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Review

Immersive Learning in Photovoltaic Energy Education: A Comprehensive Review of Virtual Reality Applications

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Abstract: This paper 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 paper 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.

Keywords: virtual reality; solar energy; photovoltaics; education

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1. Introduction

According to the United Nations (UN), over 80% of global energy production is still reliant on fossil fuels [1]. The combustion of these fossil fuels is a major contributor to the rise in greenhouse gas emissions, global temperatures and extreme weather events such as floods, heat waves and cyclones, with the potential to increase global temperatures by more than 3.5 °C by the end of this century [2].

Renewable energy offers a sustainable solution to address global energy concerns as it is derived from continuously replenishing natural resources such as sunlight, wind, water and biomass, producing minimal or no greenhouse gas emissions or pollutants [1,3]. The six primary renewable energy sources are illustrated in Figure 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, on the other hand, utilizes 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 [4].

Among all renewable energy sources, solar energy stands out as the most abundant, offering a clean, renewable and sustainable alternative to fossil fuels in addressing climate change. Numerous studies have demonstrated that solar energy, with its abundance and free availability, can meet global energy demands [5].

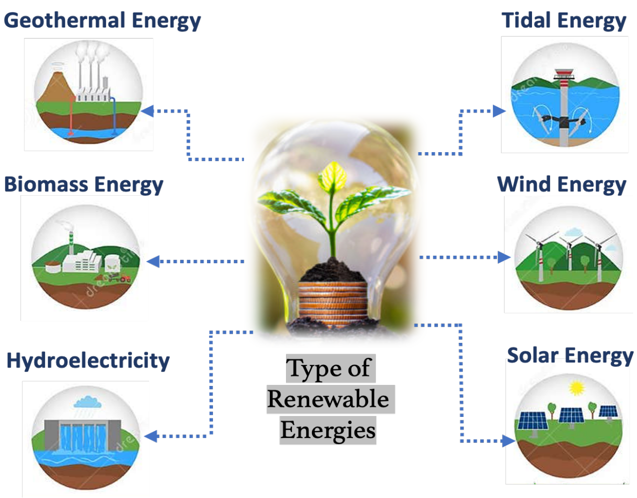

Figure 1. Types of renewable energy.

Solar energy systems are mainly categorised into two main types: photovoltaic (PV) [6] and solar thermal (ST) [7]. PV systems are the most widely used type for generating electricity, while solar thermal systems are primarily employed for heating water. Hybrid photovoltaic thermal (PVT) systems also exist, which combine both functionalities [8]. Our systematic review focuses on photovoltaic energy systems, which use PV cells to convert sunlight directly into electricity. Solar electricity generation relies on PV systems to directly transform sunlight into electricity. A typical PV system, as depicted in Figure 2, consists of PV panels (which convert solar energy into electricity), batteries (which store electricity), an inverter (which converts electricity from direct current (DC) to alternating current (AC)), and a charge controller (which regulates the rate at which electric current is added to or drawn from batteries). 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 [9]. Additionally, the complexity of solar energy systems often requires the expertise of dedicated professionals for their design and implementation.

