Alternatives to the 15% Rule

Matthew Rylander, Robert J. Broderick, Matthew J. Reno, Karina Munoz-Ramos, Jimmy E. Quiroz, Jeff Smith, Lindsey Rogers, Roger Dugan, Barry Mather, Michael Coddington, Peter Gotseff and Fei Ding

Sandia National Laboratories

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Robert J. Broderick and Jimmy E. Quiroz
Photovoltaics and Distributed Systems Integration
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1033

Matthew J. Reno
Electric Power Systems Research
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1140

Karina Munoz-Ramos
Military and Energy Systems Analysis
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1188

Jeff Smith, Matthew Rylander, Lindsey Rogers and Roger Dugan
Electric Power Research Institute
942 Corridor Park Boulevard
Knoxville, TN 37902

Barry Mather, Michael Coddington, Peter Gotseff and Fei Ding
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401

Abstract

The third solicitation of the California Solar Initiative (CSI) Research, Development, Demonstration and Deployment (RD&D) Program established by the California Public Utility Commission (CPUC) is supporting the Electric Power Research Institute (EPRI), National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL) with collaboration from Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San

Diego Gas and Electric (SDG&E), in research to improve the Utility Application Review and Approval process for interconnecting distributed energy resources to the distribution system. Currently this process is the most time-consuming of any step on the path to generating power on the distribution system[3].

This CSI RD&D solicitation three project has completed the tasks of collecting data from the three utilities, clustering feeder characteristic data to attain representative feeders, detailed modeling of 16 representative feeders, analysis of PV impacts to those feeders, refinement of current screening processes, and validation of those suggested refinements. In this report each task is summarized to produce a final summary of all components of the overall project.

ACKNOWLEDGMENTS

EXECUTIVE SUMMARY

The third solicitation of the California Solar Initiative (CSI) Research, Development, Demonstration and Deployment (RD&D) Program established by the California Public Utility Commission (CPUC) is supporting the Electric Power Research Institute (EPRI), National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL) with collaboration from Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E), in research to improve the Utility Application Review and Approval process for interconnecting distributed energy resources to the distribution system. Currently this process is the most time-consuming of any step on the path to generating power on the distribution system [1].

This CSI RD&D solicitation three project has completed the tasks of collecting data from the three utilities, clustering feeder characteristic data, detailed modeling of 16 representative feeders, and analysis of PV impacts to those feeders. In this report, gaps and limitations in the current screening process – California Rule 21 [2] are identified. Technically-based suggestions to improve Rule 21 are made along with a validation of those methods.

Industry Challenge

Various incentive programs have increased the number of solar PV system interconnection requests to levels never before seen. Utilities must evaluate these interconnection requests to ensure proper operation of the grid is maintained. To assist utilities in quickly evaluating these systems, certain "screens" have been developed over the years that help identify when issues may or may not arise. The most common screening method takes into account the ratio of solar PV to peak load (15%), however it does not take into account the locational impact of PV nor the feeder-specific characteristics that can strongly factor in to whether issues may occur. EPRI has shown that a feeder's hosting capacity for accommodating PV is strongly determined by location of PV as well as a specific feeder's characteristics [3].

Project Goal

This project is part of the third solicitation of California Solar Initiative (CSI) Research, Development and Demonstration program created by the California Public Utilities Commission (CPUC) in 2006 to support solar research in California. The objective of this project, entitled *Screening Distribution Feeders: Alternatives to the 15% Rule*, is to develop a screening methodology that efficiently evaluates new interconnection requests while taking into account PV and feeder-specific factors. This method will not only consider peak load levels, but also other critical factors including PV location, aggregate PV effects, and most importantly specific feeder characteristics such as voltage class, voltage regulation schemes, and operating criteria.

The modifications suggested for CA Rule 21 are made based on the technical analysis conducted within this project's detailed PV impact study. The recommendations are based on PV while Rule 21 is inclusive of all forms of distributed generation.

Benefits

This effort will result in improved methods that will allow utilities to more quickly and accurately perform engineering screens for new interconnection requests of solar PV, thus reducing time and costs associated with interconnection studies.

Approach

This project seeks to provide utilities in California (CA) with a useable and accurate way to determine the available capacity for PV generation on existing distribution feeders. The overall project approach will be accomplished via the key tasks outlined in Figure 1. This report will highlight each of the main tasks:

- Document current practices for screening PV interconnections both inside and outside of CA.

- Determine the range of feeder configurations for CA utilities and develop a database of feeder characteristics. Select feeders for modeling and simulation that will be used in developing and validating the proposed screening methodology.

- Complete detailed feeder electrical modeling of selected test group of feeders across CA.

- Simulate a wide range of PV deployment scenarios and penetration levels on each feeder by utilizing EPRI's Distributed PV (DPV) Feeder Analysis Method for determining hosting capacity.

- Develop practical screening criteria for evaluating new interconnection results.

- Conduct formal validation process to determine accuracy of screening methodology.

Document current practices	Characterize Distribution Feeders	Collect high-res PV data	PV Impact Analysis	Develop screening methods	Validate screening methods
(Lead: NREL)	(Lead: Sandia)	(Lead: EPRI)	(Lead: EPRI)	(Lead: EPRI)	(Lead: NREL)
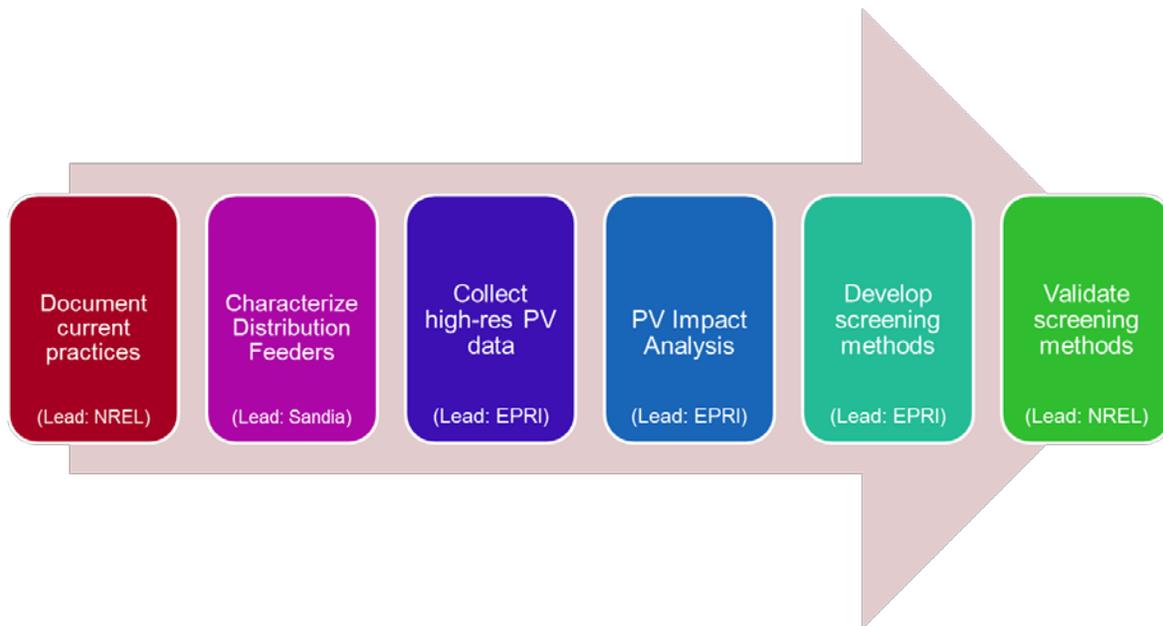
Figure 1. Project Breakdown and Task Leads.

Project Summary

Rule 21 is an interconnection procedure for California utilities to follow for distributed generation application reviews. Utilities have the opportunity to go above and beyond where necessary but at minimum must consider the contained screening methods. The interpretation and application of Rule 21 screens are based on planning procedures and the ability to conduct certain analyses. Most CA utilities have commented that even though Project Task 1 (Documentation of Current Practices) identified that the screening process can take well longer

than the allotted time if supplemental and detailed review are necessary, their proficiency in the review process is considerably better than most utilities due to the number of interconnection requests encountered to date.

Each task of this project helped progress to the final goal of improving CA Rule 21 as penetration levels and interconnection requests continue to increase. The bulk of the project consisted of selecting the feeders for detailed analysis as well as performing that analysis, suggesting updates to Rule 21, and validating those updated methods.

The selection of the utility feeders has been based on the results of a comprehensive clustering analysis where each feeder from the three CA investor-owned electric utilities has been characterized and grouped into representative sets. The representative sets are not suggesting all feeders within the set will have a similar response to distributed generation, but the sets allow selection of several feeders that will have considerably different characteristics. These representative feeders from each utility have been placed into two groups. One group of 16 for detailed analysis and another group of 6 for validation.

A detailed feeder model is developed for each of the selected feeders. The models are based on the utility planning model and converted into the OpenDSS distribution software. The OpenDSS distribution software is used so that detailed analysis can be performed similarly across the different utilities even though the original models come from different software platforms.

The analysis of the models is conducted with PV as the distributed energy resource. Rule 21 is inclusive of all distributed generation types, but this project specifically analyzes distributed PV. The hosting capacity analysis determines the amount of PV that can be accommodated on a distribution feeder without impacts exceeding predefined utility guided thresholds. The hosting capacity for each feeder is unique for voltage and protection issues.

The detailed feeder impact analysis performed identifies when potential issues from aggregate distributed generation are not properly identified and also when a feeder is capable of accommodating considerably higher levels of distributed generation. The "Alternatives to the 15% Rule" found in this project more properly address the impacts from distributed generation and are not dependent on load level alone. The improvements suggested to Rule 21 are illustrated in Figure 2 and include:

- An additional Initial Review screen that addresses if the feeder has line regulators

- A modification to the Initial Review to always account for aggregate generation

- Supplemental Review equations to be used as a guideline to address the impacts of aggregate generation for issues not solely dependent on load

Interconnection Technical Framework Overview

Complete/Valid Interconnection Request

Does the Applicant choose to go directly to Detailed Studies?
— No
— Yes → Go to Electrical Independence Tests and Detailed Studies

Non Export/Net Energy Metering (NEM) or Export?
— Export → Fast Track Eligibility MW Limit — Fail → Go to Electrical Independence Tests and Detailed Studies
— Pass

Non Export / Net Energy Metering

Initial Review Screens A - H

Networked Secondary	A	Single Phase Generator	E
Certified Equipment	B	Short Circuit Current Contribution	F
Voltage Drop	C	Short Circuit Interrupting Capability	G
Transformer Rating	D	Line Configuration	H

Pass All Screens

Fail Any Screen

Does quick review of failed screens determine requirements to address the screens?
— Yes
— No → Supplemental Review (SR)

Initial Review Screens I - M

Will power be exported across the PCC?   I
— No
— Yes

Generating Facility ≤ 11kVA?   J
— Yes
— No

Is Generating Facility a NEM project whose nameplate capacity is ≤ 500kW?   K
— Yes
— Fail No

T. Dependency / Stability Test   L
— Fail
— Pass

Aggregate generation ≤ 15% of line section peak load?   M
— No
— Yes

Screen Q: Does the feeder have Line Reg?
— Yes
— No

Proceed with interconnection subject to requirements determined by Initial Review or SR, if any

Supplemental Review (SR)

Shorthand equations

Penetration Test	N
Power Quality & Voltage Fluctuation	O
Safety and Reliability Test	P

Pass All

Fail Any Test

Are requirements determined without further study?
— Yes
— No → Go to Electrical Independence Tests and Detailed Studies

Figure 2. Suggested Modifications to CA Rule 21.

The modified screens are then applied to the validation feeders to observe and verify the new recommendations. Figure 3 illustrates the Fast Track Initial Review and Supplemental Review

validation on two feeders for centralized PV hosting capacity. The bar charts are shown for each of the six feeder issues considered. The asterisks on each bar chart show the calculated PV hosting capacity using the proposed shorthand equations which are implemented in the Supplemental Review process. Finally, the vertical dashed lines demark the loading level equal to 15% of the peak feeder load.

