Three-Dimensional Grid Visualization for Planning Activities: A Dubai Case Study

Nicholas Brunhart-Lupo,[1] Tengis Dashmunkh,[1] Shibani Ghosh,[1] Kenny Gruchalla,[1] Gayathri Krishnamoorthy,[1] Sajan K Sadanandan,[2] and Tareg Ghaoud[2]

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List of Acronyms

ANSI	American National Standards Institute
BESS	battery energy storage system
DERs	distributed energy resources
DEWA	Dubai Electricity and Water Authority
HMD	head-mounted display
NLR	National Laboratory of the Rockies
PV	photovoltaic

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Executive Summary

The National Laboratory of the Rockies (NLR), in collaboration with the Dubai Electricity and Water Authority (DEWA) and Infra-X, undertook a project to advance energy visualization and analysis. The aim of this project is to enhance analytical and three-dimensional visualization capabilities for distribution network planning and renewable energy integration processes. As the modern grid continues to evolve with large-scale solar photovoltaic deployment and emerging distributed energy resources, the ability to effectively analyze, visualize, and communicate complex grid behaviors has become increasingly critical.

This project focuses on developing empirical use cases based on real distribution feeder data and engineering workflows, ensuring the outcomes are directly aligned with operational environment. Through time-series power flow simulations and nodal hosting capacity analysis, the study quantifies the impacts of high PV penetration on voltage and thermal limits within DEWA's representative 11-kV feeders. These analyses identify specific nodes and conditions in which challenges with distributed energy resources integration arise.

Furthermore, a battery energy storage system (BESS) optimization algorithm was applied to determine the optimal size and placement of storage systems that can mitigate network constraints and enhance hosting capacity. The comparative results between base-case and BESS-augmented scenarios clearly demonstrate improvements in network stability and load management efficiency. In parallel, the NLR team developed an immersive three-dimensional visualization framework, enabling interactive exploration of grid simulations using commodity head-mounted display systems. This framework transforms conventional two-dimensional simulation data into spatially intuitive visual environments—allowing engineers to analyze feeder conditions, photovoltaic hosting potential, and BESS effects in real time.

This report represents the first foundational phase in establishing a visualization-driven analytical ecosystem. It provides a methodological foundation for data integration, visualization architecture, and simulation-based decision support, paving the way for large-scale adoption of immersive visualization across DEWA's Smart Grid Initiative, R&D activities, and future network resilience studies.

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Table of Contents

Executive Summary v
1 Introduction 1
2 Visualization Background 3
3 Research Approach 4
4 Feeder Model Development 6
4.1 Overview of Selected Distribution Feeders 6
4.2 DEWA Model Calibration 8
5 Grid Impact Analysis Using Traditional Power Grid Analysis Tools 10
5.1 Nodal Hosting Capacity Analysis 10
5.2 DER Modeling and Integration 11
5.3 Grid Impact Analysis with Energy Storage 12
5.4 A Use Case 14
6 Advancing Grid Impact Analysis With 3D Visualization 18
6.1 Role of 3D Visualization in Modern Grid Studies 19
6.2 Key Features and Capabilities of the NLR 3D Visualization Model 20
6.3 System Architecture 21
6.4 Visualization Design and Features 22
7 Conclusion and Future Works 23
References 24

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List of Figures

Figure 1. Overall research approach schematic 4
Figure 2. Total network diagram. 6
Figure 3. Single line diagram of the compressed model 7
Figure 4. Voltage profile of the compressed model 9
Figure 5. Real and reactive power measurements at the main feeder for the time-series analysis 9
Figure 6. Thematic graphic of risk level versus increasing PV hosting capacity 10
Figure 7. Voltage profile of the feeder under high PV (189%) penetration without mitgation, showing overvoltage conditions in the absence of additional BESS. 16
Figure 8. Voltage profile of the feeder under high PV (189%) penetration with mitigation using optimaly placed BESS, demonstrating improved voltage regulation. 16
Figure 9. Example 3D representation of DEWA's network: (a) front view; (b) top view 18
Figure 10. 3D visualization of 189% penetration use case with no additional BESS. Compare to the traditional voltage profile visualization of the same data in Figure 8. 20
Figure 11. 3D visualization of 189% penetration use case with additional BESS. Compare to the traditional voltage profile visualization of the same data in Figure 9. 21

List of Tables

Table 1. Nodal Hosting Capacity Statistics 11
Table 2. DER Specs for the Selected Use Case 14

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1 Introduction

In a data-rich engineering environment, critical decision-making for stakeholders (e.g., electric utilities) depends on appropriately managing, analyzing, and visualizing large and complex datasets. One prime example of such large and complex datasets comes from power delivery infrastructure and its planning and operation. Introduction of distributed resources such as solar photovoltaics (PV), battery energy storage systems (BESS), and other distributed energy resources (DERs) are making these datasets even more complex and intricate to manage. The large-scale three-dimensional (3D) immersive visualization capabilities can assist engineers, planners, and researchers with richer representation of data, showcasing depth and additional dimensions that traditional two-dimensional (2D) visuals cannot (Gruchalla and Brunhart-Lupo 2019). Challenges also lie with futuristic scenario analysis, which is a projection of how the grid operation could evolve if particular decisions are made and certain assumptions about grid assets are valid (Molnar et al. 2024). The work performed in this collaborative effort was designed to observe how immersive visualization with commodity hardware can be a useful tool to enhance power systems analysis workflows. On multiple occasions, power systems researchers and engineers have discovered features in their data using the National Laboratory of the Rockies' (NLR's) large-scale immersive visualization that they had not seen in prior investigations on traditional display options (Brunhart-Lupo, N. et al. 2020). However, the applicability of various visualization modalities is dependent on the datasets and the specific analyses of those data. This study reports findings from a collaborative project between Dubai Electricity and Water Authority (DEWA) and NLR that can provide data-backed insights into strategic decision-making for utilities by:

1. Pushing new research boundaries in power systems engineering for integrating renewable energy and other technologies in the high- and/or low-voltage system,
2. Designing detailed use cases that showcase value of data visualization for power utilities, and,
3. Identifying efficient data transfer, architecture, and fundamental requirements for what qualifies as minimal data visualization capabilities.

The primary objectives of this collaborative research project between DEWA and NLR are to:

1. *Advance power system visualization* by developing and demonstrating immersive 3D visualization tools tailored for DEWA's distribution network, enabling richer interpretation of complex grid datasets beyond traditional 2D displays
2. *Support DER integration studies* by performing hosting capacity analysis and time series power flow simulations for selected DEWA feeders to assess the impacts of high PV and battery energy storage (BESS) penetration. Hosting capacity refers to a process used by utilities, regulators and developers to determine the available grid capacity for new DERs without requiring expensive and time-consuming studies or grid upgrades (Nagarajan and Zakai 2022).
3. *Improve decision-making workflows* by providing DEWA engineers and planners with data-backed insights into optimal DER siting, sizing, and control strategies, supported by interactive visualization.

This research project's end result is an advancement of data visualization technology for the global utility industry. Future scenarios that include advanced techniques for grid modernization under the grid planning, operations, and resilience paradigm need detailed analyses with interactive visualization capabilities. This report elaborates on the research contributions around two thrust areas:

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1. Scalable planning activities on distributed resource siting, sizing, and controls and their impacts on grid operations, and,
2. 3D visualization application tailored to a commodity head-mounted display (HMD) that considers data-driven planning paradigms and can be applicable across other service areas in DEWA territory and even other electric utilities.

The rest of the report is organized to provide a comprehensive picture surrounding these two thrust areas.

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2 Visualization Background

Visualizing power flow involves a specialized form of multivariate network visualization, where both the connectivity of a system and the diverse set of attributes tied to its nodes and links must be represented concurrently. This is a particularly complex area of visualization research, as it demands a unified depiction of both the network structure and multiple variables (Nobre et al. 2019). In power grid applications, the spatial configuration—or more generally, the graph topology—dominates the visual space. As a result, encodings for other critical variables (such as voltage, frequency, phase angle, and power) are constrained to secondary visual channels such as color, line thickness or texture, and glyph-based symbols. This constraint poses challenges in discerning how variables such as voltage and power relate across the network topology, comparing phase differences, or detecting localized phenomena within subnetworks. One common solution in the visualization community is the use of multiple coordinated views (Roberts 2007), a technique that integrates multiple synchronized visual interfaces to support the exploration of complex datasets. This approach has been applied effectively to the analysis of power system data (Arunkumar et al. 2023; Gruchalla, Novachech, and Bloom 2016), enabling more granular and flexible interpretations of multivariate patterns. In recent literature, Goodwin et al. (2016) applied multivariate techniques to study energy geodemographics.

Though less frequently seen, 3D techniques have also been proposed for representing power system information. These typically expand on 2D schematics by incorporating 3D elements—such as extruded bar charts to represent attribute magnitude (Overbye and Weber 2000; Wiegmann et al. 2006), 3D component models (Xu et al. 2006), or volumetric and surface-based displays (Milano 2009; Sanchez-Hidalgo and Cano 2018). Virtual reality has emerged as another tool set, particularly in the contexts of power system training (Breen and Scott 1995; Tanaka et al. 2017) and operational control (Cardoso et al. 2013). These virtual reality environments simulate digital twins of electrical infrastructure, allowing users to interact with virtual systems in a lifelike yet safe environment. In contrast to these earlier efforts, our current work is intentionally designed to enable immersive analytic interaction with multivariate power flow data, merging spatial context with variable-rich visual feedback to enhance user insight and decision-making.

