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IMMERSIVE AND COLLABORATIVE 3D SOLAR PANEL VISUALIZATION THROUGH XR

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ABSTRACT

The widespread adoption of solar energy depends significantly on effective communication and visualization of installation designs to convince stakeholders. However, conventional 2D representations and static 3D models fail to capture critical dynamic elements such as sun path trajectories, real-time shading analysis, or energy generation forecasts. Unfortunately, such gaps can hinder project approval and implementation. This paper presents a comprehensive Extended Reality (XR) framework that proposes an alternative workflow for solar panel design through immersive visualization and collaborative configuration capabilities. We propose two complementary platforms: a mobile Augmented Reality application that provides tabletop-scale interactive exploration with accurate environmental lighting simulations, and a Virtual Reality system that enables synchronous multi-user collaboration within shared virtual environments. Both platforms are powered by a unified core architecture that ensures consistency, extensibility, and interoperability across devices. Key technical contributions include seamless integration with existing web-based design tools through QR code-based scene sharing, physically based rendering of solar panel layouts under dynamic environmental conditions, and real-time collaborative editing capabilities that enable distributed teams to refine configurations jointly. Our approach addresses the complete design-to-presentation pipeline, from initial concept exploration in AR to detailed collaborative refinement in VR. Thus, we demonstrate how XR technologies can bridge the gap between technical specifications and stakeholder comprehension, potentially reducing iteration cycles and improving decision confidence.

KEYWORDS

XR, Interaction, Collaboration, Solar Panels, Computer Graphics

1. INTRODUCTION

The global push toward renewable energy has intensified the demand for accessible, efficient, and stakeholder-friendly planning tools, particularly in the solar energy sector. In this context, visualizing solar panel layouts in realistic spatial environments is a critical part of the decision-making process for engineers, clients, architects, and project developers. However, most existing tools rely on static 2D renderings or limited static 3D visualizations, which are often abstract, unintuitive, and detached from the real installation context. These conventional approaches hinder users' understanding of key environmental factors, such as shading, orientation, and the alignment of the sun path, making collaborative planning cumbersome. As a result, decision-making is slow, miscommunication is frequent, and design iterations are resource-intensive.

Our solution builds upon an existing web-based 3D solar design tool, allowing users to create comprehensive scenes with buildings, surrounding structures, and additional entities that cast shadows, such as trees or roof obstructions. Afterward, different solar panel layouts can be generated automatically. Furthermore, users can alter solar panel layouts by adjusting parameters or manipulating panels. The resulting designs are then fed into our system.

Based on this, we present a dual-platform immersive visualization system that integrates mobile Augmented Reality (AR) and Virtual Reality (VR) for the interactive, real-time, and geospatially accurate representation of solar panel layouts. Our AR solution enables in-situ exploration and configuration, transforming mobile devices into spatial viewers for assessing sun paths and shading. At the same time, the VR application supports collaborative, multi-user design sessions with synchronized, real-time material and configuration adjustments. Both platforms are integrated with the web-based solar design tool through QR code export. They are built upon a shared codebase and consistent data pipeline, ensuring coherence, scalability, and maintainability. Therefore, our main contributions are listed as follows:

- A mobile AR system that visualizes solar layouts with integrated real-world terrain data, sun simulations, and touch-based interaction.
- A collaborative VR system that enables multi-user configuration of solar installations using synchronized interactions and spatial UI controls.
- Additionally, we propose a unified technical architecture that supports both AR and VR applications, reducing code redundancy and ensuring consistent feature availability.
- Finally, we evaluated the technical feasibility, usability, and early user feedback of the platform through internal testing and pilot deployment with industry stakeholders.

2. RELATED WORK

The global transition toward renewable energy infrastructure is increasingly dependent not merely on technological efficiency but on the effective communication of complex installation designs to a diverse range of stakeholders. However, as solar energy systems scale from residential rooftops to utility-grade farms, the limitations of conventional design tools have become a significant bottleneck in the adoption pipeline. The lack of intuitive visualizations often leads to stakeholder misalignment, delayed approvals, and suboptimal energy planning because laypeople, ranging from homeowners to municipal planners, struggle to interpret abstract numerical data or static heat maps. Consequently, a rapidly growing body of research has pivoted toward Extended Reality (XR), encompassing Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), as a transformative solution to foster alignment between technical engineering specifications and human comprehension.

