Final Report for CSI RD&D Solicitation #4: Advanced Distribution Analytics Enabling High Penetration Solar PV

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Executive Summary

Background:

With California's ambitious Renewables Portfolio Standard (RPS) to achieve 33% renewables by 2020[1], the California Solar Initiative aims to improve the economics of solar technologies by reducing technology costs and increasing system performance in order for California to reach its RPS goals. In the past, studies have been done to assess the limits of solar PV on current distribution circuits using models of large scale systems, however these findings are not reflective of the reality of PV systems to be distributed among many customers, residential and commercial, on the circuit. This study aims to develop models and use these models for determining limits for PV in this more realistic scenario using PV adoption models in GridLAB-D.

Project Goals:

The driver of this project is the desire to reduce the time and cost required to integrate high penetration of PV on numerous distribution circuits. To achieve this, the project aims to do the following: better understand current grid limits for solar penetration (native limits), develop technology strategies for California feeders to obtain 100% PV penetration, and create a cloud-based tool to study and analyze solar PV feeder limits.

Project Overview:

The project process is shown here. It includes clustering of representative circuits, modeling of these circuits, determining the native limits for PV of these circuits, and determining mitigation paths for increase PV penetration to 100%.

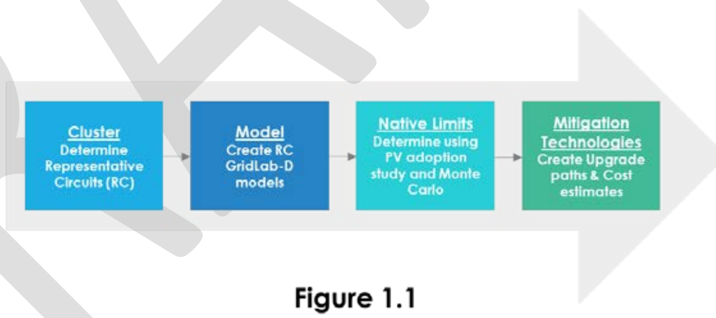

Figure 1.1

Key Findings:

The following are notable key findings and lessons learned based on detailed native limit and mitigation analysis from the project:

- 42-53% of SCE circuits are limited to approximately 50% of PV penetration or less. At least 2 to 7% of the circuits have a native limit at or above 100% PV penetration.
- The most common violations experienced were power factor and voltage based
- Determining how to achieve 100% penetration on legacy circuits can be challenging, with a mitigation leading to new violations.

[1] http://www.cpuc.ca.gov/RPS_Homepage/

- Controlling circuit voltage and circuit power factor simultaneously with capacitors is not practical at high penetrations of PV.
- Energy storage is a technically viable solution for power factor, but may not be cost effective unless it is part of a larger multi-objective control strategy.
- Inverter-based Volt-VAR is not able to address low lagging power factor and high voltages at the same time. However, Volt-VAR combined with other traditional upgrades can be highly effective.

ABSTRACT

Current utility distribution circuit infrastructure is limited in the amount of distributed generation it can withstand. Drastic increases in the level and size of future solar PV installations which will inevitably increase the complexity and cost of future interconnection studies. In order to determine the current capacity for distributed solar PV, or "native PV limit", in Southern California Edison's (SCE) territory, models of 30 representative distribution circuits were developed. Of these 30 models, 15 were analyzed for native limits and mitigation strategies. GridLAB-D, an open source software developed by Department of Energy's (DOE) Pacific Northwest National Lab (PNNL), was used to develop behind the meter models of 30 representative circuits in Southern California Edison's (SCE) territory.

1 INTRODUCTION

California has many ambitious goals to increase the amount of solar power generated and used inside its borders, such as a goal to increase Distributed Generation, and a program of incentives to support distributed solar photovoltaics, and California SB 350 that requires 50% renewable energy portfolio standard by 2030. However, there are limits on the amount of distributed generation that current systems can hold. This is because there are current operational limits on the system and its equipment. For example, high PV penetration can lead to thermal overloads at secondary transformers, voltage flicker, or high voltages on the secondary line, among other things. The limit to the amount of distributed solar that any single distribution circuit can hold is referred in this paper as the "native limit" of the system. It is the point at which any additional PV system will violate the operation constraints of the circuit.

The goal of this project, the California Solar Initiative Research Development & Demonstration (RD&D) Solicitation #4 – High Penetration Study (CSI4), is to determine these native limits of distributed solar PV penetration on the Southern California Edison (SCE) system. Once native limits were determined, then strategies for upgrading the system to allow for higher penetrations of PV were developed. These mitigation strategies will allow SCE planners and operators to help California meet its target renewable energy portfolio standard.

Additionally, a large goal of this project was to develop an online tool that would host these models and provide a platform for model analysis. It was made available to utility business managers and planners. This platform is called GridUnity™ and has been developed by project partners, Qado Energy. Using the GridUnity tool, utilities will have control over how they configure, deliver, and manage sophisticated technology-driven customer programs and analytical services. This offers utilities the flexibility to provide their customers compelling services in a rapidly changing business and regulatory environment.

Since there are over 4,500 circuits in the SCE territory, creating circuit models for all of SCE's circuits would require an exorbitant amount of time and labor. For this reason, a set of representative circuits were chosen to represent all of SCE's circuits. This was done by first clustering all of SCE's circuits based on their characteristics and then determining the circuits that would serve as representative of the rest of SCE's territory. These circuits were clustered into 30 representative circuits. This report discusses the results of the 15 most representative circuits.

With these defined representative circuits, models were created of each circuit in GridLAB-D™, an open-source software for next generation power systems simulations, created by for the U.S. Department of Energy's Office of Electricity Delivery & Energy Reliability by the Pacific Northwest National Laboratory (PNNL). Using the GridLAB-D models, native PV limits were determined for each representative circuit, after which point, the mitigation strategies were determined.

To complete this work, GridLAB-D models of SCE's distribution system were developed and used to test levels of increasing PV on each distribution circuit using a PV-adoption model and Monte-Carlo simulation. To a high level, the process taken for this work was as follows:

1. Identify representative circuits using –k-means clustering
2. Create behind-the-meter models of representative circuits in GridLab-D
3. Deploy PV adoption scenarios on models to determine native PV limits of circuits
4. Determine specific, then general, mitigation strategies to enable 100% PV penetration
5. Conduct general analysis & comparison of representative to current operational feeders
6. Develop online platform and services for utility planning and operations

This report will discuss the overall project methodology, and will highlight some key lessons learned and conclusions. More detailed results and discussions can be found in the previous task reports.

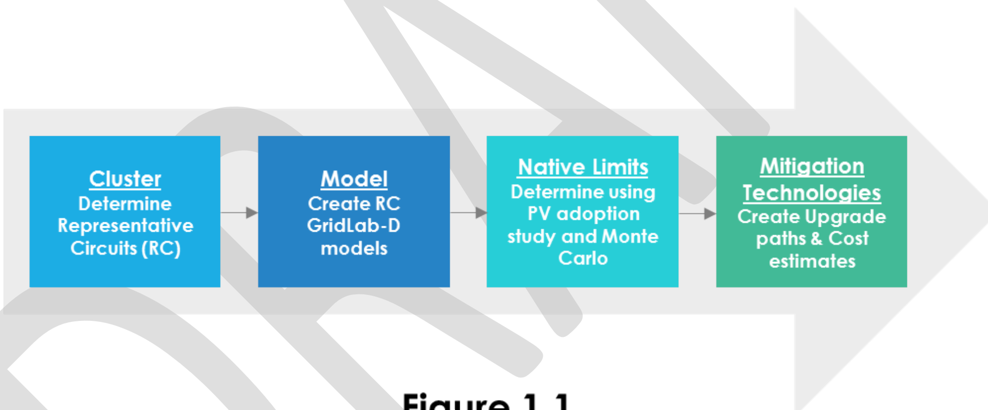

Figure 1.1

2 Clustering

2.1 Overview

The first part of the project was to determine the representative circuits by clustering all of SCE's circuits based on their characteristics. As shown in Figure 2.1, this was done by first identifying these defining characteristics, conducting K-means clustering, and finally determine the representative circuits (RCs) based on the clustered data.

Southern California Edison owns and operates approximately 4,500 distribution circuits spanning 50,000 square miles with wide varieties of climate zones and load types. In order to accurately determine the varied impacts of high penetration solar PV across the SCE service territory, it is necessary to develop and test models of circuits that effectively capture that same variety. For this study, representative circuits were selected from each of three defining classes for distribution circuits: rural circuits, urban 2-4kV class circuits, and urban 12-16kV circuits. Ultimately, 8 rural circuits, 5 circuits from the urban 2-4kV class, and 17 circuits from the urban 12-16kV were selected – a total of 30 representative circuits.

This selection process was run on the circuit data compiled for SCE's CSI RD&D Solicitation #3 project with EPRI to evaluate alternatives to the 15% rule.