This project builds upon a substantial body of immersive analytics research and development conducted at NLR, where previous efforts have explored and demonstrated the value of immersive environments for interpreting complex, multivariate energy data. Earlier work laid the groundwork for visualizing distribution-level power flow through a custom immersive application designed to reveal interactions across multiple variables (Palmintier et al. 2016; Gruchalla and Brunhart-Lupo 2019; Gruchalla et al. 2025). That foundation was further extended to city-scale analyses, where immersive tools enabled exploration of building energy simulations and their aggregate load impacts across urban environments (Macumber et al. 2016). At a national scale, prior research developed a collaborative immersive platform for comparing multivariate energy characteristics across U.S. cities (Brunhart-Lupo et al. 2020). Other prior research efforts involved immersive analytics efforts supporting the collaborative visualization of campus microgrid operations (Gould et al. 2021) and scenario analysis for electrical load planning using ensemble techniques (Bush et al. 2017; Bugbee et al. 2019).

This project extends this work to relatively low-cost extended-reality HMDs.

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3 Research Approach

This section describes the overall approach the project team developed and sheds light on the key components (as seen in Figure 1).

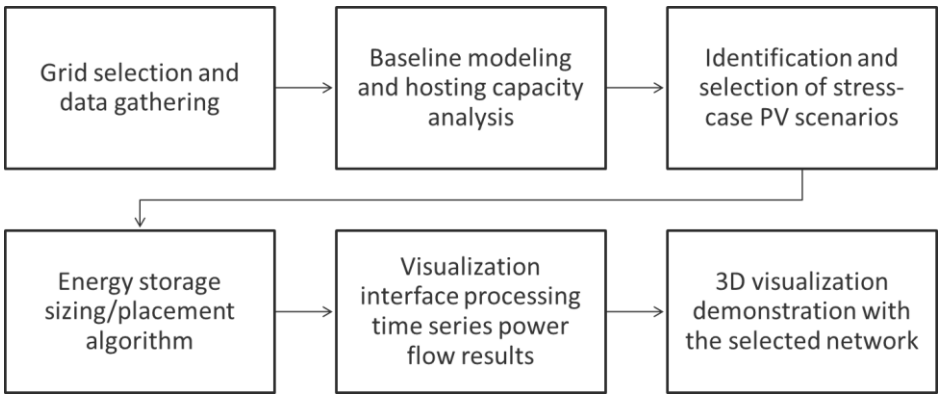

Figure 1. Overall research approach schematic

The first step to this approach is to select the appropriate regions or feeders where PV adoption is likely to be high in the near or distant future. Once a set of feeders are identified, the baseline model formulation, validation, and hosting capacity analyses are implemented. Hosting capacity analyses reveal appropriate locations in the selected feeder where more PVs can be safely integrated compared to other locations.

Based on these results, a few PV scenarios were developed that would further stress the grid and call for either upgrades or non-wire alternatives, such as energy storage, to ameliorate the impacts. This process allows the project team to assess the grid impact of PVs for the selected feeder(s) and identify any voltage and/or thermal violations. The extent of these violations guides the energy storage sizing/placement algorithm, allowing for mitigation of PV-induced grid impacts. These PV/BESS scenarios are then modeled with time-series power flow runs. The 3D visualization engine takes these power flow results and creates a demo of the feeder layout with layers of grid results that enables a technical audience to understand possible implications of PV and BESS integration scenarios. Details of these steps, as illustrated in Figure 1, are provided in following sections centered around two main thrust areas:

- Scalable grid planning analysis
    - Develop baseline feeder models in OpenDSS.
    - Conduct nodal hosting capacity analysis for PV penetration.
    - Generate DER scenarios (PV + BESS) and evaluate grid impacts (voltage and thermal violations).
    - Apply mitigation strategies such as optimized BESS placement and sizing.
- Immersive visualization development
    - Design and implement interactive 3D visualization of simulation results using commodity HMDs (e.g., commercially available virtual reality headsets).

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- Create multivariate representations (e.g., voltage, real and reactive power, line loading, DER outputs) in a spatially intuitive manner.
- Enable collaborative and accessible visualization through modular and extensible system architecture.

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4 Feeder Model Development

The project team selected four subnetworks to focus on and represented the rest of the subnetworks as composite loads provided by the DEWA team. The selected subnetworks are divided into multiple sections according to their switch placements and configurations. Each of the parallel lines connecting the buses is assumed to be transposed for phase balancing. Load shapes were attached to the distribution loads by engineering judgment to correlate the bus loadings we received to the load size. The four 11-kV load profiles were assigned across subnetworks using informed assumptions to maintain consistency with overall feeder loading characteristics. The load profiles of PV systems and battery were labeled clearly; hence, they were attached with no ambiguity. The power distribution feeders for futuristic analysis in DEWA's service territory given the OpenDSS model of the network is shown in Figure 2.

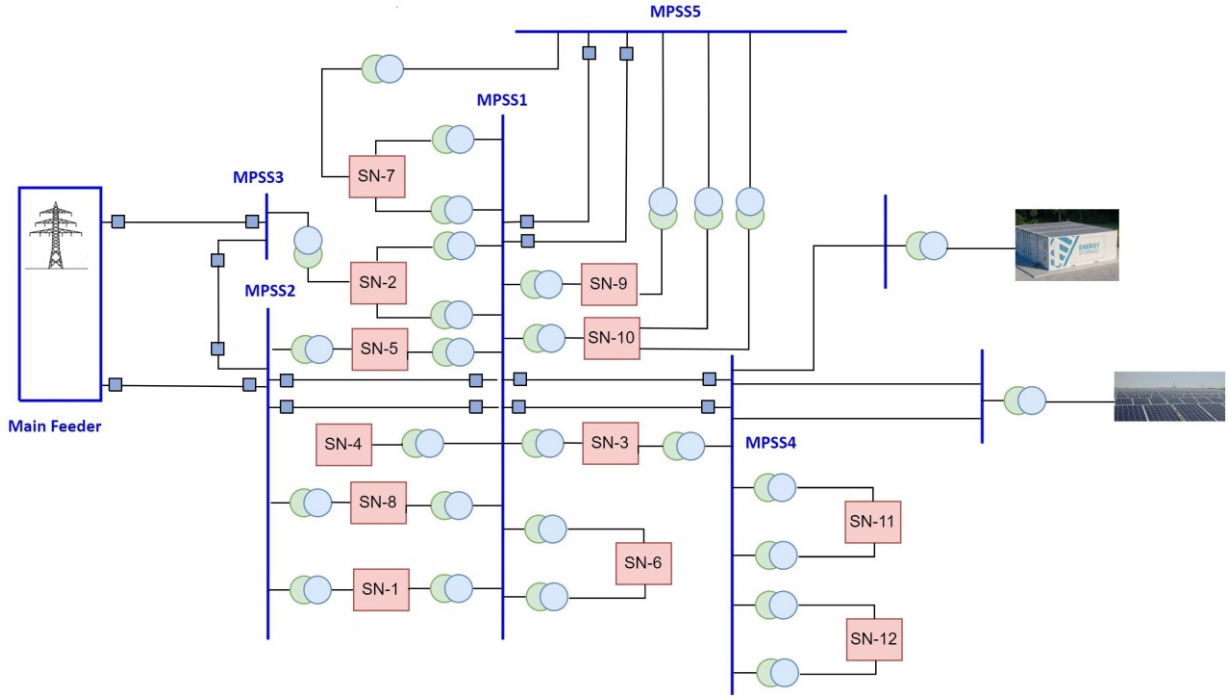

Figure 2. Total network diagram: ***Blue vertical bars denote 33 kV and 11 kV busbars; black lines represent feeders; blue squares indicate switching elements; light blue circles denote buses; green circles represent load points; SN-# labels indicate aggregated subnetworks; MPSS# labels denote substation sections; icons represent BESS and PV systems. The system operates at 33 kV (upstream) and 11 kV (downstream).***

4.1 Overview of Selected Distribution Feeders

The development of the distribution feeder model for power flow analyses involves creating a detailed simulation of the power distribution network as shown in Figure 3. This schematic includes key components such as a 132/33-kV transformer, connecting to four feeders (e.g., subnetwork-1, subnetwork-3, subnetwork-5, and subnetwork-10). The model also incorporates distributed generation sources, including a 2.4-MW battery energy storage system and a 13-MW

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solar plant. The distribution feeders operate at 11 kV and are supplied through 33/11-kV transformers, while DER assets are connected at the 33-kV level via dedicated transformers. The PV and BESS systems, specifically, are modeled as low-voltage resources (0.26 kV) interconnected to the 33-kV network through step-up transformers.

The model was developed based on the comprehensive Open-Source Distribution System Simulator (OpenDSS) files as inputs and then abstracting subnetworks that were not the focus of the simulation as distribution loads (Dugan R. 2020). OpenDSS is a comprehensive electrical system simulation tool for electric utility distribution systems developed by EPRI in 1997. This tool has found numerous applications for distribution planning and analyses for decades and is popularly used in research areas on emerging grid technologies. In this work, OpenDSS was used for its easy interface features with Python, which empowers open-source tool development.