In the realm of on-site assessment and workforce development, AR has emerged as a critical tool for in-situ visualizations, serving as a digital lens that superimposes data onto the physical world. Thereby, AR in solar energy is generally bifurcated into consumer engagement and technical workforce support. On the consumer and planning side, AR technologies have become pivotal by making invisible energy metrics visible and contextual. Mobile AR systems now enable the augmentation of real-time solar radiation data directly onto building surfaces, facilitating interactive analysis of PV module placement and energy yield forecasting (Meireles et al., 2023). This capability is further enhanced by algorithms that optimize layouts for maximum energy efficiency, effectively allowing users to visualize the spatial implications of panels before installation (Mehta et al., 2020). Beyond mere placement, recent work highlights the utility of AR in visualizing complex performance data that is typically hidden. For instance, novel systems utilizing high-fidelity headsets like the Apple Vision Pro and Magic Leap 2 have been introduced to render "power flow" glyphs, depicted as animated tubes with arrows, that visualize specific module performance in real-time (Brunhart-Lupo et al., 2024). This approach transforms abstract electrical concepts into tangible visual phenomena, significantly improving accessibility for non-experts by situating the data directly on the physical asset.

Operational efficiency and maintenance represent the second central pillar of AR literature, often categorized under the broader umbrella of Industry 4.0 applications (Alhakamy, 2024). The complexity of modern PV systems requires precise handling, and AR overlays have proven effective in guiding technicians through hazardous environments where error margins are slim. In particular, AR headsets can project step-by-step repair schematics directly onto broken inverters or pumps, significantly reducing error rates and training time by creating a guided maintenance scenario (Benbelkacem et al., 2010; Benbelkacem et al., 2013). Furthermore, integrating AR with advanced computer vision and unmanned aerial vehicles (UAVs) represents a significant leap forward in Operations and Maintenance. Methodologies combining AR with unsupervised machine learning have been demonstrated to automatically detect, segment, and visualize micro-cracks and dust accumulation on panels, achieving high performance in anomaly segmentation (Oulefki et al., 2024). By visualizing these anomalies in 3D space, maintenance teams can rapidly identify compromised modules, streamlining the workflow from detection to repair.

While AR augments physical reality, Virtual Reality (VR) enables immersive environmental simulations that allow for rigorous control over educational and training variables. By integrating large real-world datasets and GIS information, VR platforms can visualize environmental factors affecting PV panel efficiency with high fidelity (Ni et al., 2017). The level of technical sophistication in such simulations has advanced substantially in recent years. For instance, recent work has employed render-texture techniques to extract RGB color data from virtual panels, converting visual data into precise irradiance values for real-time load-flow analysis (Poudel et al., 2025). This creates a bridge between visual fidelity and engineering accuracy, allowing for simulations that are both visually convincing and technically sound. Such environments are not limited to static observation. Applications such as the *Virtual Energy Center* and *PV-VR* allow users to virtually tour concentrating solar power plants or walk through photovoltaic facilities, providing experiential learning opportunities that far exceed textbook diagrams (Ritter et al., 2016; Ritter & Chambers, 2019). These studies notably compared fully 3D-modeled environments with 360-degree panoramas, finding that the interactive nature of accurate 3D models significantly enhanced users' ability to understand complex power conversion and transmission processes.

A critical development in recent literature is the move from subjective user feedback to objective biometric validation of VR's efficacy. The educational and communicative value of these systems is now being validated through physiological data. Multi-modal sensor networks, including eye-tracking and wireless wearable sensors, have been utilized to monitor heart rate and stress levels during solar design tasks (AlQallaf et al., 2024; AlQallaf & Ghannam, 2024). Findings empirically demonstrate that immersive 3D environments generate significantly higher user engagement and lower cognitive load than traditional 2D interfaces. This suggests that VR does not just present information differently, it fundamentally changes how users process and retain complex spatial data, making it an ideal medium for explaining intricate solar concepts to stakeholders who may lack technical backgrounds. This is further supported by specific training applications like *SolarPro* and *Green STEM,* which have demonstrated high usability scores in training workers for hazardous solar farm environments without exposing them to physical risk (Frank et al., 2021; Asghar et al., 2023). These platforms allow trainees to manipulate variables such as panel angle and solar irradiation in a safe, repeatable virtual laboratory.

