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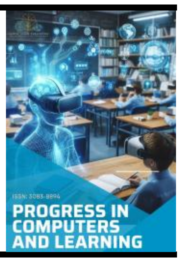

Review of Exploring the Virtual and Augmented Reality Application in Renewable Energy

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ABSTRACT

Virtual and augmented reality (VR and AR) technologies are making a significant impact across various industries, including renewable energy (RE), by offering immersive and interactive learning experiences. This review paper addresses the gap in interactive and immersive educational tools for RE, exploring the potential of VR and AR to enhance learning and understanding of RE technologies such as solar and wind. The objective of the paper is to evaluate the integration of VR and AR in RE sector, providing a comprehensive analysis of their effectiveness in fostering engagement and improving comprehension of complex RE concepts. Using a broad analysis of existing literature and case studies, the paper examines both the benefits and challenges associated with implementing these technologies in the RE sector. Key findings include the potential of VR and AR to significantly improve user engagement and knowledge retention in RE education, while also identifying barriers such as high implementation costs and the user experiences. This review highlights the promising role of VR and AR in advancing the adoption and development of sustainable energy solutions.

1. Introduction

Renewable energy (RE) is energy derived from natural sources that are replenished at a higher rate than they are consumed. Driven by environmental, economic and social factors, the adoption of RE sources such as solar, wind, hydro, geothermal and biomass power has gained significant growth. This growth is primarily propelled by the urgent need to address climate change and reduce air pollution, leading to a crucial shift in our approach to energy production. Additionally, RE enhances energy security by broadening the array of energy sources and reducing dependence on fossil fuels. Furthermore, the RE sector offers significant economic opportunities, including job creation, investment potential, and local economic growth, driven by technological advancements and supportive government policies [1,2].

Over time, RE consumption has experienced a notable evolution as shown in Figure 1. In 1965 (Figure 1a), renewable sources accounted for a marginal portion of per capita energy consumption,

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overshadowed by traditional sources like coal, oil, and natural gas. However, by 2022 (Figure 1b), this landscape had undergone a remarkable transformation. Rapid advancements in RE technologies, coupled with heightened environmental awareness, propelled a surge in per capita energy consumption from renewables. The substantial growth of solar and wind power, supported by favorable government policies, has enabled RE to play a pivotal role in meeting global energy demands. Consequently, the contribution of renewable energy has grown significantly, shifting from its limited role in 1965 to a more sustainable and resilient energy future [3]. RE is at the forefront of the global shift towards sustainability; however, its full potential remains unrealized without the proper tools for exploration, education, and engagement.

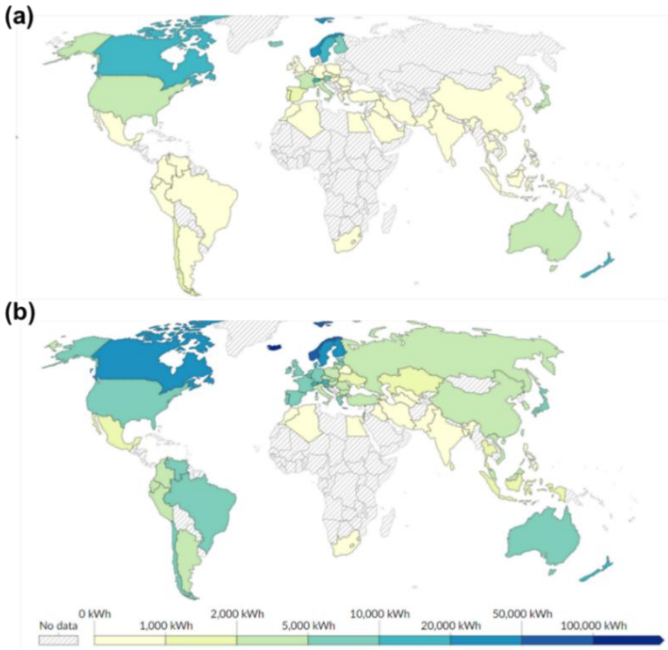

Fig. 1. Per capita energy consumption from renewable energy in (a) 1965 and (b) 2022 [3]

Gamification involves integrating aspects of video games into non-game settings to motivate and involve participants [4]. This includes incorporating challenges, rewards, and progression systems to enhance engagement and performance [5]. Affordances within gamification are specific features and mechanisms that enhance the gaming experience and encourage full engagement across various systems. When implemented effectively, gamification can increase user engagement by promoting greater effort, perseverance, and motivation [6]. On the other hand, platforms without gamification elements may see a drop in user engagement levels [7].

Virtual Reality (VR) emerges as a transformative solution, offering immersive experiences that bridge the gap between theory and practice in RE initiatives. VR technology has undergone swift progress, resulting in the development of highly immersive digital realms that closely mimic the physical world [8]. VR essentially replicates reality through artificial environments, enabled by programming that simulates real-world occurrences [9]. Recent years have witnessed significant advancements in VR, making it more accessible and widespread [10]. The goal of VR is to fully immerse individuals in either real or virtual environments, achieved through the use of computing units to recreate their presence within these spaces [11]. Typically, VR involves interaction between individuals and computer-generated worlds using computing technologies. Its applications span various sectors including medicine, military, entertainment, manufacturing, education, tourism, and retail, among others [12]. VR technology recreates the sensation of being physically present in a virtual world, allowing users to interact with digital environments and objects through digital tools [13]. In RE systems, VR simulations enable viewer to visually explore intricate components, ranging from solar farms to wind turbines, fostering a deeper understanding of their functionality and impact. Moreover, VR facilitates hands-on training for technicians and engineers, enhancing skills and safety protocols in RE installation and maintenance. By providing an interactive platform to experience RE solutions firsthand, VR accelerates the adoption and advancement of clean energy technologies, paving the way for a more sustainable future.