The primary goal of this model development process is to accurately represent the physical and operational characteristics of DEWA's distribution network. This process involved collecting extensive data on the network topology, including the layout of substations, transformers, distribution lines, switches, and load points. Additionally, historical and real-time load data for each subnetwork and distribution loads are gathered at a 30-minute resolution over 1 month to understand demand patterns, and technical specifications of all equipment are obtained to ensure accurate modeling. This baseline modeling process had a few underlying assumptions:

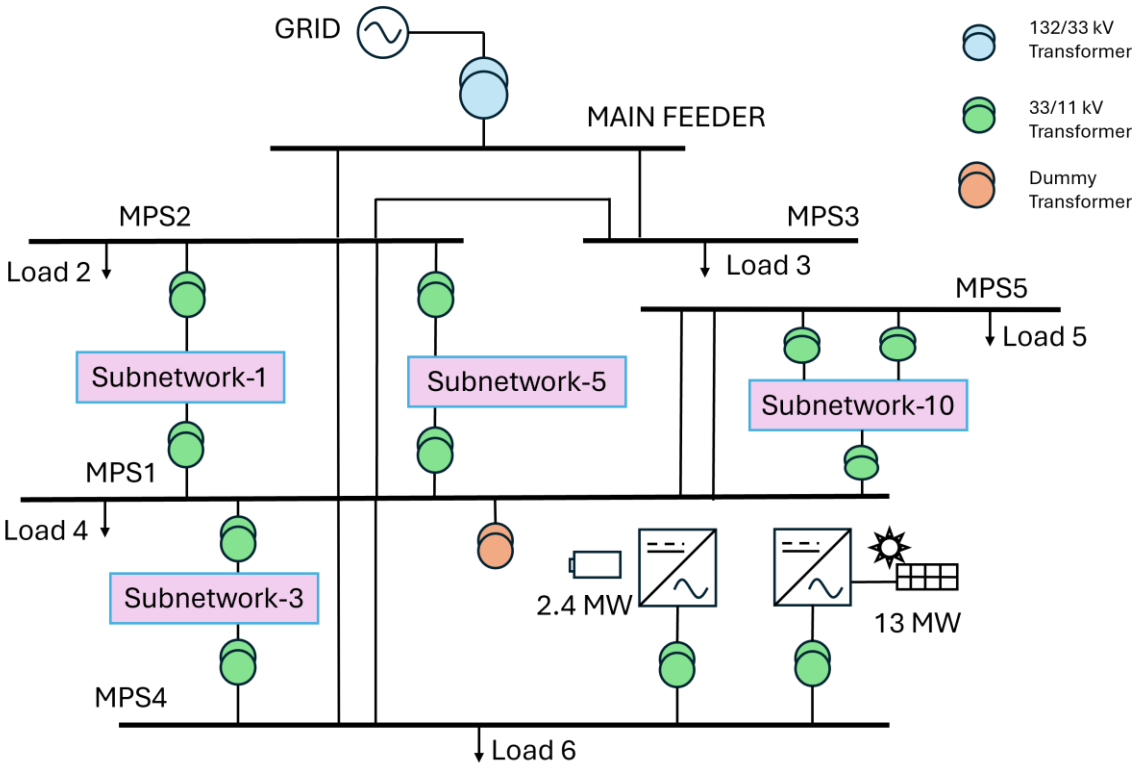

Figure 3. Single line diagram of the compressed model

- Each of the parallel distribution lines connecting the buses are transposed for phase balancing.
- The switches on the parallel distribution lines are normally closed.

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- PVs and BESSs have their respective load shapes.
- Subnetworks are assigned representative load shapes across the network, while load magnitudes are maintained based on system-level loading characteristics.
- Load profiles were attached with each distribution load based on the bus loading data provided by DEWA and engineering judgment.
- The base power of MPS4 is determined by using the maximum peak loading of bus-6 to account for the effects of PVs and battery.
- In the baseline model, the constant voltage sources were kept for the original PV system models.
- Each subnetwork is divided into multiple sections according to open switch configurations.

In this work, OpenDSS was used to create the digital representation of the network with all relevant parameters used as inputs. In-house tools were used in this work for a comprehensive time series power flow and hosting capacity analysis, providing insights into voltage profiles, power losses, and system performance under various operating conditions. This developed model and accompanying analysis enabled development of various DER and load growth scenarios and performance of grid impact studies to plan for future DER expansions and demand growth.

4.2 DEWA Model Calibration

We encountered several challenges in successfully modeling the base case. The initial OpenDSS model lacked switch configurations, resulting in loops through the sub-transmission networks and parallel lines. Even after including the missing switch configurations, the loops created by parallel lines persisted. To address this, the Newton-Raphson power flow solver in OpenDSS was used instead of the default backward/forward sweep method. Figure 4 presents the voltage profile at the primary MV level) for the final time interval of the month (based on 30-minute resolution data) for the baseline DEWA model shown in Figure 3.

For the time-series power flow analysis, time-series profile data were required for distribution loads as well as PV systems. However, the sample load dataset did not correspond to the modeled loads. To resolve this discrepancy, we per-unitized the data by using the median plus one standard deviation value as the base value and randomly assigning the resulting per-unit load shapes. (Figure 4 shows the voltage profile across the circuit and Figure 5 shows the power profiles from base case time-series for 30 days at 30 minutes' resolution). For the PV systems, we treated the two provided profiles as representative and per-unitized them using the nominal rating of each PV system as the base value. This approach led to a misalignment between the battery profile and solar power generation profiles when modeling battery operation, introducing an offset in which the battery continued discharging to the grid while the PV systems were generating power and charged when the PV systems were offline. To rectify this, we removed the offset to synchronize the battery charging cycle with solar power production. Additionally, PV systems were modeled using inverter-based representations with Volt-Var and Volt-Watt control strategies to capture their impact on voltage regulation and power flow under varying operating conditions.

During model calibration, the network was validated and refined to ensure stable and consistent performance under time-series power flow simulations, including checks on phase balance, network connectivity, and numerical convergence.

Last, the model was reviewed and refined to ensure consistency in network topology, connectivity, and alignment of generation and load representations, supporting stable and reliable simulation results.

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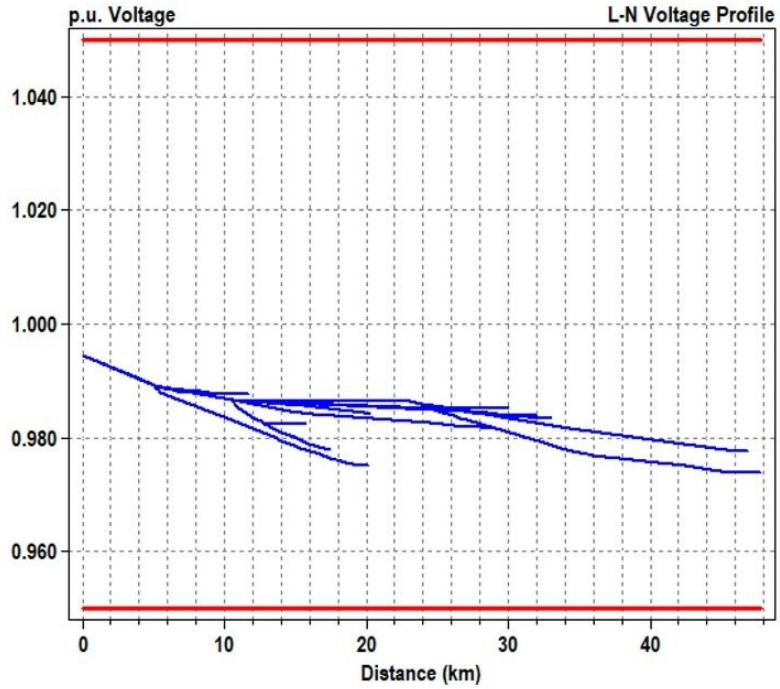

Figure 4. Voltage profile of the compressed model

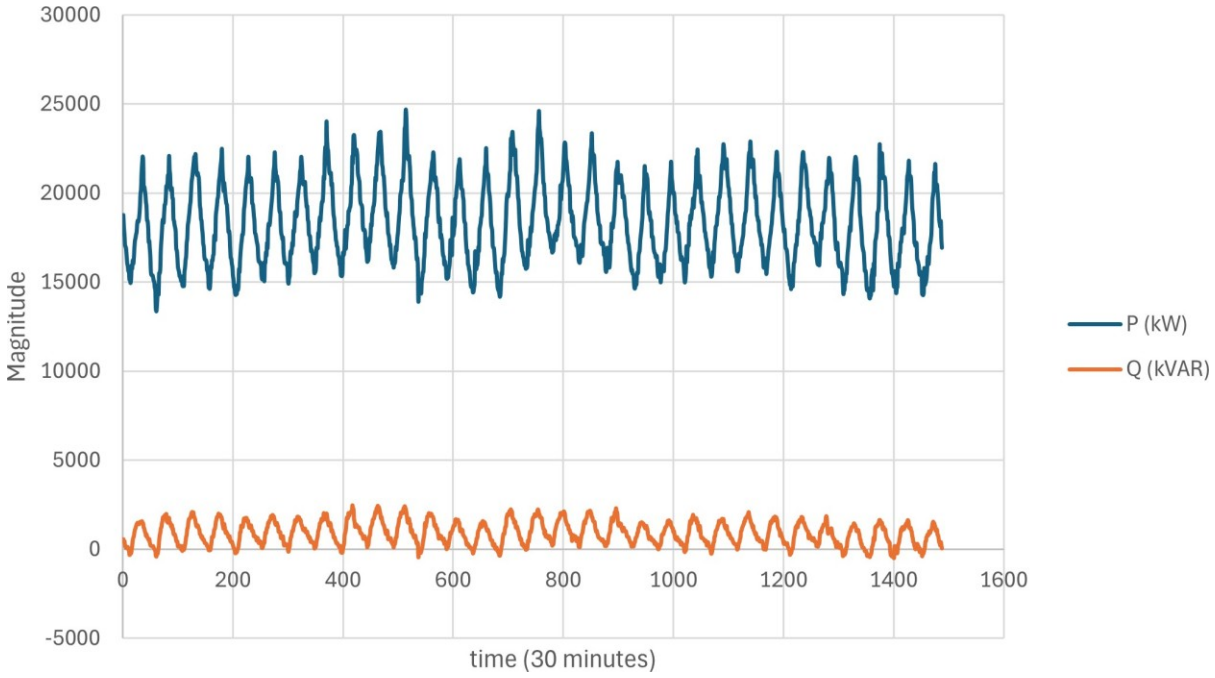

Figure 5. Real and reactive power measurements at the main feeder for the time-series analysis