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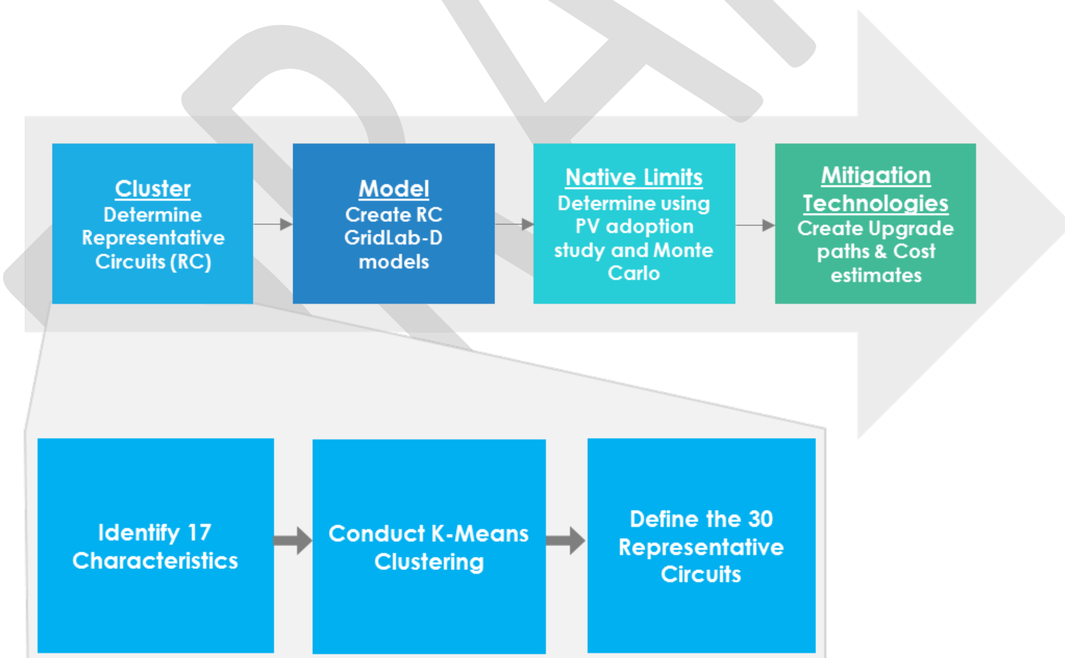


Figure 2.1

2.2 K-Means Clustering Methodology

K-means clustering is one of the most popular and straightforward methods used in cluster analysis. In this method, SCE's 4500 circuits are represented by their position in a 17-dimensional vector space. Seventeen data dimensions were taken into consideration during the selection process for the representative circuits. At a high level, the data dimensions represent areas in which a set of circuits should exhibit good similarity if they are all to be represented by a single circuit from within the group. **Table 2.1** shows the scaling of these dimensions in the k-mean clustering.

Table 2.1: Scaling Importance of Circuit Dimensions

Dimension	Scale	Dimension	Scale
Voltage Class	8	% of Energy Sold - Agricultural Customers	2
Climate Zone	8	Total Number of Customers	2
Connected Service Transformer Capacity	4	% of Residential Customers PRIZM High Income	2
Circuit Peak Load	4	% of Residential Customers PRIZM Medium Income	2
Miles of 3 Phase Circuit	2	% of Residential Customers PRIZM Low Income	2
Miles of 1 or 2 Phase Circuit	2	Number of Voltage Regulators	1
% of Energy Sold - Residential Customers	2	Number of Capacitor Banks	1
% of Energy Sold - Commercial Customers	2	Number of Circuits Tie points	1
% of Energy Sold - Industrial Customers	2		

The objective of k-means clustering is to take the total number of observations and group them into "k" clusters, where each circuit belongs to the cluster it is closest to. Each cluster has a centroid, and the circuit whose position is nearest the centroid was selected as the representative circuit for all circuits in that cluster.

There is a tradeoff between accuracy of circuit representation and the number of representative circuits to model. Given this, a sensitivity analysis was performed to determine the optimal number of clusters, k, or number of representative circuits. This was determined to be k = 30 [as actually performed, k = 8 for the rural circuits, k = 5 for the 2-4kV urban circuits, and k = 17 for the 12-16kV urban circuits]. Out of the 30 representative circuits, the 15 most representative were analyzed for native limits and mitigation strategies.

2.3 Representative Samples

The physical and demographic characteristics of the representative circuits (RCs) are discussed in this section. A summary of the representative circuits is tabulated in **Table 2.2**. The 30 clustered representative circuits represent as little as 27 circuits, and at most 301 circuits, or 1% to 7% of SCE circuits. These circuits spread through SCE's territory, in the various climate zones of California.

There are many customer characteristics that are considered in building the models of the representative circuits. These characteristics include customer type (residential, commercial, industrial, agricultural), energy consumption of the customer, geographic type (urban, suburban, second city, country), life-stage (young, family, mature), and socioeconomic class of residential customers. The representative circuits encompass a range of energy consumption by customer type, as well as a range of customer type distribution.

Additionally, understanding the customer demographics is necessary in order to build the behind-the-meter load models in GridLAB-D. When creating these models, the results are calibrated to SCE's customer energy consumption data. As part of the calibration process, the life-stage, socioeconomic class, and geography type are used by the engineers to guide their assumptions on the energy consumption behaviors of the customer.

Table 2.2: Characteristics of SCE's 15 most representative Circuits

Circuit ID#	# of SCE circuits represented	% of SCE circuits represented	Peak Loading	Existing Installed PV Capacity	Climate Zone	Customer Count
2	97	2%	Medium	Low	6	Low
3	216	5%	High	Medium	9	High
4	211	5%	High	Medium	8	High
5	118	3%	Medium	Low	6	Medium
6	211	5%	Medium	Low	8	High
7	153	4%	Medium	Medium	9	Medium
8	148	4%	Medium	Low	10	High
11	91	2%	Medium	Low	8	Medium
17	111	3%	Medium	Low	6	Medium
19	301	7%	Low	Low	9	Medium
21	252	6%	Low	Low	8	High
22	178	4%	Medium	Low	6	High
23	224	5%	Medium	Low	13	High
24	171	4%	Medium	Low	13	Medium
29	164	4%	Medium	Low	14	High

Values Used:	Peak Loading (MVA)	PV Capacity (kW)	Customer Count
low	≤ 2	≤ 100	≤ 100
medium	2 - 8	100 – 1000	100 - 900
high	≥ 8	≥ 1000	≥ 900

3 MODELING

3.1 OVERVIEW

The circuit models were created in GridLAB-D, an open-source software created by Pacific Northwest National Lab. It is a scripted software with no user interface. One of the goals of this CSI RD&D Solicitation #4 project is to provide a graphical user interface (GUI) and an online platform for creating these models in Qado Energy's GridUnity Platform.

In order to properly capture the time-varying characteristics of solar PV, this project will use quasi-static time-series simulations, which were conducted in the GridLAB-D simulation environment. Time series-simulations properly reflect the operational characteristics of solar where the maximum solar output may not be coincident with the circuit peak load. Additionally, detailed end-use load models represent how changes in circuit voltage profiles affect the duty-cycle of end-use loads, and thus total load.

Figure 3.1– Modeling Overview illustrates the model building sequence. Residential and Commercial models were created for these two distinct set of customers. These models were then incorporated into a connectivity model that encompasses the entire representative feeder. These models were then validated against the aggregate usage across the feeder for 4 weeks of the year (one week per season). Then, these models were cleared of violations to create a final base case model.

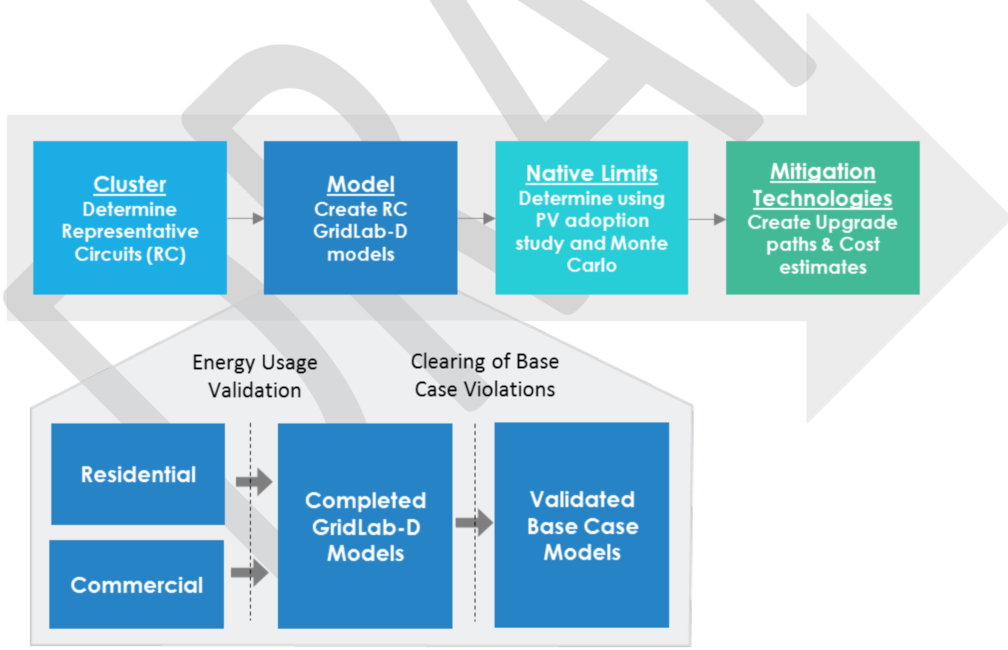


Figure 3.1: Modeling Overview

3.2 Residential Models

GridLAB-D models were created for each residential customer on each representative circuit. These granular models included load models for HVAC, lights, plug loads, pool pumps, cooking ovens, and PV systems, if any on the house. The models were also given area, size, and year built of the houses, in order for GridLAB-D to calculate thermal envelop of the house for accurate energy usage modeling. The customer data was matched to tax assessor data for that customer. SCE engineers created occupant and load schedules for the GridLAB-D models were created based on the demographics of the customers. Thus, these models are quite heuristic, and with no standard process for creation, since each engineer made his/her own judgement calls on how to re-calibrate models to fit match the usage data. **Figure 3.2** illustrates the model creation process.

In order to ensure accuracy of the residential models as a representative of the circuit, an iterative process was used to calibrate the residential model of each representative circuit. This process is illustrated in **Figure 3.2**. Each residential model was calibrated by comparing the consumption data of the customers known to be on that circuit for the given time period (July 2012 to July 2013) to the simulated GridLab-D usage for that entire year, on a 5 minute simulated interval basis. Both the simulated GridLab-D usage and the customer usage data for this time period was binned into six categories (see **Table 3.1**).

