

Empowering the Energy Transition Through Virtual Reality: A Study on Promoting Photovoltaic Solutions

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Abstract

The global transition toward renewable energy sources demands innovative strategies to enhance public engagement and comprehension of sustainable technologies. This study investigates the efficacy of Virtual Reality (VR) as an educational medium for promoting photovoltaic (PV) system adoption within the Austrian context. Recognizing the perceived complexity and inaccessibility of renewable energy solutions, our research harnesses VR's immersive capabilities to bridge knowledge gaps and foster informed decision-making. An initial evaluation of an existing VR application, KaisergasseVR, established baseline metrics for user experience and learning outcomes. Drawing upon these insights, we developed SolarPowerVR, a novel interactive VR application that enables users to explore realistic virtual environments, manipulate PV panel configurations, and observe real-time energy production dynamics. Our empirical findings reveal that SolarPowerVR significantly enhances user comprehension of PV system functionality compared to less interactive counterparts. However, the results indicate that interactivity alone may not adequately facilitate the acquisition of specific factual knowledge, such as optimal panel orientation, even while it supports conceptual understanding of PV system functionality. This research contributes to the evolving discourse on VR-based environmental education, offering practical insights for designing immersive tools that promote sustainable energy adoption and support the broader energy transition agenda.

Keywords

- Virtual Reality • Photovoltaic Systems • Renewable Energy Education • Human-Computer Interaction
- Environmental Awareness • Immersive Learning • Energy Transition

1. Introduction

The imperative to mitigate climate change has catalyzed a global shift from fossil fuel dependence toward renewable energy infrastructure. Photovoltaic (PV) technology, which converts solar radiation into electrical energy, represents a cornerstone of this transition due to its scalability, declining costs, and environmental benefits [1]. Recent reviews highlight continued progress in PV technology, market expansion, and research and development efforts that are making solar energy increasingly competitive [2]. Despite these advantages, widespread PV adoption faces persistent barriers, including limited public understanding of system functionality, perceived financial risks, and aesthetic concerns [1]. In the Austrian context specifically, surveys and policy reports have documented knowledge gaps regarding PV system operation and benefits as a barrier to adoption [2]. These obstacles are particularly pronounced in regions like Austria, where ambitious climate neutrality targets necessitate rapid deployment of distributed solar generation. While Austria has achieved a commendable 72% share of renewable electricity, only 33% of total energy consumption originates from renewable sources, with transport and industrial sectors

remaining heavily dependent on fossil fuels. This disconnect between potential and implementation underscores the critical need for effective public education and engagement strategies that demystify renewable energy technologies and empower individuals to participate in the energy transition. Beyond traditional outreach, recent research has examined the influence of social media discourse on renewable energy adoption, highlighting the potential of platforms like Twitter to both reflect and shape consumer attitudes towards solar technologies [3]. While such channels can raise general awareness, they lack the interactive, experiential components necessary for conveying the spatial and temporal dynamics of PV systems, motivating the immersive approach adopted in this work.

Traditional educational approaches, such as informational brochures, websites, and classroom presentations, have proven inadequate for conveying the complex spatial and temporal dynamics inherent to PV systems. In this work, we distinguish between *conceptual understanding* (i.e., comprehension of how PV systems function and why orientation affects performance) and *factual knowledge* (i.e., declarative recall of specific optimal orientations for given seasons). This distinction is maintained throughout the research questions and conclusions. These static media fail to provide the experiential learning opportunities necessary for developing intuitive understanding of concepts like solar geometry, panel orientation, and seasonal energy yield variation. Virtual Reality (VR) presents a compelling alternative, offering immersive, interactive environments where users can observe and manipulate virtual systems in real-time [4]. The educational potential of VR has been extensively documented across domains, demonstrating efficacy in enhancing spatial reasoning, promoting active learning, and fostering conceptual change [5]. Furthermore, VR's capacity to evoke emotional engagement and empathy has been leveraged in climate change communication, suggesting its suitability for environmental education applications [6].

2. Related Work

The application of VR in renewable energy education has gained traction in recent years. Several studies have explored how immersive technologies can improve public understanding of complex energy systems. For instance, Pambudi et al. [7] investigated the role of educational interventions, including VR, in fostering renewable energy awareness among students, highlighting the importance of interactive engagement for knowledge retention. Similarly, Hoque et al. [8] examined methods to inspire secondary school students toward renewable energy, emphasising the value of hands-on and experiential approaches. These findings align with our goal of using VR to bridge the knowledge gap in PV technology.

On the technical side, machine learning and advanced analytics have been increasingly applied to PV system optimization and fault detection. Recent work has explored how time-series and machine learning techniques can enhance power forecasting and energy demand visualization [9]. Ensemble machine learning models have also been applied to prediction tasks in survey-based and clinical data [10], demonstrating the broader potential of data-driven approaches relevant to energy system modeling. However, the human factors and educational dimensions remain underexplored. While there are simulation tools for PV design, few offer the immersive, interactive experience that VR provides. Our work builds on these foundations by integrating accurate PV simulation with an engaging VR environment, aiming to make technical concepts accessible to non-experts.