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5 Grid Impact Analysis Using Traditional Power Grid Analysis Tools

The impact of DER integration on DEWA's OpenDSS model was analyzed using open-source tools developed by NLR, such as EMeRGE and DISCO.

The EMeRGE (Emerging technologies Management and Risk evaluation on distribution Grids Evolution) tool is designed to simplify analysis of complex emerging technologies to enhance distribution network visibility. The power quality risk metrics based on critical timestamps are considered under EMeRGE, which can help utilities make decisions about solar PV integration planning for distribution networks. This work leverages risk-informed hosting capacity outputs from EMeRGE and computes the sizing ranges for PV deployment scenarios. Originally developed to define grid-risks by assessing the magnitude of power quality violations, the number of customers impacted, and the duration of violations; EMeRGE originated from a custom approach to distribution network analysis for another utility to gauge their state's power sector policies and electricity sector planning (McKenna et al. 2021). In some cases PV can help reduce power quality issues, whereas in others can cause little to no change. If the system has existing undervoltages issues PVs can push up the voltage profile, and on the other hand, if a utility faces overvoltages, PVs could exacerbate the voltage profile. Depending on the baseline, there can exist a specific level of PV capacity at which the overall risk to the utility is reduced compared to the scenario without PV, providing a net benefit (as seen in Figure 6). This capacity level represents a threshold where the risk posed by PV is equivalent to the baseline risk. Beyond this threshold, any additional PV capacity would result in a net increase in risk, which may require mitigation strategies.

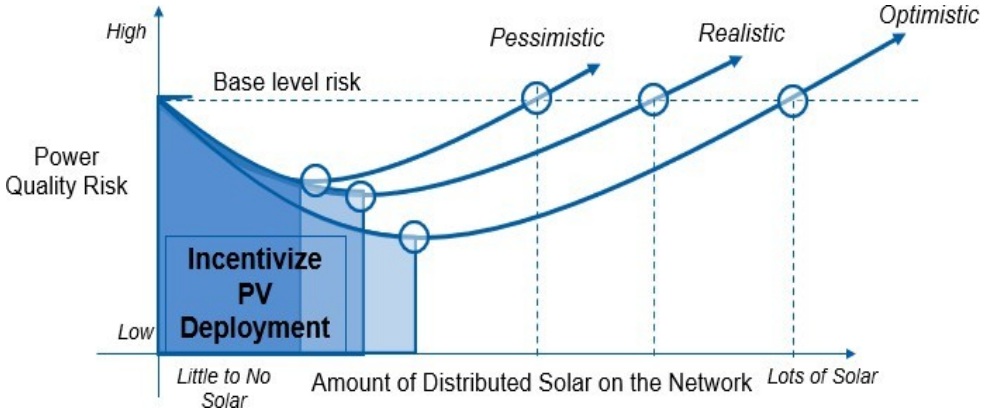

Figure 6. Thematic graphic of risk level versus increasing PV hosting capacity

5.1 Nodal Hosting Capacity Analysis

In this analysis, we focused on the subnetworks operating at 11-kV to evaluate their capacity for PV penetration. Specifically, we computed the nodal hosting capacity for the 117 subnetwork nodes within the system using EMeRGE. Nodal hosting capacity refers to the maximum amount of distributed energy resources, such as PV systems, that a specific node in the network can accommodate without violating operational constraints, such as voltage limits, thermal ratings, and protection coordination. The key statistical results of the analysis are summarized in the following table.

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Table 1. Nodal Hosting Capacity Statistics

Statistic	Value (MW)
Minimum PV hosting capacity for the network	8.09
Median PV hosting capacity for the network	8.74
Maximum PV hosting capacity for the network	9.59

The hosting capacity values across the 117 nodes are relatively consistent, with a narrow spread between the minimum (8.09 MW) and maximum (9.59 MW). This indicates that the system exhibits uniform hosting potential across most sub-networks, suggesting a fairly balanced network design without major localized bottlenecks. The median value of 8.74 MW being closer to the maximum than the minimum implies that most nodes can accommodate PV levels above 8.5 MW, with only a few outliers limiting the lower bound. These lower-capacity nodes (around 8.1 MW) are likely influenced by local constraints such as thermal limits on feeders, voltage rise sensitivity, or downstream load imbalances.

The relatively high maximum hosting capacity (9.59 MW) highlights that certain nodes can accommodate nearly 18% more PV than the most constrained nodes, offering opportunities for targeted PV siting at these locations.

However, the small overall range (nearly 1.5 MW across all nodes) suggests that system-wide upgrades (e.g., voltage regulation, protection coordination) would be required to significantly increase hosting capacity beyond this band, rather than localized reinforcement alone.

In summary, the results show a system with generally strong and uniform PV hosting capability, where incremental improvements to address a few constraint-driven nodes could raise the minimum and make capacity more equitable across the network. In the following sections, we describe how we use this input to design several test cases.

5.2 DER Modeling and Integration

We utilized another in-house tool, DISCO, to generate PV deployment scenarios targeting the 11-kV sub-network nodes (Abraham and Ghosh 2024). The maximum power capacity of each PV system was constrained to 8 MW, as this value closely aligns with the minimum nodal hosting capacity determined in the previous step.

DISCO strategically places PV systems at varying distances from the substation—categorized as close, far, and random—and generates 10 random samples, each containing PV penetration scenarios ranging from 5% to 200% in 5% increments. The additional PV systems were modeled under different inverter control modes, including volt-var control and unity power factor operation. The existing model already includes two PV systems, resulting in an initial penetration level of 29%. Consequently, DISCO generated a total of 1,020 PV deployment scenarios.

Following the scenario generation, we employed DISCO to perform time-series simulations for each of the 1,020 cases. From these simulations, we extracted key summary metrics, including voltage and thermal violations, out of the different modes to systematically rank the deployment scenarios.

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Simulation outputs were post-processed to ensure consistent and accurate representation of net power injections at each node for subsequent analysis and visualization.

We identified this by comparing PV monitor values with their supposed host bus values and observing near-perfect cancellation, leaving only small residuals at the bus. To fix this, we post-processed the monitor outputs: for each bus, we summed the negative of all attached element terminal powers and explicitly added PV/storage exports at their defined bus. This reconstruction yields the correct net bus injection (generation – load ± line flows), ensuring the time-series results now accurately reflect power at each node.

5.3 Grid Impact Analysis with Energy Storage

We selected the 10 cases exhibiting the most severe voltage violations and an additional 10 cases with the highest thermal violations for mitigation. It is important to note that the cases with the worst voltage violations also exhibited line loading violations.

For each identified case, a BESS was sized accordingly to mitigate the violations. The real power capacity of the battery was determined to alleviate excessive currents, while the reactive power capacity was selected to correct voltage deviations at the affected node. The battery was designed to operate for a duration of 6 hours, consistent with the discharge period of the existing battery in the system. To maximize its effectiveness, the battery was placed at the most overloaded bus within the network. The algorithm for BESS optimization is presented here.

5.3.1 Algorithm for BESS Placement and Sizing Optimization

With increased PV penetration, the grid is expected to face voltage and/or thermal violations. There are some non-wires alternatives such as energy storage placement that can help reduce the extent of these violations. A BESS sizing algorithm was used to address these violations. The goal of this algorithm is to determine the optimal placement and sizing (in terms of kW and kWh) of BESS on an electric distribution network to mitigate (1) thermal violations—where line loadings exceed rated capacity and (2) voltage violations—where node voltages fall outside acceptable limits. (For the remainder of this report, we assume American National Standards Institute [ANSI]) range as an example of acceptable brackets, which is defined between 0.95 and 1.05 p.u.) The algorithm seeks to identify locations and capacities of BESS units that can address these issues while minimizing system cost or resource use.

The algorithm requires the following **inputs**:

- Simulation results identifying thermal and voltage violations,
- Rated line capacities and nodal voltage values,
- Feeder topology, including bus and line configurations,
- System and line impedance data,
- Desired BESS operational duration (e.g., number of hours needed for peak support), and
- BESS cost/priority weights, if cost optimization is included.

