earth and display the location's information. (B) The second scene is where users can read about the role of each solar energy system component to become familiar with the system.

In the application, users can enter a power room to pick up the objects and place them in the necessary positions, figure3.19- A. Once the user picks up the component, the "PowerRoom-Collision" script detects what component has been picked up and shows a red box indicating the position where the component has to be placed 3.19- B (See Appendix A for the script). Once the component collides with the positioned component in the stand, the component is automatically placed in the right position. Once all three components in the power room are installed, the power then will be generated from the solar panels.

Next, users can click on the up arrow in the power room to go to the house roof, then grab and place the solar panels to generate electricity 3.20- A. Each panel placed will give a voltage depending on the stand's angle. However, the voltage will be visible in the voltage bar once all the components are placed in the power room. A gauge chart appears after installing all the system components and shows the electricity generated with this system. Users can add and remove the solar panels and change the tilt of the panels by changing the stand angle using the

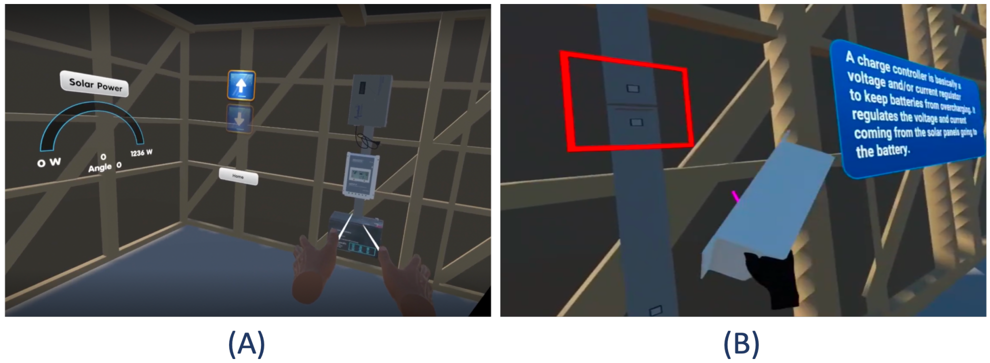


Figure 3.19: In the power room (A) users should pick up the system components and place them in the stand. (B) when users pick up one of the components, a red box appears to show the right place to install it.

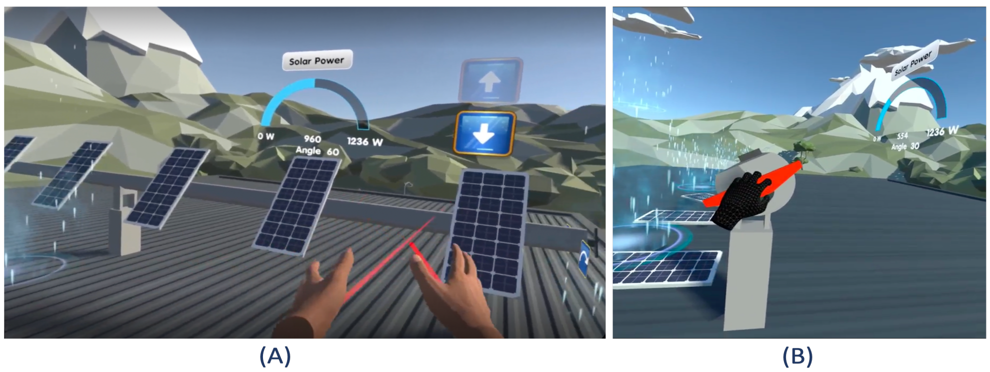


Figure 3.20: (A) Users can add, remove and change the tilt of the stand to try different scenarios of electricity. (B) Users can change the tilt of the stand using the handle.

stand's handle.

When users pick up a solar panel, the panel automatically adjusts to the right position once it is placed, this is handled by the panel collision script (See Appendix B). Also, another script detects once the panel touches the stand and automatically places it on the stand (Appendix C). In addition, the solar panels can be removed from the stand. Once the panel is removed, the gravity is enabled and constraints are removed. This makes the panel be affected by physics once again.

For the gauge chart, a script is created to control the voltage. It changes the fillamount of the bar depending on the number of panels placed. The script also detects if all the power room components are complete, only then the voltage changes in the voltage bar.

The values of electricity generated from a solar panel in different angles were taken from a commercial 2D simulation for solar energy system design. The maximum electricity generated is 1920 if all 6 panels are placed and the angle is 0 degrees. So the gauge chart will be at full when the electricity generated is 1920. The voltage is divided by 1920 to get the percentage of voltage generated. This percentage is used to fill the voltage gauge chart for pictorial representation.

Also, a script was developed and used to teleport users to the portal's position. The teleport script is attached to a portal that was created using Unity's vfx component (Appendix D).

Users can add solar panels to the stand and produce electricity trying different scenarios. They can add, remove and change the angle of the panels by rotating the stand handle 3.20- B. Appendix E shows the code used to calculate the electricity depending on the angle of the panels and the number of solar panels placed on the stand.

In this process, users can notice how the solar panels' number and tilt affect the generated electricity in a fully immersive environment. Therefore, having designed the VR application, the next chapter will demonstrate how this was used for PV system design on a cohort of learners using physiological data collected from sensors.

3.4 Conclusions

This chapter presented a comprehensive exploration of the role of Virtual Reality in renewable energy and climate change education. The findings from this chapter highlighted the potential of immersive technologies in enhancing learning, engagement, and practical skills. First, it investigated the effectiveness of a VR hackathon as an innovative approach to introduce students to VR technology in four Sustainable Development Goals of the United Nations. The VR hackathon fostered teamwork, problem-solving skills, and students' motivation allowing users to actively engage with VR environments. The findings showed that hands-on experience in VR settings enhanced students' understanding of the SDGs and climate change issues. Next, the chapter investigated user perceptions and the effectiveness of VR in delivering interactive educational experiences in solar energy system design. The findings of this study indicated that students were highly engaged in the VR environment and increased their understanding of solar energy systems. The results also revealed a strong preference for VR-based learning, praising its interaction and usability. However, some challenges were observed, such as motion sickness and interaction limitations. Next, to address the limitations of the previous sections, a refined version of the VR application was developed with many enhancements. This VR application addressed usability challenges and improved the overall learning experience. The section highlighted key design considerations to enhance the VR experience, focusing on an intuitive user interface, real-time feedback, and scenario-based learning. The next chapter evaluates the developed VR application using biofeedback analysis to measure user engagement. By leveraging physiological data, such as heart rate, cognitive load and eye tracking, the study provides deeper insights into how the VR environment influences users' engagement and enhances interactive learning experiences.

Chapter 4

Advanced Evaluation of the VR System

This chapter presents the evaluation of the developed VR application for solar energy system design. Two experiments were conducted to assess this application, the first experiment compared the users' vital signs to estimate users' engagement level in a commercial 2D application for solar energy systems design and the developed immersive VR application. Then, to deeply investigate the effectiveness of this VR application, the second experiment was about dividing the application into scenes and using many sensors including eye-tracking and wireless wearable sensors to measure users' engagement and performance in each scene. This experiment provides insight and can be considered as a guide for developers and designers to create effective VR applications, considering user experience elements and cognitive load.

4.1 Solar Energy Systems Design in 2D and 3D: A Comparison of User Vital Signs

4.1.1 Background

Since physiological monitoring technologies have advanced so quickly, it is now possible to apply several biofeedback modalities and investigate how they may impact user experience. Numerous empirical studies have presented evidence that creating an immersive virtual environment for users by collecting biofeedback can help provide a better emotional state and behaviour for users [156–158].

The sense of presence in the virtual environment, engagement and immersive level, is highly correlated with the change in heart rate and skin reaction. For instance, Felnhofer *et al* in [159], established a study where electrodermal activity was recorded that the feeling of presence is related to emotional reactions. McNeal *et al* in [160], also monitored the engagement level of students using a skin biosensor called galvanic skin response (GSR).

This experiment was conducted to compare the level of user engagement during the design of a solar energy system using a 2D simulation application with an immersive virtual reality (VR) environment via two biosensors: Frequency Modulated Continous Wave (FMCW) radar [161] and a medical grade belt [162]. Moreover, self-reported perceptions were collected to confirm the relations between the collected data.

The solar energy systems design field was chosen since the focus is on tackling some of the world's toughest climate change problems requiring a paradigm shift in the way these systems are designed. Current design methods rely on experts developing solutions on 2D flat screens using traditional CAD models [24, 163]. Moreover, these designs are often developed hundreds or even thousands of miles away from the actual site or community, leading to low levels of user engagement with the project. Therefore, It is hypothesized that higher engagement will be achieved in a 3D virtual-world environment compared to a 2D computer screen application. This project aims to mimic 2D software in designing a solar energy system in an immersive environment where users can interact with the system components and feel more engaged with the virtual environment. To visualize the application, the Oculus Quest 2 headset was used. The application uses Quest 2 hand tracking to interact with the 3D objects, which are solar energy components. This system can recognise hands well even if they are partially hidden or moving swiftly and detects the most important gestures. This feature was used to make the application interactions more realistic. The application also uses the Oculus XR Plugin package for all of Oculus's features.

4.1.2 Radar Sensor Overview

To carry out the experiment and implement the vital signs, the FMCW radar IWR6843AOPEVM from Texas Instruments [164] was used, with the Icboost carrier. This is a so-called mm-wave radar, whose wavelengths are in the order of millimetres (microwave frequency region). The IWR6843AOPEVM is a (PCB, Antenna on Package) MIMO radar chip with a FMCW transceiver consisting of 4 integrated receivers and 3 transmitters, all being patch antennas with 120° Field of View (FoV).

It operates by transmitting a sawtooth FM waveform, using Time Division Multiplexing (TDM) or Binary Phase Modulation to obtain orthogonality between transmitted signals. For the Local Oscillator (LO) signal and coherence, the chip uses a 40 MHz crystal oscillator, with a phase noise of -92 dBc/Hz at 1 MHz offset. This signal is synthesized to produce an FM chirp ranging from 60 to 64 GHz. The communication with the radar was carried out between the Universal Asynchronous Receiver Transmitter (UART) and USB interfaces through serial communication.

4.1.3 Radar Configuration for Experiment

Table 4.1, shows the final configuration for radar used to measure the vital signs during the experiment.

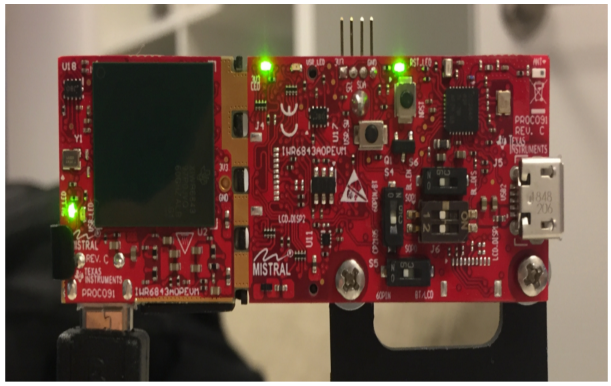


Figure 4.1: IWR6843AOPEVM radar module, for measuring participants' heart and breathing rate throughout the VR study based on mmWave sensing technology which provides real-time monitoring and non-invasive features.

Table 4.1: Parameter setting for vital sign estimation

Parameter	**Value**	**Unit**
No. of Tx	2	-
No. of Rx	4	-
Center Frequency	60	GHz
Bandwidth	2	GHz
Sampling Rate	10	Msps
ADC Samples/chirp	256	-

4.1.4 Data Collection

A total of 4 postgraduate students from the University of Glasgow volunteered to participate in this pilot study. Brief instructions were given to participants on how to complete the application, which took around 5 minutes. The experiment was conducted in a quiet lab to ensure enough area to move freely in the VR application. In the beginning, participants had to wear the medical grade belt, and then the radar was directed toward them at a distance of 50cm. Afterwards, participants designed and built a solar energy system using a 2D application. Participants were provided with a document explaining the steps and instructions they should follow. Building the solar energy system depended on dragging and dropping the system components. After collecting the vital signs from participants, they were directed to try the 3D virtual reality application to build the solar energy system. Participants were still wearing the medical-grade belt and facing the radar from a one-meter distance to monitor their vital signs while interacting with the virtual environment. Fig. 4.11, demonstrates the experiment setup for 2D application and 3D immersive virtual reality. To evaluate the engagement level and students' experience with the two different interfaces, participants were invited to complete an online self-reported questionnaire containing eight questions. Before gathering data, participants received consent forms. Students who participated in the study were told that their participation would not influence their grades and that any information they gave would be kept anonymous and private.

Figure 4.2: Overall system architecture in (a) 2D application and (b) 3D virtual reality environment with vital sign estimation.

Regarding vital signs, raw-ADC data was collected from radar using another device, the Texas Instruments DCA1000. This configuration enables real-time data capture for up to ten seconds, which is then sent to the PC over LVDS (low-voltage differential signalling) lines at a high data rate of 600Mbps. ADC samples were obtained from participants in various scenarios of virtual reality environments and saved in a separate file. As a result of the preceding process, a .bin file containing the raw ADC data is generated. This raw data is then post-processed on a host PC using the MATLAB signal processing method.

4.1.5 Radar Signal Processing

The beat signal is the combination of the transmitter and receiver mixed signal. A DSP and an ARM processor are integrated inside the radar for post-processing. The Radar data is stored in a .bin file and converted to a CSV file using MATLAB programming. The breathing signal and heartbeat signal were extracted from the raw data using a Bandpass filter with a cutoff frequency of 0.16 to 0.4 Hz for breathing and 0.8 to 4 Hz for estimating heart rate.

After filtering the raw data, the Fast Fourier Transform (FFT) technique was used to generate the peak spectrum. The FFT method provides a frequency domain vital sign estimation. The peak detection technique was employed to estimate both the breathing rate (breaths/min) and the heart rate (beats/min) in the time domain as well.

4.1.6 Results and Discussion

The study investigated the amount of engagement of users with two different interfaces. The first interface was a 2D application that operated on a laptop, while the second was a 3D VR-based application. The user was instructed to sit firmly when using the 2D interface, and radar was utilised to estimate vital signs at a distance of 50cm away from the radar user.

4.1.7 Questionnaire

Participants completed a self-reported questionnaire that measured their engagement level and application preference. The majority of the participants, 75%, already had experience with virtual reality. Interestingly, on a scale from 1 to 5, with 5 being the highest, all the participants rated their VR experience as having the highest rate of excitement. Moreover, when asking the participants whether they felt engaged, 50% mentioned that they strongly agreed while 50% agreed. The participants rated 4.5 out of 5 when asked how much engagement they found in the VR application and the feeling of real interaction during the virtual environment. All participants selected the 3D virtual reality application as it is more engaging than the 2D application. In addition, all the participants recommended VR applications for designing solar energy systems rather than 2D applications. None of the participants experiences any symptoms like nausea, dizziness, double vision, etc., while using the VR application.