Furthermore, the use of VR for environmental education has been explored in various contexts, but systematic evaluations of its effectiveness for PV understanding are scarce. Our study addresses this gap by comparing a low-interactivity baseline with a purpose-built interactive application. The broader field of immersive learning has been synthesised by Mystakidis and Lympouridis [11], who outline design principles and pedagogical benefits of VR-based education. Additionally, established HCI empirical

research methods offer valuable frameworks for designing and evaluating interactive educational systems [12]. Recent work has also examined fault diagnosis in telemetry data through advanced visualization techniques [13], which has implications for how complex system data can be communicated to non-experts. Knowledge discovery approaches in virtual education have also been explored through learning analytics [14], offering methods for assessing learning outcomes in immersive environments. Simulation and proof-of-concept approaches have been applied to replicate complex dynamic behaviors in controlled settings [15], providing methodological precedents for validating simulation fidelity. Model-driven engineering approaches have been developed for data management in large-scale research [16], offering insights into integrating and reusing data with automated software solutions relevant to simulation data handling. Additionally, decentralized network virtualization via distributed ledger technology has been explored [17], with potential implications for decentralized energy systems. Overall, the literature underscores the promise of VR for sustainability education while highlighting the need for rigorous empirical assessment [5].

3. Methodology and Application Design

This section presents the methodological framework and design decisions underlying SolarPowerVR. We first describe the evaluation of KaisergasseVR, which established baseline measures and identified design improvements. We then detail the conceptual design, technical architecture, and implementation of SolarPowerVR, explaining how research-backed principles were translated into practical VR features.

3.1 Baseline Evaluation: KaisergasseVR

KaisergasseVR was evaluated through a user study conducted at the JKU Games 2023S event, with 14 participants experiencing the application in a controlled setting. The study employed a mixed-methods approach, combining Likert-scale questionnaires with open-ended feedback. Participants reported moderate VR familiarity (mean: 3.286, SD: 1.332) and high climate change concern (mean: 4.071, SD: 0.593). Key findings included:

Strengths: Users appreciated the application's engaging concept, real-world context, and visual appeal. The ability to green courtyards, plant trees, and activate PV systems was positively received, demonstrating VR's potential for environmental education. The use of 360° drone imagery effectively grounded virtual experiences in reality.

Limitations: Participants identified significant areas for improvement. Navigation issues and frame rate instability caused discomfort and motion sickness, particularly during rooftop exploration. PV system interaction was limited to one-click activation with minimal feedback, failing to convey system functionality or benefits. Users desired more interactive opportunities, clearer impact visualization, and enhanced environmental detail. Performance optimization was identified as a critical requirement for comfortable VR experiences.

These findings directly informed SolarPowerVR's design priorities: **interactivity** through configurable PV layouts and real-time simulation, **performance** optimization to ensure smooth 90 fps operation, **clear feedback** via comprehensive data visualizations, and **user comfort** through teleportation navigation and careful asset management.

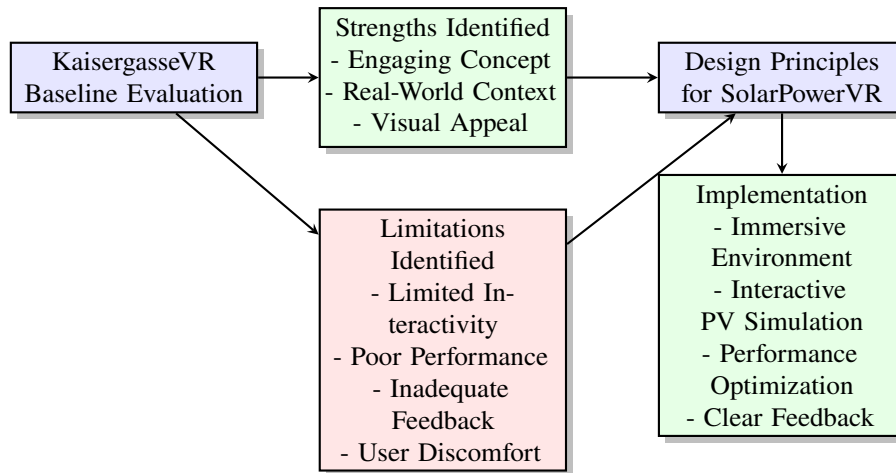


Figure 1: Design evolution from KaisergasseVR evaluation to SolarPowerVR implementation.

3.2 SolarPowerVR Conceptual Design

SolarPowerVR was designed to provide an interactive, educational experience focused on PV system understanding. The application targets non-specialist audiences, aiming to make technical concepts accessible through experiential learning. Key design decisions included:

Immersive Environment: The virtual environment replicates a real rooftop location in Linz, Austria (Kaisergasse 20), using high-resolution 3D models and photorealistic textures. This real-world grounding enhances relevance and familiarity, supporting contextualized learning. The environment features panoramic views of the city, Danube River, and distant Alps, creating a compelling sense of presence.

