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PNNL-38551

American-Made Solar Prize: Edgeli Enables DER Integration

CRADA 615 Final Report

October 2025

Shiva Poudel
Aaqib Peerzada
Jaime T. Kolln

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Cooperative Research and Development Agreement (CRADA) Final Report

Report Date:

In accordance with Requirements set forth in the terms of the CRADA, this document is the CRADA Final Report, including a list of Subject Inventions, to be provided to PNNL Information Release who will forward to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research. **PNNL acknowledges that the CRADA parties have been involved in the preparation of the report or reviewed the report.**

Parties to the Agreement:

Pacific Northwest National Laboratory

Edgeli, Inc.

CRADA number: 615

CRADA Title: Vouchers to Enable Laboratory and Organizational Collaboration for Innovation and Technology Improvements (VELOCITI)

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Sponsoring DOE Program Office(s): Solar Energy Technologies Office

Joint Work Statement Funding Table showing DOE funding commitment:

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CRADA Parties	**DOE Funding**	**Funds-In**	***In-kind**	**Total**
Participant(s)				
DOE Funding to PNNL	75,000	N/A	N/A	
Total of all Contributions	75,000			

Provide a list of publications, conference papers, or other public releases of results, developed under this CRADA:

N/A

Provide a detailed list of all subject inventions, to include patent applications, copyrights, and trademarks:

No subject inventions were generated under this CRADA.

Executive Summary of CRADA Work

The purpose of this project is to demonstrate how granular time series data and automated data transformation and impact assessment tools could speed interconnection approvals for distributed energy resource projects of various types and sizes. Types included community solar, rooftop solar, and EV charging projects. Using software routines to automate the transformation of data (e.g. GIS) to a network database and power flow model. By applying scenarios to create hourly (8760) hosting capacity values and voltage and thermal impacts for specific projects, we were able to demonstrate the feasibility of quickly assembling and analyzing key utility data sets for interconnection purposes. The outcomes of this effort will become the foundation for future work that will enhance and encapsulate the software components developed as part of this project, into web services (e.g. APIs) that can be integrated into queue management systems and automate interconnection screening processes.

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1.0 Introduction

The American-Made Challenges Round 6: was conducted to provide technical assistance to Edgeli, a software company that is helping utilities automate their interconnection screening processes using network databases and power flow model analytics. Edgeli was a Round 6 Solar Prize contest winner under the Solar Prize's voucher program which is managed by National Renewable Energy Laboratory and Sandia National Laboratory.

Pacific Northwest National Laboratory (PNNL) provided technical assistance under the voucher and developed and grid modeling and simulation testbed that models a three-phase unbalanced distribution network using OpenDSS and allows user to run time-series simulation to conduct hosting capacity analysis for distributed energy resources (DERs) as well as analyze potential grid impacts due to DER integration. Furthermore, the testbed also incorporates a module to investigate the cost for infrastructure upgrade that would be needed to accommodate additional DERs into the distribution network.

The simulation testbed described in Section 2.0 comprises OpenDSS model of a distribution network, load profiles for customers, and Python interface to drive the timeseries simulation. The grid models a stiff substation source, substation transformers, mixture of three-, two-, and single-phase lines, service transformers and customer loads.

2.0 Grid Modeling and Simulation Test Bed

The purpose of this testbed is to enable the modeling of the distribution network in the open-source simulator, OpenDSS, and conduct a time series simulation to facilitate the DER integration process.

2.1 Grid Modeling

Edgeli provided model files to PNNL in OpenDSS format generated from GIS. While containing the underlying network or connectivity model, these files do not include load objects. The rating of service transformers and the underlying triplex configurations (triplex lines and nodes) are used to populate the models with the load objects. The verification of the converted OpenDSS model was performed based on the following categories:

- Topology: Visually inspect the model and leverage graph-theory analysis to identify any and correct the isolated components and phase inconsistencies.
- Base voltage: Validate the primary and secondary voltage of service transformers.
- Voltage: After performing a load flow, the voltage profile of the feeder was analyzed to ensure the voltages are withing the acceptable range.
- Components parameters: Parameters related to line impedance (such as insulation and geometric mean radius), transformer reactance, and line lengths are verified to ensure they have non-negative and/or non-zero values, and their units are correctly cross-checked for accuracy.

After the model validation process and adding three-phase and triplex loads based on transformer configurations, the model contained primary and secondary feeder elements from the low side of the substation transformer down to the customer loads on the secondary side of the distribution service transformer. To conduct time-series simulation, we used profiles for customers from (Wilson, 2017) with OpenDSS.

2.2 Hosting Capacity (HC) Analysis

The first module in the testbed is the hosting capacity analysis where projects related to solar PV and electric vehicles are added. In this module, we aim to identify the min and maximum HC for each grid segment. The workflow for the proposed module is shown in

Figure 1, where the overall process can be categorized into four steps.

2.2.1 Graph-Theory Analysis

To analyze a distribution grid as a graph using Networkx in Python, we begin by representing the grid as a network of nodes (buses) and edges (segments connecting the buses). The buses in the graph are the potential locations for DERs in the distribution grid. Next, we identify the buses that are connected and downstream from a given segment under consideration. This enables us to identify the influence of injections at various buses to a given line segment and finally evaluate their capacity to incorporate additional loads or generation based on location.