4.1.8 Vital Sign Estimation

The breathing rate from the radar FFT approach is shown in figure 4.3, and the results are validated with a medical-grade respiration belt. As can be observed, the breathing signals vary as the user becomes more immersed in the 3D VR experience.

The same is evident for the user's heartbeat signal, as shown in figure 4.4, which shows the difference in the signature between highly engaged and moderately engaged participants during the 3D virtual reality application.

4.1.9 Validation

The user was then invited to wear the VR for the 3D interface, and the same radar was employed to assess the vital signs to determine the user's interest level. In all scenarios, a medical-grade breathing belt was used to validate the radar data. The findings from various participants are shown in table 4.2. These data are from the 3D VR environment, which reveals different breathing and heart rate variations as users become more involved. Based on the results, both participants were engaged in 2D and 3D interfaces, however, 3D was shown to be more engaged than the other.

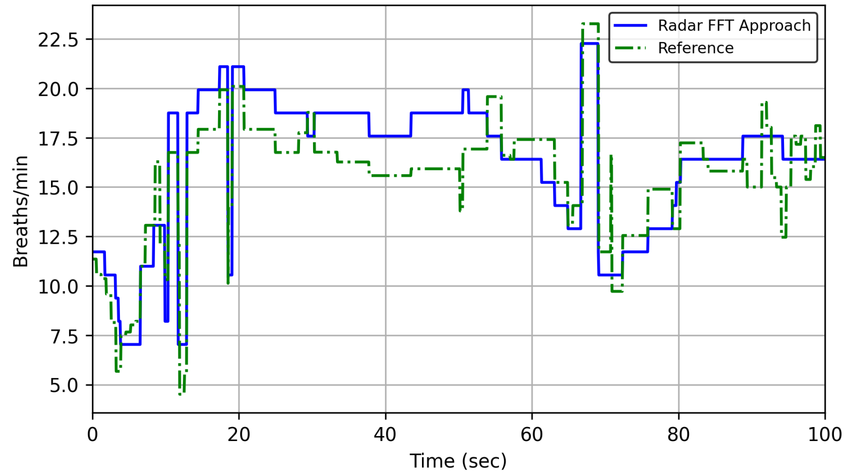


Figure 4.3: A comparative of breathing rate data captured by the Radar and the Reference sensor, demonstrating closely aligned measurements and indicating high accuracy between these sensors.

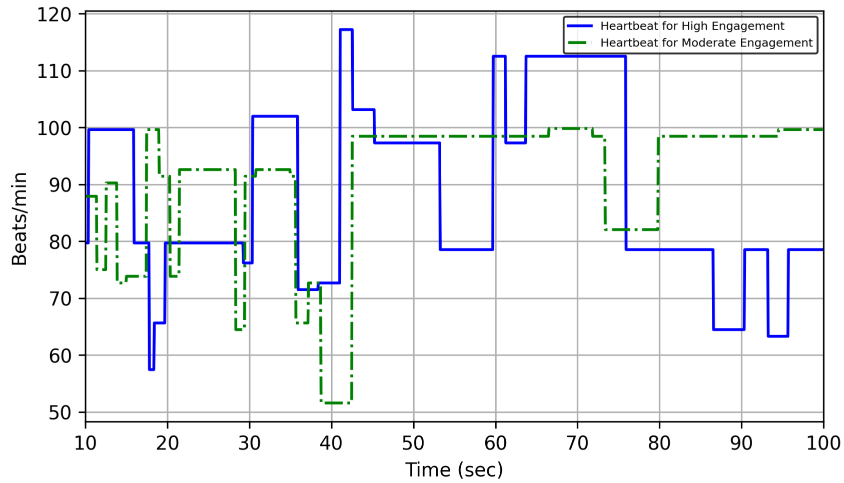


Figure 4.4: Heartbeat from two participants during 3D Virtual Reality experiment with different engagement levels taken from the questionnaire.

Table 4.2: Vital signs and the engagement level, from the self-report questionnaire, for each participant while using 3D virtual reality application

Participant	HR	BR	Ref	Engagement level (out of 5)
1	82.90	16.5	17.2	4
2	117.1	22.4	23	5
3	99.8	19	19.8	4
4	102.6	21.7	20.6	5

4.1.10 Summary

This study investigated participant engagement and behaviour in two visual modules, a 2D application and a 3D immersive virtual reality application for a solar energy system design task.

To do this, a virtual reality application was developed that mimics a 2D application. Next, the participant's vital signs were monitored while using both applications. The data was collected from participants using a non-invasive FMCW radar for estimating the vital signs and from a self-reported questionnaire. It has been found that participants enjoyed the immersive experience. Moreover, the results indicated that the virtual reality application offers greater engagement and immersion than a 2D application. The future aim of this work is to include eye-tracking technology to compare 2D and 3D interfaces. The eye-tracking technology may help in better understanding how people navigate around an application, what they look at and how their attention is drawn to the different design interfaces.

4.2 Solar Energy System Design Using Immersive Virtual Reality: A Multi-Modal Evaluation Approach

4.2.1 Background

Addressing some of the world's most pressing environmental challenges demands a shift in the way we design and develop renewable energy systems. Conventional methods rely on experts creating designs on 2D flat screens using outdated CAD models, often at large distances from the actual site or community [165]. This separation between the physical and digital environments often leads to challenges for designers who must adapt real-world site images to the limitations of 2D flat screens. However, research suggests that enabling users to virtually experience the site as if they were physically present can enhance design effectiveness and user understanding [166]. In fact, 3D visualisation tools, with their interactive and representational capabilities can further facilitate higher levels of user engagement, ultimately enhancing learning and understanding [167]. Moreover, teaching people about climate change is important because it helps them understand and solve such problems in their own communities [168, 169].

Numerous VR studies investigate the relationship between user performance and their sense of presence within the virtual environment, particularly in educational and training contexts [170,171]. It is argued that this immersion and sense of presence leads to a deeper understanding of climate change issues [113, 118].

The working principle of a VR experience for solar energy systems includes developing immersive VR environments that mimic actual solar energy generation and system design. These VR environments integrate virtual objects of solar energy system components such as solar panels, inverters, batteries and charge controller that closely resemble their real-world counterparts. These features provide users with an immersive and visually authentic experience. The VR environments allow users to navigate the virtual environment and interact with 3D objects, which are the elements of the solar energy system. Many factors should be considered to provide real-time data for the solar energy system, such as solar irradiance, panel orientation and shading effects.

Researchers are increasingly exploring and evaluating this immersive environment to enhance user experience, comprehension of content, decision-making and problem-solving [172]. Maintaining positive psychological states such as motivation and engagement is crucial to prevent boredom and loss of focus after repeated exposure to VR [173]. The latest VR headsets, including HTC Vive and Oculus Rift, deliver high levels of immersion to users [100, 174]. This immersion influences the level of presence, which is the sensation of being in the virtual world [175]. Jennett *et al.* in [51] discussed the three core concepts frequently used to characterize engagement experiences: flow, cognitive absorption and presence.

In recent human-computer interaction studies, measuring user experience (UX) typically relies on self-reported data, questionnaires, and user performance. However, questionnaires as self-assessment methods face two main challenges: the potential for misinterpretation and misunderstanding of the items' meanings, and the risk of eliciting stereotypical responses [176]. Current research advocates for the integration of physiological measures into immersive virtual reality applications and experiments, as they can significantly complement self-report data when estimating users' emotions and stress levels [177]. Furthermore, combining both objective and subjective methods leads to more reliable results [176].

Many contemporary theories of emotion view the autonomic nervous system's (ANS) activity as a significant contributor to emotional responses [178]. Bio-signals, such as electrocardiography, electroencephalography and blood pressure monitoring can provide objective data. Engagement is associated with physiological changes, including increased heart rate, sweating, tensed muscles and rapid breathing [179]. The degree of engagement affects the autonomic nervous system, which in turn influences physiological changes in the body [179]. McNeal *et al.* in [180] presented a study using galvanic skin response (GSR) to measure students' engagement levels in an Introductory Environmental Geology Course. Similarly, Lee *et al.* in [181] used electrodermal activity (EDA) measurements to gauge cognitive engagement in Maker learning activities. Darnell and Krieg used heart rate measurements via wristwatch monitors to assess cognitive engagement among medical school students [182].

Since engagement levels influence the autonomic nervous system and are linked to physiological changes in the body, these responses can be measured through specific biosignals, including those reflecting learner engagement in class. By combining physiological parameters like heart rate, breathing rate, skin conductance and other sensor data, we can gain a comprehensive understanding of users' emotional state. Therefore, this research aims to demonstrate the effectiveness of combining these evaluation methods to gain a deeper understanding of user behavior while interacting with the 3D solar energy design tool. The aim is to shift data capture from after the experiment (post-experiment) to during the experiment and move the focus from performance measures to process measures. This approach, with richer data on physiological and behavioral cues, could also lead to better mapping of emotional states and cognitive load.

4.2.2 Eye Tracking in VR

Eye trackers are tools that measure what users are unconsciously focusing on, giving valuable insights for educators [183]. Tiny sensors mounted on a headset track eye movements and where users fix their gaze [184]. Researchers use this data to understand what grabs users' attention and how long they focus on certain areas, which helps them design more user-friendly and engaging digital experiences.

Studying eye tracking in VR environments offers new ways to understand user attention and thinking, especially with head-mounted displays (HMDs) that have built-in eye tracking [185–187]. Companies like FOVE and Tobii are developing advanced eye-tracking systems specifically for VR [188, 189]. In fact, eye tracking is a well-established method for assessing usability and user experience in various settings [190]. A review by Li et al. [191] confirmed that eye tracking is useful for measuring mental workload, immersion level and user experience in VR.

Analyzing eye movements is important for evaluating cognitive function because they can reveal a person's mental state more accurately than other biological signals [192]. Eye tracking measures two main things: fixations (where the eye stays still) and saccades (quick eye movements) [193, 194]. By studying this data, researchers can gauge user engagement by looking at how many times and for how long users fixate on something [195, 196].

Another indicator of user attention is pupil dilation, which is controlled by the autonomic nervous system [197–199]. Research has shown connections between pupil dilation, how engaged someone is with a task, and how difficult the task is [200–202].

Eye blinking rates are also influenced by how someone is thinking, how engaged they are with a task and how tired they are [203]. Studies have shown a link between blinking rate and task difficulty or engagement [204–206].

The Cognitive Load Theory (CLT) suggests that learning is best when our working memory (the part of our brain that holds onto information for short periods) is not overloaded [207–209]. Researchers use eye-tracking data to measure cognitive load and ensure VR experiences are not overwhelming learners [210]. By combining eye tracking with other data, researchers can gain valuable insights into how people learn in VR environments. This information can then be used to improve VR learning experiences and ultimately help people learn more effectively.

4.2.3 Approach and Hypotheses

The previous study compared learner engagement levels in a 2D application and a 3D immersive virtual reality application for designing solar energy systems. Learner vital signs were estimated using a non-invasive radar sensor and the data was validated with self-reported questionnaires. The study confirmed the hypothesis that a 3D virtual reality application leads to higher engagement levels than a 2D application. Figure 4.5 illustrates the heart rate of a participant who designed a solar energy system using both 2D and 3D applications.

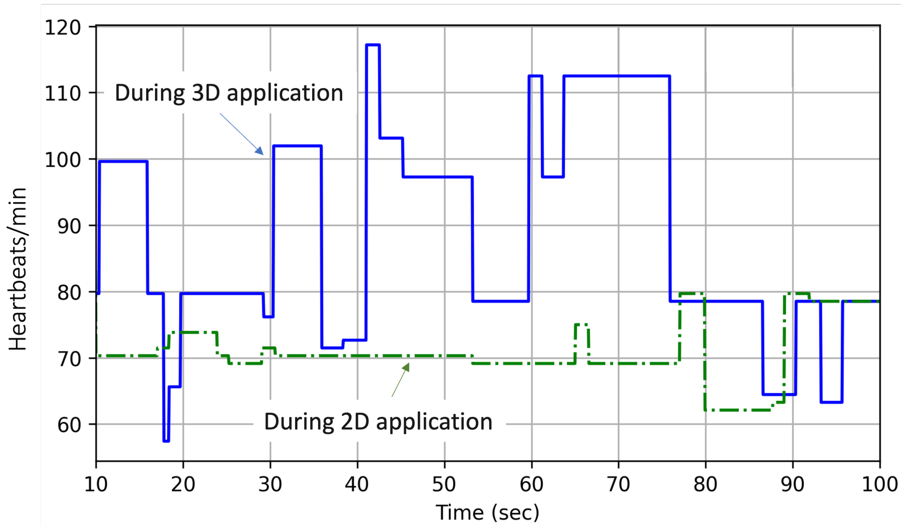


Figure 4.5: Comparison of a participant's heart rate from Radar sensor during 2D application and 3D immersive virtual reality environment.

In this study, the goal is to measure learner engagement while designing a solar energy system in a 3D immersive environment, analysing biofeedback and eye-tracking data. Biofeedback reflecting engagement levels was compared within the VR experience across different scenes. Identifying areas of low learner engagement can guide modifications to the application's design, thereby increasing learner attention and focus. Moreover, the approach to collecting data offers the key advantages of being wireless, wearable and unobtrusive compared to other methods of measuring vital signs and eye-tracking data. By integrating physiological and behavioral data, such as heart rate and eye tracking, with an immersive virtual reality environment, the aim was to gain deeper insights into user interaction and perspectives. This integration allowed for conducting in-depth analyses that reflected users' cognitive state and engagement with the virtual experience.

To further explore learner engagement and experience within the 3D immersive virtual reality environment, the focus was on specific scenes within the application and analysing eye-tracking and biofeedback data. With this focus, the following three research questions (RQs) and hypotheses (Hs) are proposed:

1. ***RQ1***: How do users' engagement levels differ across various scenes within the 3D immersive virtual reality environment when designing solar energy systems?

    - ***H1***: Users' engagement levels vary across different scenes in the 3D immersive virtual reality environment, with certain scenes eliciting higher engagement levels than others during the solar energy system design process.

2. ***RQ2***: How do eye-tracking data and biofeedback correlate with user experience (UX) and engagement levels in the 3D immersive virtual reality environment?

- ***H2***: Eye-tracking data and biofeedback effectively reflect users' UX and engagement levels, with an increased number of fixations and lower blink rates indicating higher engagement in the 3D immersive virtual reality environment.

3. ***RQ3***: To what extent do modifications in the 3D immersive virtual reality environment, informed by biofeedback and eye-tracking data, improve user engagement and focus in designing solar energy systems?