Feeder 679 does not contain a line regulator, and as expected, hosting capacities are above the 15% peak load limit. Feeder 514 does contains a line regulator, and as expected, hosting capacities are below the 15% peak load limit. The feeder with the regulator would be subjected to the Supplemental Review process immediately as opposed to allowing PV deployment up to 15% of peak load and then implementing the Supplemental Review. At some point, the aggregate generation on the feeder will cause adverse impact, thus aggregate generation should always be considered during interconnection requests. After determining the approximate hosting capacity with the Supplemental Review equations (asterisks), the feeders' ability to accommodate PV is shown to be independent of load level and better matches the detailed analysis. Therefore, the modifications to the Initial Review and Supplemental processes can improve screening interconnection requests.
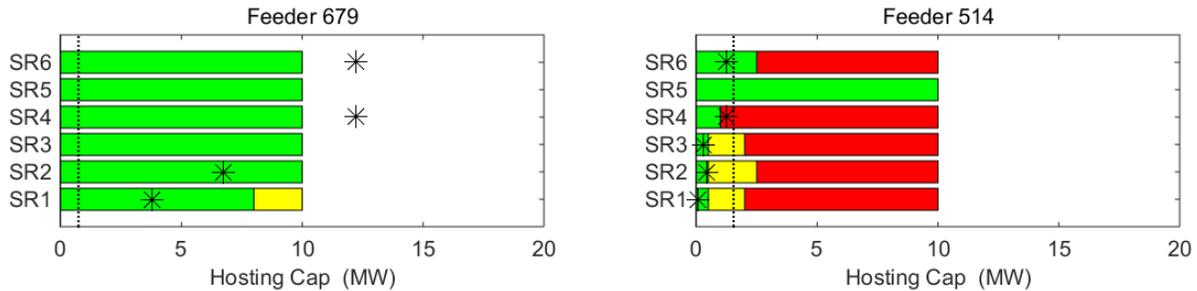

Figure 3. Centralized PV hosting capacity for Validation Feeders.
Dashed lines indicate 15% peak load
Asterisks indicate alternatives to estimating hosting capacity

In a parallel effort to this project, the California Public Utility Commission mandated that the utilities develop Distribution Resource Plans (DRP) to prepare for future growth of distributed energy resources. The DRP is not a replacement for interconnection studies or Rule 21, however the DRP can be used to further improve the analysis of aggregate generation as is done in this project (illustrated in Figure 4). If the DRP analysis is not conducted on the feeder under study, the shorthand equations can still help to better estimate aggregate PV limits for a feeder.
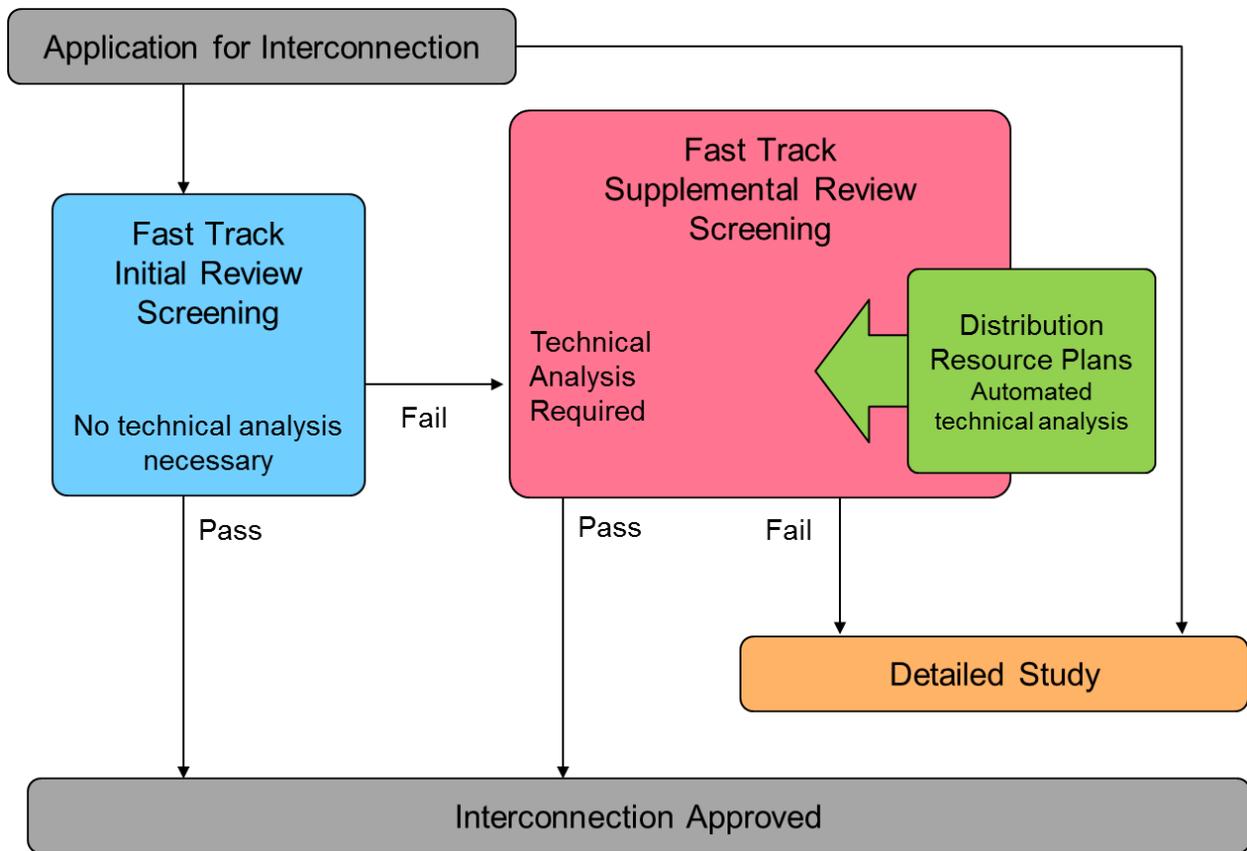
Figure 4. Screening in Coordination with Distribution Resource Plan.

Project Team

This CPUC/CSI project combines the experience of individuals across the industry, including:

- Electric Power Research Institute - Project Lead
- National Renewable Energy Laboratory
- Sandia National Laboratories
- Itron

Utility Partners:

- Southern California Edison (SCE)
- Pacific Gas & Electric (PG&E)
- San Diego Gas & Electric (SDG&E)
- Sacramento Municipal Utility District

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FIGURES

1. INTRODUCTION

The third solicitation of the California Solar Initiative (CSI) established by the California Public Utility Commission is supporting EPRI, NREL, and SNL with collaboration from SDG&E, PG&E, and SCE in research to improve the Utility Application Review and Approval process of interconnecting distributed energy resources to the distribution system.

Working with the three investor-owned utilities, the project team evaluated the impacts of PV on the distribution system through detailed hosting capacity analysis. The results of this analysis led to the identification of additional Fast Track Initial and Supplemental Review screens that could be applied alongside the existing California Electric Rule 21 screens. These new screens are derived directly from the technical analysis and will more appropriately predict the amount of PV that can be accommodated on a feeder regardless of its loading. The recommendations are based on PV while Rule 21 is inclusive of all forms of distributed generation.

The focus is on PV due to the proliferation of interconnection requests. In 2013 alone, there were approximately 155,000 interconnection requests accepted in the US with 94% connected to the distribution system. Considering a significant portion of the interconnection requests are not approved for various reasons, utilities are faced with an unprecedented amount of requests that must go through the interconnection process.

1.1 Current Practices

The California P.U.C. Rule 21 Interconnection Technical Framework is illustrated at a high level in Figure 5. The Utility Application Review and Approval process is currently the most time-consuming of any step on the path to generating power on the distribution system [1] [4]. The process includes two main pieces that will be referenced in the report. The highlighted sections indicate the Fast Track Initial Review process (blue) and Fast Track Supplemental Review process (red). All applicants enter the application process and are either directed to the Fast Track process upon eligibility or are directed to detailed studies. Once in the Initial Review process, a failure of a screen could direct the applicant's review to Supplemental or Detailed Analysis. Supplemental Review is part of the Fast Track process but an intermediate step between Initial Review and Detailed Analysis. Each process deeper in the review requires more thorough analysis and requires additional details.

The application process allows utilities approximately 15 business days to perform Initial Review screens. From that Initial Review, the utility can determine if Supplemental Review is required. Twenty additional days are allowed for Supplemental Review. If the interconnection request is not granted after Fast Track screens, detailed impact studies are preformed within less than 120 calendar days. Interconnection requests primarily fall into one of the two following categories: (1) those that are granted based on Initial Review screens and accepted within 10–15 business days, or (2) projects with significant delays 2–3 weeks beyond the allowed time. Among several reasons, the cause of longer application decisions can be attributed to utility-required Supplemental Reviews or impact studies beyond initial screens.

As a supplement to the Rule 21 process a number of the utilities in California have developed additional PV screening methods and criteria to expedite the PV interconnection process and to avoid requiring detailed studies of systems that don't warrant such analysis. The utilities and the entity requesting the PV interconnection are served best when detailed studies are only required when some form of impact mitigation needs to be defined (e.g. changing the control settings on a line regulator, reconductoring a portion of the feeder, etc.)
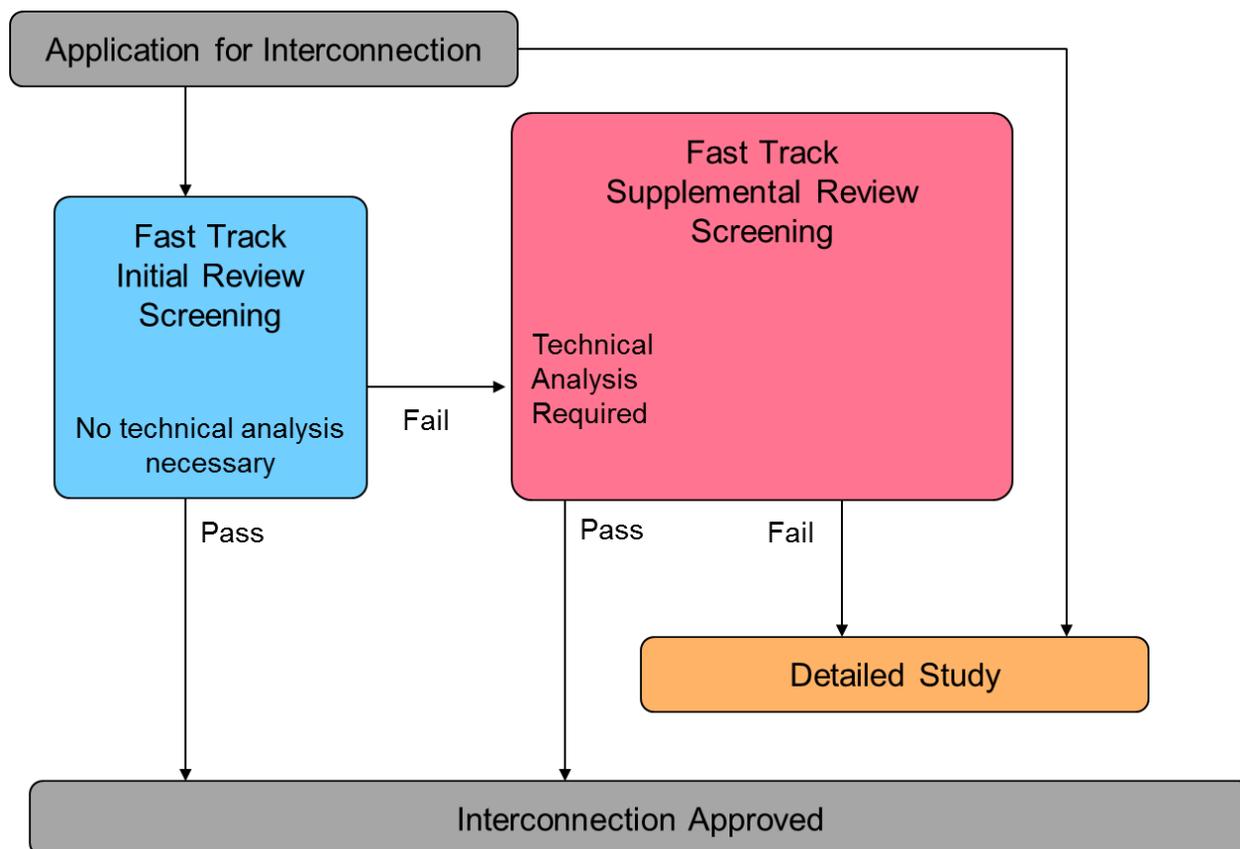
Figure 5. Basic California Rule 21 Screening Process.