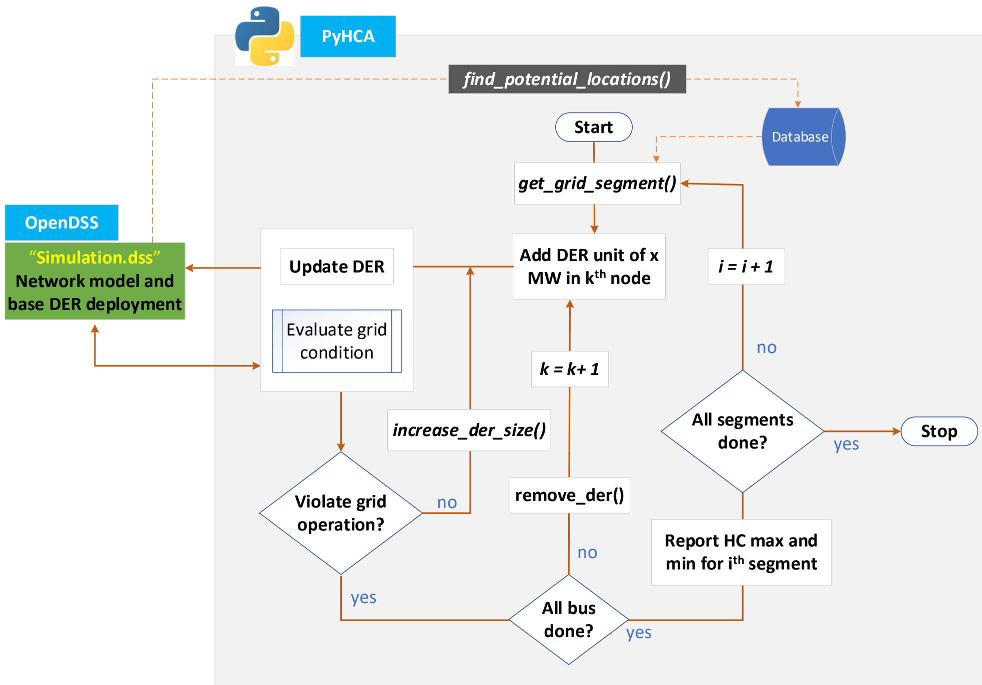

Figure 1 Workflow for DER hosting capacity analysis.

2.2.2 Adding DER Growth Scenarios

In analyzing a feeder, each line segment undergoes a sequential evaluation process. At each segment, a DER is initially set up at a bus, and the grid's condition is assessed. If no issues arise, the DER size is incremented, repeating until a violation occurs. Upon detecting a violation, the process shifts to the next bus within the segment. Once all buses associated with a segment are evaluated, the analysis proceeds to the subsequent line segment. We employed a binary search algorithm to identify the max DER that can be incorporated into a bus without causing a violation.

2.2.3 Hosting Capacity Analysis

Hosting capacity is the amount of DER (solar or EV) that can be added to distribution system before control changes or system upgrades are required to safely and reliably integrate additional DERs (Jain, 2020). Hosting capacity analysis is the process by which a utility can identify the amount of available capacity on their distribution system at various locations with the intent of interconnecting new load or generation facilities.

For this study, we aim to identify the minimum and maximum hosting capacity for individual feeder segment.

1. Min Hosting Capacity: It is an indicative of the available hosting capacity across the length of the feeder segment and most often defined by the hosting capacity value located at the most downstream node within each breakpoint. This amount of DER can be integrated anywhere on a distribution feeder determined by a segment.

2. Max. Hosting Capacity: indicative of the available hosting capacity at a specific location across the feeder segment, most often located at the upstream node within each

breakpoint. It is typically at the most upstream location of the highlighted line section (the section closest to the substation).

2.2.4 Project Impact Analysis (PIA) Module

The purpose of this module is to analyze the impact of potential Distributed Energy Resources (DERs) on the distribution grid and study the necessary infrastructure upgrades to avoid future violations. Users can input the project location and size, which the module then maps to the nearest bus in the distribution grid. By integrating the DER project into the grid model, the tool allows for a comprehensive analysis of the project's impact.

Figure 2 shows the workflow for this module.

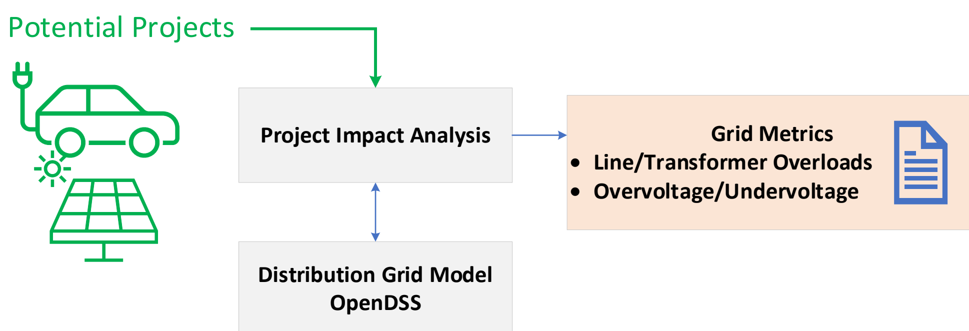

Figure 2 Project Impact Analysis Tool

Once the project is integrated into the OpenDSS model, the module runs a time series simulation for a year, with each time step set at one hour. During this simulation, the grid condition is continuously monitored. The tool checks for violations, including line and transformer issues as well as node overvoltage/undervoltage. Throughout the simulation, the module collects and compiles metrics, capturing both the magnitude and duration of any impacts. This data is crucial for understanding the full scope of the DER project's effects on the grid. At the end of the simulation, the module generates a comprehensive report detailing the impacts. This report not only highlights current issues but also provides insights into necessary infrastructure upgrades to prevent future violations.