Augmented Reality (AR) holds great potential in RE systems, complementing the advancements in VR by blending virtual elements with the real world. AR can create immersive learning experiences, like VR. It helps consumers visualize complex concepts, making learning more engaging and effective [14]. Like VR, AR can provide hands-on experiences that are crucial for developing practical skills in fields such as RE. The integration of AR in educational settings has the potential to complement existing methods, enhancing the understanding of solar energy systems and promoting sustainable practices [15]. AR superimposes computer-generated images, data, or graphics onto a user's view of the physical environment, enhancing their perception and interaction with real-world objects [16]. In the context of RE, AR can bridge the gap between theoretical concepts and practical applications, providing immediate and contextualized information directly in the field.

However, the industry is encountering significant challenges. With a growing number of workers retiring, attracting and retaining talent in a competitive labour market has become increasingly vital. To address this, industrial enterprises should focus on creating a safe working environment and integrating connected worker solutions in the RE sector to counter the effects of workforce attrition. By embracing innovative technologies, the industry can bridge skill gaps and ensure continuity in its operations.

The purpose of our paper is to explore the synergy between VR and AR in the context of RE. While VR and AR have gained traction in various sectors, their application in RE remains relatively underexplored. A significant gap exists in understanding how immersive technologies can enhance the adoption, education, and practical application of RE systems, especially in terms of training, system visualization, and consumer engagement. This research is significant because it addresses this gap by examining how VR and AR can bridge the divide between theoretical knowledge and real-world applications of RE. By integrating these technologies, the paper aims to provide valuable insights into how VR and AR can play a transformative role in accelerating the transition to sustainable energy systems. The objectives of the paper are outlined as follows: Section 2 discusses the various types of RE technologies; Section 3 provides an overview of the fundamentals of VR and AR; Section 4 explores the application of these technologies in RE; Section 5 addresses the challenges and opportunities within this multidisciplinary field; and Section 6 concludes with our key findings and recommendations.

2. Renewable Energy

RE technology encompasses a diverse array of sources, each offering unique advantages and challenges in the quest for sustainable energy production. This section provides an overview of the main RE sources, including solar, wind, hydro, geothermal, and biomass as shown in Figure 2.

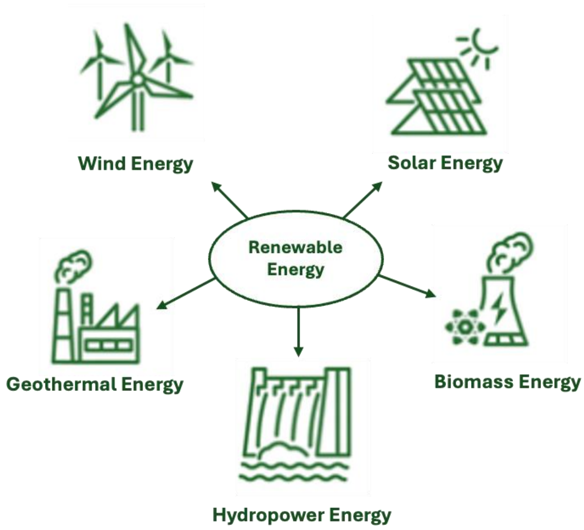

Fig. 2. Renewable Energy (RE) types; Solar, Wind, Hydrothermal, Geothermal and Biomass

2.1 Solar Energy

Solar energy stands as one of the most abundant and accessible renewable resources, with an estimated total output of 3.8 x 10^{23} kW, of which approximately 1.8 x 10^{14} kW is intercepted by Earth [17]. Although not all countries are equally endowed with solar energy, a significant contribution to the energy mix from direct solar energy is possible for every country [18]. It is important to note that much of solar radiation is not used and basically wasted [19]. Photovoltaic (PV) cells, commonly known as solar panels, harness sunlight and convert it directly into electricity. In addition to commercially available silicon-based panels, recent research has focused on the development of more sustainable materials, such as organic [20-22] and perovskite PV [23-25], as well as innovative device engineering aimed at enhancing the efficiency of solar energy conversion [26-28]. The adoption of solar energy has experienced exponential growth, driven by declining costs, technological advancements, and supportive policies.

2.2 Wind Energy

Wind energy is another plentiful and clean RE source. Wind power utilizes wind turbines to convert kinetic energy from the wind into electricity. The main characters of the success of a wind energy project lie on the factors such as the wind power density, the elevation above mean sea level, the topography of the terrain, the connectivity through the road network, the proximity to the electric grid, and the distance from conserved areas [29]. It is a mature and rapidly expanding RE source, with vast potential for both onshore and offshore installations [30]. Technological advancements in turbine design, materials, and control systems have led to substantial increases in efficiency and reliability.

2.3 Hydropower Energy

Hydroelectric energy harnesses the power from kinetic energy of flowing or falling water to generate electricity. It is one of the oldest and most widely utilized RE sources, with large-scale hydroelectric dams accounting for a significant portion of global electricity generation [31]. Advances in turbine technology, dam design, and environmental management have improved the efficiency and sustainability of hydroelectric projects.

2.4 Geothermal Energy

Geothermal energy utilizes heat from the Earth's subsurface to produce electricity. Geothermal resources come from hydrothermal (convective) systems, conductive systems and deep aquifers. The convective is from water or vapor including hot spring and fumaroles. Conductive includes hot rock and magmatic resources. Deep aquifers contain moving fluids in porous media at depths more than 3 km, but without a local magmatic heat source [32]. Using natural or humanmade permeability and fractures, the fluid flows through hot rocks, absorbing heat from the rocks that can be drawn up through wells to Earth’s surface which this heat energy is then converted to steam, which drives turbines that produce electricity. Technological advancements in drilling techniques, reservoir engineering, and power plant design have expanded the viability of geothermal projects in various geological settings.

