A User-Centered System Usability Evaluation of a Virtual Reality Application Developed for Solar Farm Training

Ikram Asghar*
University of South Wales, United kingdom, Email: ikram.asghar@southwales.ac.uk

Rahmat Ullah
University of South Wales, United kingdom, Email: rahmat.ullah@southwales.ac.uk

Mark G Griffiths
University of South Wales, United kingdom, Email: mark.griffiths@southwales.ac.uk

William Warren
University of South Wales, United kingdom, Email: William.warren@southwales.ac.uk

Luke Dando
University of South Wales, United kingdom, Email: luke.dando@southwales.ac.uk

John Davies
2 Degrees Kelvin Ltd, United kingdom, Email: john@2degreeskelvin.org

ABSTRACT

The hazardous potential of the Photovoltaic (PV) industry demands the most rigorous and professional training. However, such training requires many resources and time and has potential health and safety risks. Incorporating emerging technologies in such training can be helpful. This paper proposes SolarPro, a virtual reality application for solar farm training that can aid solar farm trainees in getting initial training in the virtual environment. The application's usability is tested through multiple testing sessions with 30 participants. The testing participants experienced the virtual scenarios, completed the tasks and filled out the system usability questionnaires. The system usability scale analysis resulted in a grade A score of 81.75. The analysis based on the demographic characteristics also showed positive results. We can conclude that the SolarPro virtual reality application has high system usability. However, it is suggested to have more than just 30 respondents for the usability test to conclude more promising results.

CCS CONCEPTS •Human-centered computing ~Human computer interaction (HCI) ~Interaction paradigms ~Virtual reality

KEYWORDS

Virtual reality, Solar farm, System usability, User testing

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*Corresponding author.

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1 INTRODUCTION

Solar power has become a significant energy source worldwide, with increasing adoption in recent years. Globally, solar power fulfils 4.4% of energy needs. The United Kingdom has seen significant growth in solar power installations in recent years, with a steady increase in solar photovoltaic (PV) technology use. According to Statista, the UK's solar photovoltaic capacity per capita rose from 51.6 watts per inhabitant in 2013 to 405.2 watts per inhabitant in 2019 [1]. These statistics indicate that solar power is becoming an increasingly popular choice for renewable energy in the UK, with significant growth in capacity and installations. The continued adoption of solar power can be critical in the UK's transition to a more sustainable energy mix, reducing carbon emissions and providing access to clean energy for millions of people.

Solar energy workers are prone to severe and life-threatening risks like falls, arc flashes, thermal burns, and electric shocks [2]. Similarly, Hartford lists various risks for workers in the solar industry, including cuts or strain injuries, stress, working on high rooftops, and electric hazards [3]. The risk of falls and injury dangers associated with the construction industry can also be added here. Finally, a report by North Carolina University's Clean Energy Technology Center states that there are potential health and safety risks associated with solar photovoltaic technology, including the risk of toxicity impacts [4]. While solar farm training may provide essential skills for working in the industry, workers need to be aware of the risks associated with the job and take appropriate safety precautions to mitigate those risks. Building dedicated infrastructure is another problem for such training as it involves considerable resources, time and cost.

Therefore, academic researchers and industry are looking into alternative solutions to help solar engineers train by using emerging technologies, and virtual reality (VR) is one such technology. In recent years, virtual reality is gaining popularity in different fields of training, as it offers a cost-effective and immersive alternative to real-world training environments. According to [5], a virtual world can be projected to integrate a photovoltaic power plant's plan and design, potentially providing trainees with a more comprehensive understanding of solar farm design and construction. Additionally, the VR solar farm model (VRSF) is another example of using VR in solar training, allowing trainees to learn about solar energy in real-life situations, thereby decreasing the expenses and dangers involved in real-life training [6].