Although AR and VR have achieved notable advancements, the existing literature highlights a substantial interoperability gap in collaborative workflows. The energy sector is inherently interdisciplinary, requiring coordination between engineers, architects, financial planners, and community stakeholders. However, most current XR tools remain isolated islands of data where users can view a model in VR but cannot easily edit it or share it with a colleague using a different device. To address this, architectures for collaborative terrain sketching on mobile devices have been proposed to facilitate better coordination (Mendoza et al., 2021). Recent research has begun to explore the *Industrial Metaverse* and Digital Twin frameworks. The rise of Digital Twins that mirror the physical behavior of solar assets has been discussed as a solution for synchronous multi-user interaction, which can be supported by full-body motion capture systems for remote collaboration (Clementi et al., 2024; Ha et al., 2022; Menezes et al., 2024).

To manage the increasing complexity of energy data within these twins, environmental information systems that unify heterogeneous data, ranging from terrain models to infrastructure data, have been proposed for use in navigable 3D environments on both desktop and HMDs (Rink et al., 2022). Furthermore, prior studies have introduced location-based services that can alternate between virtual map views and immersive AR environments, leveraging LiDAR data to depict solar potential across urban landscapes. These developments underscore the importance of enabling multiple visualization modes within a single application (Santana et al., 2016).

Ultimately, while the integration of AR, VR, and GIS has significantly increased visual accuracy and user engagement, the current literature lacks sufficient detail on streamlined workflows that connect these complementary technologies. Most existing solutions require complex data migration or manual file conversion to move between a web-based design tool, an AR visualization, and a VR simulation. This fragmentation hinders the iterative design process. Addressing these integrated system gaps is crucial for improving stakeholder communication and decision-making in the future of renewable energy (Hüsser et al., 2025). The emerging consensus in the field points to the need for unified core architectures and frameworks that support seamless, real-time collaboration across devices, enabling a design concept to move fluidly from an AR tabletop exploration to a full-scale VR walkthrough. Such an approach would not only democratize access to solar planning tools but also provide a scalable model for applying XR to complex spatial planning challenges in sustainable infrastructure development.

3. OUR APPROACH

In the following, we present our dual-platform immersive visualization and configuration solution, which is based on a unified architecture for AR and VR. Our system interfaces with an existing web-based design platform that enables end users to create representative 3D models of buildings. These models are then utilized for the automatic placement of solar panels and energy calculations. The platform serves as the backend for our work, and we access the models online via the Web. Before delving into the details of our AR and VR applications, we will first outline the architecture of our system.

3.1 System Architecture

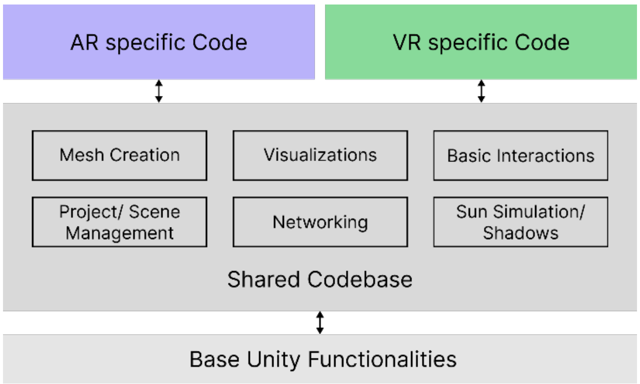


Figure 1. An overview of our system's architecture:
Both the AR and VR-specific code use a shared codebase

The architecture of our XR solution was specifically designed to unify AR and VR solutions within a shared codebase. This unified code structure enabled us to significantly reduce development time by reusing core components, including data fetching, user interactions, and environmental simulation logic, across AR and VR platforms.

This approach simplified maintenance and ensured consistent behavior across different platforms, enabling efficient development iterations and smooth future expansion. We chose Unity for its strong cross-platform support, extensive XR development features, and compatibility with external tools and SDKs.