2.5 Biomass Energy

Biomass energy derives from living organism and plants and mostly used energy source in less developed countries [33]. Biomass can be used as an energy source either combusting directly to produce heat or indirectly after converting to various form of biofuel [34]. Advances in biomass conversion technologies, feedstock sourcing, and waste management practices are essential to enhance the efficiency, sustainability, and environmental performance of biomass energy systems.

3. Fundamental of VR and AR

3.1 Virtual Reality (VR)

The basic principle of VR lies in its essential component include VR equipment, VR software, VR environment, and VR programming language. This foundational setup is further enhanced by emerging accessories like haptic devices, controllers, and omnidirectional treadmills are quickly gaining traction in the consumer VR market, complementing head mounted displays [35].

There are four different types of VR specifically identified when it comes to using it for education: completely immersive VR rooms, semi-immersive desktop VR, portable semi-immersive VR, and fully immersive VR headset assisted VR. Conversely, headset-supported VR and fully immersive VR environments deliver a significantly immersive experience. Notably, VR headsets such as the Meta Quest 2, HTC Vive, and Pico 4, have grown in popularity due to their affordable prices, superior visual quality achieving resolutions of up to 2448 x 2448 pixels per eye, intuitive design and user-friendly [36-38]. Figure 3a displays a space environment with green screen and Figure 3b one such piece of VR equipment in use.

Moreover, when creating VR experiences for individuals with health issues, it's essential to consider their ability to use VR equipment comfortably without adding any additional strain [38-40]. Unity is a widely-used application framework paired with a 3D virtual environment engine, often employed in the development of VR applications [41]. Commonly used programming languages for VR application development include C# and Java [42]. Today, VR setups often include an AI-powered virtual assistant, assisting users in handling different levels of cognitive challenges and facilitating verbal communication [36].

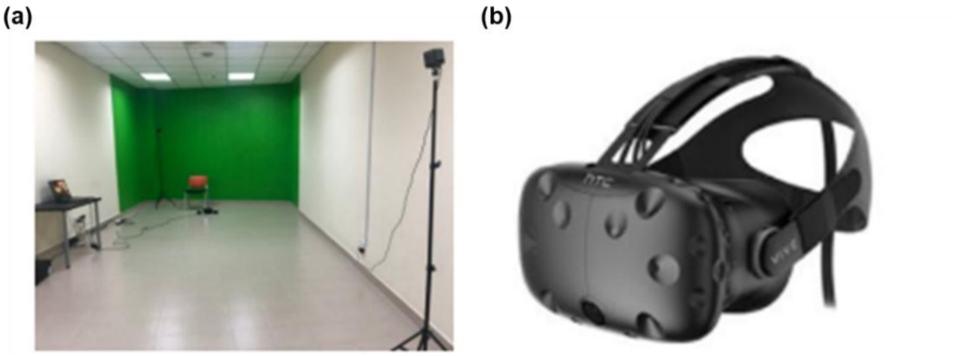

Fig. 3. (a) VR space environment with green screen background [43] and (b) VR headset oculus HTC vive

3.2 Augmented Reality (AR)

The term AR was developed in 1992 by Boeing researcher Thomas Preston Caudell, who developed an AR application for industrial use to view some assembly diagrams [44]. AR fundamentally integrates real and virtual worlds, enabling real-time interaction and accurate 3D registration of objects. This technology enhances learning experiences, as evidenced by its application in physics education, where AR videos significantly improved students' understanding of concepts, achieving an average score of 8.6 compared to 7.1 in traditional methods [15]. Furthermore, AR's design principles focus on creating engaging training scenarios, which are crucial for fields like emergency medicine and military training. The display technology behind AR is essential, as it determines the effectiveness of user interaction with augmented environments [45]. Additionally, AR's applications extend to mechanical system design, where it aids in prototyping and enhances creativity and accuracy [46]. Overall, AR is poised to transform various sectors by merging digital data with the physical world, fostering innovative solutions and improved user experiences [47].

AR is a technology that overlays digital information, such as images or videos, onto the real world, enhancing the user's perception and interaction with their environment. AR can be used in educational settings to create interactive learning experiences. It allows students to visualize complex concepts, making learning more engaging and effective [15,48]. AR is seen as a significant advancement in technology, following the shift from large computational systems to mobile devices. It integrates digital information with the real world, enhancing our interaction with our environment. AR is expected to transform various aspects of our lives by introducing new ways to interact through sight, sound, and touch. This transformation will affect how we communicate, learn, and entertain ourselves. A crucial element in making AR effective is the development of advanced display technologies. The quality of the display directly influences the user experience, making it a fundamental challenge in AR development. As AR technology continues to evolve, it holds the potential to revolutionize industries such as education, healthcare, and entertainment, making it a key area of research and development [45]. Figure 4a shown example of empower your frontline teams with remote assistance and guidance. This enables instant troubleshooting, minimizing downtime and increasing overall efficiency. Figure 4b shows an image of example of AR used in workplace.

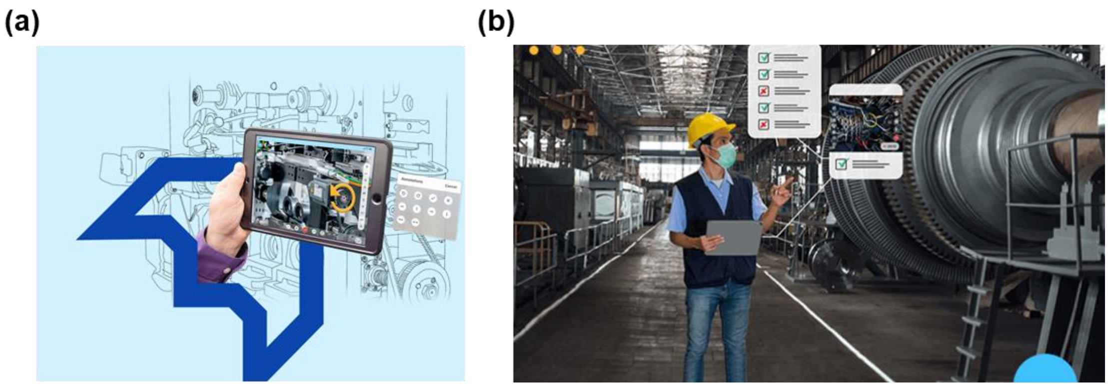

Fig. 4. (a) Frontline teams with remote assistance and guidance. (b) Image of AR in Power and RE [49]