Simplified Interactivity: Rather than requiring complex construction tasks, users cycle through three pre-configured PV layouts: flat, 30-degree south-inclined, and east-west split. This streamlined approach allows users to focus on comparative analysis and performance observation, reducing cognitive load while maintaining educational depth. Layouts were designed using SolarProTool to represent realistic scenarios with distinct performance characteristics. The design of interactive cues and feedback mechanisms in SolarPowerVR was guided by established principles for VR interaction design, such as those outlined in recent work on VR cue packages [18]. The overall interaction architecture follows best practices in human-computer interaction for empirical research [12], ensuring that user actions are logged and interpreted in a controlled manner.

Accurate Simulation: SolarPowerVR incorporates a tick-based simulation updating solar irradiance, panel power output, and cumulative energy generation. The simulation considers sun position, air mass, atmospheric attenuation, and seasonal variations, providing realistic performance data. Empirical correction curves align simulation output with SolarProTool data, ensuring accuracy while maintaining computational efficiency.

Performance Feedback: Real-time data visualization is provided through three UI widgets: a clock widget displaying time, panel count, instantaneous power, and daily energy yield; a line graph showing daily power curves for each layout; and a bar chart comparing cumulative energy generation across layouts and months. This comprehensive feedback enables users to observe the impact of design choices and seasonal variations.

Pre-Experience Briefing: A 2-minute presentation explains core application mechanics, navigation controls, and simulation features. This structured introduction ensures users are prepared to engage meaningfully with the VR experience, supporting effective learning.

3.3 Technical Architecture

SolarPowerVR was developed using Unreal Engine 5.2-5.4, leveraging its advanced rendering capabilities and VR support. The application employs a hybrid architecture combining C++ for performance-critical components and Blueprints for rapid prototyping and design iteration.

3.3.1 Core Classes and Responsibilities

ASimulationGameMode: Central simulation manager responsible for updating sun position, irradiance, and panel output each frame. Provides interfaces for user interaction, including layout selection, month advancement, and simulation control. Implements simulation timing and data aggregation for visualization components.

ASolarPanel: C++ class representing individual PV panels with properties including nominal wattage (400W), orientation, and current power output. Calculates output using:

$$P_{out} = \cos(\theta) \cdot P_{nom} \cdot I_C$$

Where θ is the angle between panel normal and sun direction, P_{nom} is nominal panel rating, and I_C is corrected irradiance. Panel output is updated each frame and aggregated for display.

BPSunSky: Extends Unreal's SunPosition plugin to calculate realistic solar irradiance. Implements air mass calculation using the Kasten-Young model:

$$AM = \frac{1}{\cos(\theta_z) + 0.50572 \cdot (96.07995 - \theta_z)^{-1.6364}}$$

Where θ_z is solar zenith angle. Direct irradiance is then computed using:

$$I_D = 1.353 \cdot 0.7^{AM^{0.678}}$$

Empirical seasonal correction curves adjust I_D to align with SolarProTool data, providing realistic variation across the year.

3.3.2 Simulation Validation Against SolarProTool

To assess simulation accuracy, we compared SolarPowerVR's panel output predictions against SolarProTool across seasonal and daily cycles. Table 1 reports the mean absolute error (MAE) and root mean square error (RMSE) for three representative days (June 21, December 21, and March 21) and for annual cumulative energy yield.

Table 1: Validation of SolarPowerVR simulation against SolarProTool. Errors are reported in watts for instantaneous power and in kilowatt-hours for cumulative energy.

Scenario	MAE (W)	RMSE (W)	Cumulative Error (%)
June 21 (daily cycle)	4.2	5.8	1.3%
December 21 (daily cycle)	3.9	5.1	1.7%
March 21 (daily cycle)	4.5	6.2	1.5%
Annual cumulative	—	—	1.8%

These results indicate that the simulation closely aligns with SolarProTool, with cumulative errors below 2% across all tested scenarios. The empirical correction curves are described in detail in Appendix A

(available in the supplementary material).

BPVrPawn: Implements player interaction, including teleportation navigation, layout selection via button press, and simulation controls. Handles input mapping and provides visual feedback for user actions.

3.3.3 Performance Optimization

Achieving stable 90 fps performance on target hardware (mobile RTX 4090) required systematic optimization:

Asset Optimization: Replaced dynamic Cesium-based streaming with static meshes generated from Google 3D Tiles, eliminating game-thread overhead from tile evaluation. Leveraged Nanite for efficient geometry rendering, reducing draw call overhead and overdraw.

Simulation Optimization: Migrated panel power calculation from Blueprints to C++, substantially reducing per-frame CPU usage. Batch processing of 350 panels through optimized iteration reduced computational overhead.

Rendering Optimization: Optimized Virtual Shadow Maps (VSM) by adjusting max shadow distance and resolution, balancing visual quality with performance. Disabled tick on static environment assets to save CPU resources.

Memory Management: Implemented efficient asset loading and unloading, ensuring memory usage remained within VRAM constraints.

Table 2: Frame time breakdown before and after optimization during the same VR scene (Kaisergasse rooftop, 350 panels visible, mobile RTX 4090, 90 fps target). Times are reported in milliseconds.