1.2 Improving Current Practices

Adequate consideration of PV throughout the interconnection process is necessary and a key focus of this project. PV is considered as the primary form of DER because of the amount of interconnection requests as well as the variability of the resource. Based on the Measurement Task [5], Figure 6 shows that various locations throughout California have daily solar variability [6] that can span the range from low to high variability.
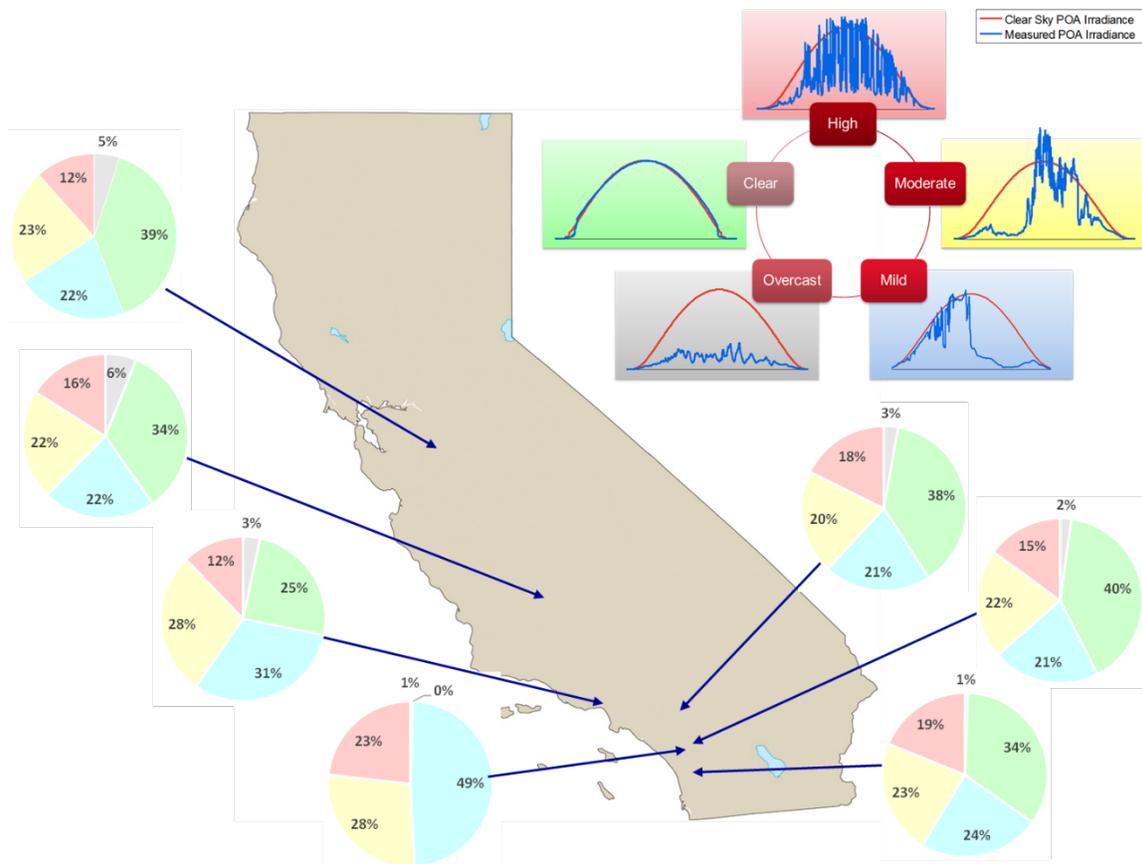
Figure 6. Solar Variability in California (pie chart colors correlate to solar data-type).

The improvement to the Fast Track process comes from identifying gaps where incorrect approval could occur as well as suggesting simple calculations to more accurately determine a feeder's ability to accommodate PV [7]. This will improve and expedite the application review and approval process.

This final report highlights the findings from each key task. Task 1 examines the current utility practices. Task 2 collects utility feeder characteristic data and clusters them to identify approximately five feeder groups for each utility. Task 5 models a feeder selected from each group. Task 6 performs a detailed PV impact analysis on each modeled feeder. These impact results then inform the additional screens and enhancements to the current California P.U.C. Rule 21 that is derived under Task 7 and validated under Task 8.

2. CURRENT APPLICATION SCREENING PRACTICES

Interconnection procedures and the various tools and techniques used to evaluate interconnection requests (applications) vary from utility to utility. Standardized interconnection procedures, permitting procedures, and building guidelines have been developed in California before other states began focusing on these topics. These procedures have been put in place to ensure that safety, reliability, and power quality are maintained throughout the grid. In the past few years, many of the utilities in California and elsewhere have worked diligently to improve their PV screening and study processes thereby reducing the costs and the total time from application through interconnection with the electrical distribution system.

This portion of the project focused on collecting the PV screening methods and interconnection practices from utilities currently seeing significant amounts of distribution-connected PV. The goal of the survey is to identify leading practices that might be considered by all utilities that have a large queue of proposed PV installations on their electric distribution systems, as well as those who are positioning themselves for new PV interconnection applications and installations. In this section the methods used to complete the survey are presented first followed by a summary of the survey findings.

2.1 Survey Methodology

Each utility that participated in the survey has been asked a series of detailed questions regarding interconnection processes, screens, tools, impact studies and mitigation methods. Some of the utility experts completed many of the questions prior to the completion of an in-person interview. Additionally, all utilities have been included in a conference call covering the same questions but with a broader participation (i.e. with multiple distribution engineers, managers, etc.).

The questionnaire used for the interviews and conference calls with each utility is developed with inputs from the CPUC, Itron, EPRI, IREC, and NREL. The details of the specific questionnaire are provided in the full report on this part of the project [4]. The primary focus of the questionnaire is designed to determine the types of impact studies, distribution modeling methodologies, and the mitigation approaches used at each utility, as well as any unique tools or methods currently being used to screen PV interconnection requests.

Southern California Edison (SCE), Pacific Gas and Electric (PG&E), San Diego Gas and Electric (SDG&E) and the Sacramento Municipal Utility District (SMUD) were interviewed between December, 2012 and January 2013.

2.2 Summary

The four utilities interviewed for the survey illustrated a number of "best practices" based on the experiences of the utility personnel interviewed. An immediate and clear finding is that each utility processes interconnection applications differently, and utilizes a myriad of distribution

modeling software tools, impact study types and various mitigation strategies when a PV system is identified as creating a significant impact on a distribution feeder.

There are a number of best practices highlighted when working with the four California utilities. The identified best practices in California for the interconnection of PV systems onto distribution systems determined through the survey and interviews are:

- Use of state-wide interconnection procedure (Rule 21 in CA)

- Use of online interconnection applications for PV developers and utility customers

- Online tracking of PV application for both utility workers and PV stakeholders (e.g. PowerClerk)

- Use of industry standard screening processes to identify Fast Track PV applications for quick approval

- Use of national standards to ensure power quality and safety (UL1741 and IEEE1547)

- Use of supplemental screens or individual reviews for interconnection agreements that fail Fast Track screens but may still qualify for quick approval

- Use of "no study solutions" (fully avoiding the cost of a detailed modeling study) to mitigate potential problems with known approaches that are often low-cost (e.g. changing service transformer or voltage regulator controls)

- Use of GIS systems to track distribution system components for use in modeling efforts

- Tracking of all DG and PV systems on GIS for fast analysis of new interconnection agreements (this includes timely updates to GIS systems with PV that are attached to the correct area in the distribution system and with significant detail on the size and type of technology)

- Use of a standard distribution-modeling platform for evaluating all DG on a circuit (while no single platform currently conducts all types of impact studies, those that can perform several studies are preferred)

- Standard application fees for PV interconnection applications and limited yet reasonable times necessary to perform analysis

As utilities in California, as well as states such as Arizona, Massachusetts, Hawaii, New Jersey, and Colorado, have seen large numbers of interconnection applications in the past five years, they are already developing better and more efficient methods to screen PV interconnection requests and ultimately aid in the more expeditious deployment of PV in a safe, reliable and cost-effective manner within their respective service territories. Additionally, public utility commissions in some states have developed their own methods for interconnection, such as the California Rule 21. As many states have yet to adopt a uniform approach for interconnection they are in a good position to adopt the most accurate and timely PV interconnection screening techniques in the near future. The more compatible these adopted state level PV interconnection regulations can be the less complex the PV interconnection landscape will be for all PV stakeholders – utilities and PV developers alike.

Clearly there are processes that have been developed by many electric utilities to manage the large numbers of interconnection applications. The best interests are served when PV applications can be approved quickly or moved to impact studies quickly, and done so with the safety, reliability, and cost-effectiveness of the utility system in mind.

3. CHARACTERIZING DISTRIBUTION FEEDERS

In order to determine alternative screening methods that can be used, the range of feeders that the PV systems might be connecting to must be evaluated. The feeder characterization task consisted of two parts: 1) characterize 8,163 distribution feeders by developing a database of feeder characteristics to determine the range of feeder configurations and 2) determine a set of representative feeders to be used in the project by analyzing the statistical range/distribution of feeder configurations, types, and electrical characteristics. The primary goal of this task is to understand the overall statistical feeder population, cluster the feeders into representative groups, and then select specific representative feeders for study/analysis.

3.1 Feeder Data

This task identified feeder characteristics that represent the known range of feeder types in California and are known to affect hosting capacity. Extensive experience with distribution impact studies and familiarity with utility databases is utilized to compose a set of feeder characteristics to describe the variation in the feeder population. The set of feeder characteristics are selected based on their likelihood to affect hosting capacity of the feeder for voltage, thermal and protection impacts. The groups of characteristics identified include:

1. Nominal voltage level (e.g., 4kV, 13kV, 25kV, etc.)

2. Feeder length and main conductor type

3. Three-phase vs. single-phase feeder length

4. Voltage regulation schemes (load tap changers, feeder regulators, switched capacitor banks)

5. Load mix (residential, commercial, industrial)

6. Load shape (peak, minimum load, seasonality)

7. Existing DG and PV deployment levels (kW)

8. Utility operational practices (e.g. use of conservation voltage reduction schemes)

9. System protection devices

3.2 Key Differences

The characteristics of the feeder data received vary significantly within a utility and even more among the different utilities. Figure 7 shows the distribution of feeder voltage class for all three utilities. The majority of feeders for Utility 1 and Utility 2 have a nominal voltage of 12 kV. Utility 3 provided data only for 12 kV feeders which is the voltage class for the majority of their feeders.
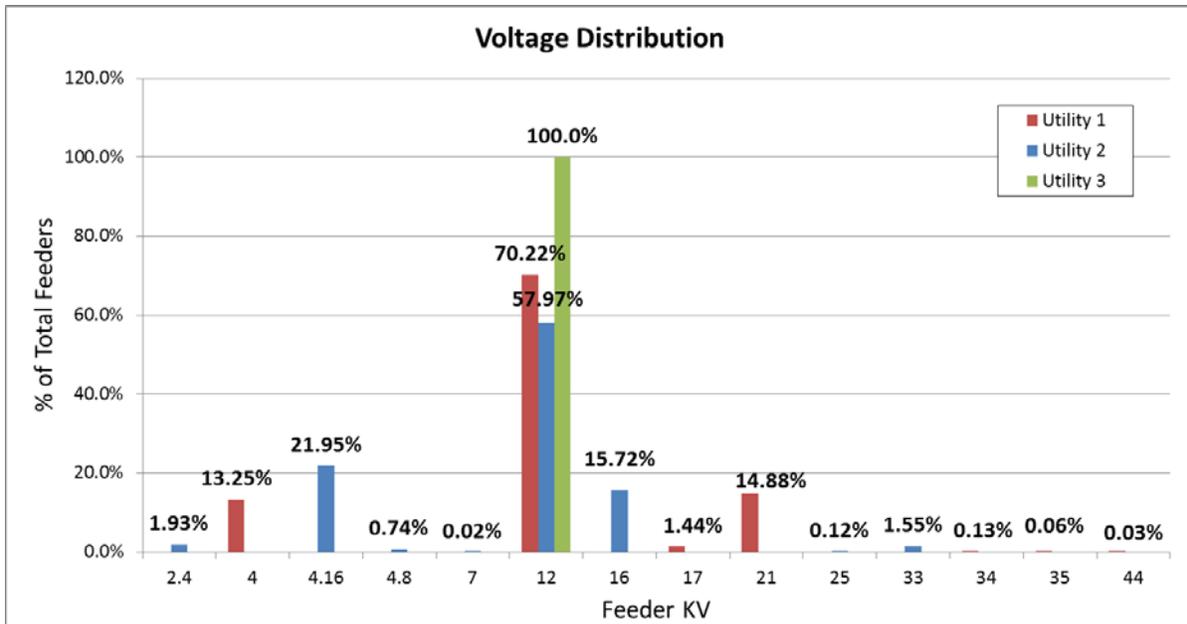
Figure 7. Voltage Class Distribution for All Three Utilities.