The primary goal of this module is to facilitate the analysis of how new DER projects will affect the distribution grid, ensuring that any potential issues are identified and addressed. By doing so, it aids in planning the necessary infrastructure upgrades to maintain grid stability and prevent future violations.

2.3 Grid Upgrade Modeling

This module is designed to capture the range of distribution system upgrades and the associated upgrade costs as new projects (PV and EV) are interconnected with the existing grid. Some of the interconnecting projects may cause a network violation (voltage and/or thermal) and thus infrastructural upgrades are required to mitigate such operational violations. The general approach for determining the upgrades and the costs is to conduct a project impact analysis to evaluate the violations, wherein upgrades are sequentially deployed, based on the nature of the violations, to enhance the network hosting capacity. The key step in the process involves mapping a set of violations to a set of upgrades, prioritizing the upgrades that mitigate the violations with the least cost. In this report, we only focus on reconductoring and transformer replacement as potential upgrades. Upgrades that leverage smart inverter functionality, adjusting the set-point of voltage regulators, and adding new line regulators and LTCs are outside the scope of this report. The basic flowchart that illustrates the ideological underpinning of the grid upgrade module is shown in Figure 3.

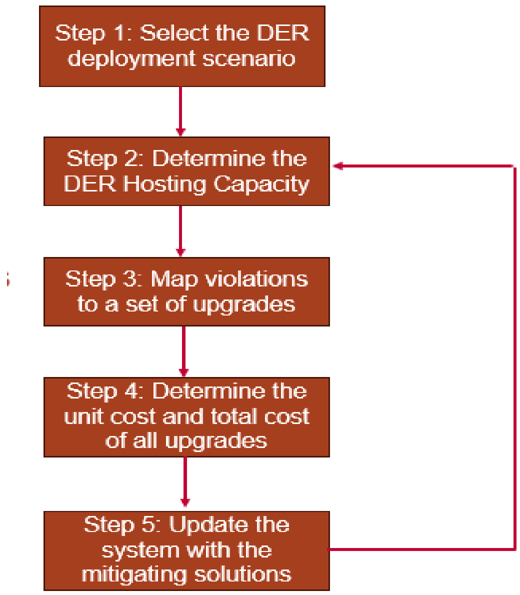

Figure 3 General workflow of the Grid Upgrade Framework

2.3.1 Mapping violations to upgrades

Mapping a set of observed violations to possible upgrades is a challenging problem. Since the set of upgrades (set of feasible solutions) is discrete or can be reduced to a discrete set, the grid cost upgrade problem can be formulated as a combinatorial optimization problem. However, in this report, we apply a heuristic-based approach to determine the grid upgrade costs and do not perform any optimization, which is outside the scope of this work. In general, the set of possible grid upgrades to mitigate certain observed violations can be grouped into two categories. The first category of upgrades includes traditional upgrades such as reconductoring, transformer replacement, adding line voltage regulators, and adjusting the set-points of regulators, load tap-changers (LTCs), etc. The second category consists of advanced grid upgrades that include smart inverter functionality, using FACTS devices such as SVCs and D-STATCOMs, and using energy storage devices for peak-shaving/load-shifting purposes. Some of the potential grid upgrades with associated costs for mitigation voltage and thermal violations are given in Figure 4.

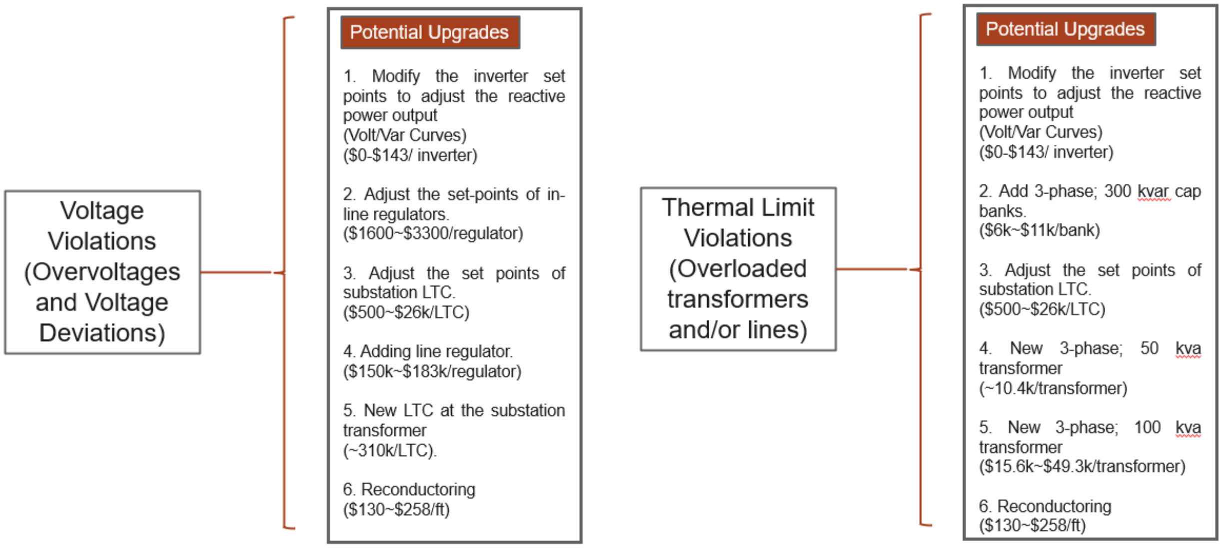

Figure 4 Mapping violations to grid upgrades.