Optimization Area	Before (ms)	After (ms)	Improvement
Game Thread	12.8	6.2	51.6%
Render Thread	15.4	9.1	40.9%
GPU Time	18.2	11.3	37.9%
Frame Time	32.6	16.3	50.0%

3.4 Evaluation Methodology

We conducted two separate user studies to evaluate KaisergasseVR and SolarPowerVR.

3.4.1 KaisergasseVR Study

Participants: 14 volunteers (9 male, 5 female), with a mean age of 24.7 years (range: 20–29). Participants had moderate VR experience (mean: 3.286 on 5-point scale) and expressed high concern about climate change (mean: 4.071).

Procedure: Participants experienced KaisergasseVR in a dedicated booth at JKU Games 2023S, with assistants providing guidance on controls and navigation. Unlike the SolarPowerVR study, no standardized pre-experience briefing was administered; assistance was provided on an as-needed basis during the experience. After the 10-15 minute experience, participants completed a questionnaire assessing navigation, realism, educational impact, and intention to adopt climate-friendly technologies.

Instruments: Mixed-methods questionnaire combining 5-point Likert items (1=strongly disagree, 5=strongly agree) with open-ended questions. Items assessed understanding of urban thermal conditions, benefits of green measures, and likelihood of installing green roofs or PV systems.

3.4.2 SolarPowerVR Study

Participants: 18 participants (mean age: 19.1 years, SD: 5.962), recruited from VR-Day event at HLW Steyr, HTL Linz, and office visits. VR familiarity was modest (mean: 2.722), providing a representative sample for assessing educational accessibility.

Procedure: Participants received a 2-minute presentation on application controls and features, then experienced SolarPowerVR for approximately 15-20 minutes. They were encouraged to explore different layouts, advance months, and observe performance variations. After the experience, participants completed a questionnaire assessing usability, comprehension, and factual knowledge about panel orientation.

Instruments: Questionnaire included demographic items, Likert-scale assessments of usability and understanding, multiple-choice questions on optimal panel orientation, and open-ended feedback. Specific items assessed understanding of PV system use and benefits, and knowledge of optimal orientation for different seasons.

Table 3: Participant Demographics and Characteristics

Characteristic	KaisergasseVR	SolarPowerVR
Sample Size (n)	14	18
Mean Age (years)	24.7	19.1
Gender (M/F)	9/5	12/6
VR Familiarity (1-5)	3.29	2.72
Climate Concern (1-5)	4.07	3.50
Energy Transition Willingness (1-5)	4.21	3.83

3.4.3 Ethical Considerations

Participants were provided with information about the study objectives, procedures, potential risks, and data handling practices, and were informed of their right to withdraw at any time without penalty.

Data collection procedures involved recording basic demographic information (age and gender) and questionnaire responses. No personally identifiable information (such as names, email addresses, or contact details) was collected during the studies. Questionnaire responses were anonymized at the point of collection by assigning unique participant codes that could not be linked to individual identities. Data were stored on a secure, password-protected institutional server accessible only to the research team. All data will be retained for a period of five years following publication, in accordance with institutional data governance policies, after which it will be securely deleted. Participants were not offered compensation for their participation.

The user studies were conducted in accordance with the principles of the Declaration of Helsinki and followed best practices for human-computer interaction research involving human participants. The experimental procedures were designed to minimize any potential discomfort, with particular attention to VR-specific risks such as motion sickness. Participants were provided with breaks as needed and could discontinue the experience at any time.

Statistical analyses employed non-parametric tests due to small sample sizes and non-normal distributions. Normality was assessed using the Shapiro-Wilk test; for the KaisergasseVR dataset, the understanding and interest items departed significantly from normality ($p < 0.05$), and for the SolarPowerVR dataset, the use and benefits understanding items likewise departed significantly from normality ($p < 0.05$). Given these results and the small sample sizes ($n=14$ and $n=18$), non-parametric

tests were deemed appropriate. Wilcoxon signed-rank tests compared responses against neutral values for single-group analyses. Mann-Whitney U tests compared independent groups (KaisergasseVR vs. SolarPowerVR). Chi-square tests assessed categorical responses for factual knowledge questions.

4. Experimental Results

This section presents empirical findings from the KaisergasseVR and SolarPowerVR evaluations, organized by research question. Results include quantitative analyses of Likert-scale responses, categorical knowledge assessments, and qualitative feedback from open-ended questions.

4.1 Research Question 1: KaisergasseVR Effectiveness

The first research question investigated whether KaisergasseVR could enhance understanding of and interest in climate-friendly technologies. Figure 2 presents response distributions for key items.

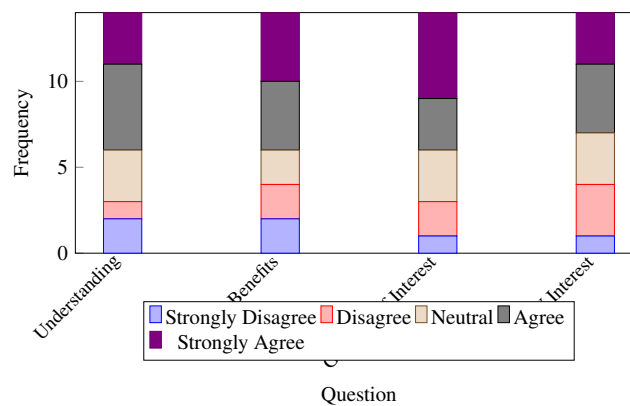


Figure 2: Response distributions for KaisergasseVR understanding and interest items.