Figure 1 depicts our system's architecture, built on Unity and incorporating a shared codebase that provides modules for geometric modeling, visualization, interaction logic, project/scene management, networking (for collaborative VR), and lighting. Platform-specific AR and VR modules interface with this shared core, enabling distinct interaction paradigms and rendering adjustments while inheriting these fundamental functionalities.

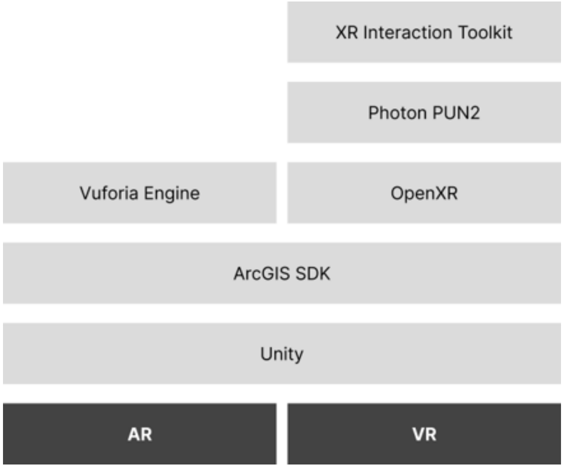
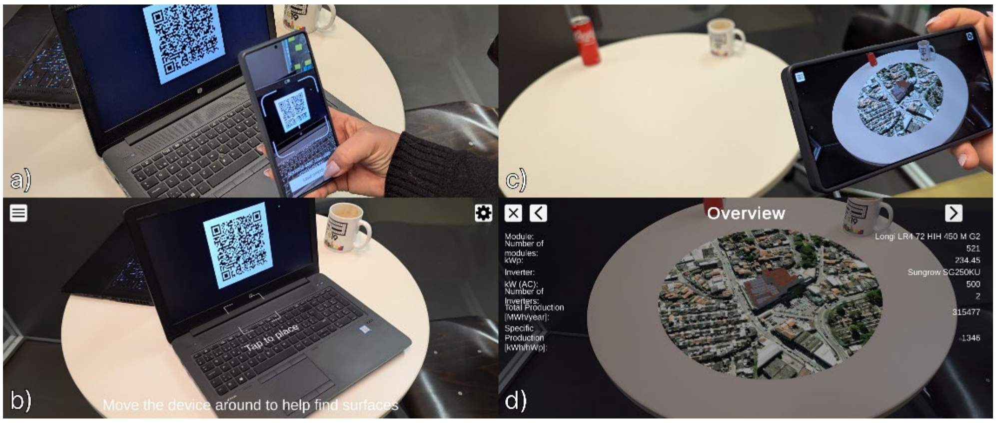


Figure 2. Overview of the tech stack for both AR and VR

Figure 2 provides a detailed overview of the technology stack employed to realize our unified vision. In the domain of Augmented Reality, geospatial data processing is handled by the ArcGIS SDK, whereas Vuforia was deliberately chosen for its markerless tracking capabilities. Thus, we ensure that the superimposition of virtual data remains stable without requiring physical fiducials. On the Virtual Reality side, our application is constructed entirely upon the OpenXR runtime environment. This decision was pivotal for maintaining the integrity of the shared codebase, as OpenXR creates a standardized interface that supports multiple headset manufacturers without requiring platform-specific code refactoring.

To enable the collaborative features inherent in our system design, Photon PUN2 was employed to address all networking requirements, including multiplayer room management and the synchronization of user transforms and state data. Finally, the XR Interaction Toolkit acts as an interface layer between the user and the simulation, standardizing all controller-based interactions, such as ray-cast pointers and UI manipulation, thereby ensuring consistent interaction logic across the different hardware platforms.

3.2 Augmented Reality



Module:	Longi LR4 72 HIH 450 M G2
Number of modules:	521
kWp:	234.45
Inverter:	Sungrow SG250KU
kW (AC):	500
Number of Inverters:	2
Total Production [MWh/year]:	315477
Specific Production [kWh/hWp]:	1346

Figure 3. AR workflow: a) scan the project QR code, b) detect the surface including visual guidance, c) augment the 3D scene on the table, and d) view the details page within the app

Our AR component is an interactive, mobile-first visualization tool that allows stakeholders to explore solar panel layouts in realistic, real-world contexts. The AR application uses markerless tracking, geographic data integration, and sun simulation to convert static layout plans into tangible, intuitive spatial representations.