This paper proposes SolarPro, a VR application that creates multiple training scenarios to supplement training for solar farm engineers. The SolarPro VR application has implemented three training scenarios across the spectrum of engineer experience levels and designated each scenario with a different prioritisation level; visual inspection, string testing, and module exchange. The trainees can go through the scenarios as often as needed and conduct this training in a risk-free environment. Multiple user testing sessions were held, and 30 participants tested the system usability aspects of the proposed VR application.

The remaining paper has four sections. Related work is covered in the second section. The research methodology is summarised in the third section. An over of the SolarPro VR application is presented in the fourth section. The fifth section discusses the data analysis and results of the current study. The conclusion of this study and potential future research directions are presented in the sixth section.

2 RELATED WORK

This section covers the current state of the art related to the use of virtual reality in different areas of training and education. It also highlights research gaps in the current literature.

2.1 General Training

VR training has gained considerable attention from industrial projects and research thanks to its potential to reduce productivity loss during training and overcome the shortage of skilled instructors. Several companies, including Walmart and Lowe's, employ VR to expedite employee training. In addition, virtual training will contribute to an increase in employment by providing hands-on experiences for retraining the workforce [7]. VR also offers a low-cost, repeatable training tool that can properly simulate a real work environment, including any potential obstacles employees may face. Several VR simulators, including those for virtual reality work-at-height, procedure training for power line maintenance and operation, and immersive virtual construction safety training experiences, have been developed to offer workers a mistake-tolerant environment, which can reduce stress and improve safety and health in high-risk occupations [8-10]. Researchers have indicated that VR technology is a potential solution for enhancing pedestrian and motorist safety at grade crossings [11]. In this study, a VR application was utilised to teach pedestrians the necessary safety skills needed to traverse a level crossing safely. Using the system usability scale (SUS) and sensation of presence (SoP) questionnaire, the user acceptance of the application was determined. Despite the fact that the sense of presence score grows with age, the SUS score drops.

2.2 First-aid Training

First aid responders often encounter hazardous situations that are not typically found in other professions [12]. To prepare for such scenarios, VR training has been employed. Mossel et al. (2017) developed a scenario prototype that simulated fire and traffic accidents with injured individuals and bystanders [13]. Another crucial VR training initiative in the first responder sector is firefighting. A gamified firefighter training simulator, operated in a CAVE, enables players to complete sixteen training levels by using sensors to interact with the virtual environment [14].

2.3 Military Training

Military training can be filled with danger, and several soldiers lose their lives each year due to noncombat incidents or accidents [15]. However, the use of VR has shown promise in improving the quality and safety of military training compared to traditional methods [16]. To address challenges such as high costs and limited instruction areas in army artillery training, Girardi and de Oliveira (2019) developed a Brazilian Army VR simulator that enables low cost trainaing without space constraints [17]. Validation of the simulator with experienced artillery officers showed that it met expectations for both sense of presence and effectiveness.

In addition, a VR-based surgical training system was created to cater the needs and skills essential to military personnel transitioning to civilian healthcare roles [18]. The system generates adaptive training tasks to enhance reskilling efficiency. A VR-based training software was developed for French Army infantry to learn the calibration procedure of the combat system [16]. In contrast to the conventional 2D software for calibration exercise, the new VR technique enables soldiers to practise in a virtual environment using a 3D-printed rifle replica that offers comparable real handling and control. An ad hoc study conducted on a group of French troops revealed that the VR approach considerably improved the soldiers' learning efficiency and intrinsic motivation to complete training activities in comparison to the conventional method.

2.4 Medical

VR has gained popularity as a tool for medical training due to its potential applications in treatment, therapy, surgery, and impairment simulation. Studies have shown that VR-based training can effectively reduce errors among healthcare workers, leading to improved patient safety. VR has been used to treat visual impairments [19] and simulate cataract effects, as well as for surgical training [20]. In healthcare training, a physical-virtual patient has been developed, which can sense touch events through infrared (IR) cameras and respond to them with an animation event [19]. This physical-virtual patient has been compared to a in a medical training scenario that was designed to train healthcare professionals in assessing neurological symptoms in patients with a stroke, and the study found that it improved the training experience [20]. Additionally, a VR-based application was developed for dentists to gain initial hand-on experience in a virtual environment [21]. The study evaluated the application with 26 dental trainees and found that the participants appreciated its usability.