The process flow to find an optimally sized BESS consists of four steps:

1. *Identification of critical scenarios*

   Analyze simulation outputs to identify critical scenarios that trigger either thermal or voltage violations:

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- Thermal violation: If line loading exceeds 100% of its thermal rating.
- Voltage violation: If node voltage exceeds 1.05 p.u. or falls below 0.95 p.u..

Each violation scenario is flagged and documented with scenario metadata (e.g., scenario ID, loading percentage, maximum/minimum voltage observed).

2. *Candidate node selection*

   For each identified violation:

   - Select nodes in proximity to overloaded lines (for thermal violations).
   - Select nodes exhibiting the most extreme voltage deviations (for voltage violations).

   These nodes are considered candidate locations for BESS placement, under the assumption that strategic local injections of power or reactive support can mitigate violations.

3. *Power capacity estimation*

   Estimate the minimum power capacity (in kW) of a BESS required to address the violation:

   - For thermal violations: The battery should reduce the line current to keep the loading below the thermal limit (e.g., 100% of line rating).
   - For voltage violations: The battery should inject or absorb reactive power to bring voltages within the prescribed limits.

4. Energy capacity *estimation*

   Calculate the total duration for which the battery will operate (e.g., hours of peak loading or voltage support).

The following formulas were used to calculate the kilowatts (kW, power capacity) and kilowatt-hours (kWh, energy capacity) of a battery for mitigating thermal or voltage violations:

- **Thermal violation**: The battery should reduce the line current to keep the loading below the thermal limit (e.g., 100% of line rating).

  $$\text{Power (kW)} = \text{Reduction in current} \times \text{line voltage} \times \sqrt{3} \text{ for a three-phase system}$$

- **Voltage violation**: The battery should inject or absorb reactive power (kVAR) to bring voltages within the limits.

  $$\text{Reactive power (kVAR)} = \text{Voltage deviation} \times \text{system impedance (approximation)}$$

- **Energy requirement**: Calculate the total duration for which the battery will operate (e.g., hours of peak loading or voltage support).

  $$\text{Energy (kWh)} = \text{Power (kW)} \times \text{required duration (hours)}$$

This algorithm was implemented to calculate the BESS sizing that is showcased in the use case in the following section.

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5.4 A Use Case

The selected use case is based on a detailed OpenDSS representation of a DEWA 11-kV distribution feeder supplied through a 132/33kV substation and composed of multiple interconnected subnetworks. The feeder includes both mid- and far-end sections with long radial branches, making it sensitive to reverse power flow and voltage rise under high distributed generation scenarios. Following baseline model calibration and nodal hosting capacity analysis, photovoltaic (PV) systems were incrementally added using the DISCO framework. PV deployments were capped at individual node capacities consistent with hosting capacity results and placed at varying electrical distances from the substation. As PV penetration increased beyond the baseline level of approximately 29%, voltage and thermal conditions remained largely within acceptable limits until penetration levels exceeded approximately 150%. At higher penetrations, particularly in random siting scenarios, widespread overvoltage conditions and line loading violations emerged, driven by concentrated PV installations on electrically weak downstream branches.

The violation case illustrates the interaction between high penetrations of distributed PV and the feeder's hosting capacity, and how targeted storage deployment can mitigate the resulting stress. The PV units are distributed across the mid- and far-end sections of the feeder, while the BESS is sited close to the area of concentrated PV generation.

The use case highlighted here represents one of the most severe violation scenarios identified, with total PV penetration reaching approximately 189%. In this scenario, multiple feeder extremities exceeded the ANSI upper voltage limit of 1.05 p.u., and reverse power flow resulted in elevated current levels along critical feeder segments. To mitigate these impacts, a battery energy storage system (BESS) was strategically placed at the most overloaded bus identified through the violation screening process. The BESS was designed to provide both real and reactive power support over a six-hour duration, enabling it to absorb excess PV generation during peak export periods while simultaneously providing voltage regulation. When enabled, the BESS significantly flattened the voltage profile, reduced upstream power flows, and alleviated thermal stress on heavily loaded lines, as demonstrated in the after-mitigation results. This use case illustrates how targeted, data-driven storage placement can enable substantially higher PV penetration levels while maintaining compliance with operational voltage and thermal constraints.

Specific sizing of these added DERs (besides existing ones) are given in Table 2. The BESS is sized to reduce the impacts of these distributed PV systems and has a capacity of 378.5 MVARh. All these DERs are connected to 11-kV ties and are three-phase balanced units. Table 2 does not include existing PV and BESS units.

Table 2. DER Specs for the Selected Use Case

Bus	Rated Power (MW)
ss73 (PV)	**8**
ss226 (PV)	**8**
ss51 (PV)	**8**
ss25 (PV)	**8**
ss4 (PV)	**8**

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Bus	Rated Power (MW)
ss75 (PV)	**8**
ss14 (PV)	**8**
ss57 (PV)	**7.93**
ss50 (PV)	**6.6**
ss67 (PV)	**3.2**
ss50 (BESS)	**63.1**

The “before” case, shown in Figure 7 represents the feeder under high PV export without mitigation. At this operating point, the voltage profile exhibits clear violations of the upper voltage limit of 1.05 p.u. Several buses at the feeder extremities rise above the limit, with the steepest increases coinciding with branches that host multiple PV systems. This condition indicates that random siting of PV at high penetration levels can cause widespread overvoltage events, and the magnitude of reverse power flow is evident from the thickened lines on the network map.

The “after” case, presented in Figure 8, demonstrates the effect of enabling the BESS to charge during this same time step. The voltage profile is substantially flattened across the feeder, and most buses are brought back within the acceptable 0.95–1.05 p.u. range. Some of the most severe overvoltage peaks are eliminated by targeted BESS placement, and the upstream line flows are reduced as the storage system absorbs local PV generation instead of allowing it to back-feed toward the substation. This action not only restores compliance with voltage standards but also reduces thermal stress on critical line segments. It is important to note that, in the mitigated case, the overall voltage profile appears to shift slightly downward relative to the unmitigated scenario. This expected behavior takes place here in this use case as the BESS absorbs real and reactive power during periods of high PV export, reducing reverse power flow and lowering voltage not only at the most critical overvoltage nodes but also across sections of the feeder that were previously operating close to 1.0 p.u. The resulting profile reflects a system-wide rebalancing toward nominal voltage levels rather than localized correction alone.

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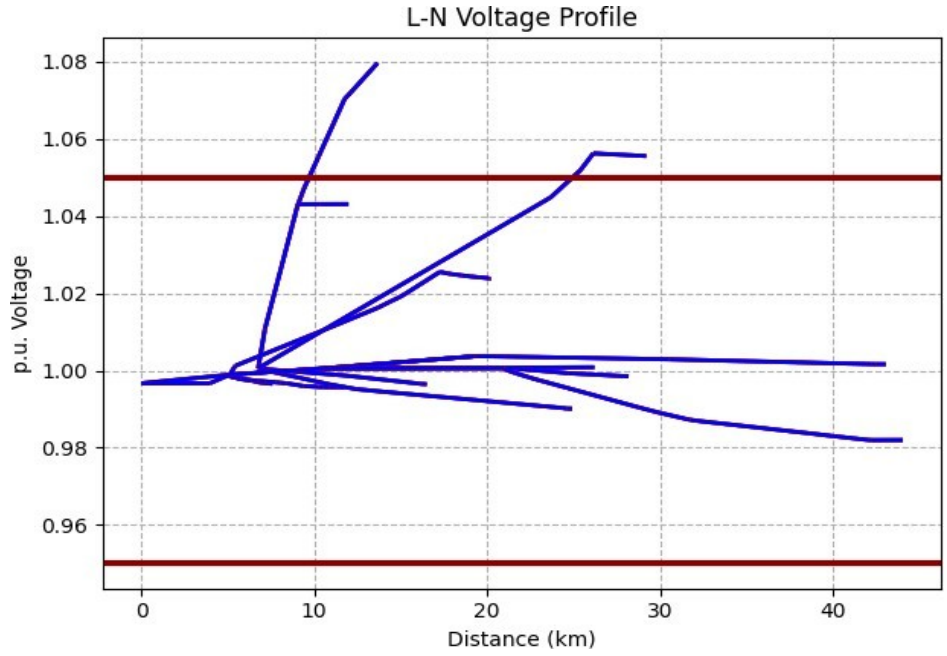

Figure 7. Voltage profile of the feeder under high PV (189%) penetration without mitgation, showing overvoltage conditions in the absence of additional BESS.