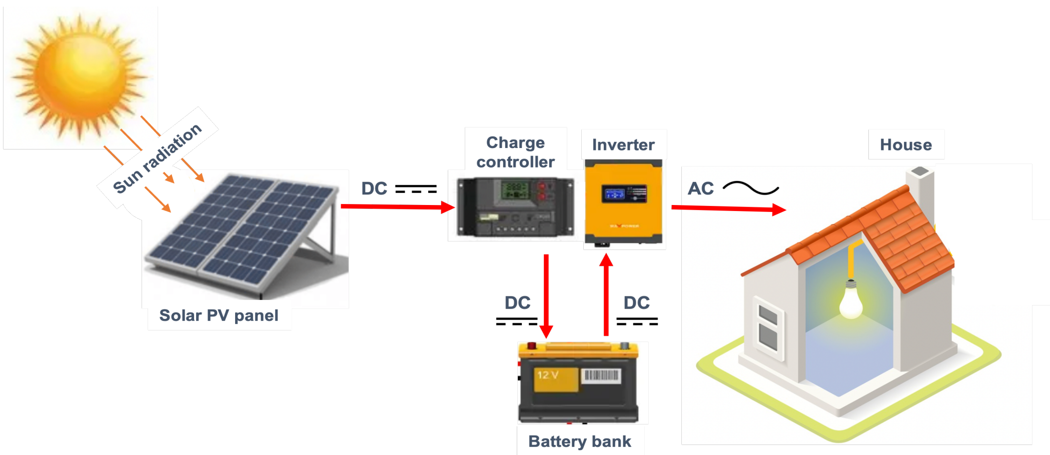

Figure 2. Schematic diagram of a typical PV system, which consists of PV panels, a charge controller and an inverter. Autonomous systems also often include a battery bank.

As the need to transition to environmentally friendly and more efficient energy resources grows, education plays a pivotal role in cultivating and inspiring a workforce that drives innovation and expansion in the renewable energy sector. In this context, numerous simulation tools have been employed to simulate photovoltaic (PV) systems [10,11]. Additionally, the integration of extended reality (XR) technologies, including augmented reality

(AR) and virtual reality (VR), into solar energy design offers users an immersive, real-time experience. This technology enhances the understanding of solar energy systems, thereby fostering the growth of more sustainable and efficient solar installations.

Virtual reality (VR) has emerged as a transformative technology that offers a unique approach to enhancing the learning experience of students in the renewable energy field by simulating an immersive and interactive 3D environment. VR effectively bridges the gap between theoretical knowledge and practical application by providing learners with dynamic 3D representations of complex concepts and real-world scenarios [12]. It is noteworthy that VR has been successfully employed in various educational settings, including military training simulations [13], gaming and entertainment [14] and training for the mining industry [15,16]. VR's ability to replicate real-life scenarios makes it an ideal tool for conducting hazardous experiments that would be impractical or dangerous to perform in a traditional laboratory setting [17]. Additionally, VR facilitates distance learning and virtual laboratories, enabling students to access educational resources from anywhere in the world [18]. As a novel pedagogical approach, VR has demonstrated its effectiveness in boosting student motivation, a crucial factor in shaping student attitudes towards learning [19]. Furthermore, VR's integration of game-based learning elements enhances engagement and fosters a more enjoyable learning experience [20]. By incorporating game-like characteristics, such as rewards, challenges and interactive scenarios, gamification effectively transforms the complexities of solar energy system design into an engaging and enjoyable experience. This innovative approach holds promise as a democratization tool, making solar energy concepts more accessible and appealing to a broader audience.

This review paper explores the numerous applications, advantages, problems and implications of integrating VR technology into solar energy education, especially photovoltaic (PV) systems. We discuss how VR has been used to reshape pedagogy and contribute to developing workforce skills. We focus on solar energy since it is a promising and cost-effective energy source that can address our energy challenges. Moreover, the continuous expansion of the PV industry has necessitated the development of structured solar energy education programs. Our review aims to provide a comprehensive understanding of how VR can reshape pedagogical practices and foster the development of essential workforce skills for the PV sector.

Our paper is therefore organised as follows: Section 2 demonstrates the state of the art in the current 2D simulation methods that are used for PV systems design. Section 3 presents our methodology for gathering research articles that match our inclusion criteria. Next, this paper presents the results regarding the publications found in the Web of Science search engine. In Section 4, we analyse and discuss the results that match our criteria; we discuss the latest studies on using virtual reality in solar energy education in Section 5, explaining the benefits and limitations and the role of virtual reality in enhancing the engagement and participation of students. Then, we highlight possible recommendations for developing future VR applications in renewable energy education in Section 6. Finally, we discuss our concluding remarks in Section 7.