2.5 Education

A VR-based mobile-rendered head-mounted display (HMD) on English as a Foreign Language (EFL) learners' vocabulary learning was investigated in [23]. The study involved 49 seventh-grade students in Taiwan who were assigned to a VR or a video-watching group. The VR group used the Mondly VR application, which provided immersive and interactive vocabulary learning activities. In the other hand, the video-watching group watched a demonstration of the app on a PCAccording to a study, the group of participants who learned vocabulary through VR showed a more significant improvement in learning and retention compared to the group who learned through video-watching. Most participants found VR-based vocabulary learning to be more beneficial.

Similarly, a VR-based curriculum adaptation to solve problems of the restricted classroom in schools was proposed in [24]. Six life adaptation themes were identified, and objectives, design principles, specific content, and teaching evaluation were set. The study results showed that the curriculum is appropriate and interesting, providing students with a safe and effective practice channel.

Another study investigated the use of VR to teach dancing to high school students [25]. The study compared the effectiveness of traditional instruction, instruction with 2D simulations, and instruction with VR simulations. The results showed that the students in the VR group performed much better than those in the traditional instruction and 2D simulation groups. Moreover, the students in the VR group reported higher levels of engagement and interest in the subject matter. The study indicates that virtual reality can be a useful tool in science teaching by offering students with immersive and engaging experiences that improve learning outcomes and motivation. An iThinkSmart VR application designed to enhance students' computational thinking (CT) knowledge was proposed and evaluated in [26]. The study involved 47 computer science students from a Nigerian university, and the results suggested that VR not only increased motivation but also facilitated the development of CT skills. The study highlights the potential of using visualisation of CT concepts in a VR educational application to increase the competency of students in programming education. The benefits of immersion, interaction, and engagement provided by the VR technology are also discussed in the study.

2.6 Solar Farm Training

For Solar farm training, some work has been done using Augmented reality (AR). AR-based training applications have been proposed for solar farm training. The main objective is to enhance the learning experience by providing trainees with a simulated, interactive environment to practice real-world tasks and procedures without needing physical equipment. The technology significantly reduces training costs, increases knowledge retention, and improves safety by minimising the risk of accidents during training. According to [27], a conceptual design for a mobile application with augmented reality capabilities was offered to aid elementary school kids in learning about the solar system. The author intends to construct the programme using Unity and Microsoft Visual Studio for Scripting, and research is currently ongoing. The objective is to develop an AR technology that can assist elementary pupils in learning about the solar system.

From the literature, the research team only found one example of VR used for solar farm training [6]. A VR Solar Farm Model (VRSF) was proposed that aims to give learners with a virtual learning environment and lower the expense and difficulties of training in physical venues. The model is divided into four points. Each point has an icon explaining the information about the solar farm system in video, message, or picture format. The VRSF was tested on a small sample group. The results showed that the VRSF is high quality and suitable for solar energy training, with a learning achievement rate of 80%. The article describes the research design, and experiment, which involved a pre-test and post-test in assessing the knowledge of the sample group. The questionnaire and stratification assessment were used to collect data for the VRSF users' efficiency test and satisfaction evaluation.

In another study , a VR laboratory module was developed for green manufacturing. The module centers around addressing solar energy efficiency concerns and aims to lessen the industry's environmental impact. Utilising Unity 3D and the Steam VR development kit, the VR solar panel laboratory module was designed to enable students to acquire knowledge and practical experience without the need for physical equipment [28].

The comprehensive literature review shows that VR is popularly used in many fields of education and training. However, there is still a lack of research on VR-based applications for training solar farm trainees. Therefore, this study is focused on contributing to this research area as indicated in the introduction section.