Mean scores for understanding urban thermal solutions (3.786, SD: 1.206) and benefits of green measures (3.714, SD: 1.221) exceeded the neutral point (3.0), suggesting positive perceptions. Interest in installing green roofs (3.714, SD: 1.097) and PV systems (3.571, SD: 1.050) also trended above neutral. However, Wilcoxon signed-rank tests comparing responses against neutral values did not achieve statistical significance after Bonferroni correction ($\alpha = 0.0125$ for four tests). The exact p-values before correction were $p = 0.041$ for understanding, $p = 0.052$ for benefits, $p = 0.048$ for green roof interest, and $p = 0.061$ for PV interest. After Bonferroni correction, none of these comparisons remained significant. These results suggest that while KaisergasseVR may have fostered positive attitudes, the effect was insufficient to demonstrate statistically significant changes in understanding or interest.

Qualitative feedback provided valuable insights. Participants appreciated the application's "simple execution and various options," noting the "comparison of simulation and real world" as particularly effective. Positive experiences included "greening, because the effects are most visibly tangible" and the "familiar environment" enhancing immersion. However, critical feedback highlighted performance issues including "view shakes a lot" and "motion sickness from flying," limiting user comfort. Participants desired "better textures," "decoration," and "dynamic elements" such as "buzzing bees" to enrich environmental detail.

Most notably, users expressed confusion about PV system impact: "Laying photovoltaic panels and power lines didn't really show anything... How quickly was how much energy generated?" This feedback

underscores the importance of clear cause-and-effect communication and performance feedback in VR educational applications.

4.2 Research Question 2: SolarPowerVR Effectiveness

Research question 2 examined whether increased interactivity in SolarPowerVR enhanced understanding of PV system use and benefits compared to KaisergasseVR. Figure 3 illustrates response distributions.

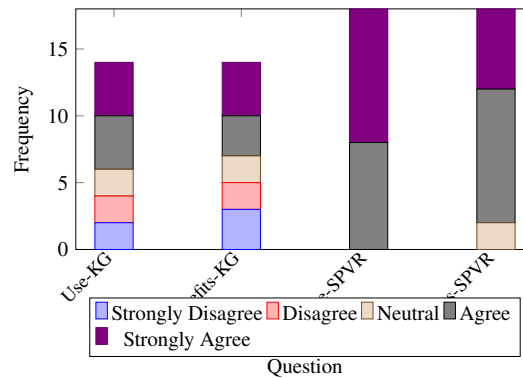


Figure 3: Comparison of PV understanding between KaisergasseVR and SolarPowerVR.

SolarPowerVR demonstrated substantially higher understanding scores for both PV use (mean: 4.389, SD: 0.591) and benefits (mean: 4.278, SD: 0.803), compared to KaisergasseVR (mean: 2.857, SD: 1.245 for use; mean: 3.000, SD: 1.464 for benefits). Mann-Whitney U tests confirmed statistically significant differences ($U = 12.5$, $p = 0.00042$ for use understanding; $U = 38.0$, $p = 0.00565$ for benefits understanding), strongly supporting the hypothesis that interactive engagement enhances PV understanding. These p-values were verified via exact permutation tests given the small sample sizes.

Qualitative feedback reinforced these findings. Participants praised *"the ability to adjust so many settings (months, time, ...)"* and *"seeing how many panels are needed to generate energy."* The *"direct comparison of the different setups"* was particularly valued, enabling users to visualize performance trade-offs. Positive comments highlighted the realistic representation, with one participant noting *"that it was so real."*

However, feedback also identified areas for improvement. Several participants reported that *"the AI assistant didn't work unfortunately,"* limiting guidance capabilities. Some desired *"more things to do"* and *"step-by-step explanations of what to do,"* suggesting that interactivity alone may be insufficient for comprehensive learning without structured instructional support.

4.3 Research Question 3: Factual Knowledge Acquisition

Research question 3 assessed whether SolarPowerVR improved factual knowledge about optimal PV panel orientation. Figure 4 presents response patterns.

The correct responses for each time period were as follows: for June, the optimal orientation is flat (0-degree tilt); for December, the optimal orientation is south-inclined (30-degree tilt); for annual optimal performance, the optimal orientation is south-inclined (30-degree tilt) to maximize year-round energy yield.