Figure 8 shows the distribution of three-phase line length for all three utilities. The three-phase length distribution is defined as the sum of all three-phase sections within the feeder. Utility 1 has long feeders with several over 80 miles in length. The majority of three-phase feeders for Utility 2 and Utility 3 are less than 20 miles in length and all of them are less than 80 miles in length.
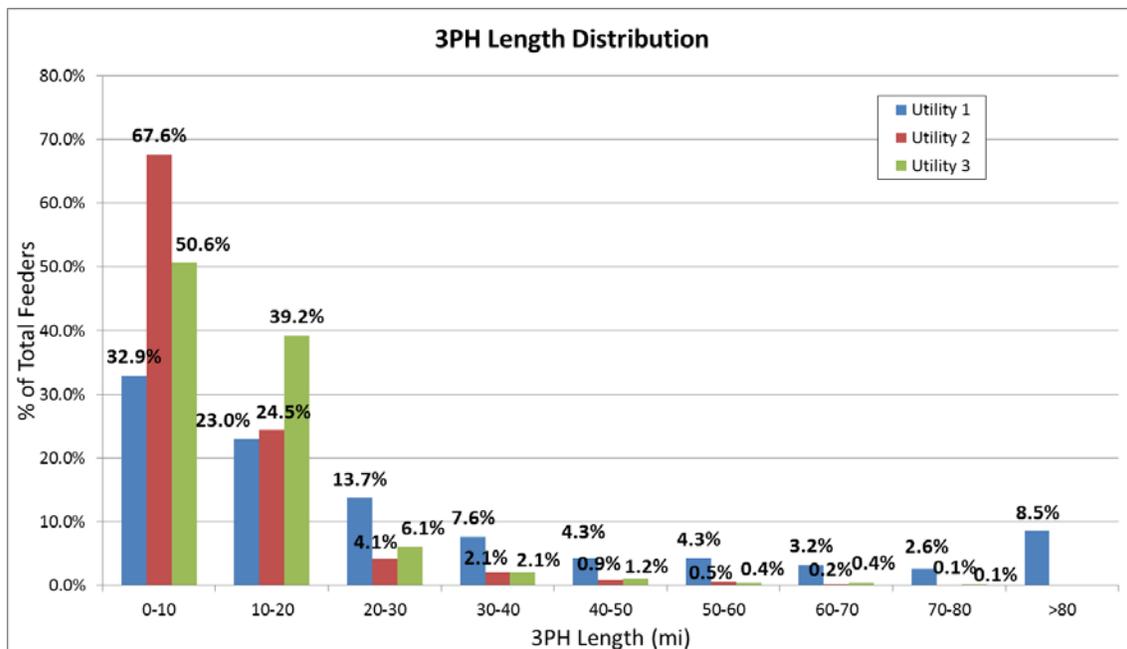
Figure 8. Three-Phase Line Length Distribution for All Three Utilities.

Figure 9 shows the distribution of voltage regulators for all three utilities. Less than 10% of the feeders within Utility 2 and Utility 3 have voltage regulators. Utility 1 uses regulators more often.
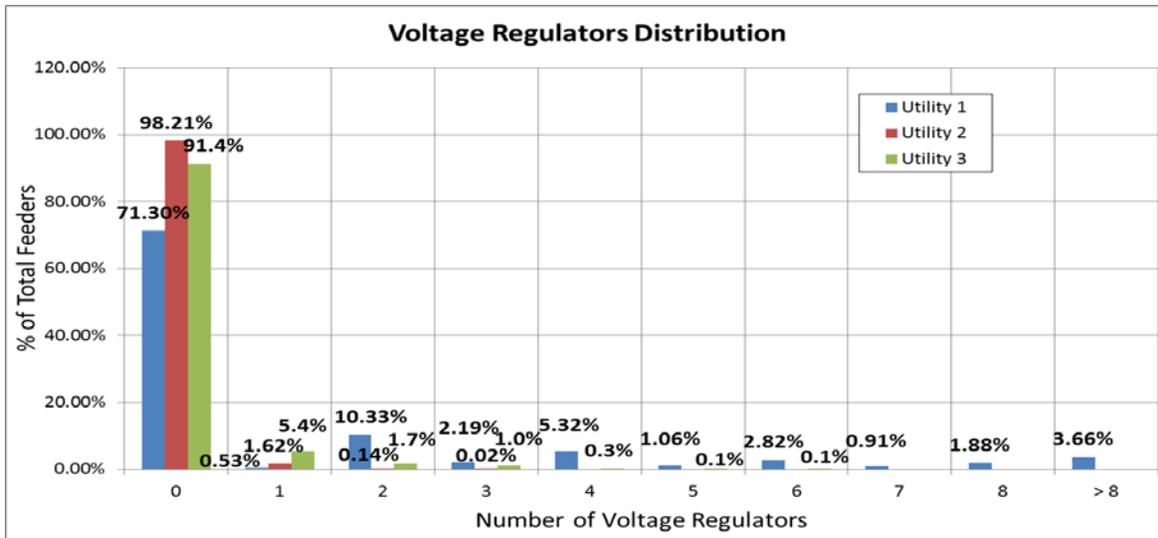
Figure 9. Voltage Regulator Distribution for All Three Utilities.

3.3 Clustering Approach

The goal of this task is to develop a method to classify distribution feeders into clusters and to select representative feeders from each cluster. The K-means clustering methodology is used for grouping distribution feeders and the Cubic Clustering Criterion (CCC) is used for determining the optimum number of clusters. One of the main advantages of the K-means algorithm is its quick convergence for large data sets (greater than 200 elements) making it more popular than hierarchical clustering approaches. For this project the K-means expectation-maximization algorithm (used by SAS JMP [8]) is used as it is known for its ability to accommodate clusters of variable size much better than the original K-means algorithm. For more details on the clustering methodology see [9].

3.3.1 Initial Data Review and Cleanup

Although the same data request had been sent to all utilities, data received differed due to availability and ease of retrieval. The review process consisted of the following steps:

- *Histogram generation.* Histogram plots can be found in the *EPRI RD&D Solicitation Three Feeder Database and User's Guide* [10] for each utility.
- *Data clarification.*
- *Outlier identification.*
- *Boundary definition.*
- *Data anomaly documentation.*
- *Data set preparation.*

3.3.2 Selecting Variables for Clustering

Initial variables are selected based on the impact they might have on differentiating feeder types and on DG hosting capacity. The initial variables varied among utilities as needed to account for differences in availability of data from each utility. These initial variables are analyzed using a correlation map to show the degree of correlation among all variables. Because the optimum

number of clusters is more accurately achieved when the chosen variables are independent of each other, pairs of highly correlated variables are examined more closely to determine if it is beneficial to remove one of the variables before clustering. The degree of correlation is used to develop a list of candidate pairs for evaluation. For example, *Total 3-Phase Circuit Miles* and *Total 3-Phase Overhead Circuit Miles* had a strong positive correlation. Therefore one of these two variables is removed before clustering. Once an optimal clustering has been obtained, no further variables are removed.

3.3.3 Removing Outliers

Feeders labeled as outliers are those that are not representative of the overall data set. K-means clustering algorithms can be very sensitive to outliers, especially if the initial cluster means are chosen based on the outliers, which is often the case since many algorithms start by choosing initial cluster means as far apart from each other as possible. Therefore, when using K-means as the clustering technique, removing outliers can help improve convergence speed and will make the clustering more reliable. Outliers in the dataset are identified by *Distance* – a multivariate calculation that is a measure of how similar a particular feeder is to its closest neighbor. Although two feeders may share similar characteristics (and thus have a small distance between them) they themselves may be unique among the dataset. Therefore, rather than basing outlier removal on the distance between a feeder and its closest neighbor, a distance measure from each feeder to its twelve closest neighbors is computed and these distances are used to compute an average distance. If the average distance is above a certain threshold (different for all utilities) the feeder is considered an outlier and removed from the clustering process.

3.3.4 Cubic Clustering Criterion

The optimum number of clusters can be derived from a cubic clustering criterion value based on minimizing the within-cluster sum of squares. Although not a mathematical law and more of a rule of thumb that has been accepted in the statistical community, the optimal number of clusters can be determined by plotting the CCC value against the number of clusters and finding a local maximum after the CCC rises above 2 and before it drops below 2. Statistical analysis is performed using the SAS JMP software tool to calculate the CCC value for each cluster number.

As discussed previously, the variables selected for clustering are down selected from a larger set by excluding certain highly correlated variables. The down-select process for the variables to be used in the clustering algorithm helps with selecting the optimum number of clusters for a given data set as shown below in Figure 10. Two example CCC plots are shown below in Figure 10. In Figure 10 (left) all of the original variables are used in the clustering algorithm to compute the CCC value. As the number of clusters increases, there is a continual rise in the CCC value with no definitive peaks up until 22 clusters. The CCC value never drops back below 2. Figure 10 (right) shows a CCC plot using the down-selected variables based on correlation. There is a definitive peak occurring at 12 clusters, followed by a drop in the CCC value that goes below 2. This indicates that the ideal number of clusters for this data set is 12.
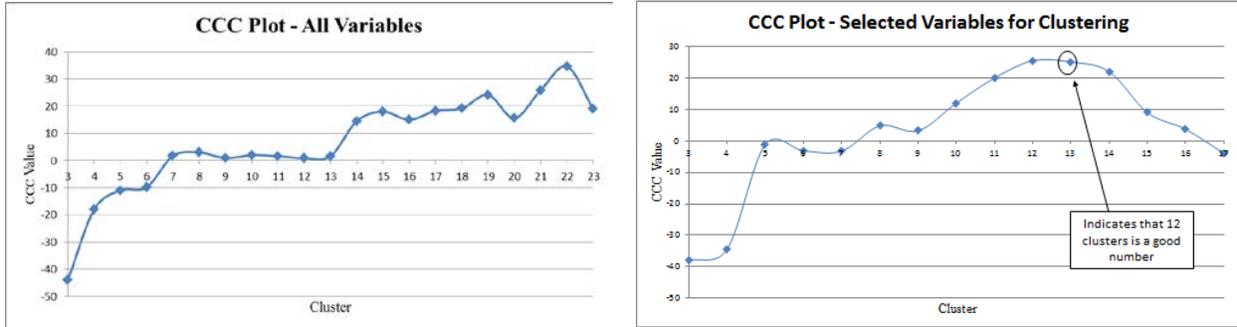
Figure 10. CCC Plot with All Variables (left) and with Selected Variables (right).