    - ***H3***: Modifications to the 3D immersive virtual reality environment, based on biofeedback and eye-tracking data, lead to significant improvements in user engagement and focus in designing solar energy systems.

4.2.4 Methodology

As mentioned earlier, traditional evaluation methods such as quizzes, multiple-choice questions and self-reported questionnaires may not always provide the most accurate assessment of VR experiences. Instead, researchers should consider using operational, protocol and behavioral measurements that are combined with neurocognitive methods to evaluate user experience for a more comprehensive evaluation [211–214]. Operational measurements often assess a learner's ability to correctly operate equipment or machinery, while protocol measurements evaluate whether the learner adheres to a prescribed process for a specific job task. In contrast, behavioral measurements examine whether the learner exhibits the desired behavior in a given situation. Given that solar energy systems design involves a set of procedures and best practices (a protocol) that designers must follow, a methodology was developed to evaluate the effectiveness of the VR experience.

To gain a deeper understanding of learner engagement, the VR experience was divided into distinct scenes. The objective was to observe participants as they interacted with the VR experience, identifying the aspects that captured their interest, the elements they grasped quickly, the parts they wanted to explore further and the areas they found challenging. The aim was also to pinpoint unclear rules and mechanics that were not yet fully developed within the VR experience. By analyzing participants' interactions, it was sought to determine which mechanics were enjoyable and which ones needed fine-tuning to balance the experience and guide users towards the intended learning objectives at an appropriate pace. The motivation behind this approach was to gain valuable insights into the design of the VR experience and refine it accordingly. To collect real-time data during this process, physiological sensors were used as an additional evaluation tool.

In the methodology, the VR application was divided into three main scenes, each corresponding to a crucial task in a typical solar energy system design project. These tasks are vital for ensuring the efficiency, functionality and optimal performance of the solar energy system. Here is a summary of the tasks associated with each scene:

Scene 1: Site Selection - Users begin by choosing a location for installing the solar energy system. Accurate site selection is crucial for maximizing solar energy production, as it accounts for factors such as available sunlight, local weather conditions and physical constraints.

Scene 2: Power Room - In this scene, users explore the power room, where they can interact with the essential system components, such as batteries, inverters and charge controllers. Users can use the VR controllers to grab and install the components on a stand. Familiarizing themselves with these components and understanding their roles is essential for designing a functional solar energy system that meets energy production and storage requirements.

Scene 3: Solar Panel Installation - The third scene takes users to the house's roof, where they can experiment with the arrangement of solar panels on a stand. Users can add, remove and adjust the tilt of the panels, observing the effects of these changes on the solar power output and electricity generation, as displayed by a gauge. This task is critical in the design process, as optimizing the solar panel arrangement can significantly impact the system's overall efficiency and energy production.

Users can move around the VR environment using a teleporting system with the ability to walk steps in the virtual environment. The purpose of using this system is to minimise motion sickness while moving around the environment.

By incorporating these essential tasks into the VR experience, the aim was to give users hands-on experience and develop a comprehensive understanding of the solar energy systems design process.

In the following sections, a detailed account of the hardware and software used for developing and evaluating the effectiveness of the VR experience is presented.

4.2.5 Hardware

Psychophysiological signals were collected using the Shimmer Sensing Kit [215], which featured a sampling rate of 204 Hz for measuring electrocardiogram (ECG). The ECG electrodes were positioned on the chest as shown in Figure 4.6: Right Arm (RA), Right Leg (RL), Left Arm (LA), Left Leg (LL), and V1.

The virtual environment was displayed through the HP Reverb G2 Omnicept [58], equipped with an integrated eye-tracking system powered by Tobii. This Head Mounted Display (HMD) offers a field of view of 114 degrees, presenting the scene with a resolution of 2160 x 2160 pixels per eye and a combined resolution of 4320 x 2160 pixels. The headset also features a refresh rate of 90 Hz. Furthermore, the integrated sensors in the headset provide heart rate, cognitive load, and eye-tracking data, enabling the tracking of user engagement and the evaluation of user responses in real-time. These data also facilitate a deeper understanding of user performance and inform decision-making regarding the application's design.

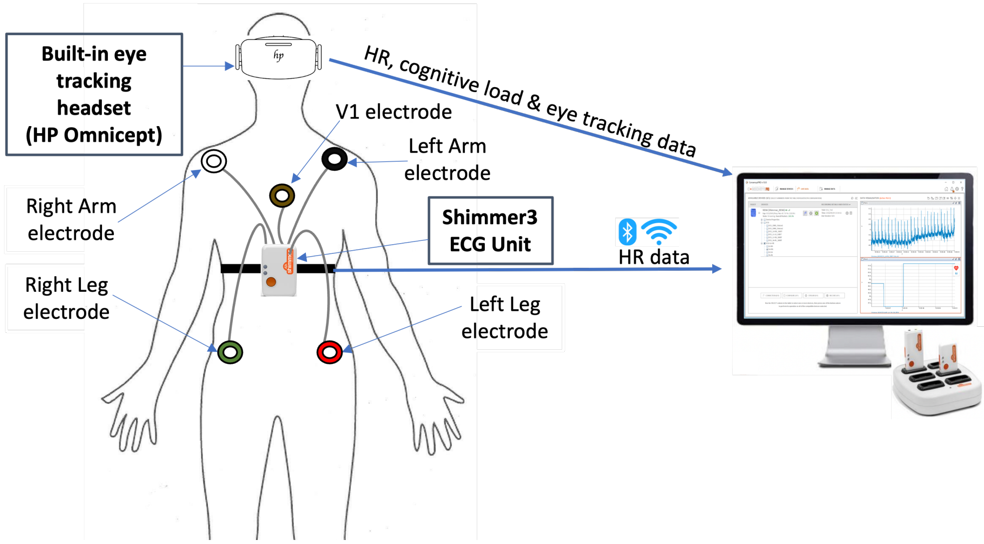


Figure 4.6: Hardware setup and electrode placement: A wireless Shimmer3 ECG system employing Bluetooth and WiFi for heart rate data streaming. The Shimmer kit collected data using ConsensysPRO software. The HP Reverb G2 Omnicept has a built-in eye-tracking headset and other sensors that were used to gather participants' heart rate, cognitive load and eye-tracking data.

4.2.6 ECG and Eye-Tracking Data

Heartbeats are decomposed into five main waves: P, Q, R, S and T [216]. The R waves can be used from the electrocardiogram to determine the heart rate in beats per minute (BPM). This wave is a part of the QRS complex, which is the main spike shown in the ECG signals representing Ventricular depolarization. Figure 4.7 shows the ECG Waveform and QRS complex, which can be used to calculate the heartbeats from the ECG signals.

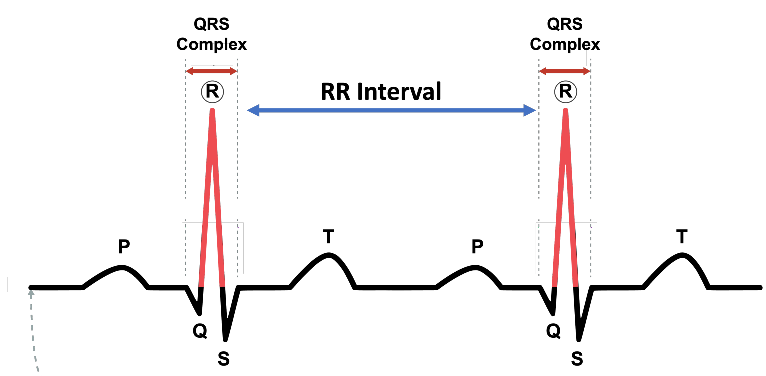


Figure 4.7: ECG signals that show QRS wave for calculating heartbeats.

The Shimmer software, known as ConsensysPRO, employs an ECG-to-HR algorithm that allows users to access heart rate data from the ECG sensor. ECG signals were concurrently collected from participants via five disposable electrodes attached to their skin. Data were streamed to ConsensysPRO using Bluetooth and saved in a CSV file for each participant. Additionally, three scripts are developed by extending the HP Omicept headset Software Development Kit (SDK) using C# programming language and subscribing to the needed information messages provider of the SDK to capture heart rate, cognitive load, eye-tracking data and timestamp. The scripts are attached to their corresponding scene and are activated once a scene gets started, where the eye information associated with each frame gets recorded in real-time. These data were stored in separate files for each scene of the VR application and for each participant (See Appendix I).

The header information captured from the HP Omicept VR headset can be represented succinctly as the sum of the following components, $\mathscr{D}$:

$$\begin{aligned}\mathscr{D} = T &+ \vec{G}_{\mathrm{L}} + \vec{P}_{\mathrm{L}} + D_{\mathrm{L}} + C_{D_{\mathrm{L}}} + O_{\mathrm{L}} + C_{O_{\mathrm{L}}} + \vec{G}_{\mathrm{R}} + \vec{P}_{\mathrm{R}} + D_{\mathrm{R}} + C_{D_{\mathrm{R}}} + O_{\mathrm{R}} + C_{O_{\mathrm{R}}} + \\ &\vec{G}_{\mathrm{C}} + HR + SDNN + RMSSD + CL + \sigma_{CL} + S_{CL}\end{aligned} \tag{4.1}$$

where each term is defined as follows:

- T: OmniceptTimeMicroSeconds.
- $\vec{G}_{\mathrm{L}}, \vec{G}_{\mathrm{R}}, \vec{G}_{\mathrm{C}}$: Gaze vectors for the left, right, and combined eyes respectively, with components in x, y, z coordinates.
- $\vec{P}_{\mathrm{L}}, \vec{P}_{\mathrm{R}}$: Pupil position vectors for the left and right eyes, respectively, with components in x, y coordinates.
- $D_{\mathrm{L}}, D_{\mathrm{R}}; C_{D_{\mathrm{L}}}, C_{D_{\mathrm{R}}}$: Pupil dilation and its confidence for the left and right eyes.
- $O_{\mathrm{L}}, O_{\mathrm{R}}; C_{O_{\mathrm{L}}}, C_{O_{\mathrm{R}}}$: Eye openness and its confidence for the left and right eyes.
- HR: Heart Rate in BPM. $SDNN$ and $RMSSD$: Heart Rate Variability metrics.
- CL, σ_{CL}, S_{CL}: Cognitive Load, its standard deviation, and state, respectively.

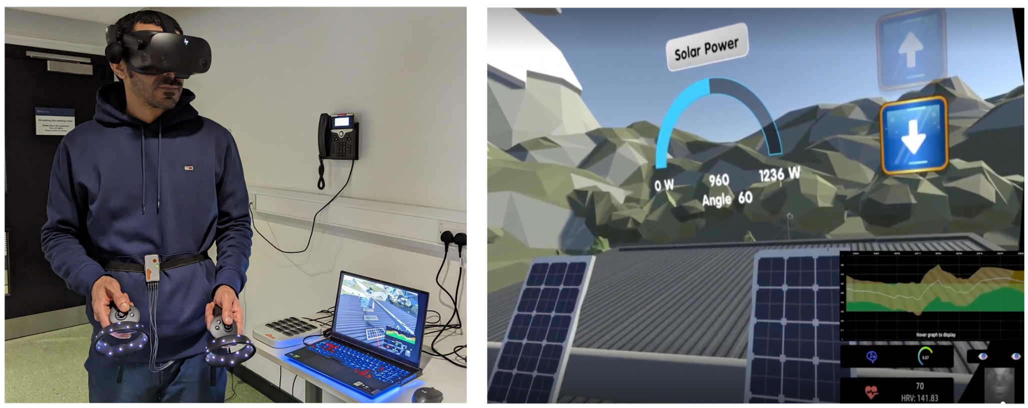
At this stage, a low-pass filter was applied to the ECG signals to preserve crucial low-frequency components while attenuating high-frequency noise.

Similarly, eye-tracking data were cleaned and pre-processed using Python (3.9). Filtering the eye-tracking data from the VR headset involved using a confidence level of 1, which refers to selecting only the most certain and reliable data for analysis, ensuring the analyzed data is free from errors and biases.

As the three scenes in the VR application have varying durations and are task-based, blinking and the number of fixations were normalized using the MinMaxScaler function. This transformation adjusted the values to a range between 0 and 1, facilitating data comparison across different scenes while also eliminating the effects of varying scene durations or individual characteristics.

4.2.7 Virtual Reality Setup

The experiment was conducted in a VR lab, with participants taking part voluntarily via an ethically approved consent form that was approved by the university. Initially, participants were briefed on the instructions and the purpose of the experiment. Then, they were asked for permission to place the ECG electrodes at the specified positions. Figure 4.8-(A) shows a participant wearing the ECG electrodes and the VR headset. Omnicept Overlay was utilized to visualize heart rate and cognitive load data concurrently. Open Broadcaster Software (OBS) was employed to record and live-stream the VR application, including the overlay screen, as shown in Figure 4.8-(B). Prior to starting the VR application, calibration was carried out for each participant to ensure optimal accuracy when performing the eye-tracking measurements, as depicted in Figure 4.9.



(A) (B)

Figure 4.8: The experiment setup. (A) the user is wearing the ECG sensor and the HP headset to perform the VR application. At the same time, the application was live-streaming and recorded on a laptop. The picture was taken from a VR lab at the University of Glasgow. (B) The screen of the OBS studio where the overlay app transparently appeared for casting the heart rate and cognitive load data from the HP headset.

Moreover, the 3D application was developed using the Unity3D game engine [150], version 2020.3.25f1. All the scripts were developed using C# in Visual Studio within the game engine. OpenXR was used in this application to create VR functionality such as grabbing and locomotion. The OpenXR Plugin package was used for implementing all VR-specific features. The 3D objects for the VR application were taken from the Unity assets store. Blender software was used for modelling the solar panels' stand and its handle. As previously mentioned, the application was divided into the three main scenes shown in figure 4.10. The VR application development involved overcoming several obstacles which are represented in simulating PV system behaviour in real-time. This step required creating many scripts that ensure all the system components are installed in the power room (the battery, inverter and charge controller), and calculating the amount of electricity based on the number of solar panels and the angle of

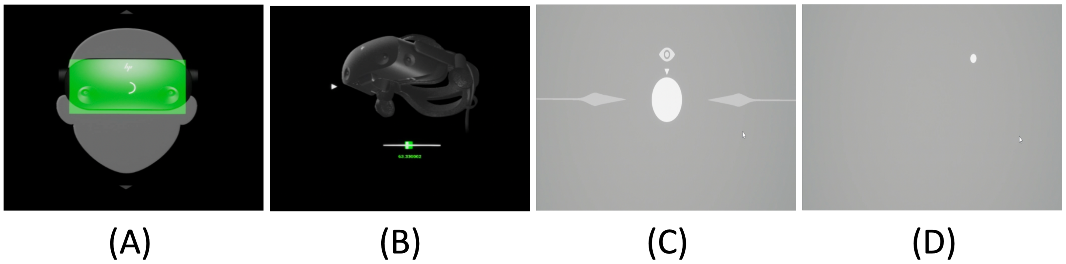


Figure 4.9: Before starting the VR application, participants performed a calibration for the eye-tracking to ensure optimal data accuracy. The procedure involved (a) adjusting the head position, followed by (b) setting the interpupillary distance (IPD) using the slider. Subsequently, (c) participants focused on the centre of the screen, and finally, (d) they were instructed to follow the dot.