3 RESEARCH METHODOLOGY

This study is conducted by following the participatory co-design research process. Throughout the project, a team of researchers, designers, developers, experts from the solar industry and end-users remained involved.

3.1 Literature Review

The study began with an investigation into recent academic literature to understand the depth and breadth of this research area. The literature review helped to identify research gaps and set out study objectives.

3.2 Requirements Elicitation Workshop

The research team held multiple requirements elicitations workshops with solar industry experts and end-users to understand their requirements from virtual reality-based solar training applications. These workshops resulted in a project MoSCoW, to determine Must-have, Should-have, Could-have, and Wont-have priorities of the project. The MoSCoW helps to scope out the project and set realistic research and development goals.

3.3 Prototype Approach

For the development part of the project, a prototyping approach was used. The agile methodology helped to apply the prototyping approach systematically. Multiple sprint reviews were conducted in which the research team showcased the incremental prototypes of the virtual reality application to the solar industry experts and end users. In every sprint review, the experts provided feedback, and relevant changes/modifications were carried out by the research and development team until the final sprint.

3.4 User Testing and Feedback

For user testing, 30 participants were recruited for system usability tests. The participants went through the training scenarios. After that, they recorded user testing feedback by completing the System Usability Scale (SUS) questionnaires.

Figure 1: Solar Management Station

3.5 Analysis of Data

The research team followed the standard SUS data analysis process to evaluate system usability through the SUS questionnaires [29].

4 SOLARPRO VR APPLICATION OVERVIEW

The SolarPro VR application consists of three primary modes. In the training mode, the user can get training in the VR environment. The second mode provides practice material, whereas the third mode can be used to take tests. This section provides an overview of the SolarPro VR application.

4.1 Application Platform

For developing the SolarPro VR application, the Unity games engine is used. The SolarPro VR application is an Android application which will be run on a Meta Quest 2 VR headset. Firebase is used because of its ease and development speed; it is also suitable for all data storage needs. Other cloud providers are available, and switching to another provider is relatively easy; examples of alternatives include Amazon AWS and Microsoft Azure.

4.2 SolarPro VR Application Features

A new user of the SolarPro VR application will have to be assigned login credentials. This can be done through the sign-up web page.

4.2.1 Main Menu. The main menu is where the user enters the SolarPro VR application. The user must enter their login credentials in order to access the app. Here the user information stored in the database contains a list of the training materials/scenarios that the user can access when the user logs in. This helps modularise the training and support the typical structure of training delivery (as opposed to giving all users access to all training scenarios).

4.2.2 Solar Management Station. Figure 1 shows the Solar Management Station (SMS), where the user will pick their training scenario for the next session. Auxiliary purposes of this area are to provide onboarding instructions and a safe area to practice the controls, such as, using tools, movement, and teleporting before entering the training scenario. A carousel of training options allows the user to decide which scenario to undertake. Whether they wish to undertake guided training, practice with no guidance but more detailed feedback, or test condition training, which, upon completion, states if the user passed or failed the test.

Once a scenario has been chosen, the solar farm will load, the map will be generated, and the site overview screens will populate with information about the scenario. The map provides the user with the ability to access the solar farm. By selecting one of the possible teleport locations throughout the site, the user can relocate to the desired spot and begin detecting, diagnosing, and repairing faults as appropriate for the given scenario.

4.2.3 Solar Farm. Figure 2 shows the solar farm, where the user will spend the majority of their training time. Depending on the scenario, the engineer may be expected to identify, diagnose and fix one or more faults. The time of day will vary depending on the scenario chosen. Currently, only one solar farm configuration is used for all three scenarios; however, the project has been set up to support variations of the farm in future.

4.3 Training Scenarios

This subsection details the three training scenarios and the tools that can be used during their training sessions.