3.3.5 Feeder Selection

Figure 11 shows an example of a biplot for the feeders within a single cluster. The multiple data dimensions have been reduced using Principle Component Analysis (PCA) to the two dominant aspects of variation. The '*90% radius*' depicted in Figure 11 is the length from the cluster's center to a circle that captures 90% of the feeders. This radius represents how tightly grouped the feeders are within the cluster. Feeder selection from within the cluster is accomplished by sorting the feeders based on their distance from the center and selecting feeders that are closest to the center of the cluster (therefore highly representative of the cluster). Other important parameters used to make final feeder selection included significant PV system presence and the existence of feeder SCADA data. These parameters are critical for developing the accurate feeder models needed for analysis.
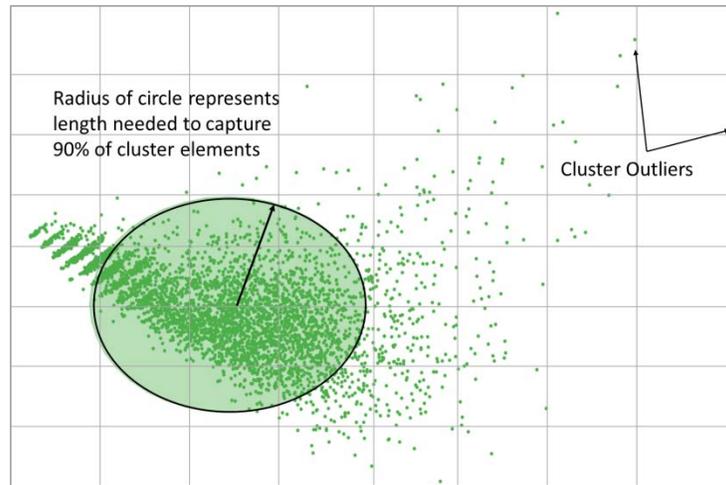
Figure 11. Example of Cluster Biplot.

3.4 Summary

This task identified feeders to be used in the development of a modified screening method. Ideally, one feeder would be chosen from each identified cluster to represent all of the three participating utilities appropriately, however, more than sixteen total clusters have been identified. The clusters are further examined to determine similar primary characteristics to reduce the number of clusters from which feeders are chosen for detailed analysis.

One of the primary characteristics to manually reduce clusters is voltage class. The utility feeder clusters represent a wide range of voltage classes from 4 kV to 33 kV. The majority of the feeders fall into the 12 kV class, therefore, the majority of the feeders chosen for analysis are selected from that voltage class. Three clusters are used to represent outlying voltage classes such as 4 kV and 33 kV.

There are twenty two feeders selected from those identified in the clustering. The final set includes sixteen feeders for detailed analysis and development of the screening methodology, while six feeders are reserved for validation of the methodology.

More recent work [11] has investigated the accuracy of clustering distribution system for determining hosting capacity. While it has been shown that clustering does not necessarily perfectly group all feeders into narrow hosting capacity bands, clustering does provide a nice method to select a subset of feeders that represent the range of all feeders.

4. FEEDER MODELING AND ANALYSIS

Utilizing the sixteen feeders selected in the clustering, detailed feeder modeling and analysis is performed to understand the hosting capacity. How a feeder responds to photovoltaic generation is dependent on the individual feeder's characteristics. Although feeder characteristics are a key factor in the feeder response from distributed PV, additional factors include the PV size, location, and output. The distribution system connected PV will ultimately mold the overall feeder response. The main characteristics of each feeder analyzed are shown in Figure 12. The characteristics cover a range in values as indicated by the maximum and minimum values. All characteristics have an impact on feeder hosting capacity, however, not all are equally important.
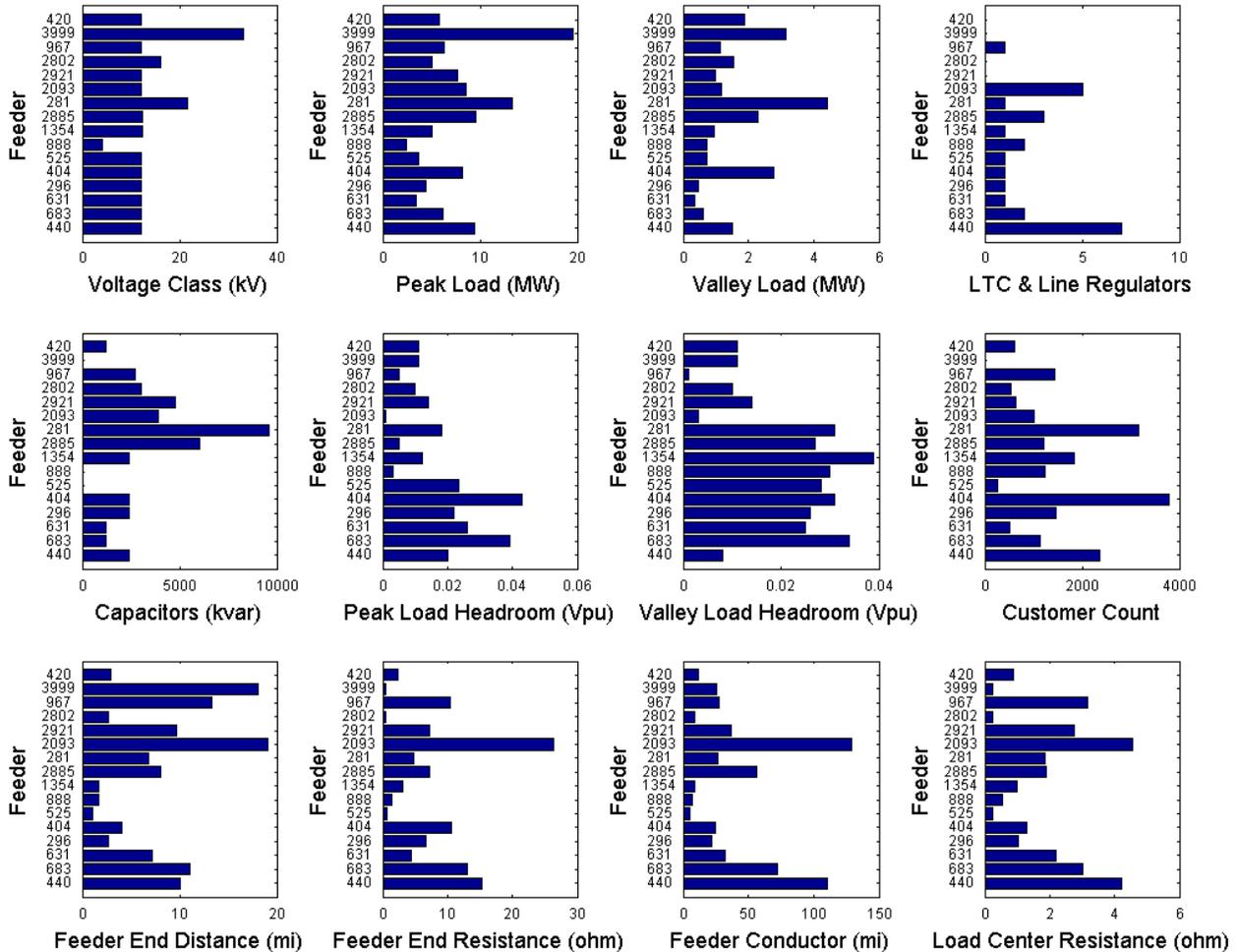
Figure 12. Characteristics of Analyzed Feeders.

4.1 Detailed Hosting Capacity

Hosting capacity is calculated separately for each potential issue on each feeder. The summary of hosting capacity for each feeder are provided in this section. The primary issues used to identify aggregate feeder hosting capacity include:

1. Primary Overvoltage

2. Primary Voltage Deviation
3. Regulator Voltage Deviation
4. Secondary Voltage Deviation
5. Secondary Overvoltage
6. Sympathetic Breaker Tripping
7. Breaker Reduction of Reach
8. Breaker/Fuse Coordination
9. Element Fault Current

The feeders identified from each utility for modeling and analysis have been chosen based on their different characteristics – a goal of the clustering analysis. These characteristics inherently make each feeder more/less susceptible to impact from distributed generation. The range of impact based on hosting capacity is shown in Figure 13 for both residential/commercial rooftop PV and utility-class centralized PV. Each colored region represents no issues (green), issues dependent upon PV location (yellow), and issues regardless of PV location (red) [12].

The residential/commercial PV analysis looks at behind-the-meter PV while the utility-class PV analysis examines large PV systems interconnected behind dedicated interconnect transformers. There are two separate scenarios in the utility-scale analysis that examine two types of interconnect transformers that have different impacts during feeder faults. Contribution of ground fault zero sequence current from ground-source interconnect transformers (Grounded Wye-Delta) significantly limits the hosting capacity. The maximum penetration analyzed in the residential/commercial PV scenario is limited by the total load on the feeder, while the maximum utility-class PV is based on the voltage class of the feeder (10/20 MW below/above 15 kV, respectively). All PV scenarios assume fixed unity power factor PV injections. Future work investigates how advanced inverter functions can increase the feeder's PV hosting capacity [13].

Hosting capacities for each feeder between the residential/commercial and utility-scale PV scenarios is different due to the possible PV locations. In the utility-scale analysis, the deployed PV could be located close to the start-of-circuit (i.e. the substation) or could be located in the extremities of the feeder whereas in the residential/commercial analysis the PV location is more dependent on the customer location.

The key takeaway from this figure is that no two feeders have the same ability to accommodate PV without the need to modify the feeder or implement mitigation measures (i.e. the initial PV hosting capacity of the feeder). This is expected based on the feeders chosen from clusters of different characteristics.
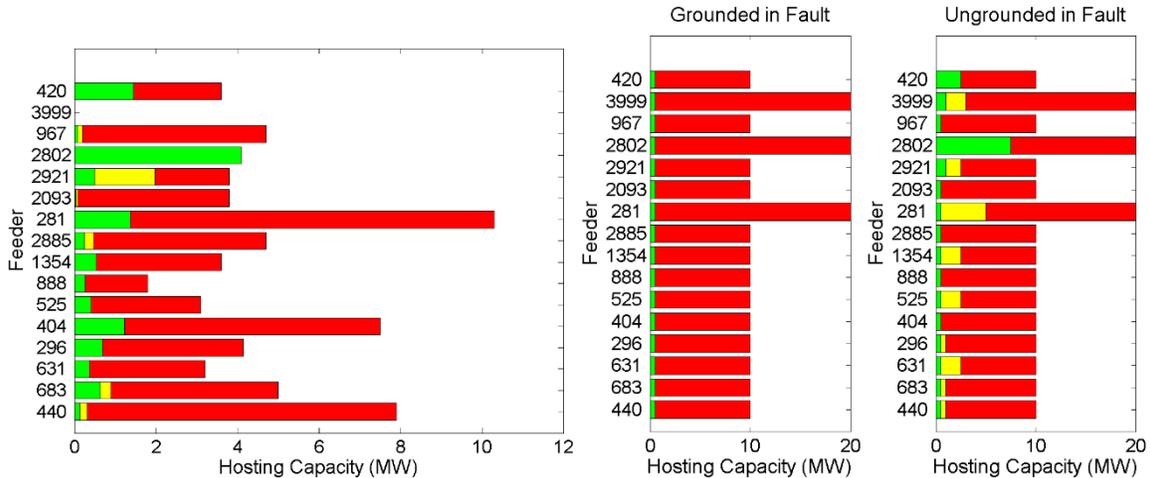
Figure 13. Detailed Hosting Capacity for Analyzed Feeders a) Residential/Commercial PV* b) Utility Class PV.

*Feeder 3999 is a solely industrial circuit and is not included in hosting capacity analysis for residential/commercial PV deployment.

4.1.1 Residential/Commercial Rooftop PV

The issue specific results shown in Figure 14 illustrate the range in hosting capacity across the three utilities. The results also show that even though high impact/low hosting capacity feeders can be identified with the clustering analysis, two feeders that are highly susceptible to adverse impact can accommodate different levels of PV. This is easily ascertained from the results for feeder 440 and 2093. The issue specific hosting capacities are considerably different for several issues. Additionally, the low hosting capacity feeder 967 has high hosting capacity with regards to protection.