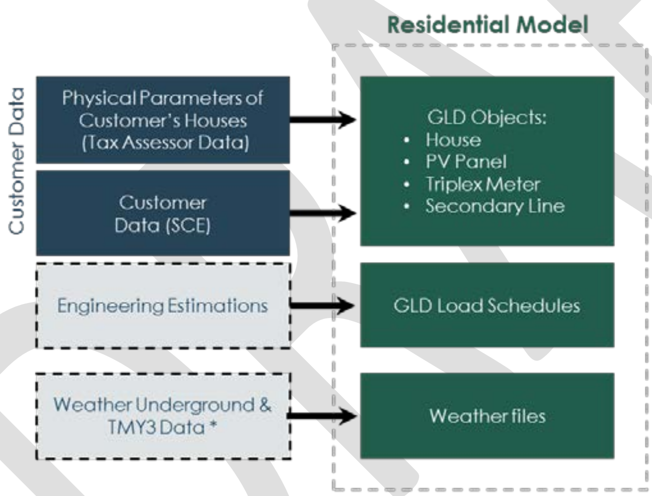


Table 3.1 Usage Bins for Validation (kWh per month)
Bin 1: < 200
Bin 2: [200, 400)
Bin 3: [400, 600)
Bin 4: [600, 800)
Bin 5: [800, 1000)
Bin 6: > 1000

Figure 3.2: Residential model components and overview

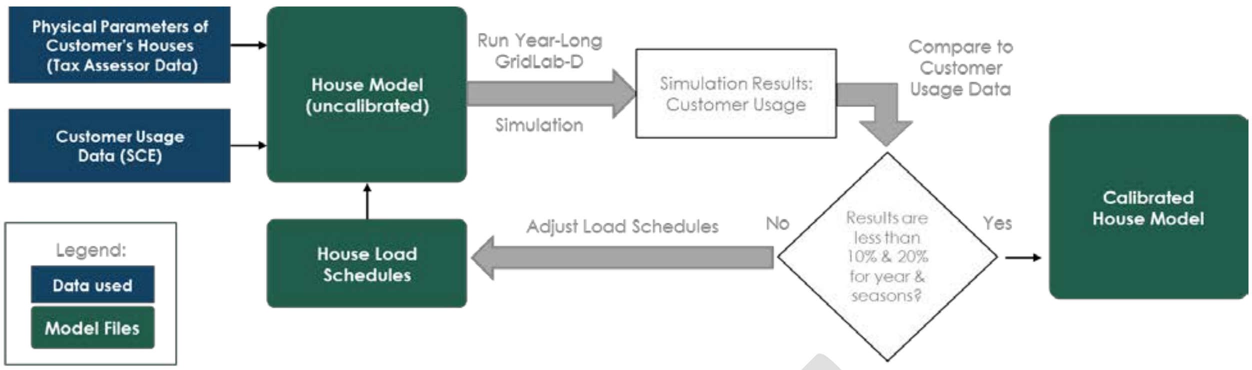


Figure 3.3: Overall Process of Residential Model Validation

3.3 COMMERCIAL MODELS

Unlike the heuristic nature of the models of residential customers, the nature of the commercial customers was statistical. Commercial loads were modelled via regression equations that were fit to historical customer AMI demand and weather data.

Customers were first grouped into cohorts by Climate Zone, Building Type and NAICS Code (North American Industry Classification System). An assumption was made that for each cohort, a regression equation could be developed describing the customer's demand. The regression equations and their coefficients were developed by fitting historical AMI information and weather data to the customer's demand as a function of the hour of day, month of year, day of week and ambient temperature. The average annual consumption of each customer was then used to derive a scaled energy demand profile for each individual customer. Refer to figure 3.4 below:

The user is required to enter the "Building Type", "Climate Zone", "NAICS code" and "average daily usage" for each commercial customer. Based on these input values, the model chooses the appropriate regression equation and calculates the demand based on the Simulation Parameters. **Refer to figure 3.4 below:**

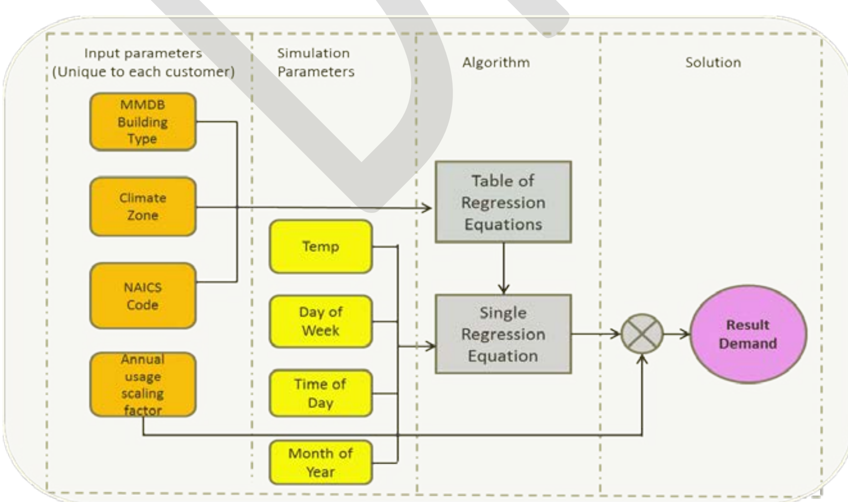


Figure 3.4: Commercial Load Calculation

3.4 PV Adoption Models

Customer data provided locations and sizes of existing PV installations, which were incorporated into the models. However, in order to determine native PV limits of the circuit, a PV adoption methodology was needed. Many PV penetration studies focus on the limit of single large-scale installations on the primary backbone; however, this study focused on the impacts of distributed solar attached behind the customer meter (including residential, commercial, and industrial). To do this, a method was developed to allocate new solar PV installations as penetration levels increased. Guided by a pair of PV adoption models that have been generated to fit base diffusion curves to historical SCE data, the scenarios under analysis represent more accurate PV adoption in terms of installed size and location than has been modeled before at this scale.

Residential PV Adoption

The residential PV adoption model has been developed in conjunction with the California Institute of Technology (Caltech) and specifies the install size and likelihood of PV adoption for residential customers based on both their average monthly energy usage and the rate paid for their electricity.

Commercial PV Adoption

The commercial and industrial (C&I) PV adoption model was developed with the University of California Riverside (UCR) and specifies the install size and likelihood of future PV adoption for C&I customers based on their building type. The base level of solar for each circuit, as of 2014, is shown in **Table 3.2**.

Table 3.2 Base Level Solar Penetrations

Circuit (#)	Residential PV in 2014 (kW)	C&I PV in 2014 (kW)	Residential Fraction	C&I Fraction	Peak Load (KVA)
2	0	3	0%	100%	5783
3	377	28	93%	7%	11106
4	167	12	93%	7%	8846
6	44	31	59%	41%	7016
7	48	32	60%	40%	6231
8	158	41	79%	21%	6076
11	0	22	0%	100%	5971
17	1	65	2%	98%	7917
19	51	5	91%	9%	1750
21	12	9	57%	43%	1578
22	87	1	99%	1%	2096
23	227	32	88%	12%	7923
24	15	19	44%	56%	2951
29	130	27	83%	17%	7081

3.5 MONTE-CARLO BASED SIMULATION

Examining potential future deployments of a large number of small distributed PV systems is significantly more difficult than previous studies' examination of small numbers of large PV deployments. Because of the larger number of units, and the large number of available locations, it is not appropriate to examine a single deployment scenario, since it is only one of many possible scenarios.

A common practice to address the deployment uncertainty is to examine a large number of simulations assuming various uniform distributions of PV on the circuit. While this approach does capture some aspects associated with the uncertainty, a uniform distribution of PV is not a realistic representation of how PV is typically deployed. When a utility has system specific information about where PV may be deployed, as SCE does, a combination of an informed socio-economic adoption model and Monte Carlo simulations can provide insight into the range of possible scenarios for future PV deployment. This Monte Carlo approach was used to ensure that the analysis accounts for the uncertainty associated with estimating future deployments, thus making the analysis more useful for planning purposes. For each circuit, time-series simulations were conducted from 0% penetration of PV up to 100%, in 5% increments. At each 5% increment, 50 cases were examined, each with a different deployment of PV; each deployment was pseudo-random with a bias based on the socio-economical classification of each customer. For each of the 50 cases, four one-week time-series simulations were conducted, one in each season. This resulted in 4,000 one-week time-series simulations being conducted for each circuit.

4 DETERMINING NATIVE LIMITS OF REPRESENTATIVE CIRCUITS

4.1 OVERVIEW

Once base circuit models (with known existing PV installations) were completed, the Monte Carlo PV adoption of new PV installations were added to each model. A total of 50 deployment scenarios were investigated for each circuit. PV was added at penetration levels from 5% to 100% in increments of 5%. For more information on the methodology for simulation and testing, see "*Determine PV Penetration Native Limits of 15 Most Representative Circuits in SCE Territory*." [2]

Definition of solar penetration: Penetration level of PV was defined as the ratio of the installed inverter nameplate rating to the peak circuit load (e.g., 100 kVA of installed inverter capacity on a feeder with a peak load of 1,000 kVA would have a 10% penetration level). While there are numerous other definitions for PV penetration level, this definition was the one used for the entire project.