There are four different types of AR which are;

3.2.1 Marker based AR

This type of reality is also known as Image Recognition. A camera and a visual marker such as a QR code or a 2D code is used. First the marker is recognized by the reader and then the output is given. Apps derive from this type uses a camera to differentiate a marker from any other real-world object. Markers can be anything which are distinctive yet simple (e.g. QR Code) and should be observable by the camera. Calculations of position and orientation is done. Marker Detection Algorithm includes Dividing images in regions, detecting images in the region, finding segments in the region, merging segments into lines, extending lines along the edges, keeping lines with corners and finally, finding the markers [47,50,51].

3.2.2 Marker less AR

This type of reality is also known as Location-based reality or GPS. Data provided which is based on our location and is provided with the help of a digital compass, accelerometer, velocity meter or GPS [50,51]. All these are inserted in our devices. The reality of this type is possible because of the location detection features available on our smartphones these days. It recognizes things that were not directly provided to the application in advance, unlike Marker Based AR. Here, the algorithm only must identify the patterns, the colours, and the other features to provide results.

3.2.3 Projection based AR

As the name suggests, artificial light is projected onto real-world objects. This allows for human interaction by sensing the touch of that projected light. User's touch is detected by distinguishing between an expected projection and an altered projection [50, 51]. A digital operating canvas is created on virtually any work surface. Projection based AR is used to project a 3D interactive hologram.

3.2.4 Superimposition based AR

In this type of reality, the original view of an object is either incompletely or completely replaced with a recently stoked view of that same object [50, 51]. Then, object recognition plays an important part (e.g. IKEA - AR Furniture roster). It is a virtual cabinetwork app that augments cabinetwork onto real bottom [47].

Table 1 shows the evolution of AR, tracing its development from early conceptual frameworks to its current applications in various industries. Initially, AR was limited by technological constraints, but advancements in hardware, such as smartphones and wearable devices like smart glasses, have significantly expanded its capabilities. Over the years, AR has evolved from simple overlays of static information to more sophisticated, interactive, and context-aware systems that can provide real-time data and visualizations. This evolution has paved the way for AR to be integrated into sectors such as healthcare, manufacturing, education, and RE, where it enhances productivity, learning, and decision-making. As Table 1 highlights, early AR applications were primarily research-based, but today, AR is widely used in consumer markets and professional environments, offering immersive and practical solutions across multiple domains. The continuous advancements in software algorithms, sensor technologies, and artificial intelligence are further propelling AR toward more widespread adoption and increasingly complex use cases.

Table 1
Evolution of AR

Stage	Year	Technological Advancement	Key Application	Impact on AR Evolution	Ref.
Conceptual Beginnings	1960s - 1980s	Basic AR ideas emerged; first AR devices were developed	Military flight simulators, basic research experiments	Set the foundation for AR; technology was not accessible to mainstream industries	[52]
Early Prototypes	1990s	Development of basic head-mounted displays (HMDs) and early AR software	Military, medical simulations, industrial prototyping	Prototypes demonstrated AR's potential in professional settings but were costly	[53]
Emergence of Mobile AR	2000s	Rise of smartphones with GPS, accelerometers, and cameras	Gaming (e.g., "ARQuake"), mobile navigation, retail	AR became more accessible; early consumer applications began emerging	[54]
Commercial AR	2010s	Wearables like Google Glass, AR SDKs (e.g., ARKit, ARCore)	Healthcare, education, marketing, gaming (e.g., Pokémon GO)	Expanded AR into everyday life; increased focus on user experience and interactivity	[55]
Immersive and Intelligent AR	2020s - present	Integration of AI, machine learning, 5G, and advanced sensors	Remote assistance, virtual shopping, RE, real-time industrial monitoring	AR is now intelligent, real-time, and context-aware, enabling wide-scale industrial use	[56]
Future of AR	2030s - onward	Anticipated advancements in AR glasses, full sensory integration, neural interfaces.	Autonomous systems, advanced medical procedures, smart cities	AR is expected to become ubiquitous, blending seamlessly into daily life and industry	[57]

4. Evaluation Criteria for VR and AR in RE Sector

To assess the effectiveness of VR and AR in the RE sector, it’s important to establish clear evaluation criteria. These criteria will help measure how well these technologies enhance educational outcomes in renewable energy training. The following metrics are proposed to evaluate their success:

4.1 User Engagement

User engagement refers to the level of interaction, interest, and involvement that learners exhibit while using VR and AR systems. High engagement is often correlated with deeper learning experiences and better retention of information. To evaluate engagement, the following indicators can be considered:

i. Interactivity: Measuring the extent to which users actively interact with the content (e.g., manipulating virtual elements, making decisions, solving problems).
ii. User Satisfaction: Surveys or feedback forms can capture learners' subjective experiences, including their enjoyment and perceived value of using VR/AR for learning.

4.2 Knowledge Retention

Knowledge retention ensures that learners remember and apply what they have learned. VR and AR can improve long-term retention compared to traditional methods. Evaluation metrics include:

i. Pre- and Post-Tests: Assessing learners' knowledge before and after using VR/AR systems to measure how much information they have retained.
ii. Follow-Up Assessments: Conducting assessments weeks or months after the learning experience to test how much knowledge has been retained over time.
iii. Transfer of Knowledge: Evaluating how well learners can apply the knowledge gained in VR/AR simulations to real-world renewable energy scenarios.