As is evident in Figure 4, the optimal solution would consist of a combination of upgrades that address the violation in question at the least cost with a maximum expansion to the network's hosting capacity. The combinatorial nature of the problem is clear from Fig. 4. In this report, we consider only thermal violations, and they are addressed using reconductoring and transformer replacement.

2.3.2 Grid Upgrade Cost Calculation Module

The cost calculation module is initialized with the inputs from the PIA module and the NREL distribution cost guide (Horowitz, 2019). If the rated KW capacity of the project is less than the hosting capacity value at the specified location, then it might not be necessary to run the PIA module since any project with rated KW < HCA, will not trigger infrastructure upgrades. If the rated KW of a project is greater than the hosting capacity value at the location where the project is interconnecting, then it is necessary to run the PIA module to determine the set of possible violations. The cost calculation module creates asset violation reports and performs a line loss calculation. In general, the total upgrade cost is a combination of several costs. This can be defined as

$$Total\ Cost = C_{DU} + C_{DL} + C_{IC} \tag{1}$$

In (1), C_{DU} is the cost of grid upgrades, C_{DL} is the cost associated with the total power loss, and C_{IC} is the cost of interconnection. The total cost associated with any project must be compared to a base case (network with project). This is important because a project may increase or even decrease line losses and thus the associated costs. Consequently, the total cost can be higher or lower than the base case. Since a project may trigger system upgrades at the time of interconnection, it may allow for some deferral of other upgrades in the future. For this reason, the cost of grid upgrades C_{DU} is defined as the net present value of the difference between total distribution system upgrade costs with and without the project over a planning horizon.

$$C_{DU} = \sum_{n=0}^{N} \frac{OC_{project}(n) + O\&M_{project}(n) - OC_{basecase}(n) - O\&M_{basecase}(n)}{(1+d)^n} \tag{2}$$

In (2), $OC_{project}(n)$ is the total overnight capital cost of all the upgrades in the year n with the project and $OC_{basecase}(n)$ is the overnight cost in the year n without the project. $O\&M_{project}(n)$ is the total operations and maintenance with the project in year n and $O\&M_{basecase}(n)$ is the operations and maintenance cost incurred in the base case in year n. Given the challenges in accurately identifying the O&M costs associated with interconnection requests, we forego calculating these costs and make some reasonable assumptions to capture the O&M costs. For the case with an interconnecting project, the O&M costs are assumed to be 15% of the overnight capital cost whereas in the base case the O&M costs are assumed to be 10% of the capital costs. In (1), C_{DL} is the cost associated with the line losses and can be readily calculated by comparing the results of the time-series power flow with and without the project. The NPV of C_{DL} is calculated as

$$C_{DL} = c_{Loss}\left(\sum_{n=0}^{N} \frac{P_{loss}(project) - P_{loss}(basecase)}{(1+d)^n}\right)\Delta t \tag{3}$$

In (3), c_{Loss} is the cost of loss compensation in \$/kWh assumed to be 50 \$/kWh in this report, $P_{loss}(project)$ is the cumulative line losses with the interconnecting project, $P_{loss}(basecase)$ is the cumulative line loss without the project in kW, Δt is the time-step of the time-series power flow, and d is the discount rate. Given the fuzzy nature of the interconnection costs and the difficulties associated in accurately quantifying such costs, they are ignored in this work. The flowchart illustrating the functionality, and the workflow of the cost module is shown in Figure 5.