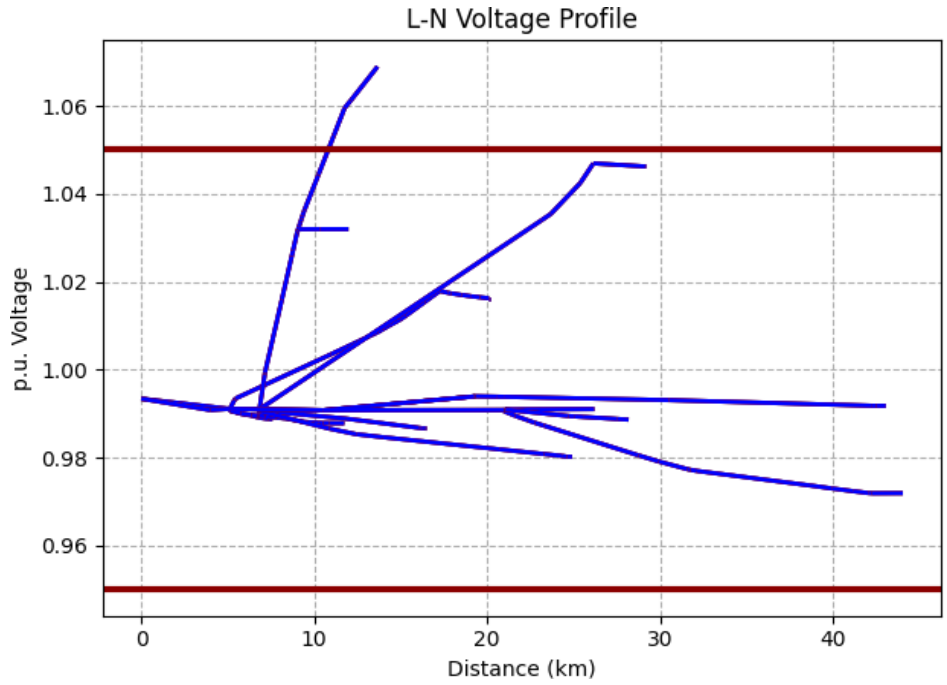

Figure 8. Voltage profile of the feeder under high PV (189%) penetration with mitigation using optimaly placed BESS, demonstrating improved voltage regulation.

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Taken together, these results highlight the effectiveness of strategically located storage in mitigating the risks of high PV penetration. By absorbing excess generation during peak export periods, the BESS alleviates both voltage and thermal violations without requiring curtailment across the entire feeder.

After the violation cases are run, node voltages and branch powers are captured in a format that is compatible with the 3D visualization pipeline. This pipeline utilizes the map/topology information as available in the 2D power system models and superimposes technical metrics to demonstrate how the feeder behavior may vary with the inclusion of these DERs.

This and similar violation scenarios (use cases) were also reconstructed in the 3D visualization environment to complement the 2D OpenDSS results, providing \gls{dewa} with an intuitive spatial understanding of where PV hosting risks emerge and how mitigation alters both voltage and thermal performance. The combination of OpenDSS power flow simulations and the visualization framework strengthen the case for targeted storage deployment to enable higher penetrations of distributed PV without compromising reliability.

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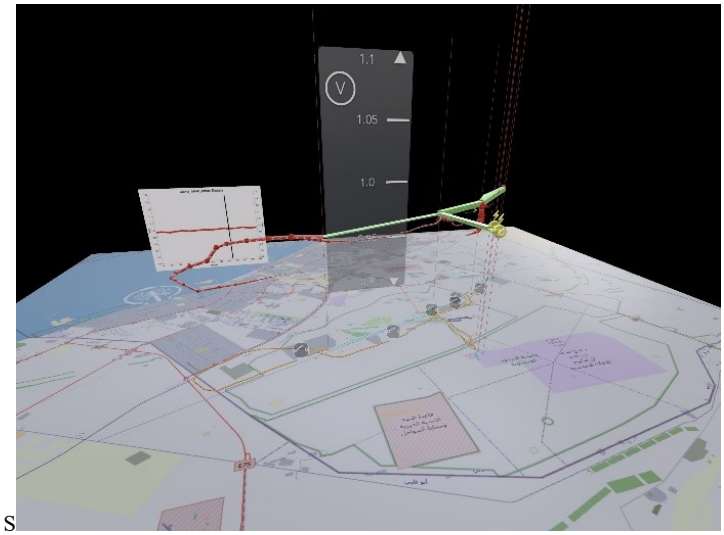
6 Advancing Grid Impact Analysis With 3D Visualization

The increasing integration of distributed PV and energy storage systems into the power grid necessitates advanced analytical tools to evaluate their impact. Traditional 2D visualizations, although effective for specific analyses, often require multiple graphs to convey the relationships among various grid parameters. To enhance planning and decision-making, we developed interactive 3D visualization tools that enable more comprehensive and intuitive analysis of energy deployment scenarios. These tools make use of a VR headset such as the Apple Vision Pro HMD, offering an economical and accessible solution for 3D grid visualization (examples shown in Figure 9).



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(a)

(b)

Figure 9. Example 3D representation of DEWA's network: (a) front view; (b) top view

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6.1 Role of 3D Visualization in Modern Grid Studies

The visualization of power system data has traditionally relied on 2D representations, such as geographic information system (GIS)-based mapping, line diagrams, and heatmaps. Although these techniques can be effective, they often present challenges in distribution system studies resulting from bus layouts' complex, geographically dense nature, and tree-like topologies. These limitations can lead to misinterpretations of system behaviors, particularly in scenarios where spatial relationships and interdependencies are crucial for decision-making (Gruchalla, Molnar, and Johnson 2023).

Recent research has demonstrated that 3D visualization techniques can offer significant perceptual benefits when dealing with complex, multivariate datasets. The added depth and spatial representation enable better differentiation of overlapping elements and facilitate a more intuitive understanding of system structures and dynamics (Gruchalla, Raghupathi, and Brunhart-Lupo 2021). This aligns with broader advancements in immersive analytics, an emerging field that integrates immersive technologies with data analytics and visualization techniques to enhance the exploration and interpretation of complex datasets.

We have successfully applied immersive analytics at NLR across multiple scientific and engineering domains. For example, we have used our large-scale immersive environment to support computational fluid dynamics analysis (Brunhart-Lupo and Gruchalla 2023), materials design, and power flow analysis (Gruchalla and Brunhart-Lupo 2019). One notable application has been the study of inverter and advanced distribution management system control strategies, particularly their effects on voltage regulation across distribution feeders (Palmintier et al. 2016). Furthermore, immersive analysis can integrate into broader analytical workflows, enhancing collaboration by linking traditional statistical interfaces, and simulation tools user interfaces with interactive 3D visualizations in immersive environments. By bridging these modalities, teams of analysts can rapidly explore high-dimensional datasets, leveraging the strengths of each platform—precision and computation from statistical tools, flexibility from general-purpose programming environments, and intuitive spatial reasoning from 3D visualization (Brunhart-Lupo et al. 2020).

Building on this foundation, our joint project with DEWA extends NLR's immersive analytics capabilities from high-end, large-scale immersive installations to state-of-the-art, commercially available HMDs. By leveraging Apple Vision Pro, we provide an economical and accessible solution for 3D grid visualization (as seen in Figure 9; this representation is realized through the Apple Vision Pro HMD). This transition democratizes access to advanced visualization tools, enabling planners, engineers, and stakeholders to engage with complex power system data in a more interactive and insightful manner.

3D visualization transforms grid impact analysis by enabling stakeholders to simultaneously assess multiple variables in a unified spatial context. Unlike traditional 2D plots, where multiple graphs are needed to depict different aspects of grid performance, a 3D representation allows users to explore multivariate relationships within a single immersive environment. By leveraging depth, spatial orientation, and interactive controls, planners and researchers can better compare deployment scenarios, identify potential siting issues for energy storage, and evaluate the grid stability (Bugbee et al. 2019). For example, consider the 189% use case presented in Section 5.4. The traditional voltage profile plots in Figure 7 and Figure 8 provide an abstracted representation of the system's voltages with little context. In contrast, Figure 10 and Figure 11 show voltage, real and reactive power (with their flow directions), and the generation sources in the geographical context.

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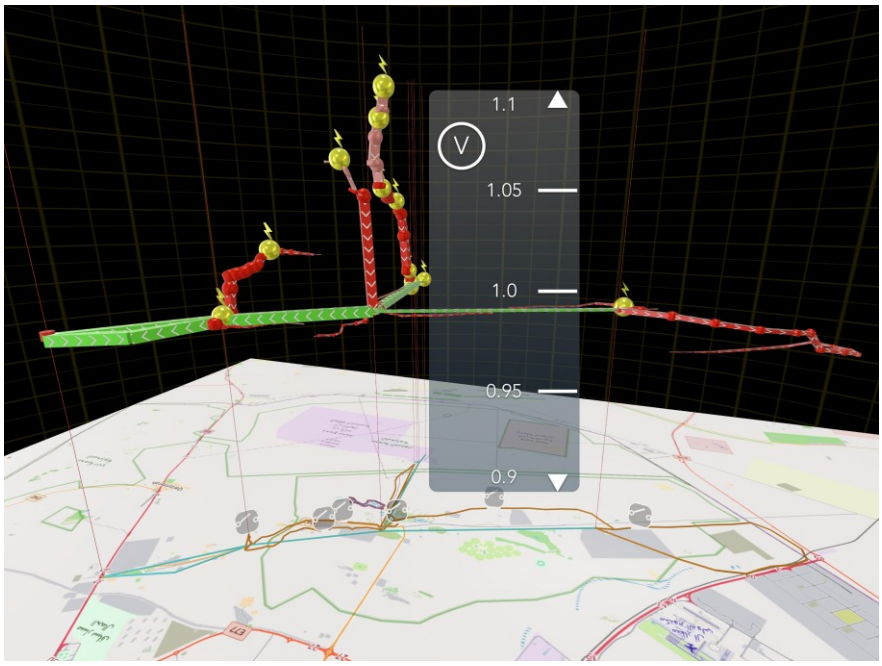

Figure 10. 3D visualization of 189% penetration use case with no additional BESS. Compare to the traditional voltage profile visualization of the same data in Figure 7.