4.3 Practical Skill Development

VR and AR technologies not only improve theoretical knowledge but also enhance practical skills, which are critical for handling complex renewable energy systems. Evaluation criteria include:

i. Skill Proficiency Assessments: Testing learners on practical renewable energy tasks before and after VR/AR training to assess skill improvement.
ii. Simulation Performance: Measuring how well learners perform tasks in VR/AR environments, like troubleshooting or system setup.
iii. Real-World Application: Evaluating how learners apply their skills in real-world renewable energy contexts, such as operating energy systems.

4.4 Usability and Accessibility

For VR and AR technologies to be effective, they must be easy to use and accessible to all learners. Key considerations include:

i. Ease of Use: How user-friendly the VR/AR system is, as assessed through user feedback and usability testing
ii. Technical Issues: Tracking any hardware or software issues that occur during the learning experience.
iii. Inclusivity: Ensuring the VR/AR experience is accessible to learners with different abilities or backgrounds, including those with physical disabilities or language barriers.

5. Applications
5.1 Virtual Reality in Renewable Energy

VR applications are being used in the RE sector industry to improve comprehension, training, and engagement. According to the literature focusing on solar RE, the following are some of the key domains where VR applications are currently being used.

Lopez *et al.,* [58] developed a VR environment for teaching and training the installation of PV power plants (Figure 5a). VR was developed with SketchUp which facilitates the sizing of installed capacity of 3D buildings and Unity was used to create the virtual environment. The outcome from this research was that this VR application helped better comprehend and visualize the technical aspects of the installation, as it supports learning in visual laboratory practice. Their VR application enabled users to interact with activities including reading boards and oral 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.,* [59] developed a VR application employing a game-based approach to instruct solar energy system design. The application integrated various features such as text, audio, quizzes, interaction with 3D objects and animations. The application presented two levels in virtual-based residences, where users engaged in energy-related tasks (Figure 5b). In the initial level, users learn the importance of using PV panels to generate energy and reduce their electricity bills. An animated demonstration illustrated the process of electricity generation, from producing electric current from solar energy to supplying a household with electricity. In subsequent level, users measured the power consumption of household electrical appliances to determine the required number of PV panels for meeting energy demands, subsequently tasked with installing the determined number of solar panels on residence rooftop.

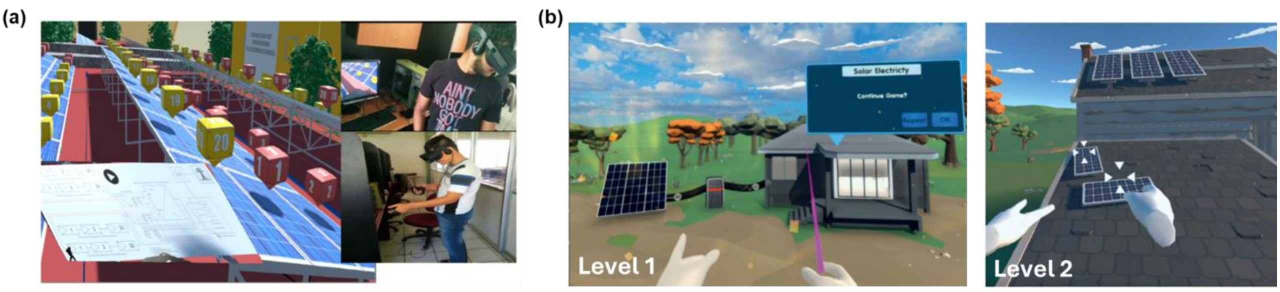

Fig. 5. (a) Supervising single line diagram for PV arrays connections [58] and (b) VR gamification layout of animation in level 1 shows the process of solar panels convert solar energy to electricity and level 2 task where user place the number of solar panel require for each household [59]

Abichandani *et al.,* [60] presents a cloud-based VR system designed specifically for educating wind energy, merging the scalability and accessibility of cloud services with the immersive capabilities of VR (Figure 6). The system consists of three main elements: first VR modules concentrating on wind energy STEM concepts, enabling students to construct virtual wind farms for optimal energy production both inside and outside the traditional classroom environment. Second, a cloud-based technological infrastructure for delivering these VR educational modules, and lastly an adaptable assessment model that evaluates students' ability to apply independent reasoning, design, and operational skills in wind farm development, including adjustment of windmill parameters. The authors predict that as educational VR platforms progress, cloud-based implementations will become more widespread, suggesting that their ecosystem and technical methodology could provide a model for future research in educational VR.

Fig. 6. Interactive controls facilitated by the VR system include modifying windmill parameters. In the top left is the basic setup to modify windmill parameters. In the top right, users can adjust parameters by adding blades, in the bottom left, they can increase blade length, and in the bottom right, they can alter windmill spacing [60].

Liu *et al.,* [61] explores the potential applications of VR technology in hydropower station production, including immersive training, virtual operation, maintenance, remote fault diagnosis, and emergency planning. VR technology offers operators enhanced training opportunities, reducing training duration and elevating technical proficiency. In Figure 7a, operators utilize VR treadmills to control movement speed within virtual environments, examining equipment parameters such as diameter and working pressure. For instance, operators can inspect attributes like diameter, working pressure, structure, and weight of the main valve of an inlet tunnel, fostering a comprehensive understanding of hydropower stations and equipment. Figure 7b highlights the complexity of turbine-generator unit thrust bearing structures, requiring collaborative maintenance efforts. VR collaborative technology facilitates virtual maintenance training, enhancing operator skills through teamwork.