A similar comparison between two feeders that have similar characteristics (967 and 683) shows that the hosting capacities are also different. These two feeders each have one line regulator, 12 kV class, ~6 MW peak load, and ~35 conductor miles. However, a closer look at additional model-based characteristics such as voltage headroom, resistance, and topology start to explain the differences in hosting capacity.
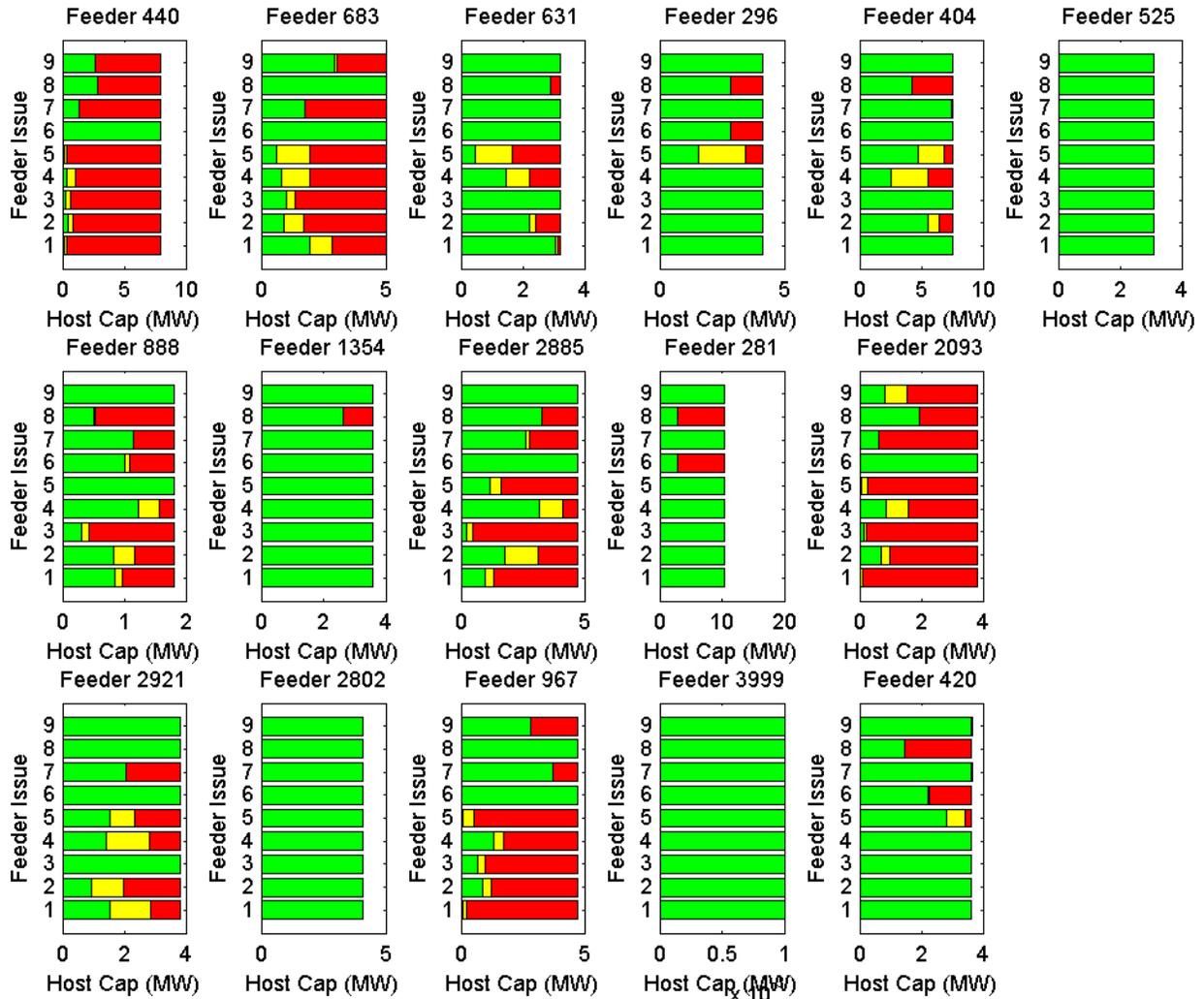
Figure 14. Issue Specific Residential/Commercial Rooftop PV Hosting Capacity.

*Note: Feeder 3999 is a solely industrial circuit and is not included in hosting capacity analysis for residential/commercial PV deployment.

4.1.2 Utility-Scale PV

The issue specific utility-scale PV hosting capacity results are shown for all feeders in Figure 15. The protection related issues shown are based on Grounded Wye-Grounded Wye interconnect transformers. The different feeders have drastically different hosting capacities. Across the different utilities, analyzed feeders such as 683 and 967 would fall into a similar cluster, however, the hosting capacities are still different.

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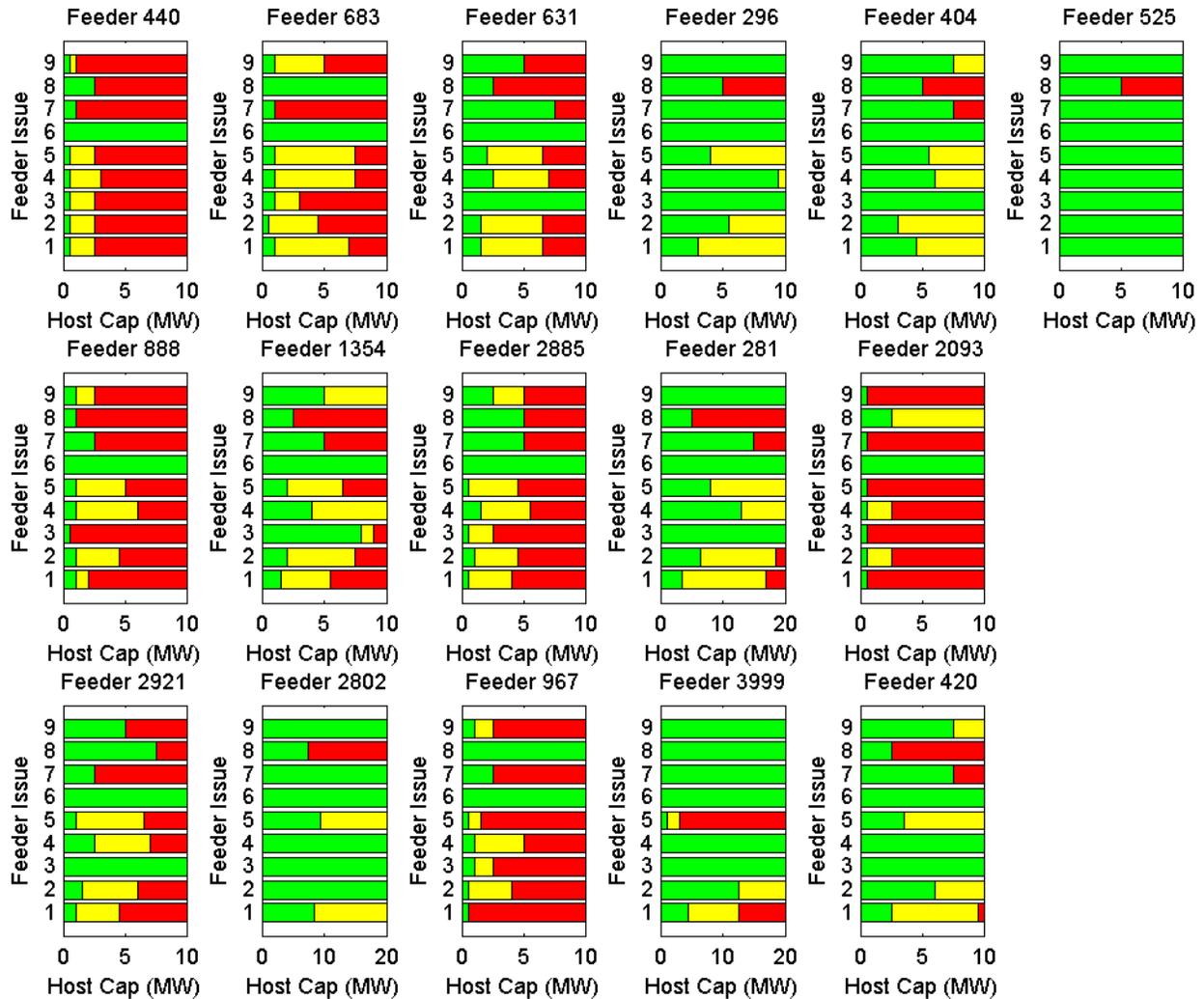
Figure 15. Issue Specific Utility-Scale PV Hosting Capacity.

4.2 Summary

The detailed feeder analysis has shown that the specific characteristics of the feeder under study have a significant influence on the impact from photovoltaics. The feeders analyzed for each utility cover a range in characteristics chosen to span the diverse set of feeders. Whether impact occurs can be generalized based on the characteristics of the feeders chosen; however, the magnitude of impact cannot be determined based solely on those characteristics. How those characteristics interact dynamically within the model ultimately dictate the amount of PV that can be hosted (accommodated). The different issues that possibly occur are also dependent on the feeder and how PV interacts with all elements.

The main factors influencing feeder impact from PV include:

- Feeder voltage class
- Feeder resistance
- Feeder regulators

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- PV system electrical location

The feeder impact from aggregate PV based on 15% of peak or 100% of minimum daytime load is typically less than what the feeder can truly accommodate. However, there are also instances where a feeder can accommodate considerably less.

The results determined through the detailed feeder analysis play a direct role in the improvement to the existing California P.U.C. Rule 21. Additional feeder characteristics will be used to update the Initial Review screening process to identify when interconnection requests should be examined more closely in Supplemental Review. Updates to Rule 21 Supplemental Review will also identify when higher levels of PV could be accommodated without initiating the detailed review process. The updates will provide the utility additional guidance on the information/data and equations needed to make a better determination of the impact from aggregate levels of PV on a feeder.

5. MODIFIED SCREEN AND VALIDATION

The modifications suggested for CA Rule 21 are made based on the technical analysis conducted within this projects detailed PV impact study. The recommendations are based on PV while Rule 21 is inclusive of all forms of distributed generation (DG). The changes suggested are primarily applicable to all forms of generation in the Initial Review process. In the Supplemental Review process, some of the recommendations could be ignored when not applicable.

The technical analysis conducted in this project is also not inclusive of all potential impacts from PV. Most of the Initial Review Screens A-H in Rule 21 are applicable to the single generation interconnection request. The current version of Rule 21 does a good job screening for the impacts of a single generator on a feeder. However, the Rule lacks detail and fails to properly address the impacts of aggregate generation on a feeder. This has been less problematic as long as there are only a few generators, but with time the number of distributed generators on single feeders will increase and require adequate aggregate generation screening.

The current screens contained within the Rule are retained since they are still applicable. The modifications suggested in this report are geared toward the improvement of Rule 21 for "Alternatives to the 15% Rule." The modifications also address the need to examine the distributed (aggregate) PV impact.

5.1 Modified Screen

The suggestions to improve the Initial Review and Supplemental Review in CA Rule 21 are shown in Figure 16. These suggestions target the methods to analyze the impact of aggregate generation and specifically provide "Alternatives to the 15% Rule." The improvements are based on the technical analysis and include:

- Adding an Initial Review screen that addresses if the feeder has line regulators

- Modifying the Initial Review to always address aggregate generation

- Adding Supplemental Review equations to be used as a guideline to address the impacts of aggregate generation

Interconnection Technical Framework Overview

Complete/Valid Interconnection Request

Does the Applicant choose to go directly to Detailed Studies?

→ No

→ Yes: Go to Electrical Independence Tests and Detailed Studies

Non Export/Net Energy Metering (NEM) or Export?

→ Export

Fast Track Eligibility MW Limit

→ Fail: Go to Electrical Independence Tests and Detailed Studies

→ Pass

Non Export / Net Energy Metering

Initial Review Screens A- H

Networked Secondary	A	Single Phase Generator	E
Certified Equipment	B	Short Circuit Current Contribution	F
Voltage Drop	C	Short Circuit Interrupting Capability	G
Transformer Rating	D	Line Configuration	H

Pass All Screens

Fail Any Screen

Does quick review of failed screens determine requirements to address the screens?

→ Yes

→ No: Supplemental Review (SR)

Initial Review Screens I- M

Will power be exported across the PCC? **I**

→ No

→ Yes

Generating Facility ≤ 11kVA? **J**

→ Yes

→ No

Is Generating Facility a NEM project whose nameplate capacity is ≤ 500kW? **K**

→ Yes

Fail → No

T. Dependency / Stability Test **L**

→ Fail

→ Pass

Aggregate generation ≤ 15% of line section peak load? **M**

→ No

→ Yes

Screen Q: Does the feeder have Line Reg?