4.3.1 Visual Inspection. Figure 3 shows the visual inspection scenario, which is a relatively easy task for a low-level trainee. The user is tasked with identifying and reporting any visual faults on any of the modules on the site. The user should enter the site and move throughout the farm, identifying the following faults: snail trail, bird droppings, dirt, delamination, browning, back sheet scorching, disconnected DC cable, back sheet deterioration, corrosion, and smashed panel.

4.3.2 Module Exchange. The module exchange scenario is shown in Figure 4. Somewhere on the solar farm is a smashed panel. The engineer must first use the readouts in the SMS to determine where the fault is and then travel to the site and perform the actions required to replace the faulted module. Because the user will need to access a string combiner box to isolate the module, there is a risk of electrocution from any electrical current.

4.3.3 String Testing. The String testing scenario shown in Figure 5 is focused on the high-risk task of performing string testing, which is only the responsibility of well-trained engineers. Multiple strings

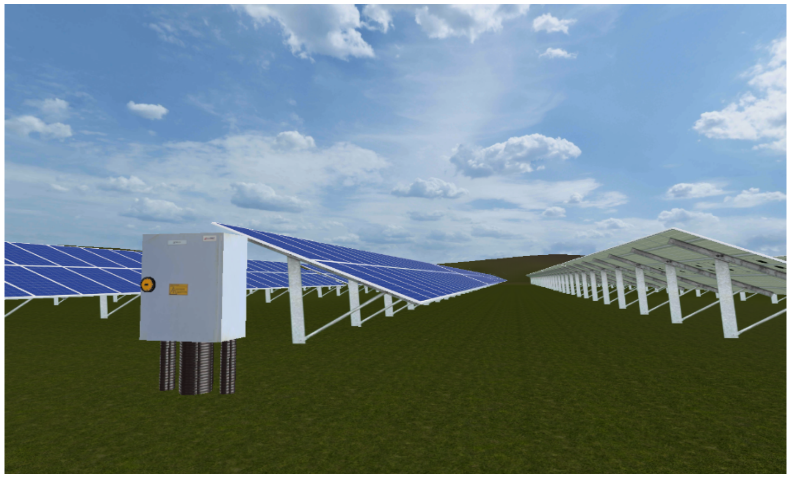

Figure 2: Solar Farm

Figure 3: Visual Inspection Scenario

Figure 4: Module Exchange Scenario

Figure 5: String Testing Scenario

on site are underperforming. The user should determine which string combiner box the string(s) are attached to, travel to the site and conduct tests to determine the fault and the follow-up actions required. Once each training mode is completed the user can enter a test mode of the scenario, which, depending on how closely they follow the training will either result in a pass or fail. Additionally if the user is exposed to live wires the character would receive an electric shock that would prove fatal in real-world scenarios

4.3.4 Tools Used. There are several tools that the user can use during their training sessions, as shown in Figure 6.

1. The tablet is helpful in all sessions. Through this, the user will log any defects, follow up actions, travel back from the solar farm, and end their training session.
2. The clamp meter is used to measure the current in a clamped wire. By grabbing the clamp meter in either hand, the user can attempt to take a reading by pressing either the X or A button on the Quest 2 controller. An audio indicator should signify that a reading has been taken. The central panel will update with the appropriate values when a reading is taken. If no wire is within the clamp, then the clamp meter will take a reading of nothing.
3. The PV tester performs a similar task to the clamp meter but measures readings across two wire locations rather than taking a reading on one wire. The PV tester tool will show a translucent pair of crocodile clips by grabbing and aiming the tester at a pair of wires (in a String Combiner Box). When the user presses the X or A button on the Quest 2 controller, reading will be taken across those two wires.
4. The DC Connector tool disconnects the DC wiring on the reverse of a module before removing it from its housing. By grabbing the DC Connector tool and approaching the DC cable, on the rear of a module, the tool will snap into place and be forcefully released from your grasp. When you subsequently grab and rotate the DC connector, it will disconnect the DC cable. Clicking the X or A buttons on the Quest 2 controllers has no effect when holding this tool.
5. The torque wrench is only designed for the module exchange scenario. The torque wrench behaves similarly to the DC Connector Tool in that it will release from your hand and snap into position when you introduce it into the vicinity of a proper nut. Clicking the X or A buttons on the Quest 2 controllers has no effect when holding this tool.

