Interactive 3D Visualization and Configuration of Solar Panel Layouts in XR

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Introduction

The transition to renewable energy demands accessible planning tools that effectively communicate solar panel designs to diverse stakeholders. Conventional approaches rely on static 2D renderings or limited 3D visualizations, which fail to convey critical environmental factors such as shading patterns, sun paths, building surroundings and spatial relationships, creating barriers to effective decision-making and collaborative design.

Recent XR technologies offer promising solutions for environmental visualization and collaborative design in the field of solar energy. AR has already been successfully applied to evaluate solar energy setups on site and enables the interactive analysis of photovoltaic setups (Meireles et al., 2023) and the detection of damaged PV modules (Oulefki et al., 2024). Complementary, VR applications demonstrate value in immersive environmental representations, enabling visualization of complex factors like dust accumulation effects (Ni et al., 2017) and supporting collaborative design through multi-user virtual environments (Ha et al., 2022).

However, there is still a lack of dual-platform AR/VR tools specifically designed for solar panel layout visualization that integrate seamlessly with existing design workflows. This work addresses this limitation. We present a comprehensive and fast system that bridges collaborative, digital planning in VR with immersive, collaborative experiences in AR.

System Architecture

Our solution features a unified architecture that supports both AR and VR applications through a shared codebase, significantly reducing development time and ensuring consistent functionality across platforms. Built on Unity with strong cross-platform support, our architecture provides modules for geometric modelling, visualization, interaction logic, project management, networking, and sun simulation.

Thereby, our system interfaces with an existing web-based 3D solar design tool, accessing 3D setups via RESTful APIs. The fetched scene data includes geospatial coordinates, mesh data for buildings and panels, and environmental elements for shadow simulation. We use lightweight deserialization of the gathered data to recreate 3D models, which are then rendered using custom mesh builders and lighting logic.

Platform-specific AR and VR modules interface with our shared core code basis to enable different interaction paradigms and rendering optimizations. This approach ensures scalability, maintainability, and seamless feature consistency across different platforms.

Augmented Reality

Our AR component transforms mobile devices into spatial viewers for interactive solar layout exploration. Built using Unity 2022.3 LTS and Vuforia Engine, the system provides markerless tracking, geographic data integration, and real-time sun simulation.

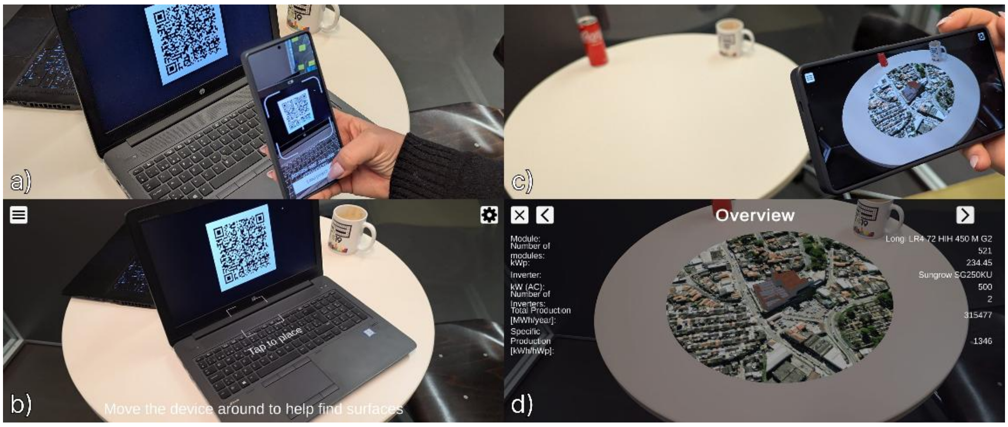

Figure 1 Our AR workflow: a) Scan the project QR code, b) detect the projection surface including visual guidance, c) augment the 3D scene on the surface, and d) view the details page within the app.

The user workflow begins with QR code scanning from the web-based design platform. These QR codes contain AR flags and backend URLs that trigger project data retrieval and spatial calibration. Afterwards, visual placement guides assist users in anchoring 3D scenes in their physical environment (*Figure 1*).

The rendered AR scene includes all buildings and panel placements from the web platform, enhanced with terrain data dynamically fetched from ArcGIS services. This provides crucial spatial context through geographic base layers beneath installation sites. Users can explore scenes through device movement and gesture interactions, including pinch-to-zoom, drag, and tap controls.

Performance optimization includes static batching and custom mobile-optimized shaders that preserve visual quality. Our application is publicly available on Google Play Store's open-testing channel and demonstrates consistent performance across midrange Android devices.