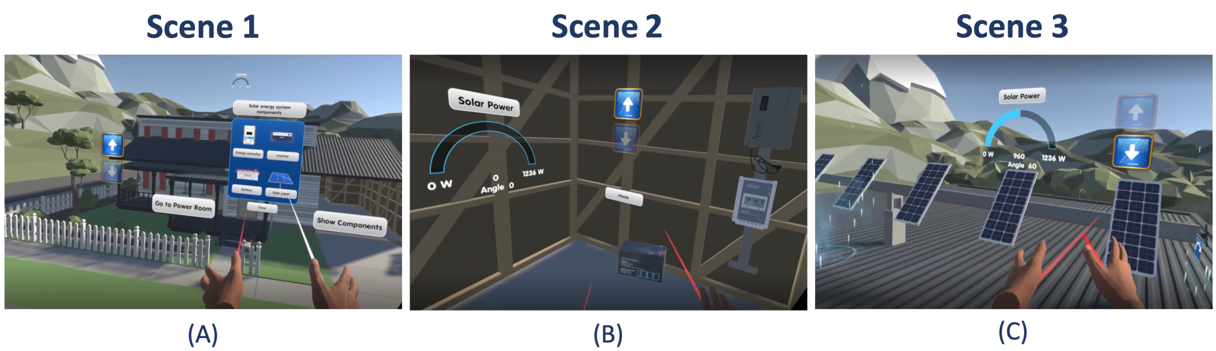


Figure 4.10: The three main scenes in the VR application: (A) Site Selection, where users are positioned in front of the house, learning about system components before installing the solar energy system. (B) The Power Room, where users can grab and place the system components on the designated stand. (C) Solar Power Installation, where users can add, remove, and adjust the angle of the stand, observing changes in the power generated from the system via the gauge chart.

the stand. A sprite image was added to display the electricity generated by the system using the fillamount property to show the amount of electricity generated.

Furthermore, the VR application was implemented on a Lenovo laptop with Windows 11, which has a 64-bit operating system, and an Intel Core i7 with an NVIDIA GeForce RTX 3070 graphics card.

4.2.8 Finding the Average Brightness for the VR Scenes

Numerous studies have reported that eye-tracking data, particularly pupil dilation, can be influenced by the luminance of the environment. As a result, the brightness levels of the three scenes were analyzed in the VR application. A 30-second video for each scene was recorded and Python code with the OpenCV video processing library was used to extract frames from the videos and convert them to grayscale (See Appendix F). Subsequently, the lightness value was

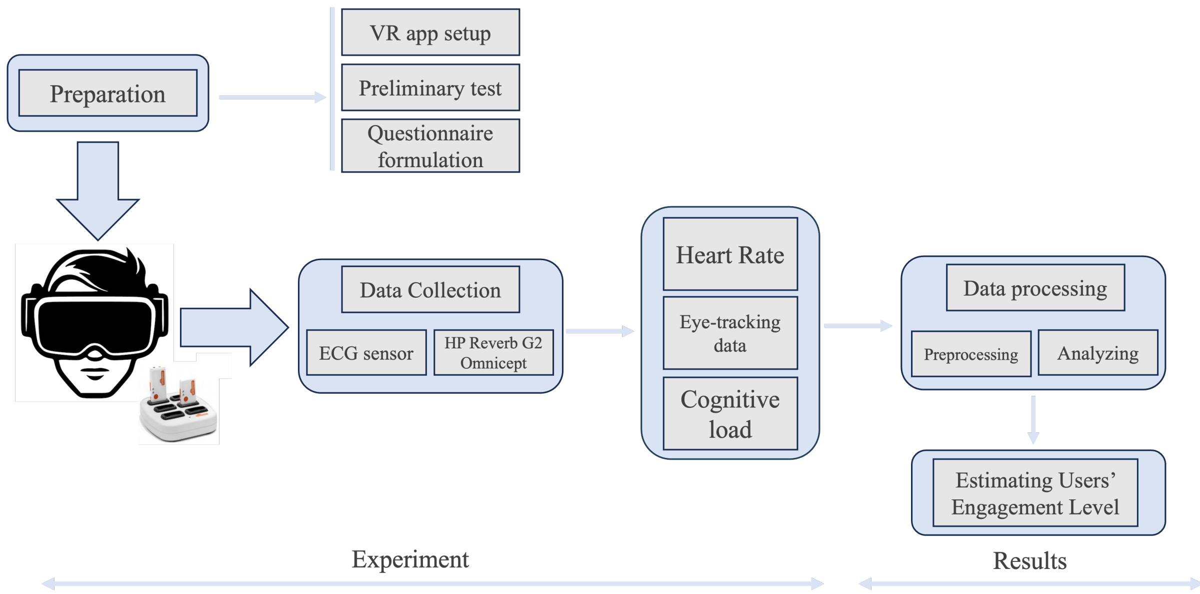


Figure 4.11: The experimental design of the virtual reality study. The preparation phase of the study was about developing and testing the VR application and then creating a questionnaire for evaluating the VR experience. During the experiment, the ECG sensor and HP omnicept headset were used to collect heart rate, eye-tracking data and cognitive load for the participants. The data has been processed and analyzed in order to estimate the users' engagement level.

calculated for each frame by determining the mean pixel value of the grayscale frame, summing up all pixel values, and dividing by the total pixel count. Finally, the average lightness values were computed for the entire video by adding all the lightness values and dividing by the total number of frames.

4.2.9 Self-Report Questionnaire Design

Participants took part in the project voluntarily via ethically approved consent using anonymous and confidential online self-report questionnaires after experiencing the virtual reality application and collecting the vital data using the headset and the ECG sensor. They were also informed that they were able to withdraw their participation from the project at any time. The questionnaire consists of fourteen questions designed to measure the engagement and immersion level of the participants in general and for each scene. The first question was whether the participants had a previous experience with virtual reality. The second question asked participants to rate how easy the application was from 1 to 5, where 1 (Extremely Difficult) and 5 (Extremely easy). The third question was about asking the participants if they felt engaged in the virtual environment or not. The fourth question enabled the participants to select the scene they felt more engaged in, in front of the house, the power room, or the roof. In questions 5, 6 and 7, participants rated their engagement level in each scene from 1 to 5, where 5 is the highest engagement level. Questions 8 to 14 were taken from the unified questionnaire on user experience (UX) in an immersive virtual environment(IVEQ) proposed by [176] related to measuring engagement and immersion sub-scales.

4.2.10 Participants

A total of 27 students from the University of Glasgow volunteered to take part in the experiment. These participants included 17 males and 10 females, ranging from 25 to 42 years old. All participants were healthy and did not take medication for heart problems or mental diseases. Figure 4.11 explains the experimental design of this VR study.

4.2.11 Results

4.2.11.1 Self-Reported Questionnaire Results

Participants completed self-report questionnaires that assessed their sense of immersion and engagement in each scene of the application. Out of the 27 users, 12 (44% of the participants) had previous experience with VR. On a scale of 1 to 5, with 1 being extremely difficult and 5 being extremely easy, 23 participants (85% of the population) rated the application as easy to use, selecting scores of 4 and 5. Meanwhile, 4 participants (15%) chose scores of 3 or below.

Regarding engagement in VR, 48% of participants strongly agreed that they felt engaged, 44% agreed, 4% were neutral, and 4% strongly disagreed. When asked which scene they felt most engaged in, 4% chose the front of the house scene, 30% chose the power room scene, and 67% chose the house roof scene. Figure 4.12 illustrates participants' responses when rating their engagement level during the three scenes.

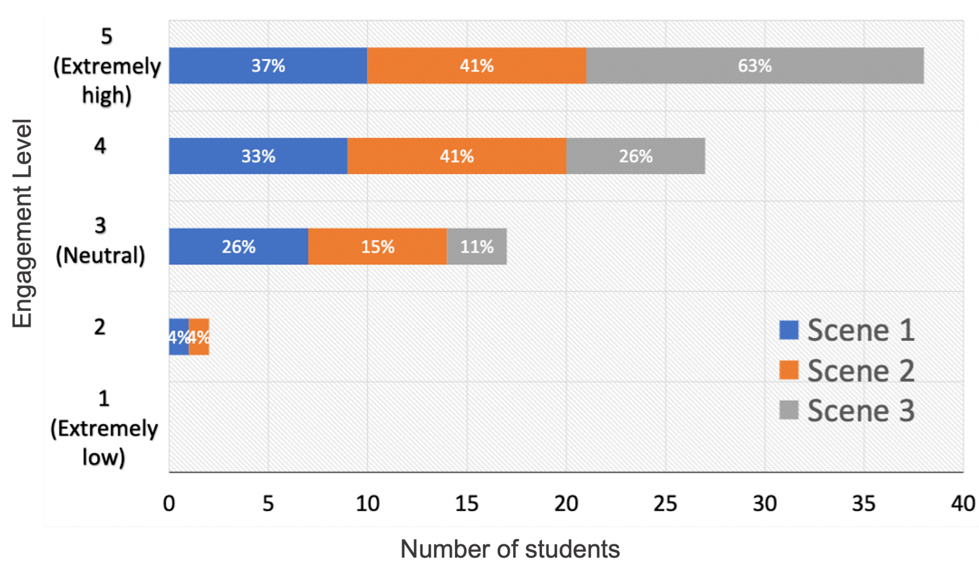


Figure 4.12: Figure illustrates the participants' engagement levels during the three scenes, with 5 representing extremely high engagement and 1 representing extremely low engagement.

When asked if the visual aspects of the virtual environment engaged them, 44% of participants rated the engagement as extremely high (5), 41% chose 4, and 15% chose 3. In terms of feeling compelled or motivated to move around inside the virtual environment and complete the application, 41% of participants rated this aspect as extremely high (5). Furthermore, 59% of participants rated their involvement in the virtual environment as extremely high (5).

Regarding stimulation from the virtual environment, 52% of participants selected an extremely high rating (5), while only one participant (4%) chose a neutral rating (3). As for becoming so involved in the virtual environment that they were unaware of things happening around them, 33% rated this aspect as extremely high (5) and 37% rated it as 4. When asked if they felt physically present in the virtual environment, 30% rated this aspect as 5 and 52% rated it as 4. Finally, 33% rated their involvement in the virtual environment as extremely high (5) when it came to losing track of time, while 37% rated it as 4.

4.2.11.2 Vital Signs and Eye Tracking Data

Based on the literature, the data representing users' engagement level was analysed, such as heart rate, cognitive load, blinking rate, pupil dilation and the number of fixations. Headset data was subsequently analysed to provide real-time insights.

Heart Rate

After analysing the heart rate data from the ECG sensor and the sensor from the HP headset, the accuracy for the HP headset was 86.72% compared with the ECG sensor. Therefore, it was decided to rely on the ECG data for analysing the heartbeat signals. Interestingly, the mean heart rate across the three scenes was nearly identical, figure 4.13. This suggests that heart rate data may not be a significant factor in measuring engagement in a VR environment.

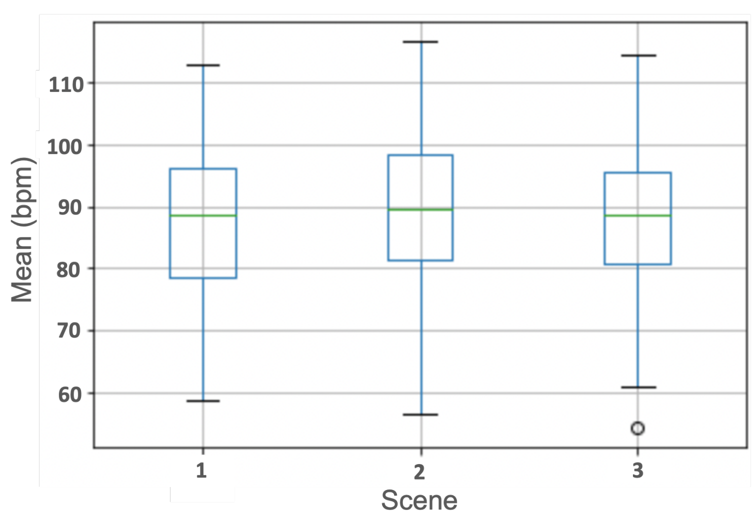


Figure 4.13: The mean heart rate values during the three scenes. The finding shows that there is no significant difference in the ECG signals for the three scenes, which indicates that there is no impact of the heart rate data in measuring the level of engagement in a virtual reality environment.

Cognitive Load

As anticipated, the results show that the highest cognitive load was observed in Scene 1 due to the amount of text included in this scene. Users in the first scene had to read and comprehend the role of each component in the solar energy system. This may indicate that the cognitive demands of processing textual information, particularly when learning new concepts, are higher compared to the other tasks.

Scene 2 exhibited the lowest cognitive load values, as the task involved grabbing and placing 3D objects, the system components, on a stand. This suggests that the task in Scene 2 was more intuitive and relied primarily on users' motor skills, thus requiring less cognitive effort. Scene 3 was intermediate, as it combined interactions with 3D objects and observation of the results generated by the system. This could be interpreted as an indication that users were engaged in both cognitive processing and motor skills, balancing the overall cognitive load.

Figure 4.14 displays the box plot of cognitive load data across the three scenes. These findings can inform future refinements of the VR experience by optimizing the amount and presentation of information in each scene, balancing cognitive load and ensuring that users remain engaged throughout the experience.

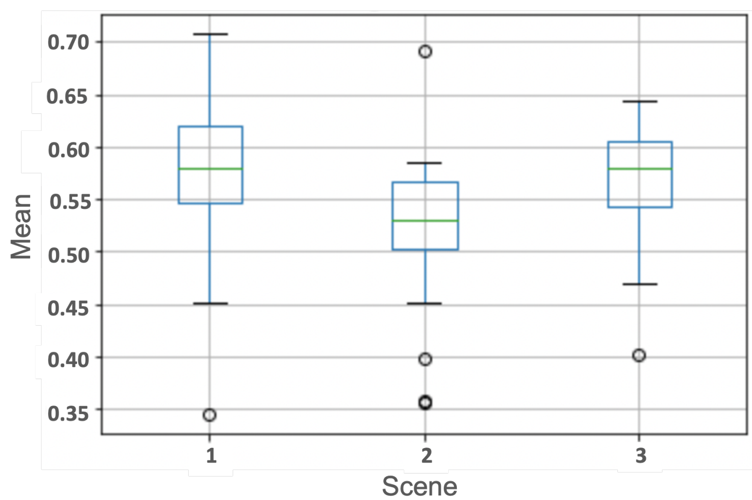


Figure 4.14: The cognitive load of the users during the three scenes in the virtual reality application. The results showed that Scene 1 had the highest cognitive load while Scene 2 had the lowest.