2. State of the Art

Many PV device modelling tools have been explored in the literature, which includes 2D and 3D methods, as highlighted in [21]. Currently, many 2D simulation methods are used for PV systems design. These include software programs such as PVsyst, RETScreen, VelaSolaris and Solar Pro, as shown from the snapshots in Figure 3. Using these software programs, users can test and analyse the performance of their PV systems under varying conditions. This includes assessing solar irradiance, shading, temperature and system configurations that affect the production of energy. It also includes data about the weather conditions in many areas of the world. In fact, previous research has demonstrated how 2D visualisations using Polysun can improve student learning of solar energy systems design, as shown in [22].

Despite the advantages of 2D simulations for PV system design, many of these software tools are complicated and time-consuming [23]. Moreover, many 2D simulations do not support more advanced calculations [24]. In 2D simulations, the visualisation of the PV system components is greatly simplified, which may cause users to miss important details of the system such as batteries, inverters, charge controllers and other components. This might hinder a comprehensive understanding of the entire system. In addition, it is difficult for a 2D simulation to accurately represent shading effects, which makes it a challenge for users to visualise and modify PV system components accordingly. In terms of user experience (UX), interactivity in 2D simulations is often limited. Users have a restricted ability to manipulate PV system components while designing the system and cannot observe dynamic changes in real time, which can impact engagement and learning. Moreover, the flat representation of PV systems can be disengaged for users, as it lacks the realism of a real-world system.

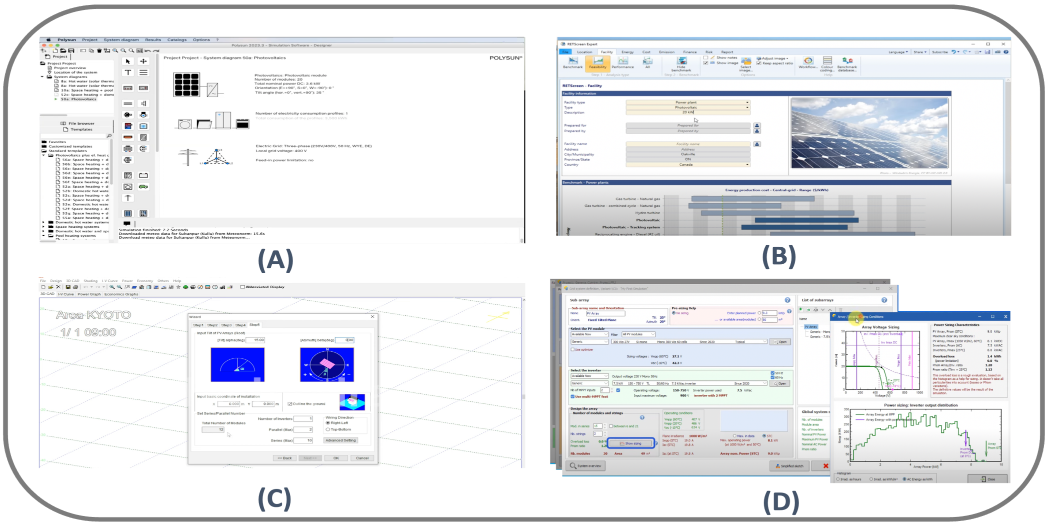

Figure 3. Screenshots of 2D simulations for PV systems design. (**A**) VelaSolaris (Polysun), version 2022.4, users can select a template from the software and add more components to the system or create and design a PV system from scratch. (**B**) RETScreen, Expert version, where users can identify their location and the amount of sunshine in this location, and then calculate how much energy they can produce. (**C**) Solar Pro, version 2.4, users can specify the tilt and azimuth values for the PV arrays and electrical assembly that users prefer, and (**D**) PVsyst, version 7.4, users build electrical organization of the system such as photovoltaic panels, inverters, batteries and others.