4.2 OPERATIONAL LIMITS

In order to determine the native PV limits of the circuit models, a set of operating limits were first defined by SCE engineers that were used for all of the simulations. These limits were used to determine the level at which no solar PV can be added to a circuit without upgrading one or more components. If any of the simulations for a given penetration level reaches any of these limits then the circuit is considered to have reached its native PV limit. The operational limits are listed below:

Table 4.1 - Circuit Operational Limits and Thresholds For determining Native Limits

Violation #	Violation	Violation Description
1	Thermal Overloads	Limit: Exceeding any device thermal limit, 100% rating (200% for secondary service transformers)
2	High Instant Voltage	Limit: Any instantaneous voltage over 1.10 p.u. at any point in the system.
3	5 min ANSI Violation	Limit: ANSI C84.1: 0.95>V>1.05 p.u. for 5 minutes at >10% of meters in the system.
4	Moderate Reverse Power	Warning: Any reverse power that exceeds 50% of the minimum trip setting of the substation breaker or a recloser. (Requires analysis of protection coordination)
5	High Reverse Power	Limit: Any reverse power that exceeds 75% of the minimum trip setting of the substation breaker or a recloser.
6	Voltage Flicker	Limit: any voltage change at a PV point of common coupling that is greater than 5% between two one-minute simulation time-steps. (Adapted from the Voltage fluctuation design limits, May 1994)

[2] http://www.calsolarresearch.ca.gov/funded-projects/111-advanced-distribution-analytic-services-enabling-high-penetration-solar-pv

7	Voltage Drop/Rise on Secondary	Limit: 3V drop or 5V rise across the secondary distribution system (Defined as the high side of the service transformer to the customer meter)
8	Low Average PF	Warning: Average circuit power factor <0.85 (Measured at substation)
9	Circuit Plan Loading Limit	Warning: Nameplate solar exceeds 10MVA for a 12 kV circuit, 13 MVA for a 16 kV circuit, or 32 MVA for a 33 kV circuit.
10	High Short Circuit Contribution	Warning: Total short circuit contribution from downstream generation not to exceed 87.5% of substation circuit breaker rating

4.3 Summary of Results

Table 4.2 lists the native PV limits for each of the 15 circuits that were investigated. The native limit is given for both 5% and 10% thresholds for the number of simulations that experiences violations within a given penetration level. Note that thresholds are used to indicate what percentage of simulations must contain violations at a given penetration level to consider the circuit to have failed and require upgrades. Table 4.2 also identifies which of the operational limits (**Table 4.1**) were observed on each of the 15 circuits.

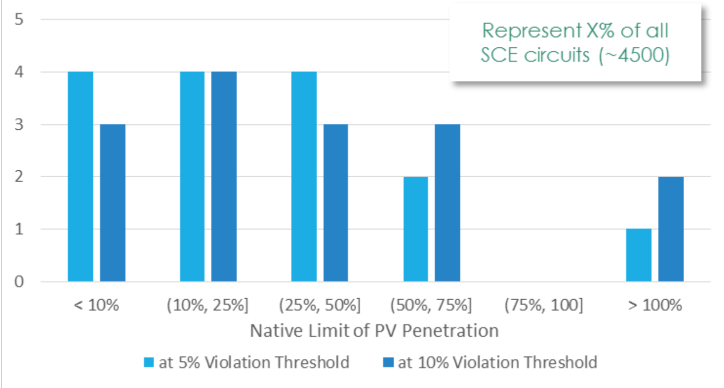
Table 4.2: Summary of Circuit Native PV Limits

Circuit #	Native Limit (5%)	Native Limit (10%)	Peak Load (MW)	Limiting Violation(s)	Nominal Voltage (kV)
2	>100%	>100%	5.8	N/A	12
3	15%	15%	11.1	8, 2, 3	16.34
4	0%*	>100%	8.8	1	12
5	30%	30%	5.7	8	16.34
6	65%	65%	7	8, 1	12
7	20%	20%	6.2	6, 8, 1, 7	12
8	30%	30%	6.1	8	12
11	15%	15%	6	8	12
17	75%	75%	7.9	8	12
19	15%	15%	1.8	6, 8, 3	4.16
21	50%	60%	1.6	3, 8	4.16
22	30%	30%	2.1	8, 1	4.16
23	10%	10%	7.9	8, 7	12
24	10%	10%	3	8, 6, 1, 3	12
29	5%	5%	7.1	8, 1, 3	12

* This is a secondary violation. Limit is >100% for primary violations.

Figure 3.1 shows a histogram of these native limits as well as the percentage of SCE circuits that are represented by the circuits of these limits. For example, assuming a 5% threshold of scenarios with violations, 18% of SCE circuits have native limits of PV equal to or less than 10%, and just 2% of SCE circuits have a native limit larger than 100%.

Figure 4.1: Histogram of Native Limits for 15 Circuits



5 MITIGATION STRATEGIES

5.1 OVERVIEW

Two types of mitigation upgrade paths were developed to enable 100% penetration of solar for each circuit. The first mitigation upgrade path utilizes traditional mitigation strategies and the second utilizes emerging technologies. **Table 5.1** lists the specific mitigation strategies that were investigated in this study to surpass the native PV limits of the circuit models to achieve 100% solar PV penetration.

Table 5.1 - Summary of Mitigation Types and Strategies

Traditional Upgrade Paths		Non Traditional mitigations	
T1	Adjustment of existing shunt capacitor set points	NT1	Fixed power factor on solar inverters
T2	Removal of exisitng shunt capacitors	NT2	Advanced Controls on PV inverter
T3	Addition of shunt capacitors	NT3	Centralized Energy Storage (Utility)
T4	Installation of voltage regulators (regulating their output voltage magnitude)	NT4	Commercial Behind Meter Energy Storage
T5	Reconductoring of a primary line/cable segment		
T6	Reconductoring of a secondary line/cable segment		
T7	upgrade of secondary service transformer		

5.2 SUMMARY OF FINDINGS

The simulations conducted in this study have shown that it is technically feasible for each of the 15 prototypical circuits to support at least a 100% penetration of solar PV if the proper upgrades are conducted. For each of the 15 prototypical circuits, a single traditional and single non-traditional mitigation upgrade plan was presented. These mitigation upgrade plans are representative and are not the only upgrade solution; they are only representative.

The goal of this study was to develop a complete upgrade for each circuit up to 100% penetration. On a number of circuits, it was observed that it was relatively easy to clear violations up to 70%-80% but clearing all violations in the last 20% became more difficult. The difficulty in the last 20% can be attributed to the fact that the simulations are attempting to clear violations in 50 different cases at each solar penetration level. By 100%, there can be a wide diversity in the PV deployment scenario, making it difficult to identify a single solution for all 50 cases. As a result, while it is possible to develop comprehensive plans from 0% to 100% for all circuits, it may be more practical to develop a plan from 0% to 70%, and then to update the plan as actual deployment reach penetration past 35%. This type of stages approach would alleviate the computational complexity and better align mitigation strategies with the actual deployment of solar PV.

5.3 Effectiveness of Non-Traditional Mitigation strategies

This sections examines the ability of the non-traditional mitigation strategies to clear the ten operational limits, compared to traditional mitigation pathways. This section is examining the technical capabilities of the mitigation strategies and not their cost-effectiveness. **Table 5.2** is a summary of how the traditional and non-traditional mitigation strategies were deployed to address the ten violations. Table 5.2 is a summary of the generalized mitigation approach discussed in Section 4. As discussed in previous sections, Violations 4, 5, 9, and 10 were not encountered.

Table 5.2 Mapping of Technologies to Violations

	Violation 1	Violation 2	Violation 3	Violation 4	Violation 5	Violation 6	Violation 7	Violation 8	Violation 9	Violation 10
Shunt Capacitors			X					X		
Voltage Regulator		X	X							
Reconductor (primary)	X									
Reconductor (secondary)	X					X	X			
Upgrade Transformer	X					X	X			
Inverter (fixed pf)		X	X					X		
Inverter (Volt-VAR)		X	X					X		
Storage (central)	X							X		
Storage (distributed)	X									

5.4 Fixed Power Factor on Solar Inverters

Having the solar inverters operate in a fixed power factor mode allows for the production or absorption of reactive power. In this mode of operation, the value of power factor is constant. For a circuit that always has a lagging power factor this mode of operation is well suited to address occurrences of Violation 8. However, this mode of operation can cause additional violations if it is not properly coordinated. Two specific examples of this were seen.

The first example is seen in circuits that have a power factor that swings between lagging and leading due to the reactive load of commercial and/or industrial loads. When a circuit experiences variations in reactive power demand such as this, a fixed power factor control on the inverters is more difficult to implement. While a scheduled power factor can address some of these issues, it could require complex schedules to address the weekly, monthly, and seasonal variations in end-use load.

The second example where fixed power factor inverters are not helpful is when there are multiple high voltage conditions at the end of the circuit due to high penetrations of PV. In this situation there are two options: operate the inverters in a lagging mode to reduce voltage, or in a leading mode to improve power factor. In either case, occurrences of the other violation can increase. With the inverters in a lagging mode, the local voltages will be reduced but the substation has to supply more reactive power, possibly causing Violation 8 occurrences. If the inverters are operated in a leading mode to improve power factor, then the local voltages will increase, possibly causing Violation 2 and/or Violation 3 occurrences.

From this study, it can be seen that fixed power factor controls on PV inverters can be used to address a single violation type if the circuit characteristics are well understood. However, any changes in load over time, or increases in PV penetration, may require the value of the fixed power factor to be changed. Additionally, for circuits with varying reactive power and/or high voltage, fixed power factor control may not provide the necessary operational flexibility unless diurnal schedules are used.

5.5 ADVANCED CONTROLS ON SOLAR PV INVERTERS

Placing advanced controls on the solar inverters alleviates some of the challenges associated with the fixed power factor mode of operation. Specifically, the ability to produce or absorb reactive power, allows the inverters to operate on circuits where the reactive power at the substation swings between leading and lagging.