Pupil Dilation

The changes in pupil dilation among participants across the three scenes were examined. The findings show the greatest pupil dilation for participants in Scene 2, the power room. As previously mentioned, pupil size tends to decrease as the brightness of the visual environment increases. Figure 4.15 illustrates the noticeable difference in average brightness in Scene 2 compared to the other scenes, which led to increased pupil size for participants.

The brightness level for Scenes 1 and 3 is nearly the same, but the pupil size for participants in Scene 3 is larger than in Scene 1. This discrepancy may be attributed to the difference in the tasks' difficulty and the nature of the environment, as pupil size typically increases with a rise in mental activity and engagement level.

These results suggest that the tasks in Scene 2 and Scene 3 could have been more cognitively engaging or demanding for participants, while Scene 1, despite its textual information, may not have induced the same level of mental effort. Additionally, the variations in brightness between scenes may have influenced pupil dilation, further affecting the interpretation of cognitive load or engagement. Future iterations of the VR experience may benefit from taking these factors into account to optimize the balance between engagement, cognitive load, and visual design.

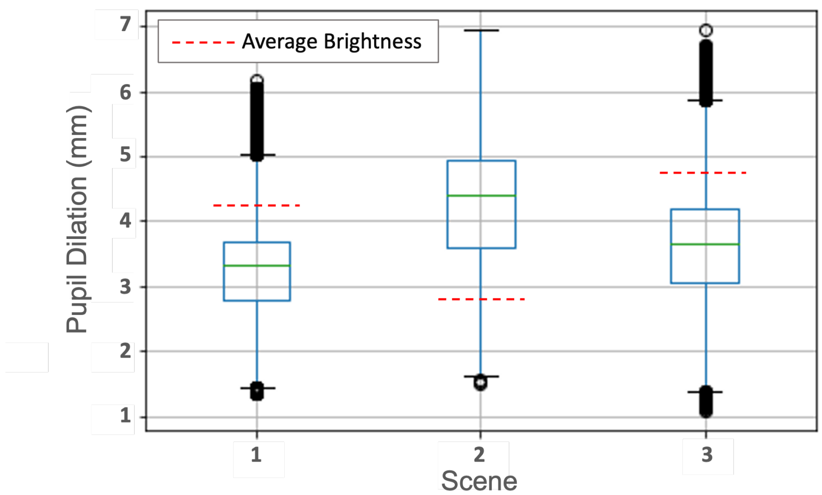


Figure 4.15: The pupil dilation for the participants within the three scenes. The results showed that the largest pupil dilation occurred in scene 2 while the smallest dilation appeared in scene 1. The red line represents the average brightness level for each scene in 30 seconds. Scene 2 had the lowest brightness level, while scenes 1 and 3 had close brightness levels.

Blinking Rate

Figure 4.16 illustrates the normalized blinking rate for participants across the three scenes. The data for the blinking rate was normalized in each scene to account for the differences in duration between them. The highest number of blinks occurred in Scene 2, followed by Scene 3 and Scene 1, respectively.

The differences in blinking rates among the scenes could suggest varying levels of cognitive load, attention, or visual engagement for the participants. A higher blinking rate in Scene 2 might indicate increased cognitive effort, possibly due to the interaction with 3D objects or the lower brightness level in that scene. Meanwhile, the lower blinking rates in Scenes 1 and 3 might be indicative of reduced cognitive load or increased focus on the tasks at hand. It is essential to consider these factors when evaluating user engagement and cognitive load in the VR experience. Further analysis of the relationship between blinking rate and other physiological or behavioral data might offer additional insights into the effectiveness of each scene in promoting learning and engagement.

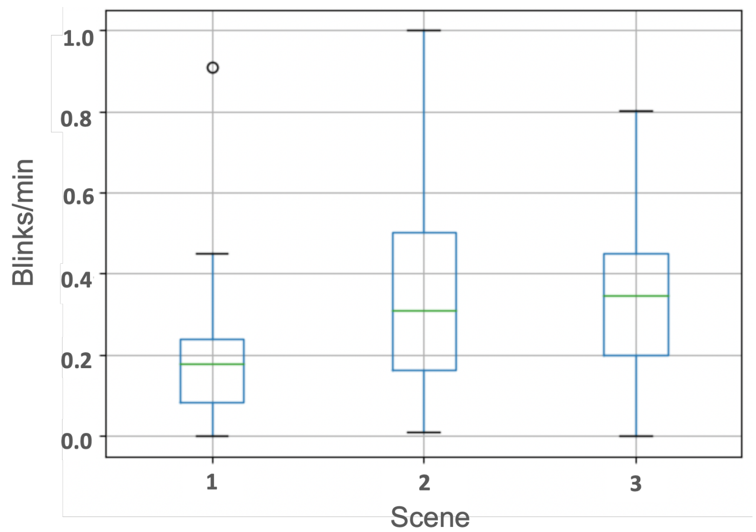


Figure 4.16: The difference in blinking among the three scenes. The results showed that Scene 2 had the highest blinking rate, while Scene 1 had the lowest.

Number of Fixations

Figure 4.17 presents the number of fixations for participants during the three scenes. The findings reveal a significant difference in the number of fixations across the scenes, with Scene 2 having the highest number of fixations.

The higher number of fixations in Scene 2 could be indicative of increased visual attention or cognitive effort, as participants may have been more focused on manipulating and placing the 3D objects in the power room. This could also suggest that Scene 2 was more engaging or required more intricate interactions, drawing the participants' gaze more frequently to various elements within the scene.

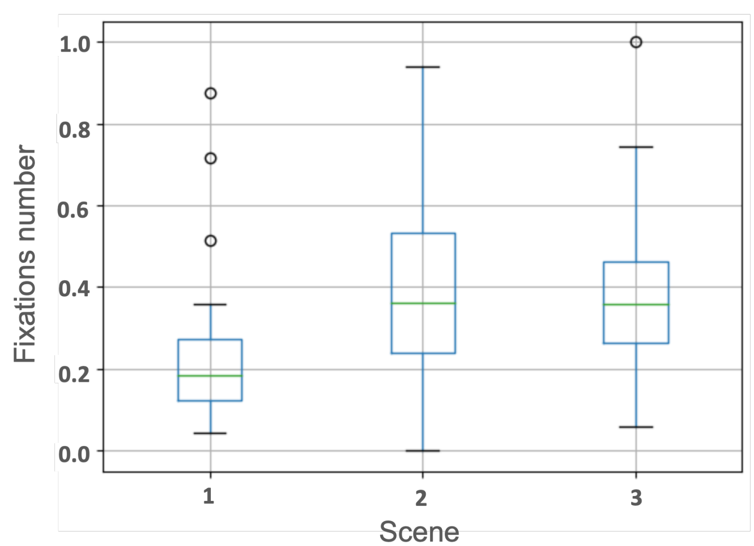


Figure 4.17: The number of fixations during the three scenes. Scene 2 had the highest fixations number, while Scene 1 had the lowest.

Table 4.3: Summary of the Collected Data Analysis

Parameters	Scene#	Mean	SD
Heart Rate	1	88.15	16.28
	2	88.06	16.07
	3	88.04	13.94
Cognitive Load	1	0.582	0.132
	2	0.513	0.163
	3	0.567	0.135
Pupil Dilation	1	3.260	0.717
	2	4.314	0.929
	3	3.636	0.857
Blinking Rate	1	0.20	0.18
	2	0.36	0.28
	3	0.34	0.20
Number of Fixations	1	0.24	0.20
	2	0.40	0.25
	3	0.38	0.20

Conversely, the lower number of fixations in Scenes 1 and 3 might imply that participants found these scenes less visually demanding or cognitively challenging. However, it is essential to consider the context of the tasks and the nature of the interactions within each scene when interpreting these findings. A more detailed analysis of the spatial distribution and duration of fixations, alongside other physiological or behavioral data, could offer a deeper understanding of the participants' engagement, learning, and cognitive load during each scene in the VR experience.

Finally, table 4.3 provides a summary of the mean and standard deviation values for all parameters across the three scenes in the VR application.

4.2.12 Discussion

Human-computer interaction innovations depend heavily on understanding users' mental states. This study investigated UX during a 3D immersive virtual environment using an HP Omnicept headset and the ECG sensor on a solar energy systems design task. An investigation was conducted into whether eye tracking, heart rate and cognitive load data would be associated with increasing engagement and cognitive level in each scene of the VR application. Also, three RQs and hypotheses were formulated at the start of the experiment around these areas and the findings will be discussed related to these hypotheses.

It was hypothesised that diverse emotional responses within the three scenes would have produced various attention patterns. Results from the study showed that the user experience and engagement level could be estimated by analysing eye-tracking data, as the eyes can reveal much more about a person's emotions than most people realise and are a slightly more enigmatic indicator of their emotions.

Despite the survey showing greater engagement in a specific scene, there is no difference in the heart rate data. The participants in the three scenes had almost equal heart rate levels, and there was no significant impact from the ECG signals related to the engagement level. The VR game was likely immersive and engaging for all participants during the three scenes. The finding with the ECG sensor contradicts what was shown by the study of Murphy and Higgins in [217]. They used ECG and EEG sensors to assess user engagement in an immersive virtual reality environment. Their findings showed that the heart rate is a good indicator for measuring the users' engagement level in virtual reality.

It was hypothesised that utilising an approach that increased cognitive load when teaching a topic to students would have an adverse effect on their performance [218]. A task becomes more challenging and places a heavier intrinsic load on working memory when it has a greater number of interconnected informational components. The cognitive load in Scene 1 is higher than in Scenes 2 and 3. This was to be expected because participants needed to read and understand the role of the solar energy system components, as there is a lot of text in this scene.

Psychologists have long been curious about how changes in pupil size and mental activity relate to one another [219]. Also, mental activities are closely connected with problem difficulty, which affects pupil response [201] [220]. There was a prediction that pupil dilation would be affected by the users' engagement and performance in the VR application in different scenes. Pupil diameter is a complicated parameter in eye-tracking because it is affected by the brightness of the visual stimulation [221] and cognitive load [222]. The study results showed increased pupil dilation in Scene 2, which had a lower average brightness level than in Scenes 1 and 3. This was aligned with the literature that the pupil size and brightness of the visual environment are found to be inversely proportional [223]. This finding suggests the importance of considering the effect of visual brightness on pupil size while reliably measuring the user experience in virtual reality applications. Moreover, when comparing Scenes 1 and 3, there is no significant difference in the average brightness level between them, but the pupil dilation in Scene 3 is larger than in Scene 1. This indicated the relationship between pupil dilation and task difficulty [224], increasing the level of interest and arousal [225] and users' attention [226].

As mentioned earlier, scenes 1 and scene 3 have different physical efforts. In Scene 1, users read and understand the role of the solar energy system components by clicking on buttons and demonstrating the information. While in scene 3, users interact more with the 3D objects as they grab and place the solar panels and try different situations of the system. This physical activity has an impact on pupil dilation. The results revealed that the size of the pupil increased in response to physical exertion like one of a previous study indicated that pupil size increased during physical effort [227].

Higher blink rates are frequently observed in insight problem-solving situations and creativity performance [228] [229]. However, a previous study observed the relationship between the blinking rate and visual attention [204]. The result of this study indicated that the blinking rate increases when visual attention is engaging and vice versa. The findings indicated the relation between the blinking rate and task difficulty. The blinking rate in scene 1 was lower than in scenes 2 and 3, as the task in scene 1 was very easy to perform. This aligned with the finding from the study by Tanaka and Yamaoka [206], which shows that the blinking rate with the difficult task was higher than for the easy task. In addition, the blinking rate is affected by the nature of the task. Users experienced different types of tasks during the three scenes, which produced different levels of blinking rates. Also, endogenous blinks are reduced when a task demands more concentration [230], which was clearly obvious with the blinking rate in scene 1. The amount of text in Scene 1 reduced the blinking rate of the participants as they had to be focused on comprehending the presented information. This finding matches the literature that indicated that the blinking rate reduced during reading [205].

The relationship between blink rate and cognitive load is often found to be inverse. The fundamental hypothesis from earlier studies is that when cognitive load is at its lowest, we blink more frequently because we believe we can blink without missing anything. Moreover, blinking inhibition may be an adaptive strategy that shields delicate cognitive processes from disruption when a mental load is raised [231].

The number of fixations in eye-tracking data can provide insights into several aspects of visual processing, attention, and cognitive engagement. The number of fixations might indicate which parts of a visual environment appeal to the user. A scene with a higher fixation number may show that the user finds that area more visually attractive or interesting. The number of fixations may also be a good indicator of the difficulty of a task or stimuli. As expected, a user moves his eyes to absorb information and make sense of the visual input. Scene 2 had the highest number of fixations which suggests the high level of users' interest in this scene. Increasing the number of fixations in scene 3 may suggest that the user spent more time processing and integrating information from various scene areas. It was expected that participants would look more at the solar energy power, the output, of the system they already built simultaneously with trying a new design. This process attracted users' attention and motivated them to try different design scenarios.

A high number of fixations, which occur when a user revisits the same place or object repeatedly, may indicate a high level of interest. That might, however, also be a sign of understanding issues [232]. It's crucial to know that fixation numbers may not always give a full understanding of visual processing. Other eye-tracking elements, such as fixation duration, saccades or sensory data, should be considered to interpret the data precisely. It is important to note that eye-tracking research is a complicated field, and analysing data should be done in conjunction with other relevant measures.

The findings indicated the importance of capturing several physiological data for monitoring the user experience. Data from eye tracking can be highly helpful in testing the usability and user experience of any VR game. The capacity of eye tracking to detect variations in involvement during particular tasks enables the researcher to link particular contexts to particular outcomes and demonstrate that engagement was the mediating factor [224]. Researchers can also learn more about the motivations behind users' responses and behaviours as they engage with photorealistic items, environments, and pretty much any stimuli by submerging research participants in a virtual reality world.

Numerous studies in the literature on solar energy system design have evaluated the effectiveness, usability, and user experience of their VR applications via common assessment techniques. These techniques include gathering quantitative and qualitative data from users about their experience via surveys [79, 81, 83], pre and post test [77, 82] and interviews [84]. Despite the advantages of using these methods in assessing VR experiences and proving their validity in measuring UX [176], they also have certain limitations. As mentioned earlier, these methods rely on self-reported data and subjective interpretations of users' behaviours and attitudes. This can lead to biases and inaccurate feedback, as many users prefer to provide answers that are socially acceptable or have difficulty expressing how they feel.