→ Yes

→ No

Proceed with interconnection subject to requirements determined by Initial Review or SR, if any

Supplemental Review (SR)

Shorthand equations

Penetration Test	N
Power Quality & Voltage Fluctuation	O
Safety and Reliability Test	P

Pass All

→ Fail Any Test

Are requirements determined without further study?

→ Yes

→ No: Go to Electrical Independence Tests and Detailed Studies

Figure 16. Suggested Modifications to CA Rule 21.

5.2 Improvements to Initial Review

In the Initial Review, the aggregate penetration of PV becomes a factor if Screen M (15% peak load) is applied. Screen M is a main aggregate penetration test currently contained within the Rule (aggregate impact is also addressed in Screen F for fault current contribution). The Screen M aggregate penetration test is based on peak load at an automatic sectionalizing line section and is designed to provide conservative penetration limits. Commonly, the only line section load data available is at the feeder breaker. Using the peak feeder load for Screen M, the value to pass/fail is identified and plotted as the dashed vertical line on the detailed hosting capacity results shown in Figure 17.

The feeder issues in which aggregate generation hosting capacity are shown include the following list. The first three are geared toward voltage issues while the last three focus on protection issues.

1. Primary Node Overvoltage
    a. If voltages might exceed ANSI limits
2. Primary Node Voltage Deviation
    a. If the variable resource could impact sensitive equipment or cause slow variation flicker
3. Voltage Regulation Node Voltage Deviation
    a. If additional tapping might occur
4. Element Fault Current
    a. If protection devices may need to be rated higher due to additional fault current
5. Sympathetic Breaker Tripping
    a. If the breaker might inadvertently trip on ground current due to a parallel feeder fault
6. Breaker Reduction of Reach
    a. If the breaker may lose visibility to remote feeder faults

The green regions indicate aggregate penetration where adverse impact does not occur. The yellow regions indicate that issues may occur due to the aggregate generation. Whether or not issues occur in this range is dependent on the location of individual PV systems. Impact dependency on individual system location primarily occurs for voltage issues. Location is less of a factor for protection issues since inverter-based generators are typically constant power/current limited devices. Aggregate penetration in the red region indicates adverse impact despite individual system location. Adverse impact is defined as the feeder response deviating - from the base case operation without generation - greater than a specified threshold. Thresholds applied are based on utility guided input.
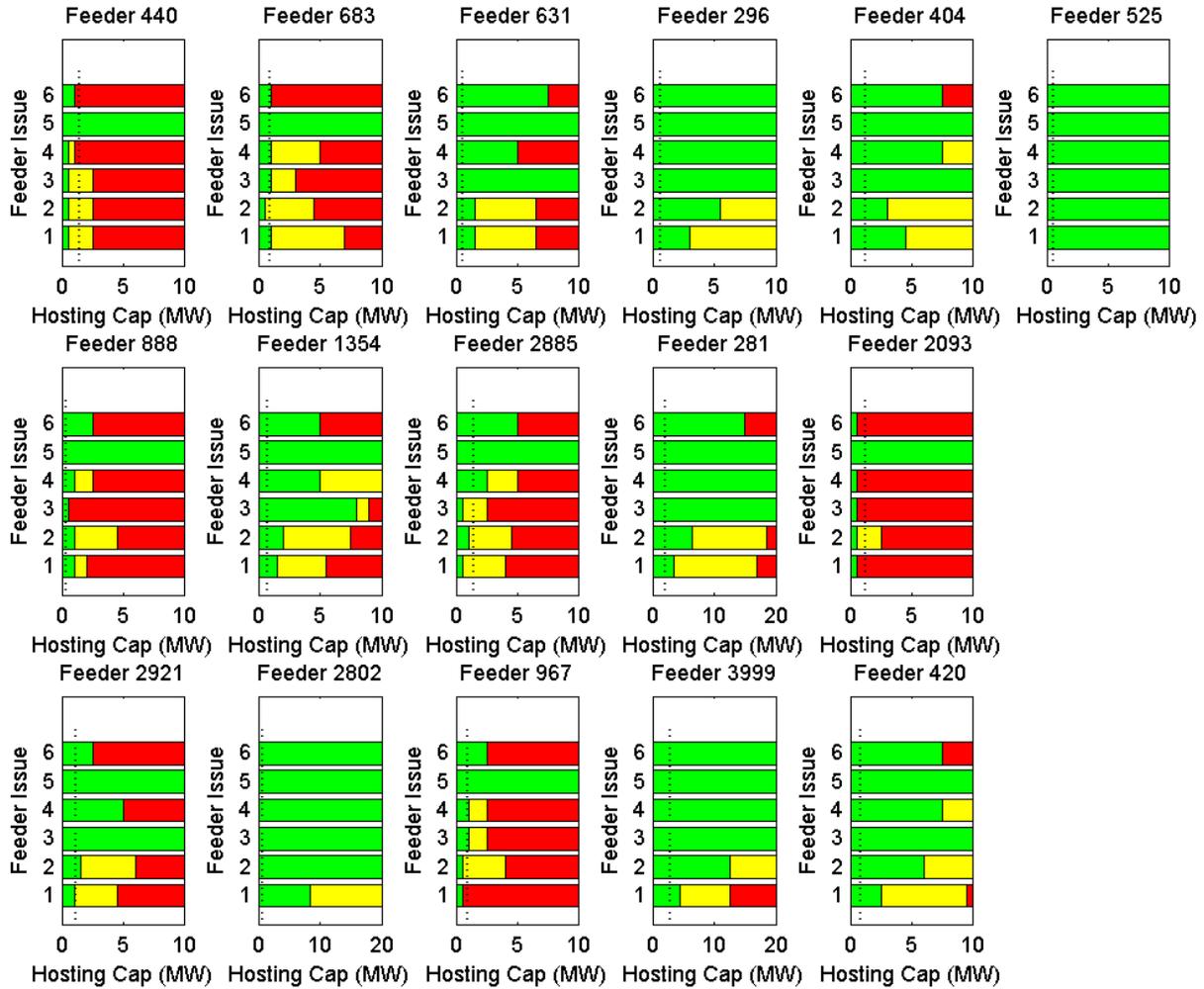
Figure 17. Utility-Scale PV Detailed Hosting Capacity (Dashed lines indicate 15% of breaker peak load).

5.2.1 Line Voltage Regulators

The feeders that have hosting capacities lower than that determined from Screen M all have line regulators (Feeders 440, 683, 2885, 2093, 967). A suggestion to improve the Initial Review screening process for aggregate generation is to include a screen dedicated to line regulators. Line regulators are commonly an indication that there are voltage regulation issues already on the feeder. If line regulation exists on a feeder under review, the application would be directed to Supplemental Review.

5.2.2 Aggregate Generation

The aggregate generation test Screen M is not always considered especially if Screen I (non-exporting) or Screen J (small system) are satisfied. This identifies a major gap in the Initial Review process where the aggregate generation test can be bypassed. For example, if all PV systems interconnecting to the feeder are less than 10 kW, the impacts from aggregate distributed generation would not be addressed through Screen M. Therefore, it is suggested that screen I and

J must still go through Screen M before a decision is made. Obviously, it will not be the final 10 kW system that ends up causing a violation, but at some point prior to reaching that limit, potential feeder impacts could be identified.

5.3 Improvements to Supplemental Review

The next limitation of Rule 21 is that many feeders can host considerably more PV than identified by Screen M (15% peak load) as shown in Figure 17. Screen N (100% minimum load) is actually the Supplemental Review screen that can limit the overall hosting capacity as identified in Rule 21, but Screen N is still based on line section loading and commonly produces similar values to Screen M. The implications of failing Screen N are that 1) there may be reverse power flow such that all inline devices should be bi-directional and 2) that islanding issues could occur.

What is not addressed explicitly in the Supplemental Review are the intermediate steps to address impact to voltage and protection issues. The recommended modifications should provide these steps to clearly identify the aggregate hosting capacity of a feeder. These recommendations are the "Alternatives to the 15% Rule." These recommended screens should be simple such as shorthand equations since the Supplemental Review is not a detailed study.

5.3.1 Shorthand Analysis

With limited additional information in the Supplemental Review, a more accurate yet still conservative feeder hosting capacity limit can be calculated using simple equations. For each of the issues shown previously, a shorthand equation has been derived [14]. The shorthand equation for each issue should show a hosting capacity within the green region of the detailed analysis results. Therefore the equations would still produce conservative hosting capacity values that describe an aggregate PV scenario worse than any analyzed in the detailed analysis. Figure 18 shows an asterisk for each issue at the calculated amount of allowable utility-scale PV on the feeder.

One thing to note from the figure is that the simple equations seldom overestimate the hosting capacity (asterisks rarely falling in the red region). Most of the asterisks fall near the transition from green to yellow or green to red (transition produced by the worst-case condition analyzed in the detailed analysis). The hosting capacity from the detailed analysis can be higher (wider yellow region) because there are more optimal PV scenarios. The asterisk also occasionally falls well within the green region. One reason that this can occur is due to the actual feeder topology providing lateral diversity. The simple equations do not account for lateral diversity and thus provide more conservative hosting capacities.

The main objective is to show where hosting capacity can be higher than the hosting capacity determined based on load. The values calculated for a feeder would be compared to the actual aggregate PV on the feeder after the interconnection request. If the calculated values are higher, then the interconnection request would have a better chance passing Supplemental Review with regards to the issues analyzed.
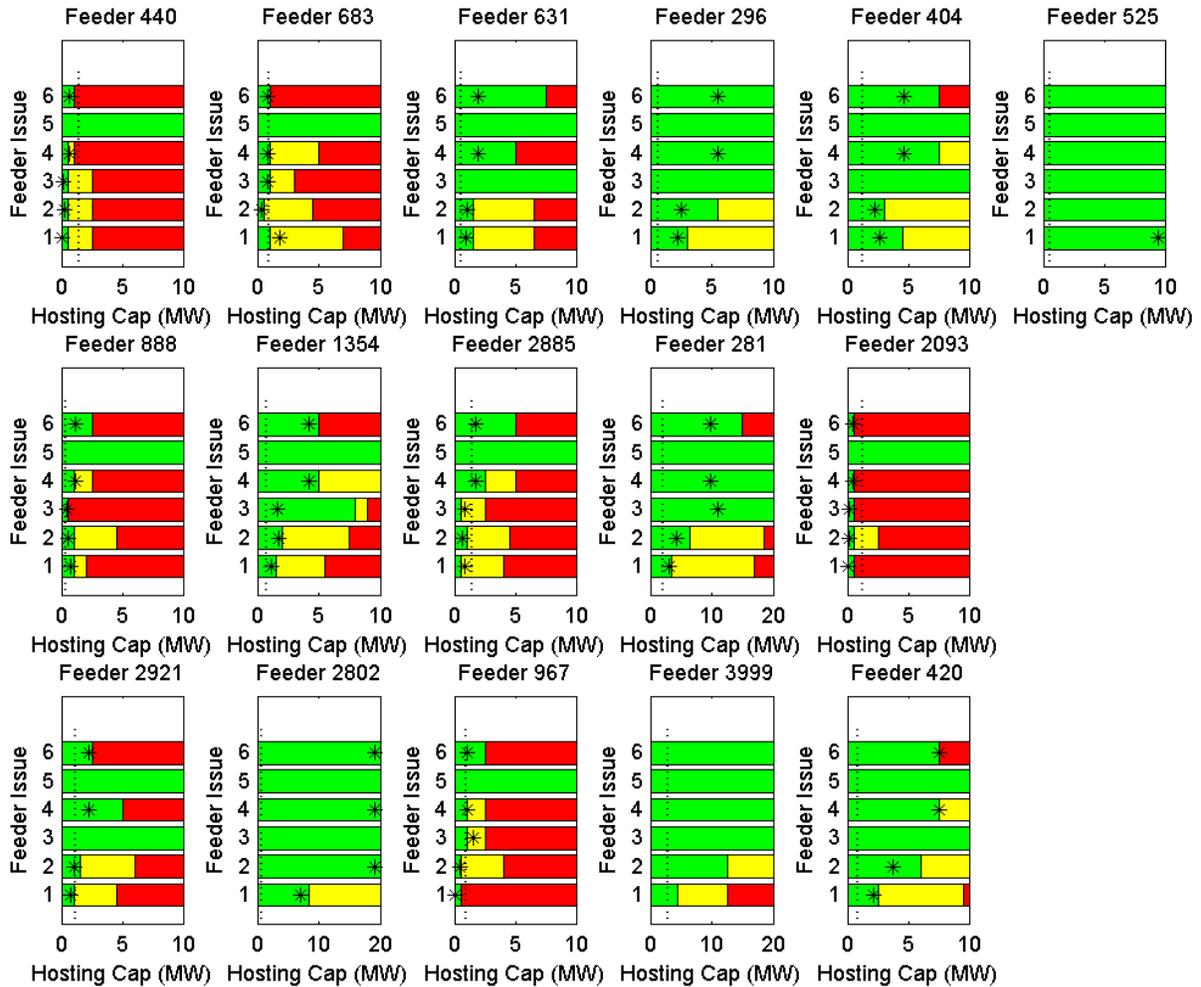
Figure 18. Utility-Scale PV Short-Hand Hosting Capacity.