Furthermore, 3D simulations are valuable tools for designing PV systems. These simulations offer a more comprehensive view of the system, considering the main factors like tilt, shading from surrounding objects and geographical changes in a more accurate representation of real-world conditions than 2D simulations. Some of these simulations can be performed using software tools such as Sketchup, Helioscope, PVSOL and Energy3D. Sketchup enables users to visualise the exact location of the Sun and shadows over objects during the day. Users are able to imagine the whole system in 3D images and how the solar installation will appear on their property [25]. 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 [26]. Nevertheless, 3D simulations also come with several limitations. Similar to 2D simulation tools, they lack immersion, realism and interactive features that enable users to manipulate PV systems in real time. 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 their parts to better understand their functionality. VR tools enable irradiance calculations to be visualised on surfaces. Additionally, VR offers a realistic feeling when users interact with, inspect and design a PV system.

3. Methodology

This section defines our 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.

Our 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 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 our review. Publications were scanned within three stages based on their title, abstract and full text after removing duplications, Figure 4.

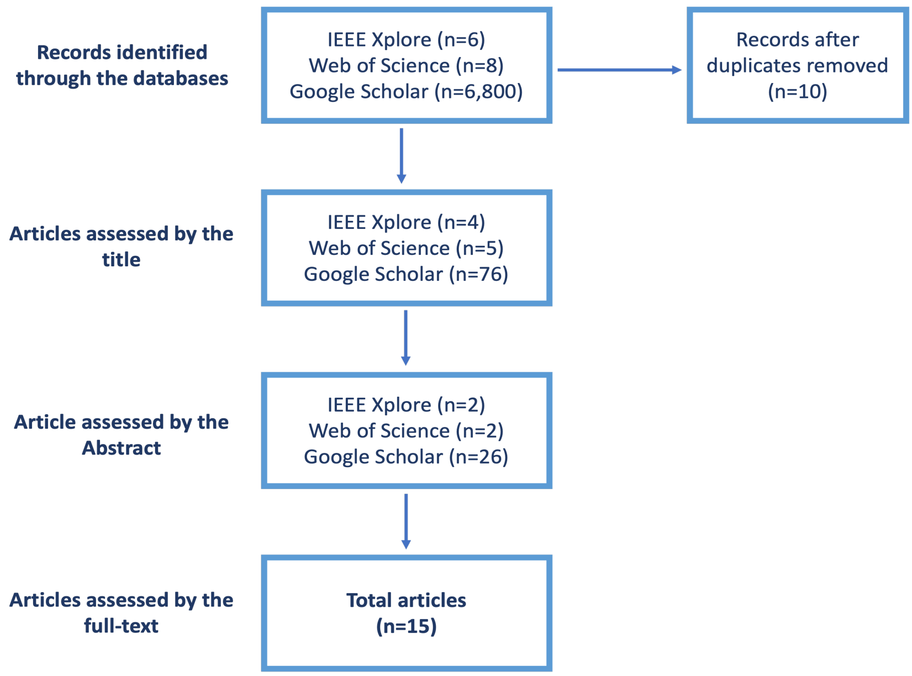

Figure 4. The process of scanning articles from three search engines: IEEE Xplore, Web of Science and Google Scholar. The first filter was removing the duplication. Then, we manually scanned the articles based on reading the title, abstract and full text, respectively. The process resulted in a total of 15 articles.

Table 1. Descriptors and synonyms used for our search.

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	[27]
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	[28]
Education	"A process of teaching, training, and learning, especially in schools or colleges, to improve knowledge and develop skills"	Learning, teaching, and training.	[29]

To ensure a rigorous literature review, we first established clear research questions and inclusion criteria. Next, we selected manuscripts adhering to these criteria. Finally, we analysed and interpreted our search results. In this study, we posed the following research questions (RQs):

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?
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. InC1: Articles written in English.
2. InC2: Articles matching the definitions and descriptors mentioned in Table 1.
3. InC3: 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.