The system is built with Unity (2022.3 LTS) and extended with the Vuforia Engine for plane detection and spatial anchoring. Scene data is retrieved via RESTful APIs from an existing web-based 3D solar design tool, including geospatial coordinates, mesh data for buildings, panels, and simple scene elements, to simulate and visualize shadows. Unity's JSON Utility is used to deserialize these payloads into in-memory models. The retrieved models are then rendered using custom mesh builders and lighting logic.

The user journey begins with scanning a QR code exported from a web-based design platform. These codes include a special AR flag and a backend URL. Once scanned and validated, the application requests the corresponding project plan and layouts, loads the data, and initiates spatial calibration of the camera stream. A visual placement guide helps users anchor the 3D scene in their environment. This process is illustrated in Figure 3.

The fully rendered AR scene includes all buildings and panel placements from the web-based design platform, as well as a terrain disk underneath that is dynamically fetched from an online geographic information system (ArcGIS). Thus, spatial context is provided by rendering a base layer of geographic data beneath the installation site. Figure 4 illustrates a detailed AR rendering depicting-built structures, trees, solar panels, and the underlying geospatial reference layer. Two UI menu buttons provide user interaction and control for simulation, visualization, and project settings, with the latter enabling rescanning of QR codes and adjusting the simulation date.

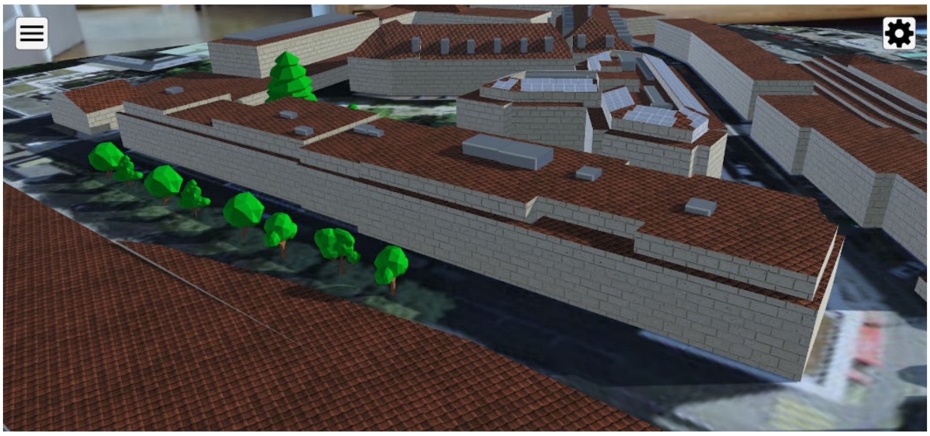


Figure 4. A close-up of an AR scene from within the mobile application, showcasing a larger scene with several buildings and trees

While the scene can be explored by moving the mobile device, additional gesture interactions are supported through Unity’s Input System, enabling pinch-to-zoom, drag, and tap gestures for navigating and modifying the scene. Visual feedback for loading states, interaction hints, and errors ensures an accessible experience even for non-technical users. Additionally, an automated zoom function is implemented that scales based on the distance between the phone and the scene. This allows users to examine buildings and solar panels in detail while maintaining Vuforia’s surface detection and preserving scene anchoring.

Optimized for Android devices, the application uses static batching via Unity's URP pipeline and custom shaders designed for mobile devices, preserving the visual quality of solar panels and roof structures. The final app is publicly available on the Google Play Store via the open testing channel. It has been tested on a variety of mid-range Android devices, demonstrating consistent performance and stability.

3.3 Virtual Reality

The VR component of our solution complements the AR application by offering an immersive collaborative environment for spatial assessment. Designed for standalone VR headsets (e.g., Meta Quest), the application allows users to explore and customize solar installation scenarios retrieved directly from the back-end services.