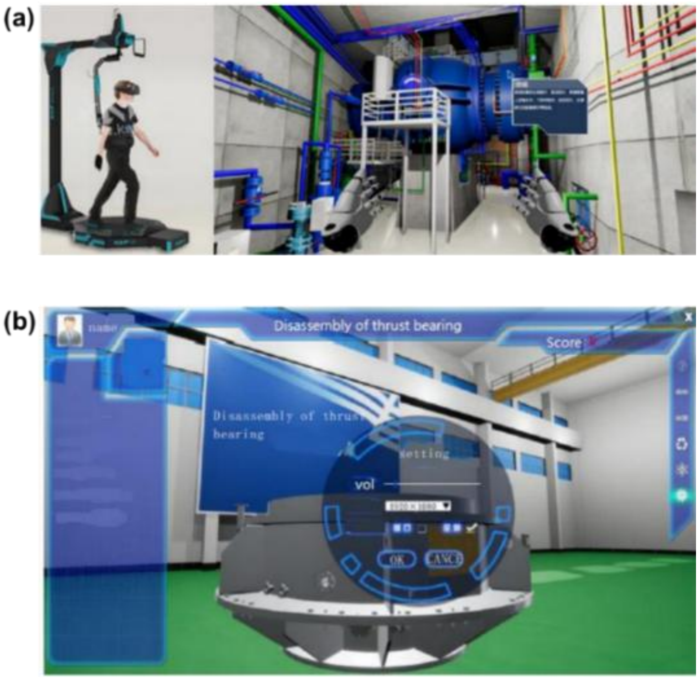

Fig. 7. (a) Image of operator walking on VR treadmill to control the walking rate in the virtual environment. (b) Structure of thrust bearing of turbine generator unit [61]

5.2 Augmented Reality in Renewable Energy

AR is gaining attention for its potential in the RE sector, particularly in improving the understanding and maintenance of complex energy systems. AR can offer interactive visualizations that make it easier for users to grasp complex concepts related to RE technologies. By applying AR, users can gain a better understanding of large-scale power unit installations and how they work, providing a clearer picture of their functionality [62].

There are four key contributions of AR in RE. First, AR enables enhancement on visualization in RE. AR allows users to overlay technical information about renewable energy systems like solar panels, wind turbines, or hydroelectric generators onto their actual physical environment. For instance, AR can show real-time performance metrics (such as energy output or efficiency rates) of a solar panel or the operational status of a wind turbine when viewed through AR-enabled devices like smart glasses or smartphones. This real-time, contextual information helps technicians and engineers monitor and optimize system performance. Second, AR serves as a valuable tool for training and maintenance support. It facilitates hands-on learning by providing step-by-step, interactive 3D instructions overlaid on machinery during complex installations or repairs. This reduces errors, improves efficiency, and minimizes the need for extensive theoretical training or physical manuals. In remote or challenging locations, AR also offers remote assistance capabilities. On-site technicians can connect with off-site experts through AR interfaces, receiving real-time guidance with visual cues directly integrated into their field of view. This approach reduces downtime, streamlines troubleshooting, and minimizes travel requirements. Third, AR plays a vital role in public engagement with RE technologies. It can be used for educational and awareness purposes, enabling users to interact with RE solutions in an immersive way. For instance, AR applications can simulate the installation of solar panels on residential properties or visualize the operation of wind farms within a local environment. Such interactivity fosters a deeper understanding of RE technologies, encourages adoption, and demystifies the complexities of sustainable energy systems. Lastly, the synergy between AR and VR offers a comprehensive ecosystem for education, training, and operations in RE. While VR immerses users in fully simulated environments for exploring complex scenarios, AR integrates digital overlays into real-world settings, enhancing operational efficiency. Together, they accelerate understanding and adoption of sustainable energy solutions. By providing real-time, context-sensitive visualizations and simulations, AR and VR drive innovation and practical application in the RE sector, contributing to the advancement of global energy sustainability.

In 2019, Salehuddin *et al.,* [63] proposed a game designed to help children learn about RE. This game, built around a set of flashcards, covers six types of RE plants found in Indonesia. The game also incorporates AR technology, offering detailed explanations of RE theories and tracking game points. This interactive approach can motivate children by providing an engaging way to learn about RE while achieving a sense of accomplishment. However, because the game is specifically aimed at children, its applicability to other age groups or educational settings may be limited, reducing its potential for broader impact.

An AR Based Modular Platform for Solar Energy Education in 2020. The primary method involves applying AR technology to enhance the training process for individuals learning about solar energy systems [64]. The platform uses AR to improve the learning process for those training in solar energy systems, offering a more interactive and engaging experience. The use of AR ensures that all trainees follow a consistent set of steps during their training, which is crucial for maintaining safety and quality in solar system installation and maintenance. However, the effectiveness of this approach is highly dependent on the functionality and availability of AR technology. Any technical issues with the tools could impact both the training experience and its outcomes.

Sawilla *et al.,* [65] in 2023 presented a novel approach that combines AR with tangible interaction to help visualize energy transformations in RE production. The method involves projecting real-time data onto an AR surface, where users can interact with the information by placing or moving physical objects. This hands-on, interactive approach provides an engaging way for users to explore RE data. However, this method may require users to be somewhat familiar with AR technology, which could exclude those who are less comfortable with tech tools from fully participating.

Besides, in 2024 researcher [66] have study employs a quantitative descriptive methodology to assess the impact of various technologies and leadership styles on industrial sustainability in waste management in Indonesia. The study examines the role of VR, AR, RE, and green leadership in promoting sustainable practices, with a focus on leaders of medium- and large-sized companies. However, the study’s narrow focus on these company leaders may limit its applicability to smaller enterprises or to other regions, potentially restricting the broader relevance of the findings.

These various studies demonstrate the growing integration of AR and other innovative technologies in the RE sector. From educational tools for children to interactive training platforms for professionals, AR is increasingly being used to simplify complex concepts and provide hands-on, engaging learning experiences. These advancements highlight AR’s potential to improve understanding, enhance skills, and contribute to sustainability efforts across different sectors. However, while the effectiveness of these technologies is promising, their applicability can be limited by factors such as age group, technological access, and the specific focus of each study. As AR continues to evolve, its broader application could significantly impact on how we approach RE education and training. Table 2 shows the summary of the studies discussed, highlighting the different approaches, strength, and the limitation across the various applications of AR in RE contexts.