4. 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 [30]. 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 5. 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 [31,32]. 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.

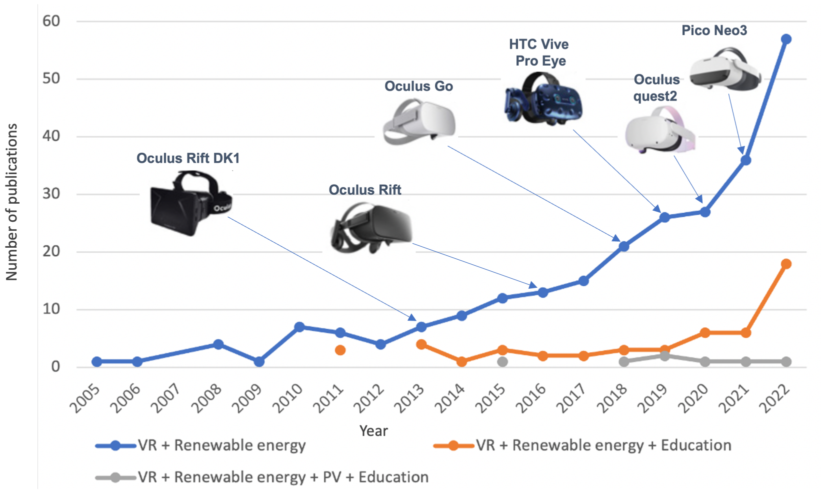

Figure 5. Number of publications on using virtual reality for renewable energy (the keywords are virtual reality OR VR AND renewable energy OR sustainable) and using virtual reality in renewable energy education (The keywords are virtual reality OR VR AND renewable energy OR sustainable AND education 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 6 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.

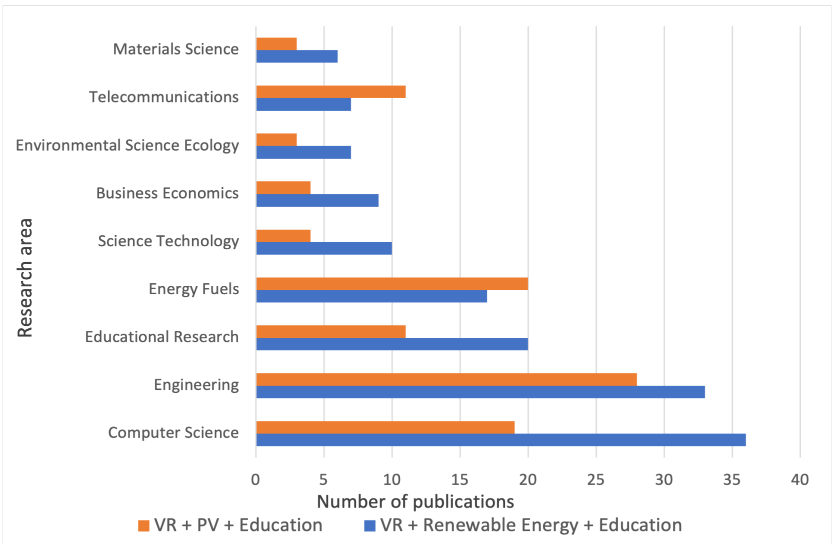

Figure 6. Distribution of publications on VR in Renewable Energy Education vs. PV Education by research area.

Figure 7 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 [33].