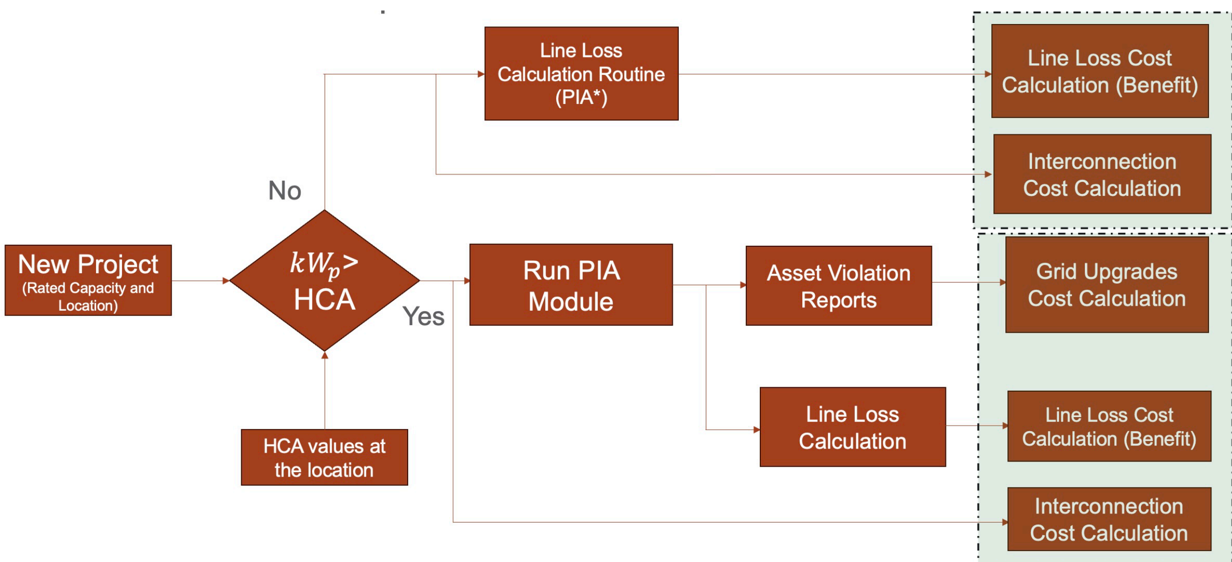

Figure 5 A general outline of the Cost Module

3.0 Demonstration

In this section, we present the proposed modeling and simulation framework, showcasing the results for each capability developed during the project. To protect the sensitivity of utility data and models, we refrain from disclosing specific grid-related outcomes. Instead, we share results that, while not containing sensitive information, demonstrate the applicability of the proposed framework.

3.1 Base Case

The base case simulation represents grid operation without adding DERs. To analyze Dynamic Hosting Capacity (DHC), it’s essential to first establish a baseline, known as the base case, which reflects the system’s behavior under normal, business-as-usual conditions. This baseline serves as a critical reference point for assessing how the introduction of DERs impacts the system over time. By running the base case, we can observe the system's performance during periods of varying stress, such as lower stress during off-peak hours with reduced demand, and higher stress during peak demand periods. This temporal variation is crucial in understanding how DERs might affect grid operations, as their impact can significantly differ depending on the grid's current state.

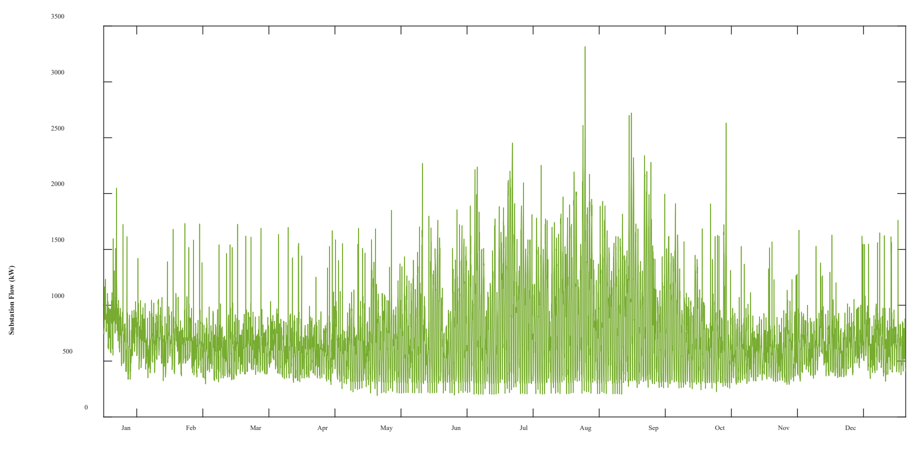

Figure 6 Substation Flow (yearly simulation)

Once the base case is established, simulations can be run to introduce DERs into the system and observe their impact over time. The temporal behavior of DERs, which refers to how their generation or load characteristics change throughout the day, is critical. For example, during periods of low stress, DERs might operate without causing significant issues, while during high-stress periods, they could exacerbate existing challenges by pushing voltages above acceptable limits or causing line segments to exceed their thermal ratings.

Figure 6 shows the yearly profile of feeder at the substation level. Similarly, Figure 7 shows the maximum and minimum voltage of the system for a yearly simulation. It is observed that the system operates without violation during normal condition. This indicates that the system has some available capacity for extra load/generation.

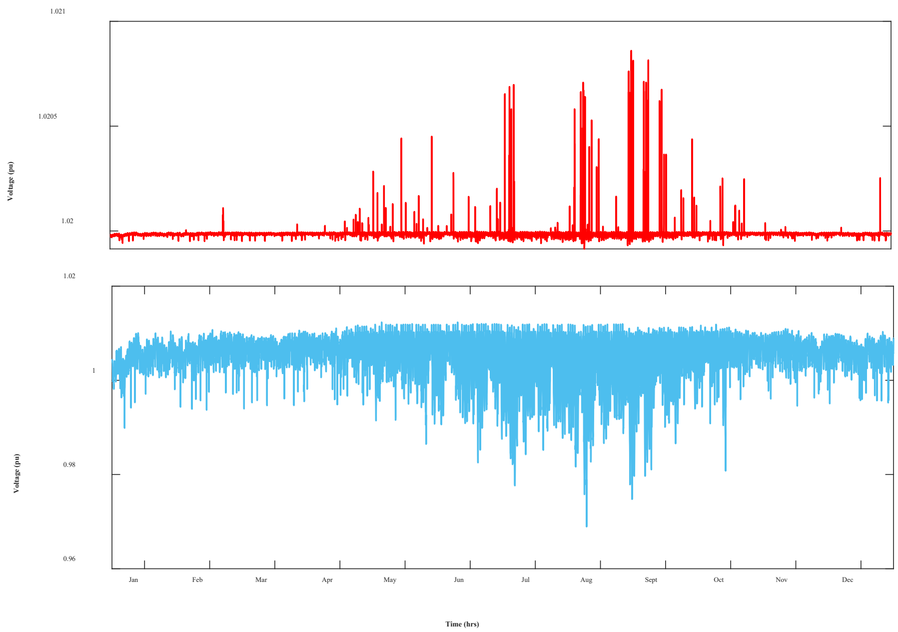

Figure 7 Maximum (top) and minimum (bottom) voltage of the feeder for yearly simulation.