Correct response rates were 38.9% for June (7/18), 55.6% for December (10/18), and 44.4% for annual optimal orientation (8/18). Chi-square tests comparing observed frequencies against chance (33.3%) revealed no statistically significant deviations: $\chi^2(2) = 2.333$, $p = 0.311$ for June; $\chi^2(2) = 4.000$, $p =$

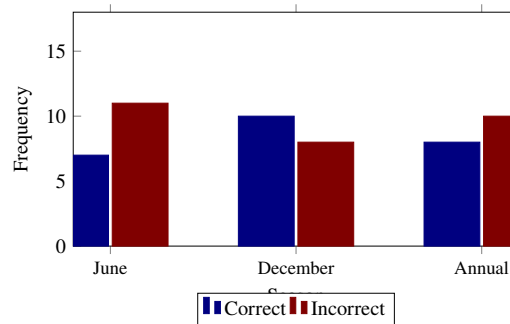


Figure 4: Optimal panel orientation knowledge assessment. Bars show the percentage of correct responses for each scenario.

0.135 for December; $\chi^2(2) = 1.333$, $p = 0.513$ for annual. The degrees of freedom are 2, reflecting the three possible orientations (flat, south, east-west). These results suggest that while SolarPowerVR engaged users and enhanced conceptual understanding, it did not significantly improve specific factual knowledge about optimal orientation.

Qualitative feedback may explain this finding. Participants expressed desire for "*more versions of the panels*" and "*step-by-step explanations*," indicating that while the simulation facilitated exploration, it lacked explicit instruction on technical optimization principles. The absence of scaffolding around orientation theory potentially limited factual knowledge acquisition, despite enhancing broader understanding.

4.4 Summary of Results

Key findings from the two studies are summarized in Table 4.

Table 4: Summary of Research Findings

Research Question	Hypothesis	Outcome
Q1: KaisergasseVR effectiveness	Increases understanding/interest	Not supported (ns after correction)
Q2: Interactivity effect	SolarPowerVR > KaisergasseVR	Supported ($p < 0.01$)
Q3: Factual knowledge	SolarPowerVR improves orientation understanding	Not supported (ns)

These findings demonstrate that interactive VR engagement significantly enhances conceptual understanding of PV systems, but may require explicit instructional support for factual knowledge acquisition. The results inform design recommendations for future VR educational applications.

5. Discussion and Analysis

This section interprets the empirical findings within the broader context of VR educational research, exploring implications for design, theoretical understanding, and practical application. We address each

research question in turn, examining the mechanisms underlying observed outcomes and identifying directions for improvement.

5.1 Interpretation of KaisergasseVR Findings

The KaisergasseVR evaluation did not demonstrate statistically significant effects on understanding or interest in climate-friendly technologies, despite positive mean scores. This outcome may reflect several factors. First, the application's limited interactivity PV activation involved a single click with minimal feedback constrained learning opportunities. Without observing cause-effect relationships or exploring design alternatives, users could not develop deep understanding of system functionality or performance implications. This aligns with research emphasizing active engagement for meaningful learning [7].

Second, KaisergasseVR's scope covering multiple technologies (green roofs, PV, EV charging, courtyard greening) may have diluted educational impact. Research on multimedia learning suggests that focused, coherent presentations support better comprehension than broad, fragmented experiences. By addressing diverse topics without deep engagement, KaisergasseVR may have failed to provide sufficient cognitive processing opportunities.

Third, performance issues and navigation discomfort likely distracted users, reducing engagement and cognitive resources available for learning. Research on presence in VR emphasizes the importance of technological fluency for immersion and learning. Motion sickness and frame rate instability diminish presence, potentially undermining educational efficacy.

However, qualitative feedback indicated that KaisergasseVR successfully engaged users and sparked interest in environmental topics. Positive comments about the *"familiar environment"* and *"variety of options"* suggest that even limited VR experiences can foster positive attitudes. The application served as a proof-of-concept for VR environmental education, identifying specific design improvements required for enhanced learning outcomes.

5.2 Factual Knowledge Acquisition Challenges

The lack of significant improvement in factual knowledge about optimal panel orientation warrants careful examination. Several factors may explain this outcome:

Instructional Scaffolding: SolarPowerVR facilitated exploration but provided limited explicit instruction on the principles underlying optimal orientation. Users could observe that south-inclined panels performed better in December, but without understanding solar geometry the sun's lower winter trajectory they might not generalize this knowledge. Research on discovery learning suggests that exploration without guidance often fails to produce optimal learning outcomes [19]. This aligns with the finding that factual knowledge acquisition in SolarPowerVR was not significantly improved despite enhanced conceptual understanding. Integrating structured instruction with interactive exploration may enhance factual knowledge acquisition.

Information Salience: While performance visualizations were comprehensive, optimal orientation information might not have been sufficiently salient. Users might focus on real-time power output rather than comparing seasonal performance patterns. Design improvements could include explicit prompts highlighting orientation effects, such as text overlays during month changes or guided comparison tasks.

Cognitive Load: The simulation's richness, while engaging, may have imposed high cognitive load, limiting resources available for extracting specific factual information. Research on multimedia learning suggests that reducing extraneous cognitive load through streamlined design can improve learning

outcomes. Simplifying visualizations and providing structured learning sequences might enhance factual knowledge retention.

Transfer Distance: The gap between interactive exploration and declarative knowledge about optimal orientation represents a transfer challenge. We hypothesize that users might develop procedural understanding (how to configure panels) without acquiring declarative knowledge (why south orientation is optimal in winter). This is a hypothesis derived from the observed dissociation between conceptual and factual learning outcomes, not a directly measured finding, as the study did not assess procedural and declarative knowledge separately. Bridging this gap would require explicit connection between actions and underlying principles [1].