The VR application thereby shares its core data pipeline and mesh generation routines with its AR counterpart. Scene data, including 3D building structures, solar panel layouts, and simulation metadata, is fetched via HTTP requests from the web server's back-end and parsed using the same model classes. Instantiated scenes replicate the layouts generated in the web-based design tool, ensuring consistency across platforms. As mentioned above, this architecture simplifies maintenance and ensures consistent, synchronized functionality across AR and VR.

VR interaction is implemented using Unity’s XR Interaction Toolkit and the OpenXR runtime, both of which are industry standards and compatible with many VR devices. Hence, users manipulate the environment with typical VR controllers. The left controller opens a hand-attached UI menu that allows configuration of roof and facade materials and solar panel styles. Each of these settings is contained within dedicated UI panels accessible via ray-cast pointer interactions. Figure 5 shows the interface and user interaction with the customization menu. Navigation within the scene is accomplished through thumbstick-controlled teleportation, allowing users to move around large-scale scenes without motion sickness. Additionally, users can scale the entire scene using the right thumbstick or through the handheld menu. This scaling feature enables detailed inspection of roof-mounted installations and evaluation on a 1:1 scale.

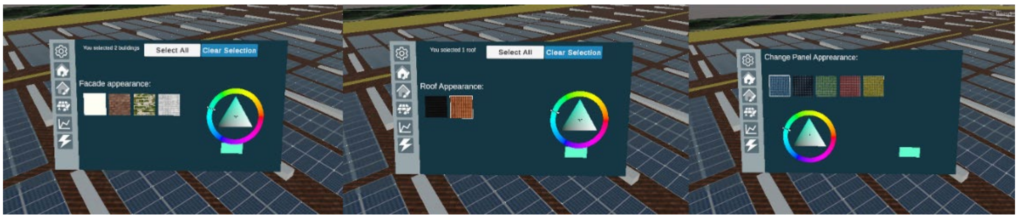


Figure 5. Controller attached VR menu, allowing for customization of materials and textures for facades, roofs, and panels. User can switch between several screens through the navigation pane on the left, selecting which components to adjust visually or accessing settings and data graphs. The UI also allow users to manage the selection of multiple buildings

To enhance stakeholders' spatial perception and improve the accuracy of shadow visualization, the VR application explicitly visualizes the understructures of solar panels. To prevent the rendering of floating panels, our system automatically generates structural elements that visually connect each panel to its corresponding mounting surface (Figure 6).

To efficiently render the thousands of necessary struts without compromising performance, a custom shader that leverages GPU indirect instancing is used. This technique significantly reduces CPU overhead by delegating geometry management to the GPU. In practice, the system stores global pole positions within a structured buffer, which the vertex shader accesses index-wise to apply vertex displacements for each instance. By removing the need for individual draw calls, we mitigate a significant rendering bottleneck and enable the application to exploit the GPU's extensive parallelization capabilities for real-time visualization.

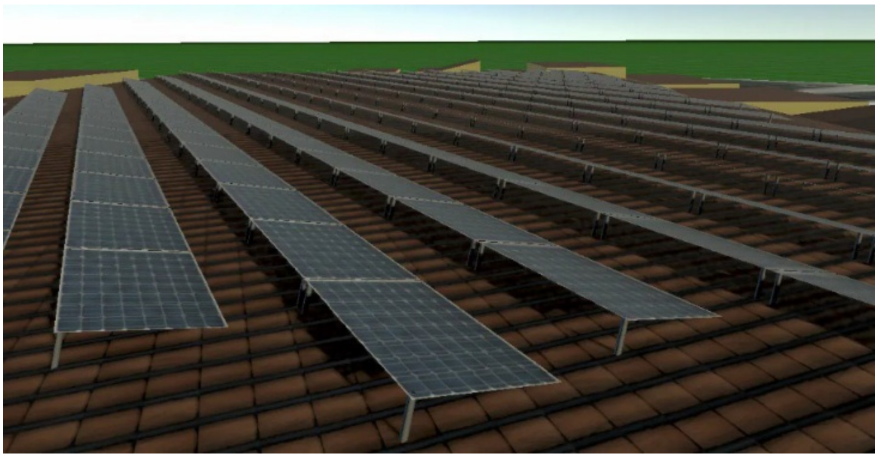


Figure 6. Visible understructures rendered through a custom GPU instancing shader

To support collaborative planning, our VR system integrates Photon PUN2 as its multiplayer networking layer. Collaborative scenes can be created and managed using a companion Android application, which allows users to log in to the backend and select an existing scene to share.