The study provides valuable contributions to the learning technology field and highlights the educational benefits of using virtual reality in learning. Analysing eye-tracking and Electrocardiography data offers insights into the enhancement of instructional design and understanding what keeps engaged to develop educational content more effectively. Also, through monitoring engagement and bio-feedback alongside post-experience assessments, researchers will be able to assess the VR effectiveness in conveying knowledge and skills. Researchers can detect the most effective elements of the VR application that motivate and engage learners. This information can be utilised to develop better strategies to enhance involvement in educational materials. In addition, the findings can inspire further research that combines engagement, multi-modal physiological data and learning outcomes for assessing VR applications that help comprehend the mechanisms of immersive learning.

4.2.13 Summary

This section summarises the findings of the study:

It was hypothesized that diverse emotional responses within the three scenes would produce various attention patterns. Results from the study showed that the user experience and engagement level could be estimated by analyzing eye-tracking data, as the eyes can reveal much more about a person's emotions than most people realize and are a slightly more enigmatic indicator of their emotions. The number of fixations might indicate which parts of a visual environment appeal to the user. Scene 2 had the highest number of fixations, which suggests a high level of users' interest in this scene. Increasing the number of fixations in Scene 3 may suggest that the user spent more time processing and integrating information from various scene areas.

It was predicted that pupil dilation would be affected by user engagement and performance in the VR application in different scenes. The results showed increased pupil dilation in Scene 2, which had a lower average brightness level than in Scenes 1 and 3. The findings align with existing literature, which suggests an inverse relationship between pupil size and the brightness of the visual environment. This finding highlights the importance of considering the impact of visual brightness on pupil size when reliably measuring user experience in virtual reality applications. Moreover, when comparing Scenes 1 and 3, there is no significant difference in average brightness between them, but the pupil dilation in Scene 3 is larger than in Scene 1. This indicated the relationship between pupil dilation and task difficulty, potentially leading to heightened user engagement and attention.

It was hypothesized that using an approach that increased cognitive load during instruction would negatively impact student performance. The results confirmed this hypothesis, showing that cognitive load was highest in Scene 1. This was unsurprising, as Scene 1 presented a complex topic with extensive text requiring participants to read and understand various solar energy system components. Furthermore, the findings aligned with previous research by Tanaka and Yamaoka [206]. The blink rate in Scene 1, which involved a simpler task, was lower compared to Scenes 2 and 3. This supports the notion that the blink rate increases with task difficulty.

In summary, the VR application fosters higher engagement and intuitive interaction with 3D objects. By incorporating physiological sensors and eye-tracking, it provides valuable insights into user engagement and cognitive load, allowing future optimization of the learning experience. The VR setup's ability to simulate real-world conditions and provide immediate feedback on design choices accelerates learning and improves accuracy compared to traditional 2D design methods. Furthermore, the application's user-friendly interface and positive user reception suggest that the VR approach can significantly enhance learning outcomes in solar energy system design education. However, while integrating physiological measures offers a more comprehensive understanding of user engagement, it comes with the added complexity of data analysis and interpretation, requiring specialized tools and expertise. Moreover, although the impact of scene brightness on pupil dilation was explored, further work is clearly required for careful visual design to optimise user engagement and learning outcomes without causing visual strain or misinterpreting cognitive load.

4.2.14 Conclusions

This study highlights how combining multimodal data channels, which include a variety of objective and subjective metrics, can offer insights into a more comprehensive understanding of learner engagement and evaluate user experience. The captured data was compared in different scenes of a VR solar energy systems design task to investigate learner engagement levels. The findings showed that analysing eye-tracking and vital signs data allows a comprehensive analysis of user engagement and cognitive load measurements for designers and developers to develop applications that meet user expectations. For example, the majority of the participants found the VR application easy to use and felt highly engaged. Most users rated their engagement as extremely high, indicating the application's effectiveness in capturing user interest and attention. Moreover, cognitive load varied across different scenes, with the highest cognitive load observed in the text-heavy first scene and the lowest in the more interactive second scene. This demonstrates the importance of balancing informational content and interactive elements to maintain user engagement. Moreover, pupil dilation varied significantly across scenes, with the greatest dilation in Scene 2. This finding suggests a correlation between pupil dilation and the level of cognitive engagement, offering a valuable metric for assessing user attention in VR environments. The blinking rate and number of fixations varied among scenes, providing insights into the varying cognitive demands and user focus in different parts of the VR experience.

The impact of these findings is multifaceted, as they contribute to understanding user engagement and experience in immersive virtual environments. By highlighting the importance of multimodal data channels and revealing the limitations of heart rate data in representing user engagement, this study offers valuable insights for developers, designers and educators. Future research should explore the optimization of content and interaction balance in VR applications, aiming to maximize user engagement and learning outcomes. Further investigation into the relationship between physiological responses and user experience can provide deeper insights into effective VR design strategies.

Chapter 5

Conclusion

5.1 Introduction

The design of solar energy systems is very crucial to the global transition towards renewable energy. However, the conventional approaches to teaching solar energy system design often rely on 2D simulations and traditional classroom lectures that hinder the depth of the learning and practical comprehension. Integrating VR technology into solar energy system design allows users to be immersed in a more realistic environment to try complex system designs in a more intuitive manner. In addition, VR technology fosters users engagement and retention levels since it offers direct interaction with the system components and processes that lead to enhance decision-making and design precision. This chapter concludes with contributions, implications and provides directions for future work.

5.2 Summary of the thesis

This study was undertaken in the field of solar energy and revealed the limitations of the traditional methods of teaching solar energy system design. The traditional simulations in this field lack user interaction and engagement with systems components. The current simulations are static and out-of-date in representing system performance which reflects on struggle to model the dynamic effects of sunlight intensity, temperature and load demand changes. The study started with a literature review of the use of virtual reality technology in solar PV systems education, which gave the ability to form a new approach to develop and evaluate a VR application for solar PV system design. This review has been conducted to gain insight and collect data about the VR applications that are related to the PV systems design. The results of the literature review were used as guidance for developing and evaluating the proposed VR application. The review presented the VR applications in different solar energy aspects, the benefits and limitations of using VR applications for PV systems design, the contribution of VR technology in enhancing users' engagement level and the innovative approaches for integrating real-time data in these applications.

First, this thesis presents a novel approach to climate change education through a three-day Virtual Reality (VR) Hackathon. The hackathon focused on four United Nations Sustainable Development Goals (SDGs) - Quality Education, Affordable and Clean Energy, Sustainable Cities and Communities, and Climate Action. Using VR technology and game design software, engineering students worked in teams and competed against each other in designing immersive environments that demonstrated their understanding of these SDGs and climate change. The goal was to encourage the development of empathy, education, and awareness around these critical global issues. The hackathon also integrated authentic assessments, mirroring real-world engineering tasks and providing a more practical and relevant learning experience. The findings suggest that this VR Hackathon has significantly enhanced students' understanding of the SDGs and climate change issues, their competency with VR technologies, as well as their teamwork and problem-solving skills.

Then the first virtual reality application was developed for teaching the basics of solar energy systems. The purpose of this application is to showcase the approach to teaching solar energy systems design to higher education students using a game-based virtual reality approach. This approach enabled students to immerse themselves in a virtual environment, which was safe for both students and their teachers. The game consisted of two levels, where students were invited to solve an energy-related task in two different homes. Based on user feedback, the interactive learning tool improved student awareness of solar energy systems and how they can be used to satisfy domestic energy demands.

The second VR application for solar energy system design was developed to mimic a 2D commercial application. The purpose was to measure user engagement or stress levels in both a 2D and 3D immersive virtual reality environment during a solar energy systems design task. User engagement was measured by estimating a user's vital signs using a non-invasive FMCW radar. In this study, four participants tried a 2D and 3D interface while their vital signs were being monitored. According to participant feedback from self-reported questionnaires, the results clearly indicate that 3D virtual reality offers higher user engagement. These findings could have a tremendous impact on the way we develop renewable energy systems of the future.

After measuring the engagement level in a 2D and 3D virtual reality application, a unique approach was conducted to evaluate the effectiveness of an immersive VR experience for solar energy systems design training, using a multi-module approach and a detailed analysis of user engagement. To better understand the effectiveness of this VR experience, the experiment was divided into several scenes and employed a range of sensors, including eye-tracking and wireless wearable sensors, to accurately assess users' engagement and performance in each scene. The results demonstrated that the immersive VR experience was effective in improving users' understanding of solar energy systems design and their ability to perform complex tasks. Moreover, by using sensors to measure user engagement, specific areas that required improvement were identified and insights for enhancing the design of future VR training experiences for solar energy systems design were provided. This research not only advanced VR applications in solar energy education but also offered valuable insights for designing effective and engaging training modules using multi-modal sensory input and real-time user engagement analytics.

5.3 Summary of Contributions

This thesis introduces the virtual reality technology in solar energy system design, offering the main guidance that can enhance learners' comprehension and engagement during the VR experience. This section revisits the research questions with an explanation of each.

- **What strategies can be used to make learning about solar energy system design more engaging for students by using immersive technologies?**

  Using immersive technologies such as virtual reality in solar energy system design provides opportunities to increase learners' engagement levels and transform the teaching of solar energy systems from passive to active and engaging learning. VR allows users to virtually interact with 3D components of the solar energy system such as solar panels, inverters, batteries and charge controllers. This offers a hands-on experience that fosters exploration and experimentation. Also, the immediate feedback that users receive for instance when adjusting the orientation of solar panels and placement they can instantly see the impact on energy output, provides a dynamic and engaging learning experience and makes students involved in real-time decision-making. This strategy engages users as it allows them to grasp cause-and-effect relationships instantly and make the learning process interesting and dynamic.

  The immersive feature of VR allows students to be completely absorbed in the educational content, providing high concentration and reducing distraction. This sense of presence encourages users to interact and engage with the content and helps them understand complex concepts in ways that would not be possible through other methods. The findings of this thesis align with previous research conducted by Sokolov *et al.* in [80], which also demonstrated that their VR application improved the sense of presence that correlates with cognitive abilities when developed virtual objects that were very close to real equipment.

- **What specific technical skills can students gain by using VR technology in the design of solar energy systems?**

  Virtual reality environments enable students to interact with highly realistic, full-scale, photorealistic models of solar panels, inverters, and other related parts in the VR setting. This gives students a touch of how solar system arrangements look like hence having a practical feeling of layout, installation and system integration. Also, VR technology enables users to simulate real-life tasks including controlling the solar panel orientation, adjusting the tilt angle and changing the location of the modules for better solar energy harvesting. Also, visualising the flow of electricity in the VR environment allows users to observe how the sun's energy is transformed into electricity. This assists users in comprehending concepts such as photovoltaic energy conversion, direct current generation and alternating current conversion. The ability to observe this process in practice helps strengthen theoretical knowledge and gives a good idea of how solar panels function in practice. Similar trends were reported by Gonzalez *et al.* in [79], reinforcing the validity that VR application helped students better comprehend and visualise the technical aspects of the PV installation in their application. They claim that this training tool improved students' abilities in designing and building a solar power plant appropriately.

- **How do physiological responses, such as heart rate and eye-tracking data, correlate with students' engagement when using VR technology in solar energy system design?**

  After surveying the literature, it has been clarified that physiological measures such as heart rate, breathing rate and eye-tracking data reflect a range of physical and sensory processes. These physiological responses provide valuable insights into students' engagement levels as they provide real-time feedback on how users interact with the system components in solar energy system design tasks. Variations in the heart rate may indicate the user's level of engagement. When users are highly engaged, their heart rate increases as a result of high attention and arousal. Comparing heart rate levels in a 2D application and VR environment in solar energy system design tasks can indicate the engagement level between users in the two settings. In a 2D application, users would experience less immersion setting which means that their heart rates will be relatively closer to a stable rate. This is because 2D applications do not offer a sensory depth or real-world interaction that can be experienced in the VR environments. Conversely, VR environments offer an immersive environment with more realistic settings and interactions, provoking more emotional or cognitive engagement. This immersion leads to changes in heart rate as users are more deeply engaged with the content, moving around in virtual space, interacting with objects, and solving dynamic design problems. Such differences in heart rate data can be used as a measurable indicator of the effectiveness of a VR environment compared to a traditional 2D application. In the context of VR scenes, heart rate data may not be a significant factor in estimating engagement in a VR environment as participants were likely to be engaged during all the VR scenes. The results of this study differ from those of Murphy and Higgins in [217], who indicated that the heart rate is a good indicator for measuring engagement levels in virtual reality environments.

  Increasing cognitive load in VR environments negatively affects users' performance and engagement. Reading and comprehending text in a VR environment leads to a high cognitive load, which suggests that the extent of mental load when it comes to text information processing and acquiring new knowledge is higher than in other tasks. This result aligns with the conclusions drawn by Tanaka and Yamaoka in [206]. These findings could be useful for future improvements of the VR experience by controlling the amount and type of information to be presented in each scene, balancing cognitive load and ensuring that users stay engaged in the experience the entire time.

In addition, eye-tracking data reveals users' visual engagement with the VR environment and can be used to assess the degree of focused attention.

The pupil size of the user is affected by the brightness level of the virtual scenes. In darker scenes, pupil size enlarges to allow more light in and vice versa. Also, pupil dilation serves as an indicator of users' engagement level, for instance, larger pupils indicate a higher engagement level in a specific VR scene. The findings of this study are consistent with those of [226], who also observed the relation between pupil dilation and the level of attention and engagement. Therefore, controlling the effect of brightness on pupil size should be considered in VR scenes in order to accurately measure user experience to improve visual comfort, engagement level and attention.

The blinking rate is an essential indicator linked to the VR environment, offering insight into users' level of focus and engagement. Increasing the blinking rate shows an engagement in visual attention and is connected to task difficulty. The findings align with previous research conducted by [204], which also demonstrated the estimation of visual attention by observation of eye blink frequency. Also, the nature of the task has an impact on the blinking rate. If the task requires concentration, the blink rate decreases. This is what was noticed in a reading task in the VR environment and aligned with the study of [205].

The number of fixations refers to where a user's gaze remains focused on a single point for a certain time. It might be considered a powerful metric to measure user engagement in a VR environment. High engagement levels are associated with a high number of fixations. Also, increasing the number of fixations may indicate that users have spent more time integrating new information and data, collected from various scene areas.

Therefore, eye-tracking data is essential in determining which elements of the VR-based learning experience contribute to fostering students' engagement and improving their understanding of solar energy system design. However, capturing more physiological data is essential for accurately measuring user engagement in immersive environments like Virtual Reality (VR). Capturing robust eye-tracking data improves the capacity to design VR content that optimizes the level of engagement, knowledge acquisition, and retention.