From this study, it can be seen that the use of advanced inverter controls, in the form of Volt-VAR, is well suited to address voltage-based violations. However, careful thought must be given to the specific operating points to prevent interactions between the inverters. A number of interesting observations were made of inverter-based Volt-VAR control:

1. *Distributed, autonomous Volt-VAR control does not correct power factor at the substation*. In most cases, the inverters are used to lower voltage using a lagging power factor during the day (very common) and raise voltage using a leading power factor at night (less common). This was exacerbated by the sometimes low or reverse active power flow leading to extremely lagging power factors during the day. In most cases, *VAR* controlled capacitors (often more than one) were required to bring the power factor within the required average of 0.85. Different capacitor settings and sizes were needed for each scenario; in some cases, Flexible Alternating Current Transmission System (FACTS) type devices were needed at the substation to maintain a 0.85 power factor average.
2. *VAR settings for open-loop inverter-based Volt-VAR controls are not intuitive*. California Rule 21, Phase 1 (Phase 3 was not yet released at the time of this study) describes a requirement for a Volt-VAR curve, however, by design, does not prescribe a specific solution. It was found that these settings are non-intuitive and often require adjustments for each configuration and/or penetration level. Particularly, the sensitivity of *VAR* adjustments as a function of voltage (or the slope of the curve) was different for each scenario, and often different for each device. The slope had to be "fine-tuned" to balance between enough reaction to correct the high or low voltage and not too much reaction to avoid sudden, large changes in the voltage. In general, any setting that used greater than ~25% of the available VARs resulted in large voltage fluctuations on this circuit, Violation 6. Some of these issues may be addressed by upgrading secondary systems.
3. *Lack of coordination between inverters, especially in high penetration systems, can cause adverse side effects.* As noted in Rule 21, Phase 1, utilizing curves without hysteresis can cause voltage swings. It was found that the use of a dead band, or the use of a curve without a hysteresis, caused significant voltage fluctuations, sometimes leading to system instability caused by control hunting. In addition, when the devices used similar response delays, they could become synchronized by system-wide voltage changes (e.g., a capacitor changed state or the transmission voltage changed on schedule). It was found that the "best" settings (or those with the least swings) included no dead band, a hysteresis curve, and randomized delays.

4. *Additional VAR flows increased the number of secondary transformer and line overloads in a small percent of cases*. The additional VARs from the inverter sometimes led to greater numbers of secondary transformer and line overloads (>200% and >100%, respectively). These were normally very small percent overloads (<5%), and may be a modeling / simulation artifact rather than actual issues.

5.6 Centralized Energy Storage

The inverters associated with substation-based energy storage were able to do an excellent job of mitigating occurrences of Violation 8 when operated as described in Section 2.2.3. The continuous output of the battery inverter is able to control the substation power factor even when the active power is near zero due to back feed from solar PV. The ability to regulate the power factor during periods of low active power is something that is difficult to do with traditional shunt capacitors.

Another additional case that was examined was using energy storage to address a thermal overload of a primary line or cable, Violation 1. A series of simulations were conducted that verified that it is possible to maintain the power flow on a line or cable below a desired value using a single central battery unit. This scenario was examined to evaluate the technical feasibility of deferring a primary conductor/cable upgrade by deploying an energy storage unit. In this case, a single centralized storage unit was deployed on a primary line and operated as described in Section 2.2.4. Given a battery unit with sufficient power and energy ratings, it is technically feasible to defer a conductor/cable replacement indefinitely; but it may not be cost effective.

5.7 Commercial Behind the Meter Energy Storage (Decentralized)

The commercial, behind the meter, energy storage mitigation strategy has the ability to address all violations associated with solar PV, assuming the batteries are large enough. For this study, it was assumed that individual commercial customers operated a storage unit to maintain their peak supply/demand below a desired level. This would be a scenario where the customer is avoiding a capacity charge.

With large enough batteries, it is possible to store all the solar output and discharge the battery during low load periods, but this requires extremely large batteries. For example, a 150kW commercial solar array could generate over 2.0 MW-hr. of energy during a single day. While this size of battery is not practical for most commercial deployments, it is possible to clear the violations using a smaller battery; not all of the solar PV has to be stored.

This study has shown that decentralized commercial behind the meter energy storage can work on circuits where the majority of solar PV is located at commercial sites. Conceptually this scheme could be replicated on residential circuits, but it would require a much larger number of smaller units.

5.8 Noteworthy Mitigation Strategies

This section will cover five circuits that were deemed noteworthy due to the technologies and findings of the mitigation strategies.

How to read the Mitigation Results Table: In this section, the results of this study in terms of operational limits and mitigation strategies are summarized in tabular form for each circuit. The first column states the amount of PV penetration at which a certain violation or mitigation occurred/was implemented. If an operation limit occurred at any PV penetration, it is given in the second column "Limiting Violations". Rows without a limiting violation limited in column 2, but that have mitigations stated, are the result of secondary mitigations that occurred as part of the overall mitigation strategy. Some violations (and therefore mitigations) occurred when looking to mitigate an original limiting violation. Below the traditional mitigation paths, a separate section in each table lists the non-traditional mitigation strategies used to achieve 100% PV penetration. These strategies refer to the operation limits (Limiting Violations) listed at each PV penetration in the top section of the table.

5.8.1 Circuit #7 – Inverter Control in Volt-VAR and Power Factor

Circuit #7 had four violations that prevented 100% solar penetration from being supported. The violations and the percent penetration at which they occurred were are shown in **Table 5.1**. As noted, this circuit like all other circuits were able to achieve 100% PV penetration with traditionally upgrades. For non-traditional technologies, two paths were considered: Volt/VAR control and power factor control using smart inverters.

	at X% PV	Limiting Violations	Traditional Mitigation:
Circuit #7	5%	Voltage Flicker	→ N/A
	20%	Low Average PF	→ Added two new substation capacitors One 12 kvar (Fixed) One 900 kvar (VAR controlled) → Adjusted one existing capacitor (Adjusted existing capacitor set points)
	65%	Voltage Drop/Rise on Secondary	→ Upgraded one residential service drop → Upgraded one commercial service drop
	70%	Thermal Overloads	→ Upgraded two service transformers from 50 kVA to 100 kVA
	85%	(result of mitigations)	→ Upgraded one service transformer from 75 kVA to 100 kVA
		The non-traditional mitigation upgrade path to address these violations:	
	Path 1 0%		→ Fixed power factor control on all new solar inverters, operating at 0.90 leading in the winter, and 0.85 leading in the other seasons
	65%		→ Upgraded one residential service drop → Upgraded one commercial service drop
	70%		→ Upgraded two service transformers from 50 kVA to 100 kVA
	85%		→ Upgraded one service transformer from 75 kVA to 100 kVA
	100%		→ Upgraded one service transformer from 25 kVA to 50 kVA → Added one substation regulator controlling output voltage to 7,000V
	Path 2: 0%		→ Volt-Var control on all new solar inverters
	65%		→ Upgraded one residential service drop → Upgraded one commercial service drop
	70%		→ Upgraded two service transformers from 50 kVA to 100 kVA
	85%		→ Upgraged one service transformer from 75kVA to 100 KVA
	100%		→ Upgraded one service transformer from 25 kVA to 50 kVA

Table 5.1: Limiting Violations and Mitigations for Circuit #11

5.8.2 Circuit #11 – Example of Energy Storage Mitigation

Circuit #11 had only one violation that prevented 100% solar penetration from being supported. Violation 8 occurred at 35%. The violations and the percent penetration at which they occurred were are shown in **Table 5.2**. Two non-traditional mitigation paths were considered for this circuit: a central and a decentralized energy storage. Both scenarios led to 100% PV penetration, however these types of solutions are not cost effective, thus the use of energy storage would best serve as part of a mult-objective control strategy.

Circuit #11	at X% PV	Limiting Violations	Traditional Mitigation:
	15%	Low Average PF	→ Added two new substation capacitors One 600 kvar (Fixed) One 600 kvar (VAR controlled) → Reduced the size of one existing downstream capacitor (600 kvar to 300 kvar)
	The non-traditional mitigation upgrade path to address these violations:		
	Path 1 15%	→ Central energy storage unit in Target pf 0.98, +/- 1050 kvar	
	Path 2: 15%	→ 11 decentralized storage units in peak shaving control Six Large Units, 250 kW/1,000 kWh {Charge on=-55 kW Charge off=-50 kW Discharge on=500 kW Discharge off=300kW} Five small units, 100 kW/ 50 kWh {Charge on=-0.5 kW Charge off=0 kW Discharge on=5 kW Discharge off=0kW}	

Table 5.2: Limiting Violations and Mitigations for Circuit #11

5.8.3 Circuit #19 – Inverter Power Factor Control

Circuit #19 had three violations that prevented 100% solar penetration from being supported. The violations and the percent penetration at which they occurred were are shown in **Table 5.3**. The use of power factor control in inverters was able to achieve 100% PV penetration.

Circuit #19	at X% PV	Limiting Violations	Traditional Mitigation:
	5%	Voltage Flicker	
	15%	Low Average PF	→ Added two substation Capacitors One 150 kVAR (Fixed) One 150 Kkvar (VAR controlled)
	45%	5 min ANSI Violation	→ Added one substaion regulator controlling output voltage to 2,380V
	The non-traditional mitigation upgrade path to address these violations:		
	0%	→ Fixed power factor control with 0.95 leading	

Table 5.3: Limiting Violations and Mitigations for Circuit #19

5.8.4 Circuit #21 – Energy Storage and Inverter control

Circuit #21 had two violations that prevented 100% solar penetration from being supported. The violations and the percent penetration at which they occurred were are shown in **Table 5.4**. The use of energy storage and advanced inverter controls were both investigated.

Circuit #21	at X% PV	Limiting Violations	Traditional Mitigation:
	45%		Added one substation regulator controlling output voltage to 2,420 V
	55%	5 min ANSI Violation	→ Added two substation Capacitors One 1500 kVAR (Fixed) One 1500 Kkvar (VAR controlled) → Removed one exisitng 150 kVAR capacitor
	60%	Low Average PF	
	90%		→ Changed Regulator set point (2,420 V from 2,440V)
	The non-traditional mitigation upgrade path to address these violations:		
	Path 1:		
	45%	→ Added one substation regulator controlling output voltage to 2,420V	
	55%	→ Central Energy storage unit in VAR control Target pf 0.98 +/- 1000 kVAR	
	Path 2:	*Using Advanced invert control*	
	0%	→ Fixed power factor control with 0.95 leading	
	30%	→ Changed fixed power factor control to 0.93 leading	
	40%	→ Changed fixed power factor control to 0.95 leading	
	45%	→ Added one substation regulator controlling output voltage to 2,380V	
	45%	→ Added one downstream regulator controlling output voltage to 2,400 V	
	45%	→ Added one downstream regulator controlling output voltage to 2,400 V	

Table 5.4: Limiting Violations and Mitigations for Circuit #21

5.8.5 Circuit #24 – Inverter Volt-VAR Control

Circuit #24 had four violations that prevented 100% solar penetration from being supported. The violations and the percent penetration at which they occurred were are shown in **Table 5.5.** It was possible to find Volt-VAR set points for all deployment scenarios and penetration levels, but there was not a single set of set points for all scenarios and cases (unlike Circuit #7).