VR users will then be able to join this scene directly from within the application. The companion application was developed because text input in VR is notoriously tricky and cumbersome, and splitting the duties into a manager and client application enhances usability and streamlines participation within the VR environment. Once connected, each user spawns into a shared VR environment with synchronized head and hand avatars and complete visibility into other participants' locations and interactions.

All customization events, such as material changes, panel repositioning, or scene scaling, are synchronized using Photon Remote Procedural Calls (RPCs). This enables real-time, fast, and efficient synchronization of scene data across users, ensuring a seamless multi-user experience. When joining a collaborative session, each client loads their local scene based on the shared project ID and instantiates the scene identically. The session network layer broadcasts real-time updates to building selections, color assignments, or panel configurations. Figure 7 depicts such a session with an active collaborator.

Our environment was built and tested for Meta Quest 2 and Quest Pro, achieving stable frame rates of 90-120fps through efficient mesh instancing, occlusion culling, and shader simplification. Unity’s Universal Render Pipeline (URP) uses single-pass stereo rendering and dynamic batching to minimize draw calls and optimize GPU utilization. The VR system is currently in a testing phase with industry stakeholders and is ready as a functional research prototype for field deployment and formal user evaluations.

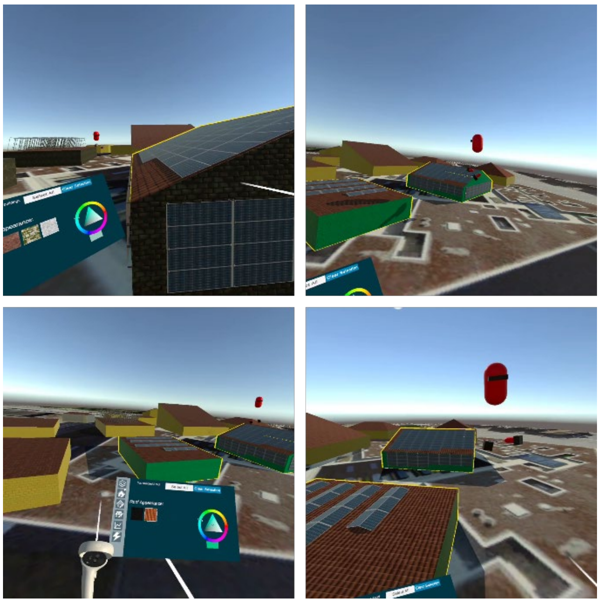


Figure 7. A selection of screens from an active VR session. The VR controller menu and ray-based building selection is shown, as well as the visualization of another user inside the collaborative VR

4. RESULTS & DISCUSSION

Our environment has demonstrated the technical feasibility and practical utility of immersive XR tools for planning and communicating solar panel layouts. By leveraging the affordances of both mobile AR and VR, our approach offers a novel, dual-mode interface for stakeholders, including designers, engineers, sales personnel, and end-users.

Both AR and VR fulfill our core functional requirements and are easy to use, even by non-technical users. The AR application integrates QR-code-based project loading, real-world geolocation reference via ArcGIS services, and accurate sun path simulation. Users scan a QR code from the web design tool, download 3D project data, and place the scene in physical space for exploration. Our system is publicly available through the Google Play Store's open testing channel and has undergone early-stage testing by project partners and internal users. The VR environment reuses and extends many backend and rendering systems from the AR application. The VR prototype supports full scene exploration, intuitive scene scaling, rich material customization, and real-time collaborative interaction. Figure 7 illustrates a session in which multiple users collaborate to analyze a solar panel installation in a virtual environment.

An initial qualitative evaluation was conducted with a diverse group of participants, including clients, academic researchers, software developers, and project stakeholders. The objective of this study was to assess the usability, perceived effectiveness, and potential application benefits of our proposed AR and VR tools.

In the AR context, participants described the system as highly accessible and visually engaging. The QR code–based onboarding process was highlighted as an effective and low-friction entry mechanism. Visual overlays such as projected solar energy yield and sun paths were considered clear, relevant, and easy to interpret. The capability to explore virtual layouts and simulate shadow dynamics across times of day and seasons offered a depth of visual insight not achievable with traditional 2D planning tools.