5 SYSTEM TESTING, RESULTS AND ANALYSIS

The system usability aspect of the SolarPro VR application has been tested through multiple testing sessions with the end users. This section highlights user testing, data collection, data analysis and discussion.

5.1 System Testing Overview

All system usability testing sessions began with introducing the SolarPro application, where its main features and how to navigate through the VR environment were explained. After going through the virtual scenarios, the users were asked to record their feedback through the SUS questionnaires. The SUS questionnaire has been a popular tool in research for the last few decades. It offers excellent insights into system usability with only a small sample population. The minimum sample size required for SUS is only five. Therefore, this tool fits the needs of the current study, as only 30 participants participated in the user testing.

5.2 System Testing Participants

In total, 30 participants got the chance to get training in the virtual environment. Table 1 gives the summary related to the demographic characteristics of the System testing participants. Most participants were male, with only a 13% representation from females. Participants were almost equally divided regarding their age, young and aged. Interestingly, the participants ranged from 28 to 62 years, indicating a good representation of young and aged people. Half of the participants already had previous VR experience, while half were experiencing VR for the first time. For the level of training, 50% tried easy scenarios while 23% tried both easy and medium, remaining 27% tried all levels of the training.

Figure 6: Tools Used in the Virtual Reality Application

Table 1: System Testing Participants Demographic Information

Demographic	Group	Distribution	
Gender	Female	4	13%
	Male	26	87%
Age	<= 40	16	53%
	> 40	14	47%
VR Experience	Yes	15	50%
	No	15	50%
Virtual Level Tried	Easy	15	50%
	Easy, Medium	7	23%
	Easy, Medium, Hard	8	27%

5.3 Data Analysis

For data analysis and interpretation, the systematic SUS data analysis procedure is followed for the system usability analysis [29]. The questionnaire used a five-point Likert scale to register the feedback of the user testing participants.

The academic literature indicates that a score of 68 is deemed an average SUS score for system usability studies [29]. A score greater than 68 shows a high system usability. A score less than 68 indicates that there are problems with the usability aspects of the system under test. The individual SUS final scores in Table 2 show that most participants scored above 68, indicating they were satisfied with the system's usability. Only one participant scored 67.50, which means he was not convinced with the system usability aspect of the SolarPro application.

There is another benchmark in SUS data analysis known as grading. The grading is distributed; for grade A (Excellent), the participants' scores should be above 80.3. For grade B (Good), the participants' scores should be 68.1 to 80.3. For grade C (Okay), the score should equal 68. A grade D (Poor) score corresponds to 51 to 67.9; any score less than or equal to 51 is considered grade E (Awful).

Table 2 indicates that the overall average score is 81.75. This score matches grade A, indicating that overall the participants were satisfied with the usability of the SolarPro application and enjoyed their virtual training experience.

5.3.1 SUS Scores for Demographics. Further data analysis explored the effect of participants' demographic characteristics on their respective system usability scores. The demographic-based system usability scores are presented in Table 3.

The female participants' average score is 84.75 (grade A), which is higher than the average score of the male participants, 81.35 (grade A). The higher score for female participants indicates they enjoyed their virtual training experience more as compared to the male participants. However, there were only four female participants, possibly because fewer females chose computing and technology-based careers [30]. This shows that females are underrepresented in technology-based industries and should be encouraged to choose this profession as a career in educational institutions.