Table 2
Summary of AR in RE

Year, Journal Title	**Method use**	**Strength**	**Limitation**	**Ref.**
2019 Development of Gameplay Design for Renewable Energy Learning based on Augmented Reality	Gameplay design specifically aimed at children to facilitate learning about RE topics. This design is structured around a flashcard system that features six types of RE plants found in Indonesia.	This technology enhances the learning experience by providing additional information on flashcards, including brief explanations of RE theories and game points. A prototype of the game was developed, which serves as a practical application of the gameplay design. This prototype is intended to engage children and motivate them to learn about RE in a fun and interactive way.	The gameplay design is specifically aimed at children, which may limit its applicability to other age groups or educational contexts. This focus could restrict the broader impact of the findings on diverse learning populations. The game features RE plants located only in Indonesia. This geographical limitation may not provide a comprehensive understanding of RE concepts applicable in other regions or countries.	[63]
2020 An Augmented Reality Based Modular Platform for Solar Energy Education	Applying AR technology to enhance the training process for individuals learning about solar energy systems. This method aims to provide a more interactive and engaging learning experience.	Ensures all trainees follow the same standard and process steps during their training. This consistency is crucial for maintaining quality and safety in the installation and maintenance of solar energy systems.	The effectiveness of the AR training method relies heavily on the availability and functionality of AR technology. Any technical issues or limitations in the AR tools used could impact on the training outcomes and the overall learning experience. The study focuses on a specific application of AR in solar energy training. The findings may not be easily generalizable to other areas of RE or different educational contexts, limiting the broader applicability of the results.	[64]
2023 Development of an Interaction Concept to Illustrate the Energy Transformation on an AR-Surface	Combines AR with tangible interaction to visualize energy transformation, particularly in RE production. A key method involved projecting databased information onto an AR surface, allowing users to interact with the displayed data by placing or moving specially designed tangible objects.	Create an engaging and interactive experience for users, allowing them to interact with real data related to RE through a tangible interface. By projecting data onto an AR surface, users can manipulate designed tangible objects, which enhances their understanding of RE concepts and performance. The results indicated that tangible interactions on the AR surface led to faster and	The interaction methods developed may require users to have some familiarity with AR technology, potentially excluding those who are less tech-savvy from fully benefiting from the experience. the effectiveness of the tangible interaction may vary based on the design and usability of the tangible objects used, which could impact user engagement and understanding.	[65]

	The user study conducted in the research involved participants interacting with a dataset on RE production, which provided insights into user engagement and understanding of the information presented.	easier engagement with the information, ultimately improving user understanding of RE performance		
2024 Green Tech and Human Dynamics: Transforming Indonesia's Waste Industry with VR, AR, and Renewable Energy Innovations	Quantitative descriptive methodology to assess the impact of various technologies and leadership styles on industrial sustainability in waste management in Indonesia.	Ease the transition to new technologies by providing visual aids and simulations that help employees adapt to changes in processes and systems. This support fosters a positive attitude towards technological advancements. The adoption of VR and AR technologies is linked to influencing HR behavior positively. By providing innovative training methods, these technologies encourage employees to embrace technological advancements and RE solutions in their work environments.	The study primarily targets leaders of large and medium-sized companies in Indonesia, which may limit the generalizability of the findings to smaller enterprises or different geographical contexts. This focus could overlook the unique challenges faced by smaller organizations in adopting VR, AR, and RE technologies.	[66]

6. Challenge and Opportunities

A key challenge with VR and AR in the RE sector is their high cost. VR systems, for example, require specialized hardware, including high-performance computers, motion-tracking devices, and headsets, which can be prohibitively expensive for smaller organizations or those working with limited budgets. Similarly, AR technologies come with their own financial hurdles, particularly with the need for specialized equipment like sensors, and high-powered devices. On top of these hardware costs, there's the additional expense of developing and maintaining the supporting software infrastructure, which further drives up the overall cost. The ongoing need for maintenance and upgrades also adds to the financial strain, making it harder for smaller RE companies to adopt these technologies on a large scale [67].

In addition to the financial challenges, integrating VR and AR into existing legacy systems within the RE sector poses its own technical difficulties. Many companies still rely on traditional data collection and maintenance systems, and syncing these with new VR and AR technologies can be both time-consuming and complex. This integration process can slow down the adoption of immersive technologies and delay their full potential in improving training, operations, and maintenance in the renewable energy industry.

Another challenge is related to ethical considerations [68,69]. As VR and AR systems often collect large amounts of data about users' behaviors, preferences, and environments, there are concerns about data privacy and the ethical use of this information. It is essential that companies implementing VR and AR technologies ensure robust data security measures are in place and obtain informed consent from users regarding the data being collected. Failure to address these ethical issues could lead to misuse of sensitive information and undermine trust in these technologies.

Furthermore, accessibility is a critical issue when integrating VR and AR into the RE sector. These technologies must be designed to accommodate users with varying abilities, including those with physical or technical limitations. For example, VR systems may not be suitable for individuals who cannot wear headsets for extended periods, and AR devices must be user-friendly for workers with different levels of technical expertise. Ensuring accessibility is essential to ensure that the benefits of VR and AR are equitably distributed among diverse populations, including those in remote or underserved areas.

Another challenges, particularly with VR, is the potential for users to experience symptoms of motion sickness, commonly known as VR sickness or cybersickness. These symptoms, including eye fatigue, disorientation, headaches, perspiration, exhaustion, and nausea, can significantly impact the user experience [70]. According to research by Chang *et al.*, [71] VR sickness is influenced by various factors, such as hardware, content, and human factors, making it challenging to pinpoint specific causes as shown in Sankey diagram Figure 8. For the hardware factors, effects of device-related features such as display types and display mode on VR sickness were widely investigated. Content factors covered various features associated with the VR scene, such as optical flow, graphic realism, rendering reference frames, and task-related features. Additionally, individual differences such as age, gender, and motion sickness history contribute to varying levels of discomfort, complicating efforts to mitigate VR sickness.