Virtual Reality

Our VR component complements the AR application by providing immersive collaborative environments for spatial assessment. Designed for standalone VR headsets (Meta Quest series), the system shares core data pipelines and mesh generation features with the AR counterpart, ensuring consistency across platforms. Additionally, our VR interaction system utilizes also Unity's XR Interaction Toolkit and OpenXR runtime for broad device compatibility.

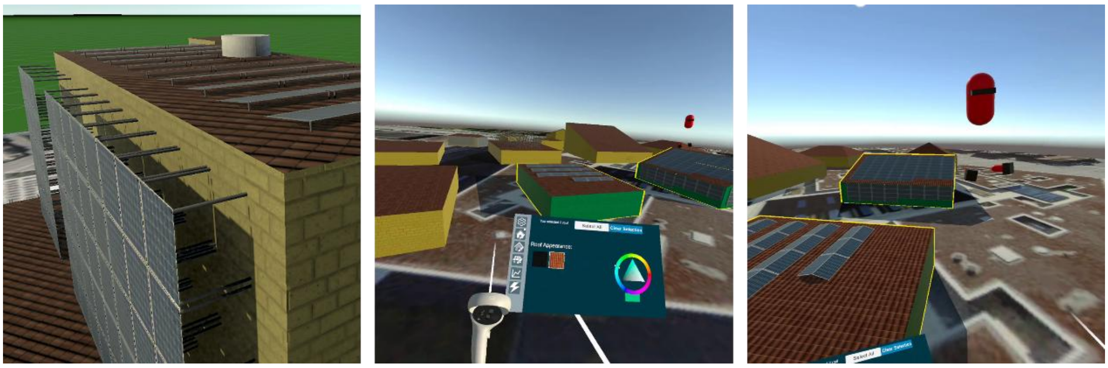

Figure 2 Example screenshots from an active VR session. The VR controller menu and ray-based building selection is shown, as well as the visualization of another user inside the collaborative VR space (red capsule). Notably, the first image showcases visualized understructures in VR, employing instancing for high rendering performance.

In a session, users manipulate environments through standard VR controllers, with the left controller providing hand-attached UI menus for material and panel customization. Ray-cast pointer interactions enable configuration of roof materials, facade options, and solar panel styles. Navigation employs thumbstick-controlled teleportation to prevent motion sickness while enabling exploration of large-scale scenes.

To achieve real-time rendering of thousands of poles of solar panels with minimal overhead, we apply custom GPU instancing shaders to visualize solar panel support structures (*Figure 2*). This significantly improves spatial understanding and shadow estimation capabilities while maintaining high frame rates.

Our collaborative functionalities are based on Photon PUN2 for networking facilities. A companion mobile application manages session creation and user authentication, avoiding the challenges of text input in VR environments. Once connected, users spawn into a shared environment with synchronized avatars and full visibility of participant locations and interactions (*Figure 2*). All customization events synchronize via Photon Remote Procedural Calls (RPCs), ensuring coherent multi-user experiences.

Our VR system achieves stable 90-120fps frame rates on Meta Quest devices through efficient mesh instancing, occlusion culling, and Unity's URP configuration with single-pass stereo rendering.

Discussion & Conclusion

Our system demonstrates the technical feasibility and practical utility of immersive XR tools for solar panel layout planning and communication. Thereby, our dual-platform approach successfully addresses different stakeholder needs: AR provides accessible, context-aware visualization for live assessment, while VR enables detailed collaborative analysis in controlled environments.

Early user feedback from internal testing sessions with researchers, developers, and industry stakeholders has been positive. Participants appreciate the AR experience's accessibility and visual clarity, particularly the QR onboarding process and energy yield visualizations. The ability to explore virtual layouts and evaluate shadow behavior over time and seasons was highlighted as particularly valuable compared to traditional 2D planning tools.

In VR, users value the interactive scaling and teleportation features that enable rapid perspective shifts and detailed configuration inspection. The controller-attached UI is considered intuitive, with scene scaling emerging as the most frequently used feature. Collaborative sessions enhance spatial awareness through visible participant positions, proving especially useful for sales meetings and remote consultations.

Our unified codebase approach proved beneficial, ensuring that improvements in scene generation, material loading, and simulation logic benefited both platforms simultaneously. This strategy reduced development and maintenance effort and improved consistency, positioning the system for scalable deployment.

We presented a scalable, immersive platform for visualizing and evaluating solar panel installations across AR and VR modalities. By bridging digital planning and real-world implementation, our system enhances communication and understanding while laying the groundwork for future innovation in renewable energy planning through immersive XR technology.

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