Circuit	at X% PV	Limiting Violations	Traditional Mitigation:
Circuit #24	10%	Voltage Flicker Low Average PF	→ Added two substation capacitors One 600 kVAR (VAR controlled) One 150 kVAR (Fixed)
	45%	Thermal Overloads	→ Upgraded two residential service transformers from 10 kVA to 25 kVA
	65%	5 min ANSI Violation	→ Added one substation regulator controlling output voltage to 7,120V → Added two downstream regulators controlling output voltage to 7,240 V
	90%		→ Upgraded one residential service transformer from 10 kVA to 25 kVA
	The non-traditional mitigation upgrade path to address these violations:		
	0%	→ Volt-VAR control on all new solar inverters	
	10%	→ Added two new substation capacitors 450 kVAR Control 450 kVAR Control	
	45%	→ upgraded two residential service transformers from 10 kVA to 25 kVA	
	90%	→ upgraded one residential service transformer from 10 kVA to 25 kVA	

Figure 5.5: Limiting Violations and Mitigations for Circuit #24

6 GRIDUNITY

Qado Energy's GridUnity platform was configured to create a stochastic distribution planning process that models distribution circuits in GridLAB-D, forecasts PV using an adoption model, determines native limits, and performs mitigation. GridUnity was used in this project to perform native limit and mitigation analysis on distribution system models with end-use loads whose creation is described in section 3. It was also used to create primary-only distribution models, run native limit analysis, and run mitigation analysis for non-representative circuits.

6.1 GRIDUNITY OVERVIEW

To ensure utilities have the flexibility to provide their customers compelling services in a rapidly changing business and regulatory environment, Qado Energy developed GridUnity. GridUnity gives business process managers control over how they configure, deliver and manage sophisticated, technology-driven customer programs and analytic services.

GridUnity is a software platform provided through a secure elastic cloud-computing platform that improves a utility's customer service, engineering analysis, and distribution system planning. It is designed to help utilities modernize their distribution system for distributed energy resources and new loads while streamlining their operations across customer service, engineering, distribution system planning, operations and market policy teams.

Qado's GridUnity™ is a secure, cloud-based Software as a Service (SaaS) platform that:

- brings a holistic visualization of grid data to a utility engineer's desktop
- enables intuitive interactions with data to help users better understand benefits, risks and trade-offs
- supports decision-making at both the detail and the macro level, assisting both engineers and policy-makers
- can be readily evolved over time in order to support changes in best practices

GridUnity's Distribution Grid Analytics can also be configured to enable engineers to perform distribution planning.

Distribution System Planning and Asset Strategy	
Type of Analysis	*Benefits*
Predictive DER growth forecasting	Pro-active System Management
Circuit hosting capacity analysis	System ability to meet RPS goals
Circuit optimization analysis	Increase efficiency and reliability
DER placement analysis	Provide certainty for DER developers

Figure 6.1: GridUnity Distribution System Planning and Optimization

Using randomized inputs based on engineering parameters, GridUnity can generate and simulate a large number of scenarios, then present results in a graphical interface in order to help engineers visualize seasonal variations and other stochastic behaviors.

GridUnity can perform:

- Automation of State Technical Screens Inspired by the FERC SGIP
- Three Phase Unbalanced Power Flow
- Time series analysis
- Protection and Coordination Analysis
- Advanced Power Flow Analytics and Automation Algorithms

The GridUnity platform is being used in a number of ways to research potential grid evolution strategies and envision future high DER penetration scenarios as well as an ideal mix of mitigation options to ensure system reliability. This section outlines one specific use of GridUnity.

6.2 Model Creation & Validation

The process created in GridUnity for this project enables users to perform analysis either by uploading GridLAB-D models they have created themselves, or by uploading a CYME file that GridUnity will then use to create a GridLAB-D model. The second method was added to enable PV adoption, native limit determination, and mitigation to be applied to any of 1,000's of distribution circuits by leveraging CYME models that SCE distribution planners already create as a part of their process. A primary-only model which uses 1 year of SCADA data (3-phase current values) to perform load allocation across the feeder using transformer size is created in this way. This provides users with a simple and streamlined process for performing native limit and mitigation analysis on models created in a program they are familiar with.

GridUnity performs validation checks on models to ensure that they were created successfully, such as checks for defaulted components, loops, unconnected nodes, and phasing inconsistency. Test cases are created to verify power flow executes at peak load levels without errors or violations. In some instances, switch states can be adjusted automatically to break loops or connect disconnected sections.

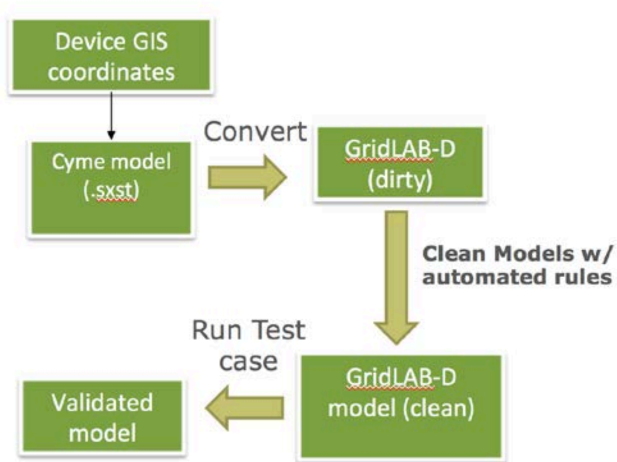


Figure 6.3: GridUnity modeling process diagram

6.3 NATIVE LIMIT ANALYSIS

Analysis scripts created by the project team were used to configure the native limit determination process in GridUnity. The PV adoption process described in section 3.4 was implemented in GridUnity. GridUnity was used to create stochastic future system state scenarios and evaluate when operational limits are reached to determine Native Limits. Results are visualized through a web interface and study files are downloadable.

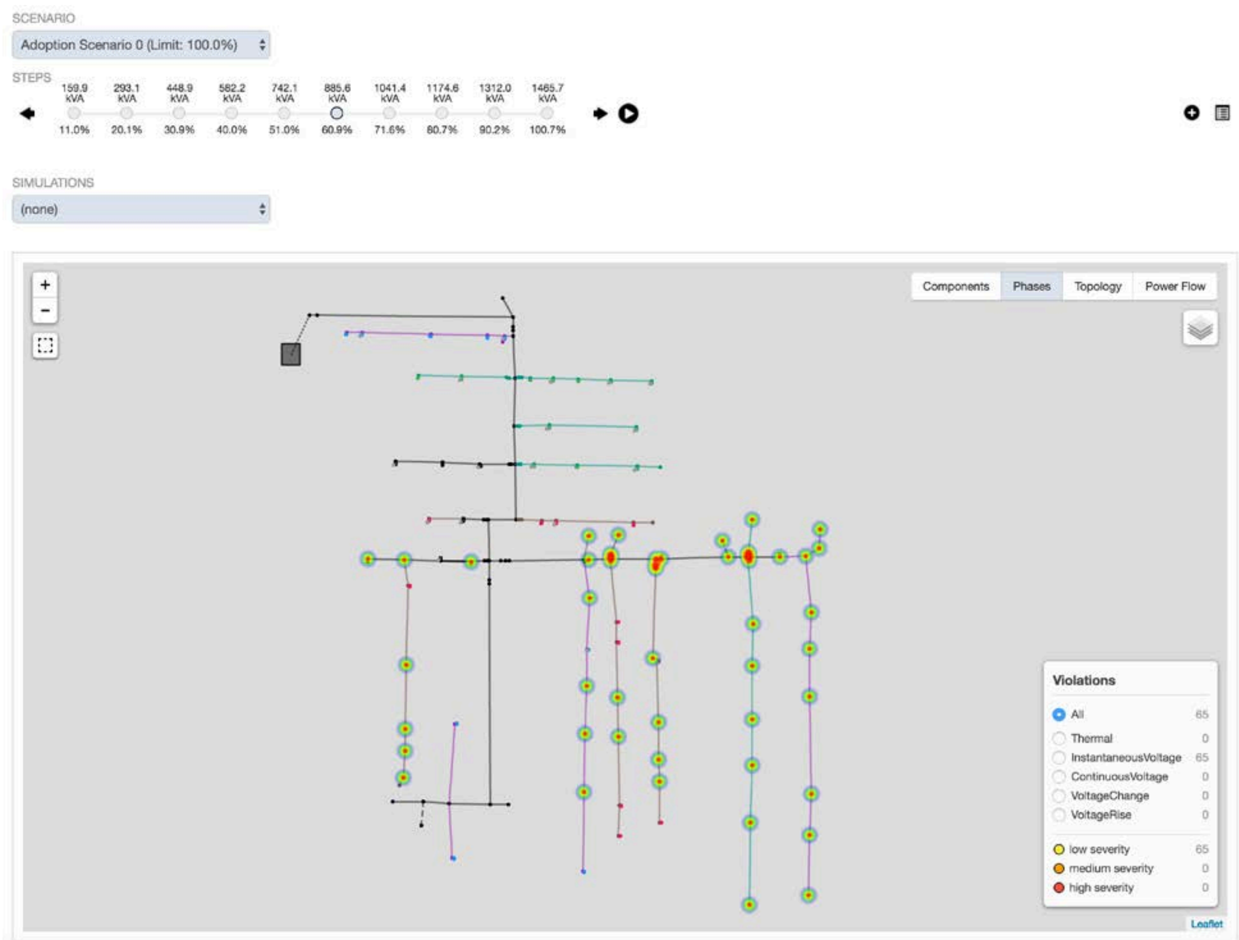


Figure 6.4: Interactive Visualization Displaying Voltage Violations on Non-representative Circuit A