5.4 Thesis Implications

This thesis takes traditional training experience in solar energy system design to a new level of engagement and interactive experience. The VR technology which is currently deployed in education and training could be an important tool to enhance and improve comprehending solar energy systems. The developed VR applications in solar energy systems help facilitate hands-on learning experiences for users and provide a more immersive virtual environment. This thesis demonstrates guidelines and directions for creating VR applications that positively affect user experience and users' engagement. Also, this thesis introduces new methods to evaluate VR applications to provide in-depth insight into user engagement and cognitive load. This study can open the prospects for extended reality to invade solar energy system design education and training and other renewable energy training.

5.5 General Guidelines for Developing VR Applications

This section provides guidelines for researchers and VR developers who intend to conduct future research on extended reality technologies in solar energy system design education.

- Future development of solar energy system design applications using VR technology will take into account innovations in integrating real-time data to visualise dynamic changes in solar energy production.
- Future VR applications in solar energy systems should contribute to the global effort to mitigate climate change and promote environmental sustainability.
- Artificial Intelligence and machine learning technology can be integrated into VR application design. This technology can be used to analyse massive amounts of data and suggest ideal configurations for more effective designs.
- Future researchers should consider expanding the sample size. Including more participants in an experiment can reveal additional insights into user experience and provide more reliable information.
- Future research could involve collaboration in VR applications. This means that the VR application enables multiple users to interact and collaborate in the same virtual environment, regardless of their actual locations.
- Future research might be focused on using Augmented Reality (AR) and Mixed Reality (MR) technologies in solar energy system design. This technology has been witnessed as a promising tool that revolutionizing education by overlaying virtual objects into the real world.

5.6 Future work

5.6.1 Augmented Reality technology in solar energy system design

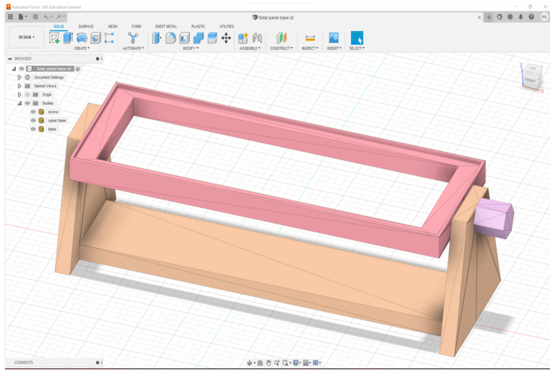
Augmented Reality (AR) has recently gained increased attention in the learning and training area. Augmented reality allows computer-generated objects to superimpose over the real environment in real-time [233]. This merging of virtual objects and the real-world enables students to visualise complex abstract concepts [234], and improve their skills and knowledge [235]. AR experience can be utilized through tablet/smartphone-based and head-worn-based AR such as Microsoft Hololens.

AR technology has the potential to provide a highly realistic learning experience and the ability to offer a tangible and practical method which changed education to become more efficient [236]. The use of augmented reality (AR) in the classroom has the ability to engage students and encourage them to view the content from a variety of different perceptions. Guo in [237], conducted a study that compares the students' performance using an AR environment and in-class environment. This study indicated that AR environment allows students to engage in hands-on training and deepen their understanding. Serio *et al* in [238], presented a study that shows the use of augmented reality in education and how this technology impacts the students' motivation level. Moreover, the study of Kaufmann *et al* in [239], was to develop a collaborative augmented reality application that used 3D dynamic geometry that aimed to facilitate mathematics and geometry education.

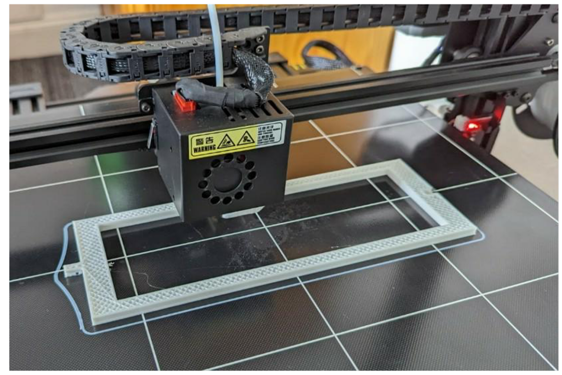
Billinghurst and Duenser in [240], mention that using AR technology in education could be an engaging and useful complement to classroom instruction, overcoming some of the drawbacks of text-based approaches and enabling students to understand the subject matter according to their learning style.

AR technology also enables remote collaboration and shares the learning experience. Several users can collaborate together in a 3D experience, interacting with the objects and sharing their thoughts and opinions in a novel education environment. Using AR technology in schools can offer an effective learning experience; however, Billinghurst *et al.* in [240], believed that integrating AR experience with conventional learning techniques may be most effective.

In general, most of the AR-related research was evaluated via questionnaire studies, resulting in an incomplete image. A questionnaire or a self-assessment is influenced by a person's experience and emotional fluctuations that lead to a decrease in the level of precision and reliability, hence cannot be generalised [241]. Subsequently, it is important to rely on physiological reactions in the study. Monitoring Psychophysiological signals would allow a better comprehension of a person's stress in many situations. Several indicators can be monitored using biosensors such as GSR, ECG, ST, EMG and HRV [242]. However, Heart Rate Variability is the most commonly used for detecting stress level [241]. HRV parameter captures how the heart responds to regulatory impulses that impact heart rhythm [243].



1



2

Figure 5.1: The process of creating the rotatable solar panel stand. Picture 1 shows the design stage using Autodesk Fusion 360 software, while picture 2 presents the printing process of the 3D stand. The stand design supports rotating at different angles.

The potential hypothesis can be as follows:

H1: The users' engagement level during the real experiment and the AR technology is almost the same.

H2: Using novelty technology such as AR increases students' motivation.

This study compares the user experience (XR) for users while designing a solar energy system in the real world and during an augmented reality headset.

5.6.1.1 Experimental Design

An experiment can be conducted to measure users' engagement level while designing a solar energy system in the real world and AR technology. In order to make this comparison, a mini kit of solar energy systems can be created and an AR application can be developed to visualise the components to enable users to build the solar energy system. A sensor from the Shimmer kit might be used to monitor the ECG signals of the users. This sensor measures the heart rate variability (HRV), which is the rate of the variability of variation between each heartbeat [244], and is considered the most commonly used indicator for stress [241].

5.6.1.2 Physical and AR experiment

Four pieces of 1.5v, 0.65W Polycrystalline Micro mini solar panels can be used in the experiment. Autodesk Fusion 360 software may be utilized to create the 3D model of the solar panels stand - figure 5.1.

In the real experiment, users have to build a solar energy system with real physical components such as mini solar panels, a charge controller, LED light which presents the sun, wires, a multimeter and a small light which shows the output of the system 5.2.

AR has strong potential to provide a novel learning experience for users as it is a hybrid form

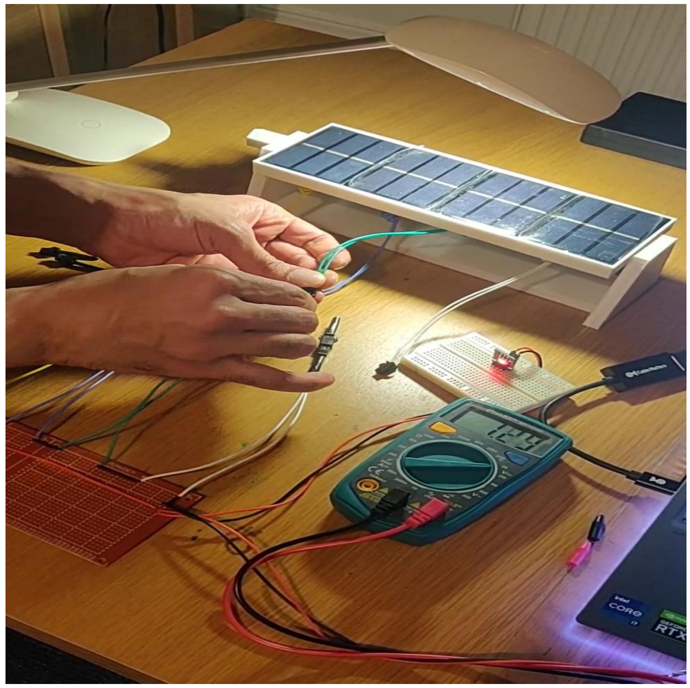


Figure 5.2: The physical experiment in building solar energy system design using mini system components. In this experiment, users can add solar panels and change the tilt of the 3D-printed stand to measure the electricity generated from the system by trying different situations.

of visualisation that blends the real environment with 3D virtual objects. In this experiment, the flow of electricity between the solar panels to the other components can be visualised in order to understand how each component of the system interacts and works together. Also, solar panel's performance and efficiency might be visualised based on the current angle and orientation. AR can label the main elements of the solar energy system, solar panels, inverter, battery, and charge controller, and describe what they are used for. Users can click or highlight a specific part to get information on how it works and its role within the entire system. Using AR technology enables the simulation of environmental factors like sunlight intensity, shading from nearby objects and seasonal variation. This allows users to switch some parameters, for example, from day to night or from summer to winter and observe the behavior of the system.

Thus, AR makes complex concepts more comprehensible by extending information overlays over the real-world system, and it is easy to explain such concepts as efficiency, performance, and even environmental impact. Also, providing hands-on experiments helps users better understand and higher retention rates.

Appendix A

PowerRoomCollision Script

This script is used to detect the collision in the power room scene. The script detects what component is picked up and shows the user the position of where it has to be placed. Once the component collides with the position component in the stand, the component is automatically placed in the right position.

```
if(this.gameObject.name == "Controller")
    {
        if (other.gameObject.name == "ControllerPosition")
        {
            ui = 0;
            this.gameObject.GetComponent<Rigidbody>().
               isKinematic = true;
            this.gameObject.transform.position = other.
               gameObject.transform.position;
            this.gameObject.transform.rotation = other.
               gameObject.transform.rotation;
            controller = true;
        }
    }
```

Appendix B

PanelColllision Script

This script is used to detect the collision in the rooftop scene.

```
if (panel1.transform.position != panelposition1.transform.
    position)
            {
                placed1 = 0;
                panel1.transform.SetParent(null);
                panel1.GetComponent<Rigidbody>().constraints =
                    RigidbodyConstraints.None;
                panel1.GetComponent<Rigidbody>().useGravity =
                    true;
                Debug.Log("␣Placed␣3" + placed3);
                panelposition1.SetActive(true);
                panelposition1E.SetActive(false);
            }
```

Appendix C

Script to place solar panels

The script detects once the panel touches the stand and automatically places it on the stand

```
if (other.gameObject.name == "SolarPanelPosition1")
        {
            if (placed1 == 0)
            {
                panelposition1E.SetActive(true);
                this.gameObject.transform.position = other.
                    gameObject.transform.position;
                this.gameObject.transform.rotation = other.
                    gameObject.transform.rotation;
                this.gameObject.GetComponent<Rigidbody>().
                    constraints = RigidbodyConstraints.
                    FreezePosition;
                this.gameObject.GetComponent<Rigidbody>().
                    constraints = RigidbodyConstraints.
                    FreezeRotation;

                this.gameObject.GetComponent<Rigidbody>().
                    useGravity = false;

                    other.gameObject.SetActive(false);

              this.gameObject.transform.SetParent(parent.
                  transform);
                    }       }
```

Appendix D

Teleport Script

The teleport script is attached to a portal which is created using Unity's vfx component. Upon clicking the portal, the move1 function is executed.

```
public void Move1()
    {
        // Destroy(gameObject);
        pos1 = new Vector3(teleport.transform.position.x,
            teleport.transform.position.y, teleport.transform.
            position.z);
        player.transform.position = pos1;

        Debug.Log("␣GameObject␣+␣" + this.gameObject.name);

        move.SetActive(false);

        move2.SetActive(true);
        move3.SetActive(true);
        move4.SetActive(true);
        move5.SetActive(true);
        move6.SetActive(true);
        // this.transform.position = pos1;
    }
```

Appendix E

Script to calculate the electricity amount

A script that calculates the amount of electricity generated depending on the angle and number of solar panels placed.

```
if (scene.name == "Solar␣Panels␣1")
        {
            if (stand.transform.eulerAngles.x == 0)
            {
                angle = 320;
                angletext.text = "0";
                //angletext.text = stand.transform.eulerAngles.
                    x.ToString();
            }

            else if (stand.transform.eulerAngles.x > 29 &&
                stand.transform.eulerAngles.x < 31)
            {
                angle = 277;
                angletext.text = "30";
                //angletext.text = stand.transform.eulerAngles.
                    x.ToString();
            }

            else if (stand.transform.eulerAngles.x > 44 &&
                stand.transform.eulerAngles.x < 46)
            {
                angle = 226;
                angletext.text = "45";
```

```
        // angletext.text = stand.transform.eulerAngles
            .x.ToString();
    }

    else if (stand.transform.eulerAngles.x > 59 &&
        stand.transform.eulerAngles.x < 61)
    {
        angle = 160;
        angletext.text = "60";
        // angletext.text = stand.transform.eulerAngles
            .x.ToString();
    }

    else if (stand.transform.eulerAngles.x > 74 &&
        stand.transform.eulerAngles.x < 76)
    {
        angle = 83;
        angletext.text = "75";
        // angletext.text = stand.transform.eulerAngles
            .x.ToString();
    }

    else if (stand.transform.eulerAngles.x > 89 &&
        stand.transform.eulerAngles.x < 91)
    {
        angle = 0;
        angletext.text = "90";
        // angletext.text = stand.transform.eulerAngles
            .x.ToString();
    }

    if (PanelRotation.endangle == 0)
    {
        angle = 320;
        angletext.text = "0";
        //angletext.text = stand.transform.eulerAngles.
            x.ToString();
    }
```

```
else if (PanelRotation.endangle > 29 &&
   PanelRotation.endangle < 31)
{
    angle = 277;
    angletext.text = "30";
    //angletext.text = PanelRotation.endangle .
       ToString();
}

else if (PanelRotation.endangle > 44 &&
   PanelRotation.endangle < 46)
{
    angle = 226;
    angletext.text = "45";
    // angletext.text = PanelRotation.endangle .
       ToString();
}

else if (PanelRotation.endangle > 59 &&
   PanelRotation.endangle < 61)
{
    angle = 160;
    angletext.text = "60";
    // angletext.text = PanelRotation.endangle .
       ToString();
}

else if (PanelRotation.endangle > 74 &&
   PanelRotation.endangle < 76)
{
    angle = 83;
    angletext.text = "75";
    // angletext.text = PanelRotation.endangle .
       ToString();
}
```

```
        else if (PanelRotation.endangle > 89 &&
           PanelRotation.endangle < 91)
        {
            angle = 0;
            angletext.text = "90";
            // angletext.text = PanelRotation.endangle .
               ToString();
        }
    }
```