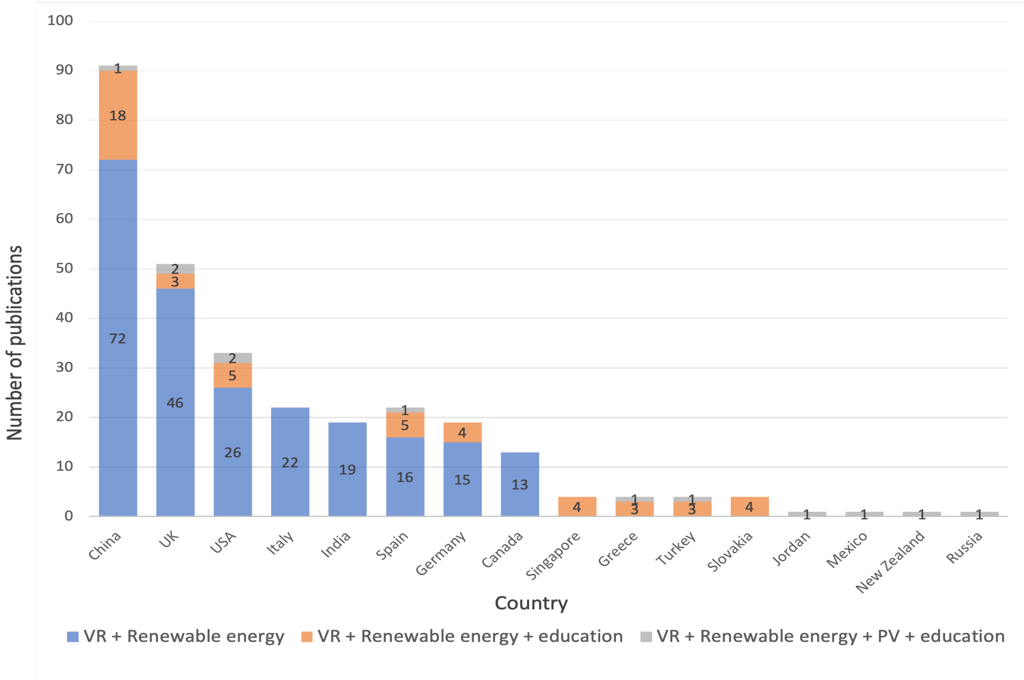

Figure 7. Number of publications by country on the use of virtual reality in renewable energy, virtual reality in renewable energy education and virtual reality in photovoltaic (PV) energy education.

5. Discussion of the Results

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

5.1. 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 [34] 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, 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 [35], 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 [36], 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 [20] 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 [37]. 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 [38] 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 [39].

Hatzilygeroudis et al. in [40] 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 [41] 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. [42] 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 [43] 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 in 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 [44], 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 [45] 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 [46] 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 [47] 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 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 [41,42] from this review explained on-grid PV systems that connected the solar systems to the utility grid, while two studies [20,43] focused on the off-grid PV systems. The rest of the 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 [43] 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 [46]. In addition, many papers mentioned the importance of an inverter's role in converting DC to AC in producing electricity. Figure 8 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.