6.2 Key Features and Capabilities of the NLR 3D Visualization Model

The NLR-developed 3D visualization model incorporates several key features that enhance grid impact analysis:

- Multivariate representation: The model enables the simultaneous visualization of multiple grid parameters, including real and reactive power flow, voltage, line loading, PV generation, and battery storage. It directly represents where the relationship between these variables is.
- Scenario comparison: Users can compare different PV and energy storage deployment scenarios side by side, identifying strengths and weaknesses in siting decisions and system performance.
- Immersive interaction: Running on the Apple Vision Pro HMD, the system allows users to interact with the grid model through natural gestures and spatial navigation, providing an intuitive and engaging analytical experience.
- Accessibility and cost-effectiveness: By utilizing commercially available hardware, the visualization tool offers an affordable and widely accessible platform for grid analysis without requiring specialized high-end computing infrastructure.

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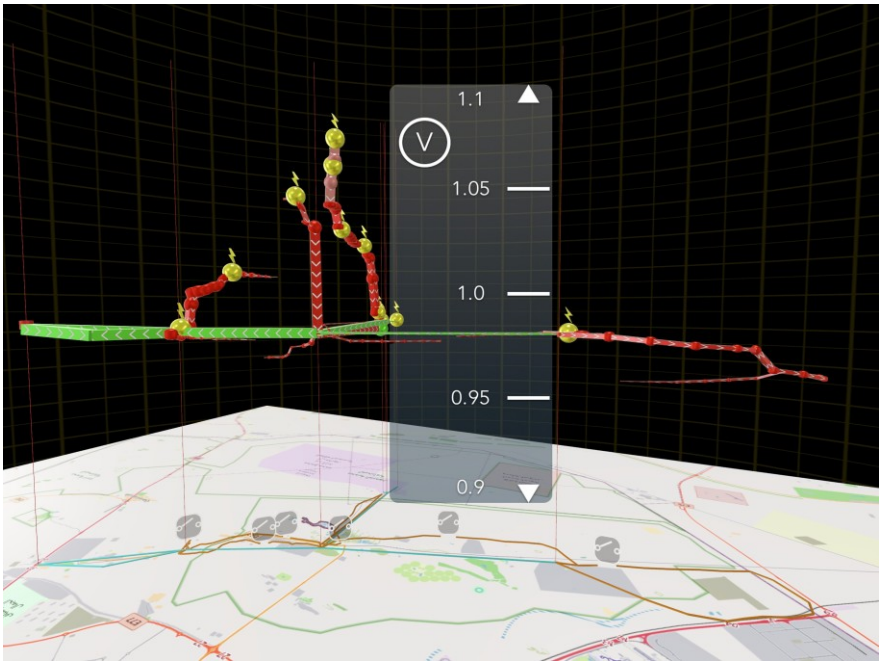

Figure 11. 3D visualization of 189% penetration use case with additional BESS. Compare to the traditional voltage profile visualization of the same data in Figure 8.

6.3 System Architecture

The underlying architecture of the 3D visualization framework is designed to be modular, extensible, and collaborative, supporting efficient data handling and real-time synchronized interactions across platforms. At the start of this system is the transformation of simulation outputs[1] into a compact and standardized format using the NLR-derived open-source PowerSystemsData specification (Brunhart-Lupo and Gruchalla 2025). This format not only ensures efficient data loading and storage but also facilitates interoperability across different analytical tools and visualization platforms.

Once the simulation data are encoded in this file format, it is ingested by the NoodlesGrid application, which serves as the central visualization engine. NoodlesGrid runs on a dedicated server and constructs a dynamic 3D representation of the grid model from the input data. This visualization is then transmitted via NOODLES, an NLR-developed protocol for synchronizing visual content across distributed environments (Brunhart-Lupo 2024). Designed for flexibility, NOODLES allows multiple clients to connect simultaneously and interact with a shared visualization space, regardless of their hardware or platform.

In this implementation, one such client is a Vision Pro application that renders the 3D grid environment in immersive mixed reality. Users equipped with Apple Vision Pro headsets can explore, manipulate, and analyze the grid by body-relative judgments, motion, and interaction. Importantly, because the visualization state is centrally managed and synchronized via NOODLES, multiple users (including

[1] Scripting has been developed for OpenDSS; however, any other simulation product output can be converted into this format.

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those on headsets, desktop applications, or web interfaces) can engage in collaborative analysis. For instance, if one user scrubs through time to view a specific moment in the simulation, all connected users see the same state update. This shared, real-time context supports deeper collective insight and facilitates team-based exploration of complex grid phenomena.

6.4 Visualization Design and Features

The visualization is designed to represent both the physical and electrical characteristics of the power grid in an intuitive spatial layout. At the base of the scene lies a flat plane displaying a world map with the geographic location of the analyzed distribution network, grounding the visualization in a recognizable and concrete local context. Overlaid on this map is a 2D schematic of the grid topology, with lines that denote the physical layout of conductors.

This 2D representation then extends into the third dimension by mapping height to line variables: proportionally to either to its p.u. voltage value or percentage line loading. The lines are colored by phase or voltage at nominal level. To support interpretation, a 3D scale is placed within the scene, offering a clear reference for height-to-value scaling. To enable the identification of voltage violations, the visualization includes horizontal ANSI voltage limit planes rendered within the 3D space. These planes represent the upper and lower acceptable bounds of voltage, as defined by standard ANSI limits. When portions of the grid, such as phase conductors, rise above or drop below these safety thresholds, the corresponding lines visually "pierce" the planes. This direct spatial violation makes it immediately apparent where and when voltage excursions occur, enhancing the user's ability to assess grid stability and power quality at a glance. This approach transforms what is traditionally a tabular or color-coded warning into a spatial, physicalized cue, aligning with the immersive nature of visualization.

Line thickness encodes power metrics: "width" corresponds to real power (watts), whereas vertical thickness—or "height" of the line in cross-section—represents reactive power (vars). Power flow direction is indicated by a chevron series that lies along the lines.

Transformer locations are marked with vertical columns, where the step level of voltage regulators is visually apparent. Generators, including PV systems and battery storage, are placed within the 3D space according to their operating voltage and scaled by their power output. Distinct graphical elements differentiate between generation sources.

In the rear of the scene, a time series performance chart offers a high-level view of the grid's behavior over time. A time indicator lets users scrub or animate through the dataset, updating the 3D visualization accordingly. Crucially, users can probe or query individual elements in the scene (such as a line or a transformer) to bring up detailed time series charts that display localized values of voltage, power, and other key metrics. This combination of spatial immersion, real-time interaction, and multivariate representation provides a rich analytical environment for modern grid studies.

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7 Conclusion and Future Works

The added spatial and perceptual dimensions offered by immersive visualization have enabled a reimagining of how complex power systems data—such as those from DEWA feeders—can be understood and analyzed. Quasi-static time-series simulations of electric power distribution networks involve numerous interdependent, time-varying variables distributed across space. Even experienced engineers face challenges in fully interpreting these interactions when constrained to conventional two-dimensional geographic visualizations. Immersive analytics is used to address this by extending traditional four-dimensional visual encodings—such as network topology with line variables mapped to color and width—into a higher-dimensional space. In this environment, voltage, real power, and reactive power can be explored simultaneously within the network topology, offering a more comprehensive and intuitive grasp of system behavior over time.

Engineers from NLR and DEWA applied this immersive tool to validate OpenDSS power flow models for DEWA's distribution feeders. The application revealed previously hidden multivariate relationships and provided utility engineers with deeper insight into the dynamics of the power flow simulations. By integrating immersive visualization into their workflow, engineers were able to detect and diagnose modeling issues in the network topology and control logic—issues that had eluded detection using standard 2D analysis techniques. The immersive environment did not replace traditional analysis but complemented it, acting as a powerful diagnostic aid that significantly enhanced model verification and situational awareness.

Some key findings from this research work are summarized below:

- The baseline model needed some modifications to resolve the loops created by parallel lines—the Newton power flow solver was employed in OpenDSS to circumvent the backward sweeping approach.
- Early on the feeder models showed errors in the modeled topology—these errors were detected in 3D models in which the project team could evaluate the size and direction of the flows. These errors were corrected by flipping the "to" and "from" grid nodes in the model.
- The 3D visualization demo revealed that the power flow directions for a few lines were off. For example, a line connected to a PV generator showed the power flow direction was toward the generator node, whereas it is expected to be flowing "out" of the generator node. After much deliberation, this was revealed to be a monitor/reporting issue with the OpenDSS model. This debugging process was another example of how 3D visualization can be helpful to figure out possible issues in planning domains, which would be otherwise harder to detect with traditional 2D graphics.

Although these applications illustrate the qualitative benefits of immersive visualization for power systems engineering, quantitative assessments of their operational and economic value remain an open research area. Future work should focus on empirical studies that measure the impact of visualization on decision-making and system performance.

This includes evaluating potential capital cost savings from earlier error detection, or improvements in reliability indices such as CML (customer minutes lost) and SAIDI (System Average Interruption Duration Index). Establishing these metrics would provide stronger evidence base for the broader adoption of advanced visualization tools in renewable energy integration and grid modernization efforts.

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References

Abraham, S., and S. Ghosh. 2024. "Distribution Integration Solution Cost Options (DISCO)." April 9, 2024. NREL/PR-6A40-89565. https://doi.org/10.2172/2346116.