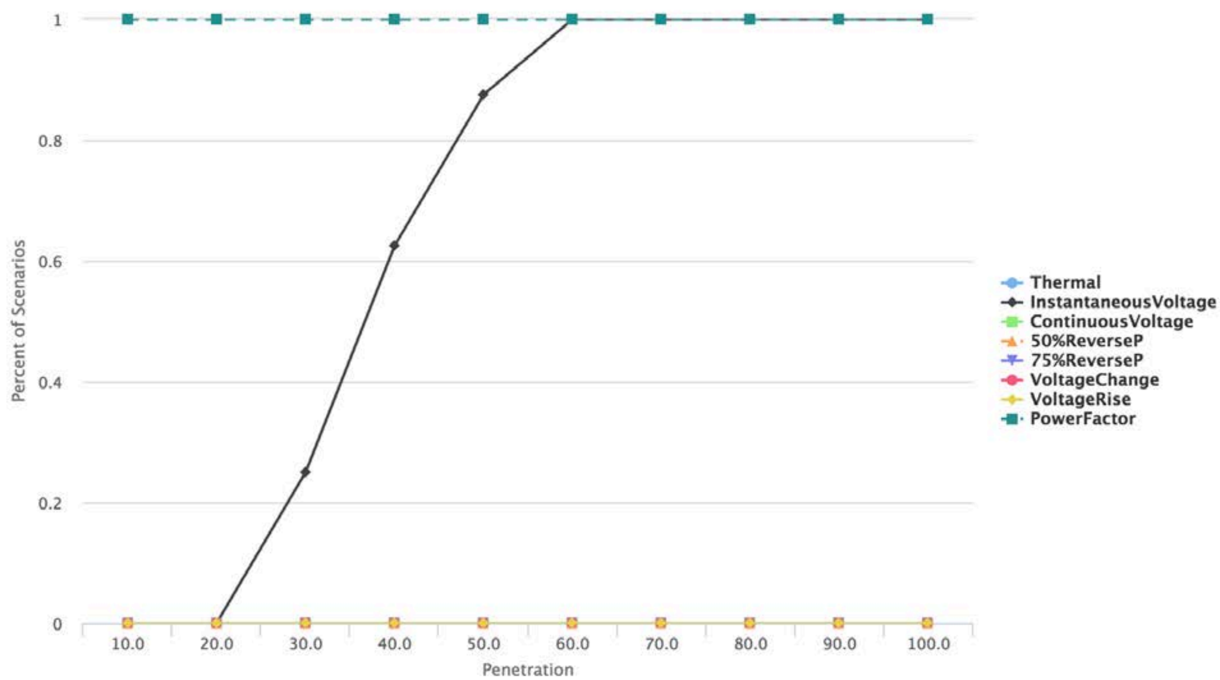


Figure 6.5: Visualization of Native Limit Results for Non-representative Circuit A, which Experienced High Voltage as the Limiting Factor

6.4 AUTOMATED MITIGATION CASE CREATION

GridUnity was configured to enable users to quantify the cost and effectiveness of various mitigation techniques in high penetration PV scenarios.

Mitigating technologies used in this project were broken into three groups based on their potential to interact with each other. Within each group (or "Step") in in figure 6.6 (below), heuristics are applied to create a case for every possible combination of mitigating technologies.

After each Step, the least cost option is selected and propagated to the next step. Dividing the process into steps allows for technologies which don't interact with each other to be simulated independently and thus reduces the total number of simulations.

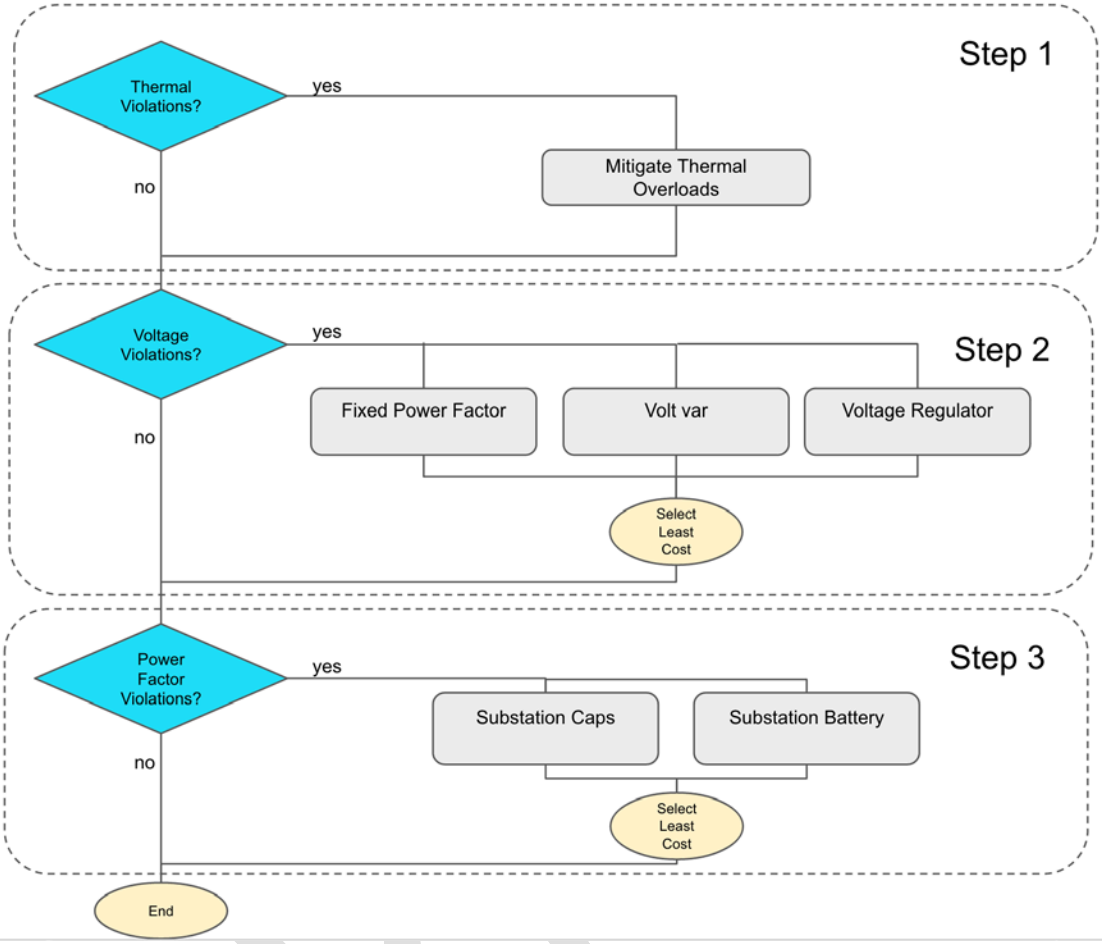


Figure 6.6: Mitigation Process Diagram

Mitigation cases which satisfy the requirements of eliminating all violations are ranked using the below cost assumptions:

Table 6.7: Cost Assumptions

Equipment	Cost	Typical DER Application
Install Line Equipment		
Install Capacitor	$32,200	Support DER Reactive Requirements
Install 12 kV Regulator	$241,800	Support voltage control due to DER
Install 33kV Regulator	$274,000	Support voltage control due to DER
Reconductoring (Per ft)		
Urban Overhead	$180	Support high levels of DER on a circuit
Rural Overhead	$130	Support high levels of DER on a circuit
Underground	$300	Support high levels of DER on a circuit
Battery Storage		
per kWh	$700	Support high levels of DER on a circuit
per kW	$550	Support high levels of DER on a circuit

This results in a summary such as the one below that displays how effective each combination of mitigation techniques was (measured by the percent of scenarios in which it successfully mitigated all violations) and the total cost. Mitigation case names that have multiple keywords (which are defined in Figure 6.8B) signify combinations of techniques.

Table 6.8A: Successful Mitigation Results Non-representative Circuit A

Name	Percent of Scenarios Where Successful	Cost
FixedPowerFactor_-0.85	1	$0
VoltVar_Steeper__Regulator_Case_4	1	$241,800
VoltVar_Steeper__Regulator_Case_2	1	$241,800
VoltVar_Steeper__Regulator_Case_3	1	$483,600
FixedPowerFactor_-0.97__Regulator_Case_3	1	$483,600
FixedPowerFactor_-0.97__Regulator_Case_5	1	$483,600
FixedPowerFactor_-0.96__Regulator_Case_3	1	$483,600
FixedPowerFactor_-0.96__Regulator_Case_5	1	$483,600
FixedPowerFactor_-0.9__Regulator_Case_1	1	$483,600
FixedPowerFactor_-0.85__Regulator_Case_1	1	$483,600

Definitions for mitigation technique keywords are below:

Table 6.8B: Definitions of Mitigation Technique Keywords

Mitigation Technique Keyword	Mitigation Technique Description
VoltVar_LessSteep	All future PV inverters set to volt/var curve: 'V_1' : '0.9','Q_1' : '0.2','V_2' : '1.00','Q_2' : '0','V_3' : '1.0','Q_3' : '0.0','V_4' : '1.1','Q_4' : '-0.2'
VoltVar_MoreSteep	All future PV inverters set to volt/var curve: 'V_1' : '0.9','Q_1' : '0.4','V_2' : '1.00','Q_2' : '0','V_3' : '1.0','Q_3' : '0.0','V_4' : '1.1','Q_4' : '-0.4'
FixedPowerFactor_[setting]	All future PV inverters set to fixed leading (absorbing) power factor. Existing generators not affected.
Regulator_Case_0	One voltage regulator added at the substation and set to: 123 Volts +/-2 Volts on a 120V base
Regulator_Case_1	Two regulators added. One at the substation and one in the middle of the line. Both set to: 123 Volts +/-2 Volts on a 120V base
Regulator_Case_2	Regulate voltage at substation to 120 Volts +/-2 Volts on a 120V base

Regulator_Case_3	Two regulators added. One at the substation and one in the middle of the line. Both set to: 122 Volts +/- 2 Volts on a 120V base
Regulator_Case_4	Regulate voltage at substation to 120 Volts +/-2 Volts on a 120V base
Regulator_Case_5	Two regulators added. One at the substation and one in the middle of the line. Both set to: 121 Volts +/- 2 Volts on a 120V base

6.5 Evaluation of Methodology on Operational Feeders

GridUnity was used to recreate high PV penetration interconnection studies previously completed by SCE engineers. The automated mitigation process described in this report was used to develop a mitigation recommendation.