3.2 DER Hosting Capacity Analysis

With the given base case profile, DERs are added into different location of the distribution grid. The relation of segment and underling buses is identified using graph theory analysis. Hosting capacity report is generated based on approach explained in Section 2.2.

Figure 8 shows the dynamic hosting capacity of a location (bus) for a month of January. Hosting capacity at this specific location is evaluated based on both voltage limits and thermal overload. It is observed that the location under consideration can host solar generation around 2 to 2.5 MW if only voltage constraint is considered. On the other hand, the hosting capacity varies from 600 kW to 2 MW if thermal constraint is imposed. While a single violation is used to limit the amount of DER that can be hosted in a location, actual thresholds used by a utility would be dependent on their comfort level to allow relatively minor and short-term violations.

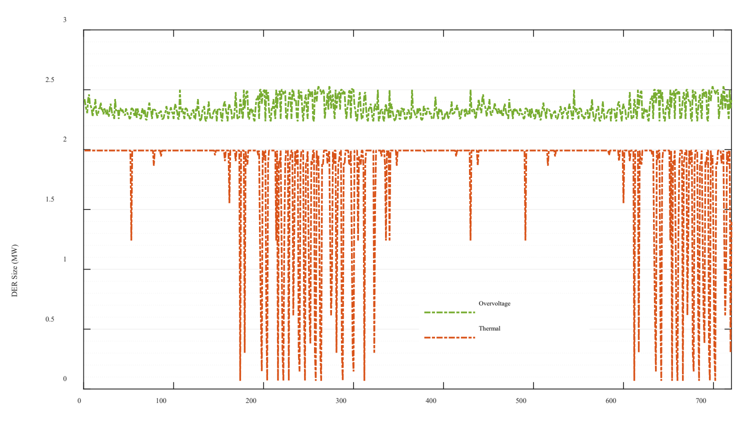

Figure 8 Dynamic hosting capacity for a bus for month of January.

After completing the analysis for all buses, the minimum and maximum hosting capacities at the segment level can be evaluated. This data is then used to generate hosting capacity maps for distribution grid, where color coding represents the hosting capacity values. Users can hover over the map to observe the minimum and maximum hosting capacity values for each grid segment. Figure 9 shows hosting capacity of different buses that will impact hosting capacity for a feeder segment. In this case, there are 262 buses that will impact hosting capacity of a selected segment. Both overvoltage and thermal violations are considered, with values reported separately for each metric. Using the hosting capacity data from these 262 buses, the algorithm identifies the minimum and maximum values for the grid segment. For example, the minimum and maximum hosting capacity values for this segment, considering only the voltage constraint, are 3.19 MW and 10 MW, respectively. This indicates that, if optimally selected, a solar project of up to 10 MW can be connected to a particular bus without violating grid voltage limits. However, when thermal constraints are considered, the maximum DER size that can be installed is 2.88 MW. This demonstrates that the hosting capacity for this segment is more constrained by thermal limits.

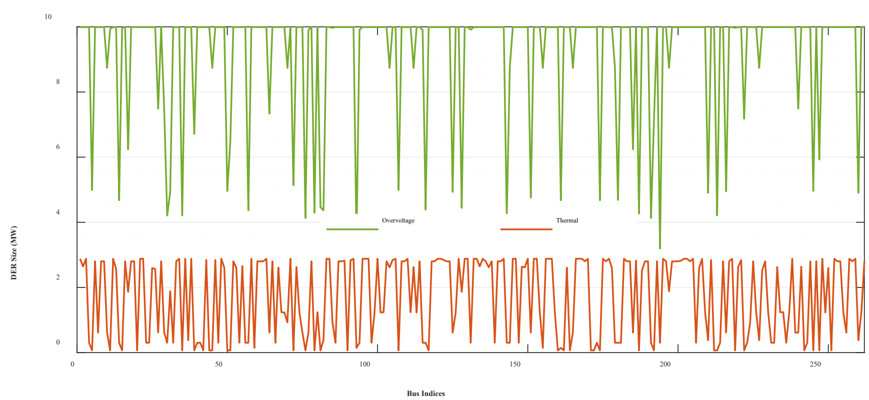

Figure 9 Hosting capacity of buses pertaining to a grid segment.

3.3 Impact and Cost Module Output

The cost module developed in this work utilizes the NREL distribution cost guide which lists the unit cost of upgrades such as reconductoring, transformer replacement, advanced mitigation options such as smart inverter functionality etc. The cost guide is a result of several surveys performed by NREL with different utilities across the country. As such, there are ranges of unit cost data available in the guide, which is reflective of the prices in different regions of the country. Other main considerations that impact the cost calculations include uncertain renewable power output (for PV systems), uncertain charging patterns in electric vehicles (EVs), locational uncertainties for new projects etc.