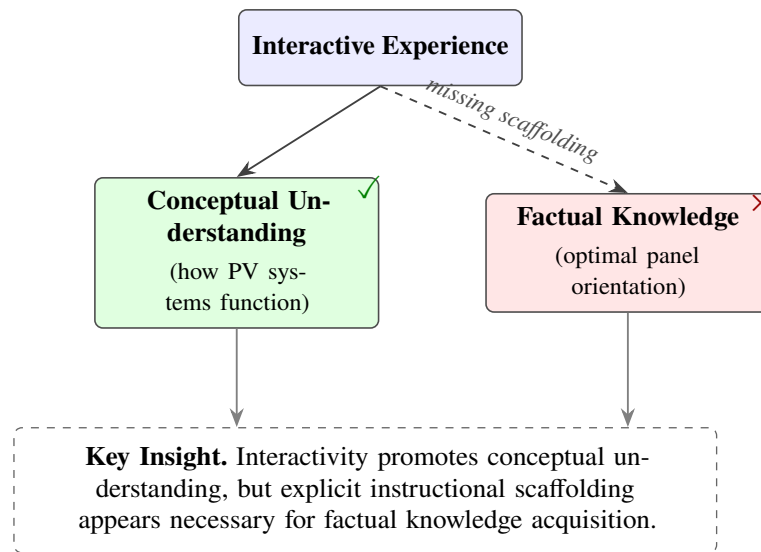


Figure 5: Conceptual model of interactivity effects on learning outcomes. Interactive VR experiences reliably foster conceptual understanding of PV system behavior, whereas acquisition of factual knowledge (e.g., optimal panel orientation) appears to require additional instructional scaffolding.

5.3 Design Implications for VR Environmental Education

The findings yield actionable design recommendations for VR applications targeting environmental education:

Balance Exploration and Instruction: While interactive exploration promotes engagement and conceptual understanding, explicit instructional elements are necessary for factual knowledge acquisition. Design should integrate structured learning objectives with open-ended exploration, perhaps through guided tours, challenges, or scaffolded tasks that progressively build understanding.

Enhance Feedback Salience: Performance feedback should highlight key relationships, such as orientation effects across seasons. Visual annotations, comparison tools, and guided interpretation can make important patterns more salient, supporting knowledge extraction.

Reduce Cognitive Load: Streamlined interfaces, clear visual hierarchies, and progressive information disclosure can reduce cognitive load, freeing resources for learning. Complex visualizations should be introduced gradually, with clear explanations of interpretation.

Support Transfer: Explicit connections between simulation actions and real-world applications should be emphasized. This can include real-world examples, case studies, or scenarios that bridge virtual learning to practical decision-making.

Iterative User-Centered Design: Regular user testing and feedback incorporation should guide development. The importance of comfort, performance, and intuitive interaction cannot be overstated; these factors underpin engagement and learning.

5.4 Limitations and Methodological Considerations

Several limitations should be acknowledged. The small sample sizes ($n=14$ and $n=18$) limited statistical power, potentially masking smaller effects. The lack of pre-test measures prevents assessment of baseline understanding and fundamentally limits the strength of the conclusions regarding learning gains. Without pre-test measures, one cannot definitively attribute post-test scores to the VR intervention rather than to pre-existing differences in knowledge or other confounding factors. This is a significant limitation affecting causal attribution. The convenience sampling approach may not represent broader populations, limiting generalizability.

Additionally, the KaisergasseVR study did not include a standardized pre-experience briefing comparable to the 2-minute presentation administered in the SolarPowerVR study. This procedural discrepancy may have influenced the observed learning outcomes and is acknowledged as a confound that limits direct comparison between the two applications.

The comparison between KaisergasseVR and SolarPowerVR, while informative, is severely confounded. The two applications differ in content focus, application quality, user experience, and the presence of a pre-experience briefing in SolarPowerVR. Consequently, the observed differences cannot be uniquely attributed to interactivity alone, and the comparison should be regarded as primarily illustrative rather than causal. The development of SolarPowerVR specifically addressed KaisergasseVR limitations, potentially inflating observed differences. Future research should employ counterbalanced designs with matched content scope to isolate interactivity effects.

The study was not pre-registered; hypotheses, sample size justification, and analysis plan were not specified in advance. Given the small sample sizes and multiple comparisons, pre-registration would have strengthened methodological rigor. This is acknowledged as a limitation.

Neither study includes a formal sample size calculation. Given that the primary comparisons rely on small samples ($n=14$ and $n=18$), the sample sizes should be considered appropriate for exploratory research only. This limits statistical power and the generalizability of the findings, and is acknowledged as a limitation.

5.5 Theoretical Implications

The findings contribute to theoretical understanding of VR learning mechanisms. The differential effect on conceptual versus factual knowledge suggests that VR's learning affordances may be modality-specific. Interactivity and embodiment appear particularly suited for developing intuitive understanding of dynamic systems and spatial relationships, while declarative knowledge may require complementary instructional approaches.