Within the VR environment, interactive scaling and teleportation functions enabled rapid perspective changes, facilitating inspection of configurations from multiple vantage points (e.g., street-level vs. rooftop or elevated viewpoints). These features were deemed crucial for presenting designs to different stakeholder groups. The controller-based menu UI was found to be intuitive, with minimal learning time required to adjust materials and environmental settings.

From a commercial perspective, customer-facing stakeholders reported that immersive visualization contributes significantly to closing sales. In particular, it assists in addressing common non-financial concerns, such as the visual integration of the installation within its surroundings, as well as optimal panel placements to minimize shading effects. The ability to present scenarios interactively and from stakeholder-relevant viewpoints proved valuable for informed decision-making.

Despite the overall positive reception, feedback indicated areas for improvement are the following: (i) an expanded selection of materials and textures for customization and (ii) streamlined VR deployment via direct distribution channels (e.g., Meta Store) to improve end-customer accessibility. These considerations will inform subsequent development cycles and more extensive user testing.

Our collaborative mode allows multiple users to join a shared session and interact with the same project data. Participants in these sessions valued the ability to see each other’s head and hand positions, which enhanced spatial awareness. This feature was particularly useful for sales meetings and remote consultations with clients and installers.

Although all these insights stem from an early exploratory evaluation, the responses indicate substantial user value and a strong commercial impact. As future work, we will conduct a comprehensive, quantitative user study to validate these promising initial results systematically. Nevertheless, our preliminary findings suggest that immersive technologies, when integrated into existing solar planning workflows, can significantly enhance both the technical accuracy and communicative power of the design process. The combination of real-world context, interactive simulation, and cross-platform consistency positions our solution as a compelling option for industry adoption.

Moreover, our unified codebase approach ensured that improvements to scene generation, material loading, and simulation logic benefited both AR and VR applications. This technical strategy reduced maintenance effort and improved consistency, which will be especially valuable as the system scales to include new features and supports a broader range of devices.

5. CONCLUSION & FUTURE WORK

In this paper, we presented comprehensive mobile AR and VR solutions that overcome the inherent limitations of traditional 2D representations of solar panel visualization. By leveraging the strengths of these immersive technologies, we achieved a more engaging, interactive, and spatially grounded decision-making process for stakeholders across the solar energy planning pipeline.

With our solution, users can visualize solar panel installations in representative 3D scenarios. Our AR solution features real-time sun simulation, shadow visualization, and geospatial alignment through ArcGIS integration. Our VR system supports multi-user sessions with real-time synchronization of scene edits and dynamic material customization. Both platforms share a unified design language and interaction model, ensuring consistency and ease of use across devices.

Our AR application is already available via the Google Play Store’s open-testing channel, and the VR system serves as a validated foundation for further collaborative planning tools. However, several key areas have been identified as promising avenues for future enhancement. While the current system allows for standard material adjustments in VR, expanding the range of textures and surface options would further enhance realism and immersion - especially for clients familiar with specific architectural contexts. Furthermore, explicit, project-specific textures can further enhance realism. In AR, however, maintaining simplicity is paramount. Instead of introducing in-app customization, preselected themes or branded variants could be embedded in the QR code to preserve a clean user experience while also enhancing visual personalization.

Both AR and VR interfaces currently support energy performance graphs and key system metrics. However, more comprehensive data layers could improve the informative value, including advanced energy storage simulations, backend-generated shadow studies, and financial estimations. Such additions would maximize the benefits, particularly during sales meetings or feasibility evaluations, where stakeholders may consider both environmental and economic issues simultaneously. Finally, larger user studies are planned to help enhance the system and identify additional feature priorities. These studies will evaluate usability, interaction efficiency, and overall impact on the decision-making process, providing empirical validation and guiding the roadmap for future releases.

In summary, this work has established a scalable, immersive platform for visualizing and evaluating solar panel installations in AR and VR. By bridging the gap between digital planning and real-world implementation, the system not only enhances communication and understanding but also lays the groundwork for future innovation in the renewable energy sector through immersive XR technology.

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