The cost module developed as part of this work focuses on the thermal overloading of the network components such as distribution lines and transformers. The projects (single or multiple) are interconnected with a detailed model of the distribution system using the PIA module and an impact assessment is conducted. The results of the impact analysis are sent to the cost module and the grid upgrade costs are calculated using reconductoring and transformer replacement as possible mitigation approaches.

Reconductoring: The thermal overloading of lines can be effectively addressed by replacing sections of the feeder lines with higher ampacity (normal and emergency) to carry more power upstream or downstream the network, based on the nature of the project. Using low-impedance conductors can also effectively address voltage concerns, if any. It is of note that unit costs for replacing feeder lines can be high and the range of reconductoring costs found in the NREL database can be quite large. An example of reconductoring costs incurred with a 1 MW PV project is shown in Figure 10.

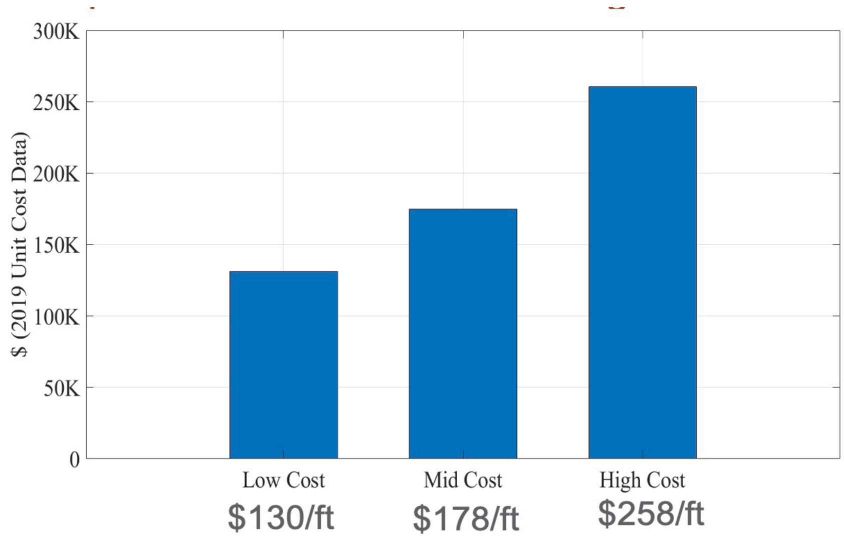

Figure 10 Range of reconductoring costs incurred with a 1MW PV project.

Table 1 lists the overloaded lines with average overload and the percentage of time overload for the network under observation.

Table 1 Thermal Overloading of Lines for the network under observation

Line Number	Line ID	Average Overload value	% Time Overload
Line 1	Line200	111.16%	100%
Line 2	Line403	111.16%	100%
Line 3	Line202	110.81%	100%
Line 4	Line89	110.64%	100%
Line 5	Line405	110.64%	100%
Line 6	Line267	110.57%	100%
Line 7	Line409	110.57%	100%

<u>Transformer Replacement</u>: The service transformers in distribution systems can be adversely affected by increasing penetrations of EV load. At higher penetration levels and with quasi-synchronous charging patterns, the distribution transformers can be overloaded beyond the peak rating for a significant amount of time. A sustained operation under such condition can significantly reduce the thermal life of the transformer and accelerated early failures. Replacing an existing transformer with a higher-capacity transformer can be an effective strategy under these conditions, especially to support a large percentage of residential and/or commercial EV load. The NREL guide lists the transformer replacement costs for transformers that are 50 KVA or less and transformers that are rated more than 50 KVA and less than 100 KVA. Table 2 lists the transformer costs as listed in the NREL cost guide.

Table 2 Transformer Costs as listed in NREL cost guide.

Transformer KVA	Number of Phases	Cost Low	Cost High
0 – 50 KVA	3	$10400	N/A
50 – 100 KVA	3	$15600	$49300

An example of transformer replacement costs is shown in Figure 11. A total of 2 PV and 3 EV projects are added to the network at different locations and the impact assessment is conducted using the PIA module and the impacted assets are queued for upgrades. Three transformers with kVA ratings 50-100 were found to be overloaded and were appropriately replaced. The impacted assets are listed in Table 3 and the cost figures are shown in Figure 11.

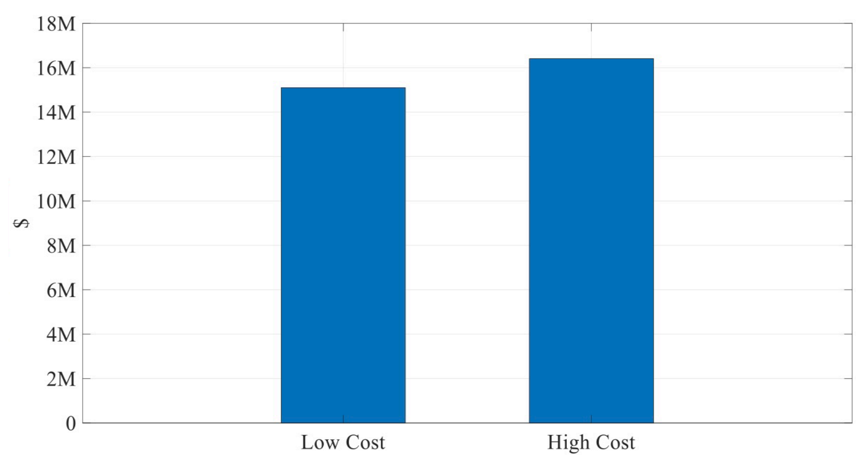

Figure 11 Example 50-100 KVA Transformer Replacement Costs

Table 3 Thermal overloading of 50-100 KVA transformers

Transformer Number	Transformer ID	Average Overload	% Time Overload
1	XFMR352	256.7%	100%
2	XFMR358	395.2%	100%
3	XFMR343	188.9%`	100%