The participants in both age groups scored A grades. Nevertheless, the younger group scores slightly higher than, the older group. Likewise, the experienced VR participants and non-experienced VR participants scored A grades. The group having no prior VR experience scored slightly higher than those with prior VR experience. The participants who only tried the easy virtual scenario scored highest, followed by those who tried both easy and medium. The participants who tried all virtual scenarios scored a B grade. This

Table 2: SUS Data Analysis for System Usability Testing Participants

Participant	Gender	Age	VR Exp	Mode	SUS Raw Score	SUS Final Score
P1	M	31	No	Easy, Medium	33	82.50
P2	M	52	No	Easy	37	92.50
P3	F	41	Yes	Easy, Medium & Hard	32	80.00
P4	M	34	No	Easy	35	87.50
P5	M	37	No	Easy, Medium	33	82.50
P6	M	47	Yes	Easy, Medium	28	70.00
P7	M	45	Yes	Easy, Medium & Hard	35	87.50
P8	M	30	Yes	Easy	33	82.50
P9	M	41	Yes	Easy, Medium & Hard	29	72.50
P10	M	59	No	Easy	30	75.00
P11	M	52	No	Easy	37	92.50
P12	M	28	Yes	Easy	34	85.00
P13	F	35	No	Easy, Medium & Hard	33	82.50
P14	M	36	Yes	Easy, Medium & Hard	35	87.50
P15	M	34	No	Easy, Medium	31	77.50
P16	M	43	No	Easy	36	90.00
P17	M	44	Yes	Easy, Medium	35	87.50
P18	M	34	Yes	Easy, Medium & Hard	27	67.50
P19	M	42	Yes	Easy	30	75.00
P20	M	36	Yes	Easy, Medium	35	87.50
P21	M	39	No	Easy, Medium & Hard	32	80.00
P22	M	40	No	Easy	33	82.50
P23	M	29	Yes	Easy	35	87.50
P24	F	33	Yes	Easy	34	85.00
P25	F	41	Yes	Easy	36	90.00
P26	M	43	No	Easy, Medium & Hard	29	72.50
P27	M	50	No	Easy, Medium	30	75.00
P28	M	62	No	Easy	32	80.00
P29	M	34	No	Easy	33	82.50
P30	M	36	Yes	Easy	29	72.50
		Average			**33**	**81.75**

Table 3: System Testing Participants Demographic Information

Demographic	Group	SUS Final Score
Gender	Female	84.38%
	Male	81.35%
Age	<= 40	82.03%
	> 40	81.43%
VR Experience	Yes	81.17%
	No	82.33%
Virtual Level Tried	Easy	84.00%
	Easy, Medium	80.36%
	Easy, Medium, Hard	78.75%

might be due to being in the virtual environment for a long time and feeling dizzy, or it may be due to the complexity of the hard scenario.

Overall, this study concludes that most user testing participants appreciated the system usability aspects of the SolarPro VR application and were happy with their virtual training experience. However, there is still a need to further investigate the hard scenario with more trials for results generalisation. These findings are consistent with our research group's previous studies on system usability investigations for different virtual reality training applications [11, 22, 31].

6 CONCLUSION AND FUTURE WORK

This paper presented SolarPro, a VR application that can be used to train solar engineers. Using the SolarPro VR application, the trainees can learn and enhance their skills related to solar farm training. The SolarPro VR application has three scenarios offering training skills, starting from easy to medium to hard training. The application offers many advantages such as a risk-free training environment, reduced need for dedicated training infrastructure, learning from mistakes, and the trainees can go through the scenarios as often as they want.

For the system usability testing, 30 participants tested the SolarPro VR application and recorded their feedback. The combined SUS score for the testing participants was 81.75, representing grade A, meaning the application scored high on the system usability scale. Further data analysis grounded on the participants' demographics mainly resulted in grade A scores, except for the participants' group who tried all the training scenarios (easy, medium and hard), which scored grade B.

Although the study results are promising, we cannot generalise these results. Only 30 user testing participants tested the SolarPro VR application. For results generalisation, more user testing is needed to analyse the long-term impact of VR applications in solar farm training. In future work, the researchers will look into developing a multi-user solar farm training platform where an experienced solar farm trainer can see and guide the trainees within the virtual scenario.

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