For AR, ensuring the durability and reliability of devices in harsh environments, such as offshore wind farms or desert solar installations, is another challenge. These devices must be able to withstand extreme conditions like heat, moisture, dust, and vibration without frequent breakdowns. Additionally, as both VR and AR systems collect and transmit large amounts of real-time data, ensuring data security and protecting against cybersecurity risks becomes increasingly important, especially in remote locations.

Furthermore, the RE workforce may not always be familiar with AR and VR technologies, particularly in regions with limited access to digital tools. Effective training and support are required to bridge the knowledge gap, ensuring that workers can operate and maintain these advanced technologies safely and effectively.

Despite these challenges, VR and AR offer significant opportunities for the RE sector. AR, in particular, is becoming increasingly valuable for training and maintenance purposes. It allows workers to engage in immersive, hands-on training for tasks such as installing solar panels, wind turbines, and inspecting grid systems. This type of training reduces the need for on-site practice and helps minimize errors, especially in complex or hazardous environments where real-world training can be risky and expensive [70].

AR can also facilitate remote maintenance and troubleshooting by overlaying real-time, contextual information onto the physical environment. Workers equipped with AR glasses or tablets can receive step-by-step instructions or view annotated diagrams while working on equipment. This remote support can drastically reduce downtime and improve the speed of repairs, especially in large-scale RE projects or remote locations such as wind farms or solar installations [72].

Furthermore, AR can display real-time performance data, enabling workers or managers to view metrics like energy output, efficiency, and maintenance needs directly in the field. This functionality allows for quicker identification of issues and better resource management, improving operational efficiency across RE sites [73].

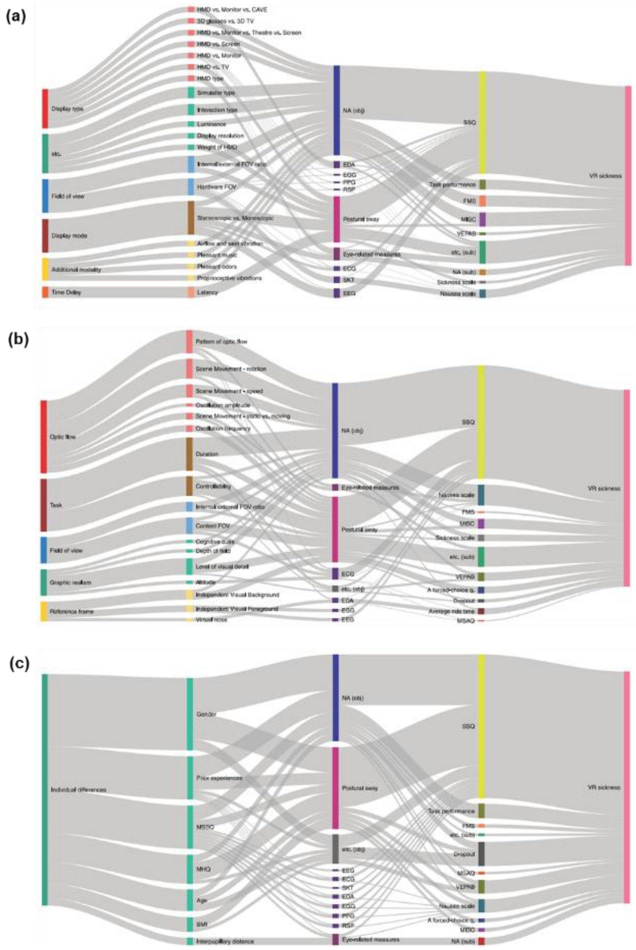

Fig. 8. A Sankey diagram of VR sickness from (a) hardware-, (b) content- and (c) human factors-related research [71]

Another promising opportunity for VR lies in its potential to create virtual mock-ups and simulations of RE infrastructure. By using VR to create detailed, interactive models of systems like wind turbines, solar farms, or energy grids, workers and engineers can simulate real-world scenarios and practice troubleshooting or emergency response without the risks and costs associated with physical models or live systems. This virtual environment also enables more precise testing and optimization of RE systems before they are built or deployed, saving both time and resources.

An important opportunity for future research in the application of VR and AR in the RE sector is the conduct of longitudinal studies to assess the long-term impact of these immersive technologies on learner behavior, knowledge retention, and attitudes toward renewable energy technologies. While short-term studies provide valuable insights into immediate educational outcomes, longitudinal studies can offer a deeper understanding of how sustained engagement with VR and AR influences learners' long-term comprehension, skill development, and decision-making. These studies will be critical in evaluating the lasting effectiveness of VR and AR interventions, helping to refine and optimize educational practices in the renewable energy field for ongoing and future workforce development.

Finally, the integration of AI with VR/AR technologies presents a significant opportunity to optimize energy management and troubleshooting. AI-enhanced VR/AR systems can accelerate the adoption of these technologies in the RE sector, improving overall system performance and operational efficiency.

7. Conclusion

The increasing demand for RE solutions has led to a growing interest in innovative educational technologies, such as VR and AR. This review emphasizes the transformative potential of VR and AR in enhancing learning experiences within the RE sector by providing immersive, interactive simulations that foster deeper comprehension, greater engagement, and improved knowledge retention. These technologies have proven to be invaluable for training, system maintenance, and real-time performance monitoring, offering users a more dynamic understanding of RE systems. However, challenges such as high costs, ethical concerns, and user experience issues such as motion sickness continue to limit the widespread adoption of VR and AR across industries. Despite these barriers, there are significant opportunities to address these challenges. With continued innovation and strategic integration, VR and AR can play a crucial role in accelerating the transition to more sustainable energy practices. This review provides key insights into the potential of incorporating VR and AR into the RE sector, offering a roadmap for future research and implementation.

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