Line loss cost sensitivity: The calculation of the cost associated with the line loss depends on several factors that are not either fixed or known with absolute accuracy. For instance, the line loss calculation is heavily influenced by the choice of the loss compensation factor which in turn can vary sufficiently across regions, line geometry and material, operating voltage level and line length. For increasing values of the loss compensation factor, the NPV of line loss increases linearly. This, however, ignores the impact of voltage levels and line geometry and construction. Figure 12 shows the relationship between the NPV of line loss cost and the loss compensation factor.

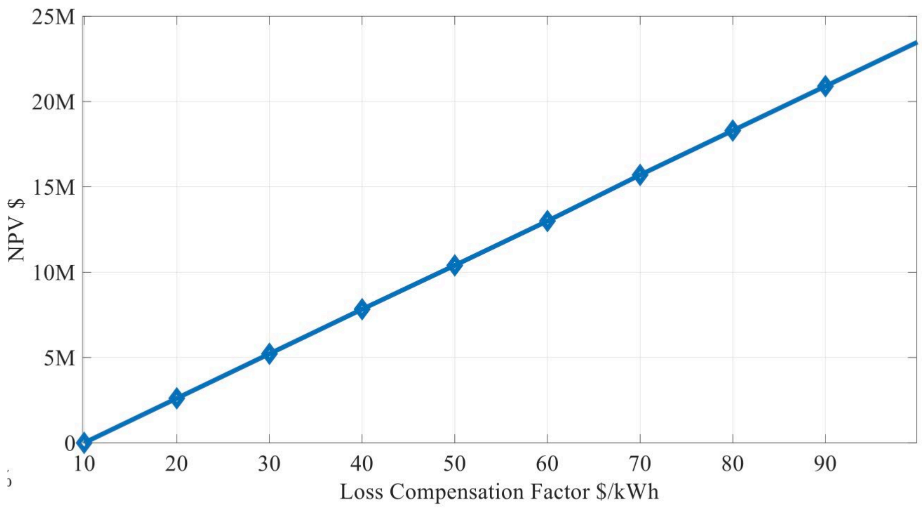

Figure 12 Sensitivity of NPV of line loss costs C_DL to changes in loss compensation factor.

The line loss cost calculation also depends on the discount rate used in the calculation. Generally, for higher values of discount rate the NPV drops in a non-linear (decreasing exponential) fashion. This suggests that higher discount rates can be economically debilitating to the profits derived from the project in the long run. Figure 13 shows the changes in the NPV of the line loss costs as the discount rate increases.

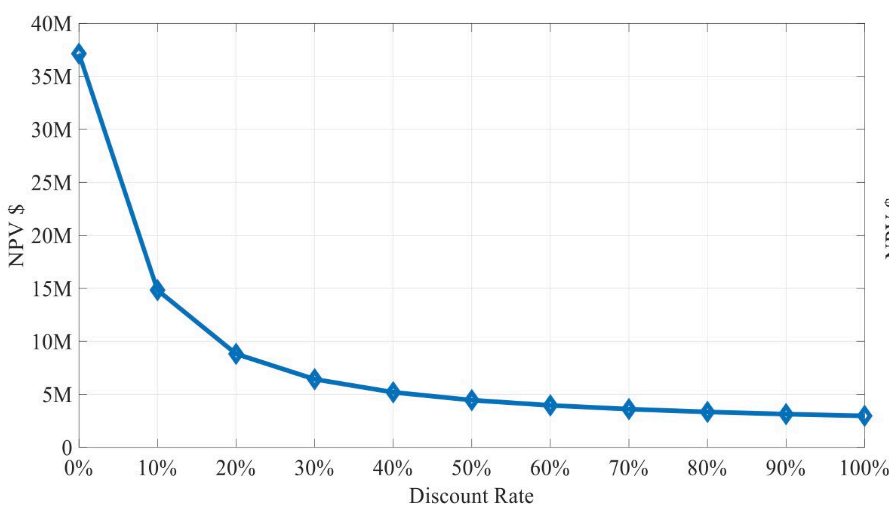

Figure 13 Sensitivity to discount rate.

4.0 Summary of Research Results

PNNL collaborated with Edgeli to enhance the maturity level of their platform designed for modeling distribution grid systems, with the goal of simplifying the interconnection requirements for integrating renewable energies set by utilities. The process began with model validation on initial grid models, followed by the establishment of a test bed for conducting time series simulations using OpenDSS. PNNL also contributed to developing essential inputs and outputs for dynamic hosting capacity studies, addressing both load and generation aspects. To further improve the hosting capacity module, utility functions were added to transform grid violations into meaningful metrics. In addition to hosting capacity, a project impact analysis tool was developed to assess the effects of additional load and generation on the grid, aiding in the identification of grid upgrades that may be needed for interconnection approval.

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