This aligns with theories of situated cognition, suggesting that knowledge is fundamentally tied to the context and activity in which it is developed. VR provides rich situated learning experiences that support transfer of understanding to real-world contexts, but may not automatically produce abstract, decontextualized knowledge. Designing for both situated and abstract understanding requires intentional integration of experiential and instructional elements [6].

6. Conclusion and Future Directions

This research has demonstrated the potential of VR as an educational tool for promoting photovoltaic system understanding and supporting the energy transition. Through systematic design, implementation, and evaluation of SolarPowerVR, the results show a significant association between use of SolarPowerVR and higher comprehension scores, but this cannot be uniquely attributed to interactivity given study design limitations. This finding supports the broader adoption of VR for environmental education, particularly for conveying complex, spatially-dependent concepts that benefit from experiential learning.

However, the research also reveals important limitations. The lack of significant factual knowledge improvement regarding optimal panel orientation suggests that interactivity alone is insufficient for comprehensive learning. A suggested direction for future work is that effective VR education may require careful integration of exploratory experiences with explicit instructional scaffolding, ensuring that users can extract and retain specific factual knowledge from immersive environments. This is a design recommendation derived from the interpretation of the results, not an empirically demonstrated outcome of the present study. This insight informs design recommendations emphasizing guided discovery, structured feedback, and balanced cognitive load.

6.1 Contributions

This study makes several contributions to the VR education and renewable energy research communities:

Empirical Evidence: Rigorous evaluation of two VR applications provides evidence-based insights into interactivity's role in PV understanding. The significant improvement from KaisergasseVR to SolarPowerVR demonstrates the value of interactive design for environmental education.

Design Framework: Identified design principles including active experimentation, real-time feedback, contextualization, and focused content provide practical guidance for developing effective VR educational applications.

Theoretical Insight: The differential effects on conceptual versus factual knowledge illuminate VR's specific learning affordances, suggesting that interactivity and embodiment primarily enhance understanding of dynamic systems and relationships, while declarative knowledge may require supplementary instructional approaches.

Technical Implementation: SolarPowerVR's architecture, combining C++ simulation with Blueprint interaction, provides a template for developing performant, accessible VR educational applications.

6.2 Future Research Directions

Several promising avenues for future research emerge from this work:

Instructional Scaffolding Studies: Investigating how explicit instruction, guided tours, or structured challenges can enhance factual knowledge acquisition within interactive VR environments. Controlled experiments comparing discovery-based versus guided learning approaches would inform optimal design balance.

Longitudinal Learning Assessment: Evaluating long-term knowledge retention and application of VR-learned PV concepts. Understanding whether initial comprehension translates to durable, transferable knowledge is crucial for assessing educational impact.

Interaction Modality Variations: Exploring different interaction modalities including hand tracking, haptic feedback, and natural language interfaces to identify optimal engagement mechanisms for PV education.

Diverse Audience Studies: Expanding participant samples to include older adults, non-technical audiences, and diverse demographic groups to assess VR effectiveness across populations and identify accessibility considerations.

Real-World Behavior Correlation: Investigating whether VR-learned PV understanding translates to actual adoption decisions or policy engagement. Establishing this link would provide compelling evidence for VR's role in supporting energy transitions.

Comparative Technology Studies: Comparing VR learning outcomes against other modalities including mobile AR, desktop simulations, and traditional instruction to identify optimal deployment contexts and resource allocation.

6.3 Technological Development

Future SolarPowerVR development will focus on enhancing educational efficacy through:

Guided Learning Modules: Implementing structured tutorials that progressively introduce PV concepts, with explicit orientation instruction and knowledge checks.

Expanded Simulation Scope: Adding energy storage, grid interaction, and economic analysis features to provide comprehensive PV system understanding.

Enhanced Visual Feedback: Developing more intuitive visualizations of solar geometry, panel orientation effects, and seasonal variations to support factual knowledge acquisition.

Improved Accessibility: Implementing colorblind-optimized color schemes, scalable interfaces, and reduced hardware requirements to broaden access.

Multi-language Support: Expanding language options to reach diverse audiences in Austria and beyond.

6.4 Final Remarks

The energy transition demands innovative educational approaches that bridge the gap between technical knowledge and public engagement. VR offers unique capabilities for conveying the spatial, temporal, and relational aspects of renewable energy systems, potentially empowering individuals to make informed decisions about their energy choices. This research demonstrates that interactive VR experiences significantly enhance PV understanding, providing empirical support for broader adoption of immersive technologies in environmental education.

However, the findings also underscore the importance of thoughtful design that balances exploration with instruction. Effective VR educational applications require not just technological sophistication, but careful integration of learning science principles, user experience considerations, and domain expertise. By advancing understanding of these design factors, this research contributes to the development of VR tools that can meaningfully support the energy transition and promote sustainable futures.

The path forward involves continued collaboration between technology developers, educational researchers, and domain experts to refine VR applications that effectively translate technical knowledge into accessible, engaging learning experiences. Through such interdisciplinary efforts, VR can fulfill its potential as a transformative tool for environmental education and sustainable development.

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