A model was created that represented the circuit before the generator interconnected. SCADA data was gathered from the year leading up to the interconnection (which would have been used by the engineer studying the interconnection). Actual generators that have applied for interconnection in the past were added manually to the corresponding locations in the circuit models before being uploaded. Results from GridUnity were compared to the results generated for the interconnection study. Feeders were selected with a variety of topology and generator size.

The impact studies performed by SCE engineers showed high voltage in every generator case. Simulation of the same generator scenarios in GridUnity also showed high voltage. Fixed power factor, Volt-Var, substation voltage regulation and midline voltage regulators were simulated as solutions.

Non-representative circuit F, which received an application for a 1.25 MW PV generator, experienced voltage violations in its impact study which were mitigated with a voltage regulator. GridUnity also selected a voltage regulator, but selected a slightly different location for it than the one selected by the engineer. GridUnity used a heuristic that selects the point on the circuit which has the voltage value closest to the midpoint between the substation voltage and the voltage at the point of interconnection on the highest phase at the time point in the simulation when the voltage is the highest.

Non-representative circuit G, which received an application for a 5 MW PV generator, also experienced voltage violations in the generator case and was mitigated with a VAR schedule by an SCE engineer. No major distribution upgrades were required. The GridUnity simulation also showed high voltage and recommended a fixed power factor after considering fixed power factor, Volt-Var, substation voltage regulation and midline voltage regulators as solutions.

6.6 Validation of Cloud Based Tool

In year two of the project, the team selected a group of stakeholders from within SCE: SCE thought leaders, potential users, and participants in existing planning and interconnection processes, to test and provide feedback on the cloud-based tool. Multiple on-site team meetings were held at SCE's offices during the weeks of January 27th, April 7th and June 1st, 2016. Additionally, frequent web meetings occurred with smaller groups throughout the project, culminating in a series of meetings in August of

2016 where feedback on the final tool was received. Participants in these "walk-through" meetings were asked to review the process used by the tool, discussed the informational value of the visuals, and reviewed results. Furthermore, Qado Energy has displayed GridUnity to other North American utilities. This was done to generate industry interest and validate that the configurability of the analytics process would meet the requirements of multiple utilities no matter their size or type of service territory. Conclusions from such discussions were shared back with the team.

Feedback and interest from stakeholders has clearly indicated that a genuine need exists in the industry for a solution to problems of high interconnection request volume and uncertainty around future states of utility distribution systems due to unknown amounts of interconnecting DERs. The widespread interest and resulting discussions have shown there is broad agreement that GridUnity can address such needs through its configurable process and use of elastic cloud-computing which offers the computational scalability necessary to derive actionable results. Feedback has indicated that this tool can be used now to inform planning decisions such as feeder upgrades and inverter operation while taking into account high penetration future system states. Team and other third-party feedback have further resulted in fruitful discussions about how GridUnity can be used to proactively determine feeder upgrades or adjustments that will increase native limits of distribution circuits.

At the end of the project, SCE renewed its GridUnity software license and will continue to work with Qado Energy to improve and develop GridUnity. Feedback from SCE indicates that there could be a benefit to adding functionality to make simulations more accurate, including the creation of customer usage profiles by rate class. During these meetings, any new ideas that would improve GridUnity and support user adoption were added to the GridUnity product roadmap. Also, some users made requests for results to be extractable in tabular format for use in other projects or for publication. Qado Energy will continue to explore ways to best present data to users.

7 CONCLUSION

A subset of the representative feeders (15 feeders which represent 63% of SCE's feeder) were used to perform 4000 time series simulations using GridLAB-D to determine the native limit of each feeder, the maximum amount of distributed solar PV that can be interconnected to each feeder without causing violation of set of operational limits. The project focused on evaluating purely distributed solar PV connected behind the customer meter. A method was developed to create more realistic PV deployment scenarios using Monte Carlo simulation guided by residential and commercial PV adoption models taking socioeconomic characteristics of SCE customers into consideration.

Further analysis was then conducted to evaluate the effectiveness of various mitigation strategies such as traditional infrastructure upgrades, implementation of advanced controls, the deployment of energy storage, and/or demand response. A set of potential "upgrade paths" consisting of both traditional and non-traditional technologies were developed from this analysis to achieve 50%, 75% and 100% PV penetration levels. It should be noted the analysis was done on individual representative feeders fed from different distribution substations located in SCE service territory and more work is needed to extend the result of this study to determine cumulative impact at the substation level using set of adjacent feeders connected to the same bus.

Traditional demand response was also considered by the project as one of the mitigation options, but it was found to be not well suited to mitigate the majority of the operational violations identified in this study which involved high voltage conditions during periods of high solar. The reduction of load also has the effect of raising voltage across the circuit. Under these conditions, what would be required is a demand response scheme that incentivizes load to turn *on*; or directly energizes load through a direct load control system. Demand response could still play a critical role in high penetration solar scenarios, but for the purposes of this project, it was deemed too speculative; fundamental research on the concept is still required.

During the final stage of the project, the team analyzed a set of non-representative and sample operational feeders in the context of the streamlined process to validate methodology developed by the project using Qado's GridUnity tool. Through the use of elastic cloud-computing, it provided insight into the computational requirements and complexity involved in performing time-series simulation with a time scale of 1 minute. Efforts were made to automate the mitigation process as well as quantify the cost and effectiveness of a combination of mitigation technologies.

7.1 KEY FINDINGS

The following are notable key findings and lessons learned based on detailed native limit and mitigation analysis from the project:

- 42-53% of SCE circuits are limited to approximately 50% of PV penetration or less. At least 2 to 7% of the circuits have a native limit at or above 100% PV penetration. These numbers are likely greater, as the subset of 15 circuits analyzed and discussed in this paper represent a total of 63% of SCE circuits.

- The most common violations experienced were power factor and voltage based. The increased penetration of solar affects the voltage of the system, changing the behavior of end-use loads, particularly the duty-cycle, resulting in coincidental loads. Low power factor can result from high penetration PV as power flow reverses, causing a swing in high reactive power.

- Determining how to achieve 100% penetration on legacy circuits can be challenging, with a mitigation leading to new violations.
- Controlling circuit voltage and circuit power factor simultaneously with capacitors is not practical at high penetrations of PV.
- Energy storage is a technically viable solution for power factor, but may not be cost effective unless it is part of a larger multi-objective control strategy.
- Inverter-based Volt-VAR is not able to address low lagging power factor and high voltages at the same time. However, Volt-VAR combined with other traditional upgrades can be highly effective.

7.2 RECOMMENDATIONS

The work from this research project will inform grid modernization efforts currently being undertaken by utilities in CA to integrate higher levels of distribution energy resources and understand the value of these resources. As the mitigation analysis from the project shows, adjustment to existing voltage regulation schemes and adoption of new control strategies are required to integrate capabilities of non-traditional technologies and smart inverter advanced controls to ensure stability and reliability of evolving distribution grid as the level of solar PV penetration increases.

The project implemented the Rule 21 SIWG Phase 1 advanced inverter control recommendations in the form of Volt-VAR. Based on the analysis of the default Volt-VAR curves, the project provided insight on implications of using the default set points from SIWG and recommended modifications to develop specific operating set points. It is anticipated the recommendations based on the simulations and analysis from this project would inform on-going CA IOU DRP Demonstration A discussions and accelerate other similar collaborative efforts to develop standard settings for wide spread application of smart inverter advanced functions. In addition, further analysis and simulations have been conducted and results and recommendations will be published in separate IEEE transaction papers benefiting external stakeholders and the industry as a whole.

Based on the overall analysis and observations from this project, while it is possible to develop comprehensive plans from 0% to 100% for all circuits, it may be more practical to develop a plan from 0% to 70%, and then to update the plan as actual deployment reaches penetration past 35%. This type of staged approach could alleviate the computational complexity and better align mitigation strategies with the actual deployment of solar PV.

7.3 PUBLIC BENEFIT

The results determined through detailed native limit and mitigation analysis would support efforts to address the integration of distributed solar power into the grid in order to maximize its value to California ratepayers. The project developed a set of mitigating options incorporating both traditional and non-traditional technologies that will enable utilities to overcome current system limitations in order to achieve 50%, 75%, and 100% penetration levels. These options and their optimized use will clearly support the goal of maximizing the value of renewables for all California ratepayers. CA IOUs could leverage the learnings from this project to streamline the interconnection process and develop proactive plans to better prepare distribution grid for high PV penetration future system states, reducing the potential for unforeseen last minute expensive upgrades.

The methodology developed by the project was demonstrated using Qado's GridUnity cloud-based platform. The GridUnity visualization was very helpful in displaying the result of the analysis and shedding light on the operational issues and challenges that would limit the high penetration of Solar PV. This would enhance the understanding of the issues associated with high solar PV penetration and complexity of utility's role in ensuring the stability and reliability of the evolving grid. It would also support efforts to increase the transparency of the interconnection process and bring greater clarity to distribution system support for high PV penetration levels. It is anticipated the learnings from this project would significantly improve the quality of the applications submitted to utilities by third parties including customers and solar developers.