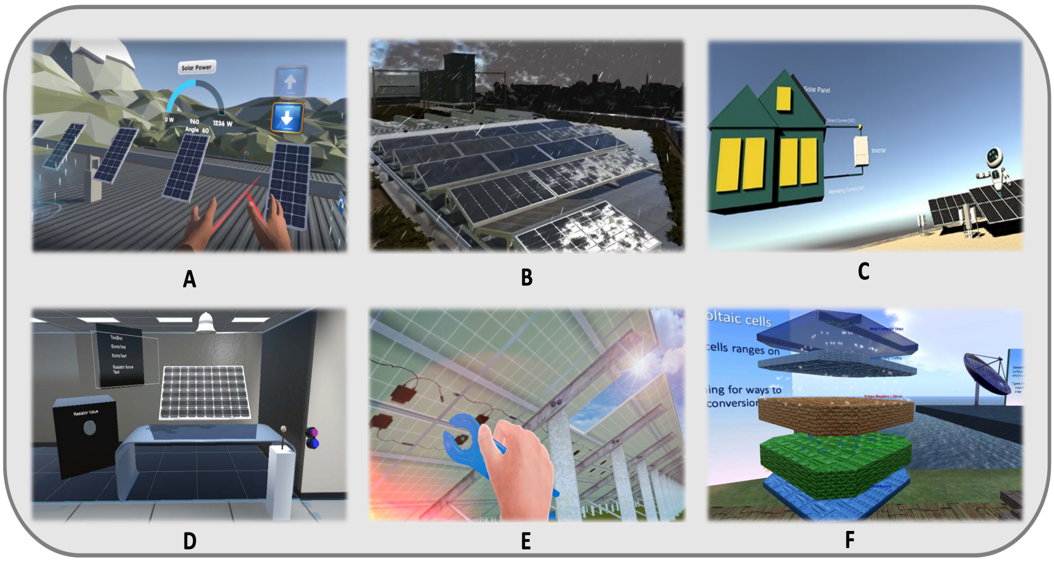

Figure 8. Screenshots for using virtual reality in PV solar education taken from the literature. (**A**) Users can install solar panels on a stand and try different scenarios: add, remove or change the tilt of the solar panels. A gauge chart appears in front of users to display the power generated from the system [43]. (**B**) Weather states are displayed based on actual weather conditions in order to promote a more comprehensive understanding (reproduced with permission from [42]). (**C**) Instructor robot in a PART Lab explains DC to AC inverter [39]. (**D**) Solar lab modules [47]. (**E**) Module exchange scenario, where users have to replace a smashed panel in the solar farm [46]. (**F**) Visualising the layers of the PV cell and the release of electrons (reproduced with permission from [44]).

5.2. 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 in [34] 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 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 students' 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 [35], 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 [35]. 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 [36], 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 [20] 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 [37], 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 [38], 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 [40].

The virtual reality application in [41] 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 was 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 [39]. 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 [42].

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 [43] 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 [44]. 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 [45], 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 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 [46]. 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 [47].

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 [48,49]. 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 [50]. 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 [51]. 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 [37], 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 [52].

Among all the studies in our review, four studies did not evaluate the effectiveness of using virtual reality technology in solar PV education [35,37,42,47]. In addition, only five studies used a mixed methods approach that combined quantitative and qualitative methods to evaluate the use of virtual reality [36,39,41,43,45]. 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 [43]. 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.

5.3. 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 [20]. In [34], 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 [37]. 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 [38]. 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 [40].

In [41], 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 [39]. 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 [42]. 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 [43]. 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 [44].

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 [53], or the sharing of personal data with third parties [54]. Accessibility concerns can be noted in terms of the use VR headsets by people with disabilities [55] and socioeconomic accessibility that refers to the affordability of VR devices [56]. Moreover, the high cost of VR headsets represents an obstacle to its widespread adoption in educational institutes, restricting access for schools with limited resources.

5.4. 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 [35] 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 [41] 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 [42]. 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 presents a summary of our 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. Summarising the papers that met the review criteria in the review.

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[34]	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.
[35]	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.
[36]	-	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.
[20]	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.

Table 2. *Cont.*

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[37]	-	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.
[38]	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.
[40]	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.

Table 2. *Cont.*

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[41]	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.
[39]	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.
[42]	-	Not tested yet	-	Pros • Provided cooperation and group work. • Changed properties of the solar PV.
[43]	-	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.

Table 2. *Cont.*

Ref	Learning Theory	Method to Evaluate the Effectiveness	HMD	Pros and Cons
[44]	-	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.
[45]	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.
[46]	-	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.
[47]	-	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.

6. Recommendations for Developing Future VR Applications in Solar PV Energy Education

According to our systematic review, we 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.

Our 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, our 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 eliminate the need for computer-generated graphics and enable accurate representation as well as a high level of immersion and sense of presence [39]. 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 [57].

7. Conclusions

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, we reviewed the use of virtual reality (VR) technology in solar PV education. Our 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, we have proposed several recommendations derived from the findings of this review.

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