Arunkumar, A., A. Pinceti, L. Sankar, and C. Bryan. 2023. "PMU Tracker: A Visualization Platform for Epicentric Event Propagation Analysis in the Power Grid." *IEEE Transactions on Visualization and Computer Graphics* 29 (1): 1081–1090. https://doi.org/10.1109/TVCG.2022.3209380.

Breen, P. T., and W. G. Scott. 1995. "Virtual Reality Applications in T&D Engineering." Presented at the Rural Electric Power Conference, 39th Annual Conference, B5/1–B5/6. April 1995. https://www.nrel.gov/docs/fy24osti/89678.pdf.

Brunhart-Lupo, N. 2024. "Introducing NOODLES: Collaborative Visualization in a Flavorful Package." NREL/PR-2C00-89678. https://www.nrel.gov/docs/fy24osti/89678.pdf.

Brunhart-Lupo, N., B. Bush, K. Gruchalla, K. Potter, and S. Smith. 2020. "Collaborative Exploration of Scientific Datasets Using Immersive and Statistical Visualization." Presented at SEA's Improving Scientific Software Conference 2020, National Center for Atmospheric Research, September 2020. NREL/CP-2C00-76783. https://www.osti.gov/biblio/1669577.

Brunhart-Lupo, N., and K. Gruchalla. 2023. "Immersive Particle Advection: Through the Scales of Renewable Energy." In *Practice and Experience in Advanced Research Computing,* 400–404. PEARC '23. Portland, OR: Association for Computing Machinery. https://doi.org/10.1145/3569951.3603641.

Brunhart-Lupo, N., and K. Gruchalla. 2025. *PowerSystemsData Specification.* NREL SWR-25-92. https://github.com/nicholasbl/PowerSystemsData.

Bugbee, B., B. W. Bush, K. Gruchalla, K. Potter, N. Brunhart-Lupo, and V. Krishnan. 2019. "Enabling Immersive Engagement in Energy System Models With Deep Learning." *Statistical Analysis and Data Mining: The ASA Data Science Journal* 12 (4): 325–337. https://doi.org/10.1002/sam.11419.

Bush, B., N. Brunhart-Lupo, B. Bugbee, V. Krishnan, K. Potter, and K. Gruchalla. 2017. "Coupling Visualization, Simulation, and Deep Learning for Ensemble Steering of Complex Energy Models." Presented at the 2017 IEEE Workshop on Data Systems for Interactive Analysis (DSIA), 1–5. October 2017. https://doi.org/10.1109/DSIA.2017.8339087.

Cardoso, A., E. A. Lamounier, G. Lima, L. C. de Oliveira, L. R. Mattioli, G. Junior, A. C. Silva, K. L. Nogueira, P. do Prado, and J. N. Ferreira. 2013. "VRCEMIG: A Virtual Reality System for Real Time Control of Electric Substations." Presented at the 2013 IEEE Virtual Reality (VR) Conference, Lake Buena Vista, FL, March 18–20, 2013, 165–166. https://doi.org/10.1109/VR.2013.6549414.

Dugan, R. C., & Montenegro, D. (2020). The Open Distribution System Simulator (OpenDSS) Reference Guide. Electric Power Research Institute. Washington, DC: Electric Power Research

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Institute.
https://sourceforge.net/p/electricdss/code/HEAD/tree/trunk/Distrib/Doc/OpenDSSManual.pdf

Goodwin, S., J. Dykes, A. Slingsby, and C. Turkay. 2016. "Visualizing Multiple Variables Across Scale and Geography." *IEEE Transactions on Visualization and Computer Graphics* 22 (1): 599–608. https://doi.org/10.1109/TVCG.2015.2467199.

Gould, E., S. Guerin, C. Smith, S. Smith, B. Bush, and K. Gruchalla. 2021. "Learning and Tracking Ad Hoc Fiducial Markers in Spatial Augmented Reality." In *Advances in Computers and Information in Engineering Research, Volume 2,* edited by J. G. Michopoulos, C. J. Paredis, D. W. Rosen, and J. M. Vance. ASME, June. Accessed June 23, 2021. https://doi.org/10.1115/1.862025_ch18.

Gruchalla, K., and N. Brunhart-Lupo. 2019. "The Utility of Virtual Reality for Science and Engineering." In *VR Developer Gems,* edited by W. R. Sherman, 383–402. Taylor Francis. https://doi.org/10.1201/b21598-21.

Gruchalla, K., N. Brunhart-Lupo, B. Palmintier, K. Doubleday, H. Palldulla, and M. Baggu. 2025. "Immersive Distribution Power Flow Analysis." *Pre-print NREL/JA-2C00-85793.*

Gruchalla, K., S. Molnar, and G. Johnson. 2023. "Reevaluating Contour Visualizations for Power Systems Data*." IEEE Transactions on Smart Grid* 14 (6): 4877–4887. https://doi.org/10.1109/TSG.2023.3252468.

Gruchalla, K., J. Novachech, and A. Bloom. 2016. "Visualization of the Eastern Renewable Generation Integration Study." In Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis, SC '16, Salt Lake City, Utah: ACM.

Gruchalla, K., S. Raghupathi, and N. Brunhart-Lupo. 2021. "Structure Perception in 3D Point Clouds." In *ACM Symposium on Applied Perception 2021.* SAP '21. Virtual Event, France: Association for Computing Machinery. https://doi.org/10.1145/3474451.3476237.

Macumber, D., K. Gruchalla, N. Brunhart-Lupo, M. Gleason, J. Abbot-Whitley, J. Robertson, B. Polly, K. Fleming, and M. Schott. 2016. "City Scale Modeling With OpenStudio." *Proceedings of SimBuild* 6, no. 1 (August). Accessed February 22, 2021. https://ibpsa-usa.org/index.php/ibpusa/article/view/350.

McKenna, K., K. Duwadi, A. Jain, K. Gaur, A. Nagarajan, and D. Palchak. 2021. *An Analysis Framework for Distribution Network DER Integration Analysis in India: Distributed Solar in Tamil Nadu*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-78114. https://doi.org/10.2172/1774840.

Milano, F. 2009. "Three-Dimensional Visualization and Animation for Power Systems Analysis." *Electric Power System Research* 79, no. 12 (December): 1638–1647. https://doi.org/10.1016/j.epsr.2009.06.009.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Molnar, S., G. Johnson, K. Gruchalla, and K. Potter. 2024. "Opportunities and Challenges in the Visualization of Energy Scenarios for Decision-Making: Preprint." Presented at the IEEEVis 2024 - EnergyVis Workshop, October 13–14, 2024.

Nagarajan, A., and Y. Zakai. 2022. *Data Validation for Hosting Capacity Analyses. Golden, CO: National Renewable Energy Laboratory*. NREL/TP-6A40-81811. https://www.nrel.gov/docs/fy22osti/81811.pdf.

Nobre, C., M. Meyer, M. Streit, and A. Lex. 2019. "The State of the Art in Visualizing Multivariate Networks." *Computer Graphics Forum* 38 (3): 807–832. https://doi.org/10.1111/cgf.13728.

Overbye, T., and J. Weber. 2000. "Visualization of Power System Data." Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, Maui, HI, 7, January 2000. https://doi.org/10.1109/HICSS.2000.926744.

Palmintier, B., J. Giraldez, K. Gruchalla, P. Gotseff, A. Nagarajan, T. Harris, B. Bugbee, J. Gantz, and M. Baggu. 2016. *Feeder Voltage Regulation With High Penetration PV Using Advanced Inverters and a Distribution Management System: A Duke Energy Case Study*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-65551. https://doi.org/10.2172/1331479.

Roberts, J. C. 2007. "State of the Art: Coordinated & Multiple Views in Exploratory Visualization." Presented at the Fifth International Conference on Coordinated and Multiple Views in Exploratory Visualization (CMV 2007), Zurich, Switzerland, 2007, 61–71. https://doi.org/10.1109/CMV.2007.20

Sanchez-Hidalgo, M.-A., and M.-D. Cano. 2018. "A Survey on Visual Data Representation for Smart Grids Control and Monitoring." *Sustainable Energy, Grids and Networks* 16 (December): 351–369. ISSN: 2352-4677, accessed January 10, 2021. https://doi.org/10.1016/j.segan.2018.09.007.

Tanaka, E. H., J. A. Paludo, R. Bacchetti, E. V. Gadbem, L. R. Domingues, C. S. Cordeiro, O. Giraldi, G. A. Gallo, A. M. da Silva, and M. H. Cascone. 2017. "Immersive Virtual Training for Substation Electricians." *2017 IEEE Virtual Reality (VR)*, 451–452. https://doi.org/10.1109/VR.2017.7892374.

Wiegmann, D. A., T. J. Overbye, S. M. Hoppe, G. R. Essenberg, and Y. Sun. 2006. "Human Factors Aspects of Three-Dimensional Visualization of Power System Information." In 2006 IEEE Power Engineering Society General Meeting. https://doi.org/10.1109/PES.2006.1709137.

Xu, B., C. Yuksel, A. Abur, and E. Akleman. 2006. "3D Visualization of Power System State Estimation." Presented at MELE-CON 2006–2006 IEEE Mediterranean Electrotechnical Conference, Malaga, Spain, May 2006, 943–947. https://ieeexplore.ieee.org/document/1653254.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.