The script that provides the number of panels placed in the stand

```
    if (PowerRoomCollision.powerroom == true)
    {
        //power.fillAmount = PanelColllision.placed * 0.17f;
        voltno = PanelColllision.placed * angle;

        voltagetxt = voltno.ToString();
        voltage.text = voltagetxt;

        power.fillAmount = ((voltno * 100) / 1920) / 100;
    }
```

Appendix F

Script to calculate the average lighting for each scene

```
import cv2

# Open the video file
cap = cv2.VideoCapture('scene3.mp4')

# Get the frame rate and number of frames
fps = cap.get(cv2.CAP_PROP_FPS)
num_frames = int(cap.get(cv2.CAP_PROP_FRAME_COUNT))

# Initialize variables for the total lightness and frame count
total_lightness = 0
frame_count = 0

# Loop through each frame of the video
while(cap.isOpened()):
    ret, frame = cap.read()

    # Check if there are any more frames
    if ret == False:
        break

    # Convert the frame to grayscale
    gray_frame = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)

    # Calculate the mean pixel value
```

```
    lightness = gray_frame.mean()

    # Add the lightness value to the total
    total_lightness += lightness
    frame_count += 1

# Calculate the average lightness for the video
avg_lightness = total_lightness / frame_count

# Print the average lightness
print("Average␣lightness:", avg_lightness)

# Release the video file
cap.release()
```

Appendix G

Python script for filtering the raw data to estimate the heart rate and breathing rate

```
import numpy as np
from scipy.signal import butter, filtfilt
import matplotlib.pyplot as plt

def butter_bandpass(lowcut, highcut, fs, order=5):
    nyquist = 0.5 * fs
    low = lowcut / nyquist
    high = highcut / nyquist
    b, a = butter(order, [low, high], btype='band')
    return b, a

def butter_bandpass_filter(data, lowcut, highcut, fs, order=5):
    b, a = butter_bandpass(lowcut, highcut, fs, order=order)
    y = filtfilt(b, a, data)
    return y

# Generate sample heart rate sensor data
fs = 1000.0  # Sample rate (Hz)
t = np.linspace(0, 10, 10 * fs, endpoint=False)  # 10 seconds
   of data
heart_rate_signal = np.sin(2 * np.pi * 1 * t) + 0.5 * np.sin(2
   * np.pi * 20 * t)  # Example heart rate signal
```

```
# Set bandpass filter parameters
lowcut = 0.8  # Lower cutoff frequency (Hz)
highcut = 4.0  # Upper cutoff frequency (Hz)
order = 4  # Filter order

# Apply bandpass filter
filtered_signal = butter_bandpass_filter(heart_rate_signal,
    lowcut, highcut, fs, order)

# Plot original and filtered signals
plt.figure()
plt.plot(t, heart_rate_signal, label='Original␣Signal')
plt.plot(t, filtered_signal, label='Filtered␣Signal')
plt.xlabel('Time␣(s)')
plt.ylabel('Amplitude')
plt.title('Heart␣Rate␣Sensor␣Data␣with␣Bandpass␣Filter')
plt.legend()
plt.grid(True)
plt.show()
```

Appendix H

Python script for the Fast Fourier Transform technique

```
import numpy as np
import matplotlib.pyplot as plt

# Generate sample signal
fs = 1000  # Sampling frequency (Hz)
t = np.arange(0, 1, 1/fs)  # Time vector from 0 to 1 second
f1 = 10  # Frequency of the signal (Hz)
f2 = 50
signal = np.sin(2 * np.pi * f1 * t) + 0.5 * np.sin(2 * np.pi *
    f2 * t)  # Sum of two sinusoids

# Perform FFT
fft_result = np.fft.fft(signal)
fft_freq = np.fft.fftfreq(len(signal), 1/fs)  # Frequency axis
    in Hz

# Plot the original signal
plt.figure(figsize=(10, 4))
plt.subplot(1, 2, 1)
plt.plot(t, signal)
plt.xlabel('Time (s)')
plt.ylabel('Amplitude')
plt.title('Original Signal')
```

```
# Plot the FFT result (frequency spectrum)
plt.subplot(1, 2, 2)
plt.plot(fft_freq, np.abs(fft_result))
plt.xlabel('Frequency (Hz)')
plt.ylabel('Magnitude')
plt.title('Frequency Spectrum (FFT)')
plt.xlim(0, fs/2)  # Plot up to Nyquist frequency
plt.tight_layout()
plt.show()
```

Appendix I

A script that is attached to the three scenes to capture Heart Rate, Cognitive Load and Eye Tracking data

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using HP.Omnicept;
using HP.Omnicept.Messaging;
using HP.Omnicept.Messaging.Messages;
using System.Text;
using System.IO;
using System;

namespace HP.Omnicept.Unity
{
    public class NewBehaviourScript_S1 : MonoBehaviour
    {
        string filename = "";
        TextWriter tw;
        private GliaBehaviour _gliaBehaviour = null;

        private GliaBehaviour gliaBehaviour
        {
```

```
        get
        {
            if (_gliaBehaviour == null)
            {
                _gliaBehaviour = FindObjectOfType<
                    GliaBehaviour>();
            }

            return _gliaBehaviour;
        }
    }

    // Subscribe to Heart Rate messages
    public void StartListeningToHeartRate()
    {
        gliaBehaviour.OnHeartRate.AddListener(
            AccumulateHeartRate);
    }


    // Unsubscribe to Heart Rate messages
    public void StopListeningToHeartRate()
    {
        gliaBehaviour.OnHeartRate.RemoveListener(
            AccumulateHeartRate);
    }


    // Your code using heart rate messages
    private void AccumulateHeartRate(HeartRate heartRate)
    {
        Debug.Log(heartRate);
    }

    // Subscribe to Heart Rate messages
    public void StartListeningToEyeTracking()
    {
        gliaBehaviour.OnEyeTracking.AddListener(
```

```
            AccumulateEyeTracking);
    }



    // Unsubscribe to Heart Rate messages
    public void StopListeningToEyeTracking()
    {
        gliaBehaviour.OnEyeTracking.RemoveListener(
            AccumulateEyeTracking);
    }



    // Your code using heart rate messages
    private void AccumulateEyeTracking(EyeTracking
        eyeTracking)
    {
        //Debug.Log(eyeTracking.Timestamp);
        //Debug.Log(gliaBehaviour.GetLastHeartRate());
        //Debug.Log(gliaBehaviour.GetLastCognitiveLoad().
            Timestamp);
        //Debug.Log(gliaBehaviour.
            GetLastHeartRateVariability().Sdnn);
        //Debug.Log
            ("-----------------------------------------------------
            ;

        //Debug.Log(eyeTracking.Timestamp.
            OmniceptTimeMicroSeconds.ToString());
        //Debug.Log(eyeTracking.Timestamp.ToString());
        //Debug.Log(type(eyeTracking.LeftEye.Gaze.X));

        //if (gliaBehaviour.GetLastHeartRate() == null)
        //    Debug.Log("yes, heartrate is nulll");
        //if (gliaBehaviour.GetLastHeartRateVariability()
            == null)
        //    Debug.Log("yes, HeartRateVariability is nulll
            ");
        //if (gliaBehaviour.GetLastCognitiveLoad() == null)
```

```
        //      Debug.Log("yes, GetLastCognitiveLoad is nulll
            ");
        //Debug.Log(hr.Timestamp);
        //Debug.Log(gliaBehaviour.GetLastCognitiveLoad());


        WriteCSV(eyeTracking, gliaBehaviour.
            GetLastHeartRate(), gliaBehaviour.
            GetLastHeartRateVariability(), gliaBehaviour.
            GetLastCognitiveLoad());
    }


    // Start is called before the first frame update
    void Start()
    {
        long milliseconds = DateTimeOffset.Now.
            ToUnixTimeMilliseconds();
        filename = milliseconds.ToString();
        Debug.Log("Pass the Start() in the script");
        filename = Application.dataPath + "/data/" +
            filename + "_S1" + ".csv";
        Debug.Log(filename);
        tw = new StreamWriter(filename, false);
        WriteCSVHeader();
        //StartListeningToHeartRate();
        StartListeningToEyeTracking();
        Debug.Log("HP eye tracking started...");
    }

    public void Update()
    {
        //Debug.Log(gliaBehaviour.GetLastHeartRate());
        //Debug.Log(gliaBehaviour.GetLastEyeTracking());
        //Debug.Log(gliaBehaviour.GetLastCognitiveLoad());
    }

    public void WriteCSVHeader()
```

```
{
    //tw.WriteLine("Time stamp," +
    //     "Left Gaze_origin_mm_X, Left Gaze_origin_mm_Y
        , Left Gaze_origin_mm_Z," +
    //     "Right Gaze_origin_mm_X, Right
        Gaze_origin_mm_Y, Right Gaze_origin_mm_Z," +
    //     "Left pupil_diameter_mm, Right
        pupil_diameter_mm");
    tw.WriteLine("OmniceptTimeMicroSeconds," +
        "LeftEye_gaze_X,LeftEye_gaze_Y,LeftEye_gaze_Z,"
            +
        "LeftEye_PupilPosition_X,
            LeftEye_PupilPosition_Y," +
        "LeftEye_PupilDilation,
            LeftEye_PupilDilationConfidence," +
        "LeftEye_Openness,LeftEye_OpennessConfidence,"
            +

        "RightEye_gaze_X,RightEye_gaze_Y,
            RightEye_gaze_Z," +
        "RightEye_PupilPosition_X,
            RightEye_PupilPosition_Y," +
        "RightEye_PupilDilation,
            RightEye_PupilDilationConfidence," +
        "RightEye_Openness,RightEye_OpennessConfidence,
            " +

        "CombinedEyes_gaze_X,CombinedEyes_gaze_Y,
            CombinedEyes_gaze_Z," +

        "HeartRate_BPM,HeartRateVariability_Sdnn,
            HeartRateVariability_Rmssd," +

        "CognitiveLoad_Value,
            CognitiveLoad_StandardDeviation,
            CognitiveLoad_DataState"
```

```
            );
        tw.Close();
    }

    //int tf, string gocl, string gdcl, string gdc, float
        openl, float openr, string ppl, string ppr, string
        gol, string gor, float pdl, float pdr, string
        gdlnorm, string gdrnorm
    public void WriteCSV(EyeTracking theEyeTracking,
        HeartRate theHeartRate, HeartRateVariability
        theHeartRateVariability, CognitiveLoad
        theCognitiveLoad)
    {
        double dummy = -100;
        string data = theEyeTracking.Timestamp.
            OmniceptTimeMicroSeconds + "," +
             theEyeTracking.LeftEye.Gaze.X + "," +
             theEyeTracking.LeftEye.Gaze.Y + "," +
             theEyeTracking.LeftEye.Gaze.Z + "," +

             theEyeTracking.LeftEye.PupilPosition.X + "," +
             theEyeTracking.LeftEye.PupilPosition.Y + "," +

             theEyeTracking.LeftEye.PupilDilation + "," +
             theEyeTracking.LeftEye.PupilDilationConfidence
                 + "," +

             theEyeTracking.LeftEye.Openness + "," +
             theEyeTracking.LeftEye.OpennessConfidence + ","
                 +

             theEyeTracking.RightEye.Gaze.X + "," +
             theEyeTracking.RightEye.Gaze.Y + "," +
             theEyeTracking.RightEye.Gaze.Z + "," +

             theEyeTracking.RightEye.PupilPosition.X + "," +
             theEyeTracking.RightEye.PupilPosition.Y + "," +
```

```
        theEyeTracking.RightEye.PupilDilation + "," +
        theEyeTracking.RightEye.PupilDilationConfidence
            + "," +

        theEyeTracking.RightEye.Openness + "," +
        theEyeTracking.RightEye.OpennessConfidence + ",
           " +

        theEyeTracking.CombinedGaze.X + "," +
        theEyeTracking.CombinedGaze.Y + "," +
        theEyeTracking.CombinedGaze.Z;

    if (theHeartRate == null)
        data = data + "," + dummy;
    else
        data = data + "," + theHeartRate.Rate;

    if (theHeartRateVariability == null)
        data = data + "," + dummy + "," + dummy;
    else
        data = data + "," + theHeartRateVariability.
           Sdnn + "," + theHeartRateVariability.Rmssd;

    if (theCognitiveLoad == null)
        data = data + "," + dummy + "," + dummy + "," +
            dummy;
    else
        data = data + "," + theCognitiveLoad.
           CognitiveLoadValue + "," + theCognitiveLoad.
           StandardDeviation + "," + theCognitiveLoad.
           DataState;

    /*
    theCognitiveLoad.CognitiveLoadValue + "," +
    theCognitiveLoad.StandardDeviation + "," +
    theCognitiveLoad.DataState;
```

```
            frame_timestamp,
            GazeOriginCombinedLocal.ToString("g").Trim(new Char
                [] { '(', ')' }),
            GazeDirectionCombinedLocal.ToString("g").Trim(new
                Char[] { '(', ')' }),
            GazeDirectionCombined.ToString("g").Trim(new Char[]
                { '(', ')' }),
            openness_left, openness_right,
            pupilPosition_left.ToString("g").Trim(new Char[] {
                '(', ')' }),
            pupilPosition_right.ToString("g").Trim(new Char[] {
                '(', ')' }),
            vdata.left.gaze_origin_mm.ToString("g").Trim(new
                Char[] { '(', ')' }),
            vdata.right.gaze_origin_mm.ToString("g").Trim(new
                Char[] { '(', ')' }),
            vdata.left.pupil_diameter_mm, vdata.right.
                pupil_diameter_mm,
            vdata.left.gaze_direction_normalized.ToString("g").
                Trim(new Char[] { '(', ')' }),
            vdata.right.gaze_direction_normalized.ToString("g")
                .Trim(new Char[] { '(', ')' });
            */
            tw = new StreamWriter(filename, true);
            //string data =
            //      tf + "," + gocl + "," + gdcl + "," + gdc +
                "," + openl + "," + openr + "," + ppl + "," +
                ppr + "," + gol + "," + gor + "," + pdl + "," +
                pdr + "," + gdlnorm + "," + gdrnorm;
            //string data = theEyeTracking.Timestamp + "," +
                theHeartRate + "," + theCognitiveLoad;
            //Debug.Log(theEyeTracking.Timestamp.
                SystemTimeMicroSeconds);
            tw.WriteLine(data);
            tw.Close(); //close now or at project stop? do it.
                try
        }
    }}
```

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