The one feeder that fails the shorthand equations is Feeder 3999 where all five loads are modeled as capacitive. The distributed load capacitance causes significant voltage rise when the distributed generation is greater than local load. The voltage rise is greater than that predicted with the shorthand equations. This scenario is an anomaly but does represent a condition that can be more problematic for distributed generation.

5.4 Validation

The proposed modifications to CA Rule 21 are validated based on their application to the project's validation feeders. These modifications include changes to the Initial Review process as well as the Supplemental Review process. The goal of the validation is to determine if the modified screening process more accurately identifies aggregate PV system impacts than the current Rule 21 framework. More effective screening allows higher levels of overall PV interconnection through the proposed Initial Review or Supplemental Review processes while correctly identifying when the hosting capacity should be lower.

Validation of the modified interconnection request process is completed on a set of six distribution feeders that have been reserved for such purposes at the beginning of the study. This allows validation to proceed with feeders whose hosting capacity characteristics had not been

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considered during the formulation of the modifications/improvements to the screening process. For validation, the Initial Review and Supplemental Review modifications are implemented within the distribution system analysis framework that has been used for the detailed analysis completed on the 16 study feeders, while identical hosting capacity analysis is completed on the validation feeders.

Figure 19 shows the detailed hosting capacity of the validation feeders for utility-scale PV. The six feeder issues analyzed are indicated by SR1, SR2, … SR6. The green regions indicate when aggregate penetration does not cause adverse impact, the yellow regions indicate when aggregate penetration may cause adverse impact, and the red regions indicate when aggregate penetration will cause adverse impact. The dashed line is added to denote 15% of peak load.
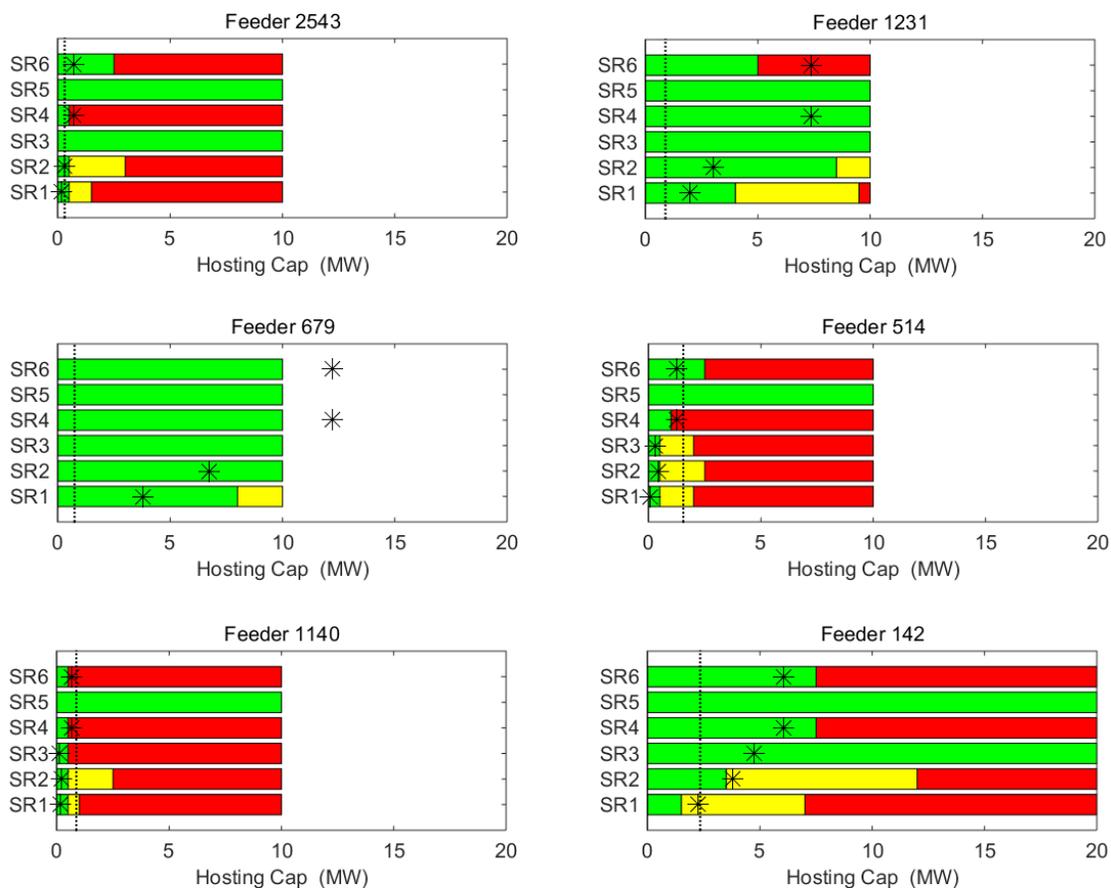
Figure 19. Utility-Scale PV Hosting Capacity (Dashed lines indicate 15% of breaker peak load).
The feeders with line regulators (514, 1140) have adverse impacts when the aggregate penetration is lower than 15% peak load. Thus, it is validated that the existence of line voltage regulators indicates a high likelihood of adverse impact.

Validation feeders that do not have a line regulator (2543, 1231, 679, 142) generally can accommodate at least 15% of peak load without adverse feeder impact. However, feeder 142 does have a detailed hosting capacity for SR-1 slightly below 15% peak load. This shows that

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load is not the best indication of hosting capacity. Therefore, the Supplemental Review can better estimate the hosting capacity for those feeders.

Supplemental Review shorthand equations are applied to the six validation feeders to approximate the hosting capacities, and the solutions are then shown on the detailed analysis results. The asterisk in each bar is the hosting capacity estimation computed using Supplemental Review shorthand equations. If the asterisk is not shown on the plot, the shorthand hosting capacity is greater than the range displayed.

Except for the asterisks in feeders 1231 and 679 exceeding the simulation data limit, all other asterisks in all validation feeders are within green areas or near the transition from green to yellow/red. Thus, it proves that shorthand equations can give a good and conservative estimation of PV hosting capacity.

5.5 Summary

The detailed feeder impact analysis performed in the previous project task has identified when potential issues from aggregate distributed generation are not properly indicated and also when a feeder is capable of accommodating considerably higher levels of distributed generation. These findings have allowed for the development of improved screens in CA Rule 21 which more accurately address the impacts from aggregate generation.

The "Alternatives to the 15% Rule" found in this project more properly address the impacts from distributed generation and are not dependent on load level alone. The improvements are based on the detailed technical analysis and include:

- Adding an Initial Review screen that addresses if the feeder has line regulators

- Modifying the Initial Review to always address aggregate generation

- Adding Supplement Review equations to be used as a guideline to address the voltage and protection impacts of aggregate generation

These improvements are based on the detailed analysis of 16 test feeders that span a wide range of characteristics. The modified screens are then applied to a new set of 6 feeders to observe and validate the new recommendations. The application of the modified screens show that the aggregate impact can be better determined for the issues analyzed.

6. DISTRIBUTION RESOURCE PLANS

In parallel to this CSI RD&D solicitation three project, the California Public Utility Commission mandated that the three large California investor owned utilities develop Distribution Resource Plans (DRP) to prepare for future growth of distributed energy resources. The DRP is not a replacement for interconnection studies or Rule 21, however the DRP can be used to further improve the analysis of aggregate generation as has been analyzed in this project. If the DRP analysis has not been conducted on the feeder under study, the Supplemental Review shorthand equations can still help to better estimate aggregate PV limits for a feeder.

Figure 20 shows how the DRP can be used to further improve Rule 21. In place of the shorthand equations outlined in this document for Supplemental Review, the DRP would already have the feeder hosting capacity calculated for each feeder on the system. From the DRP, the aggregate penetration limits of the feeder would already be known and used in place of the Supplemental Review shorthand analysis.
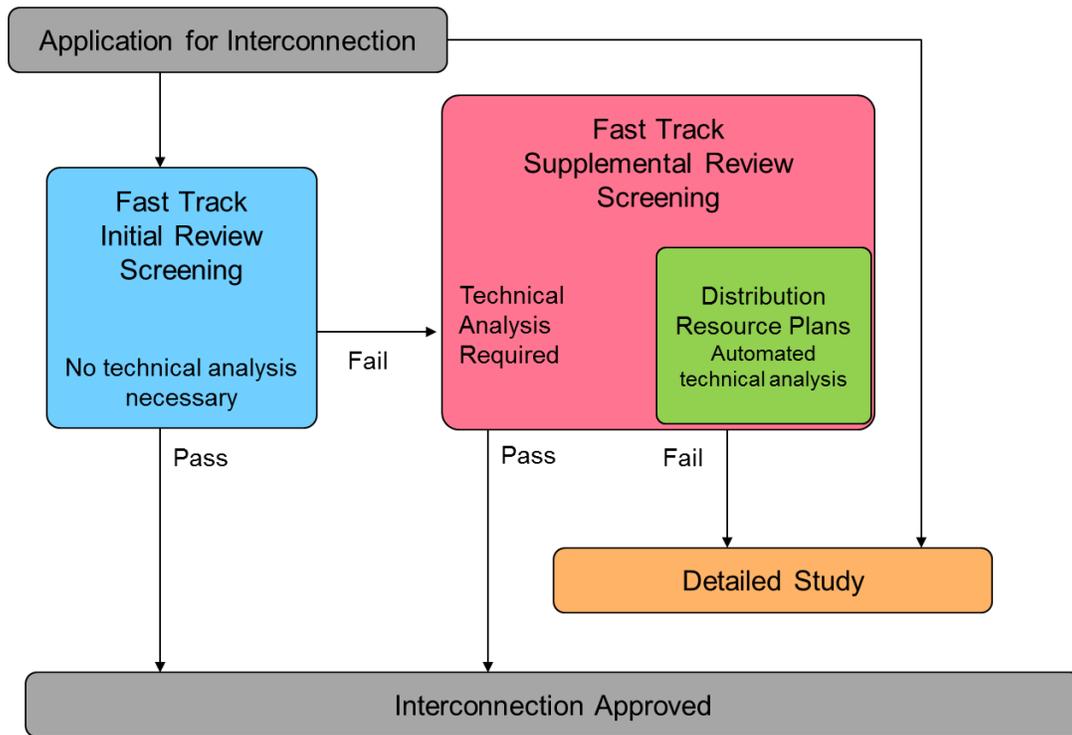

Figure 20. Screening in Coordination with Distribution Resource Plan.

A DRP could effectively be a detailed analysis on every feeder, however, as indicated from this project, the detailed analysis is very time intensive and would be less feasible. A DRP must be something that can be efficiently and effectively calculated. After several years of research, EPRI has created the Streamlined Hosting Capacity method that can be used as a form of DRP.

The streamlined hosting capacity analysis has been applied to five of the 16 study feeders. Figure 21 shows primary node overvoltage-based hosting capacity determined from the DRP, detailed analysis, and shorthand equation (SR1). Using the detailed analysis as the baseline, the DRP produces results that are closer than the shorthand equation. Because the shorthand analysis is not performed with the full detailed model, the estimates can be slightly higher/lower than the

detailed result while the DRP remains slightly lower. Ultimately, the DRP can be used in lieu of the shorthand equations for the interconnection issues identified in this project as well as others.
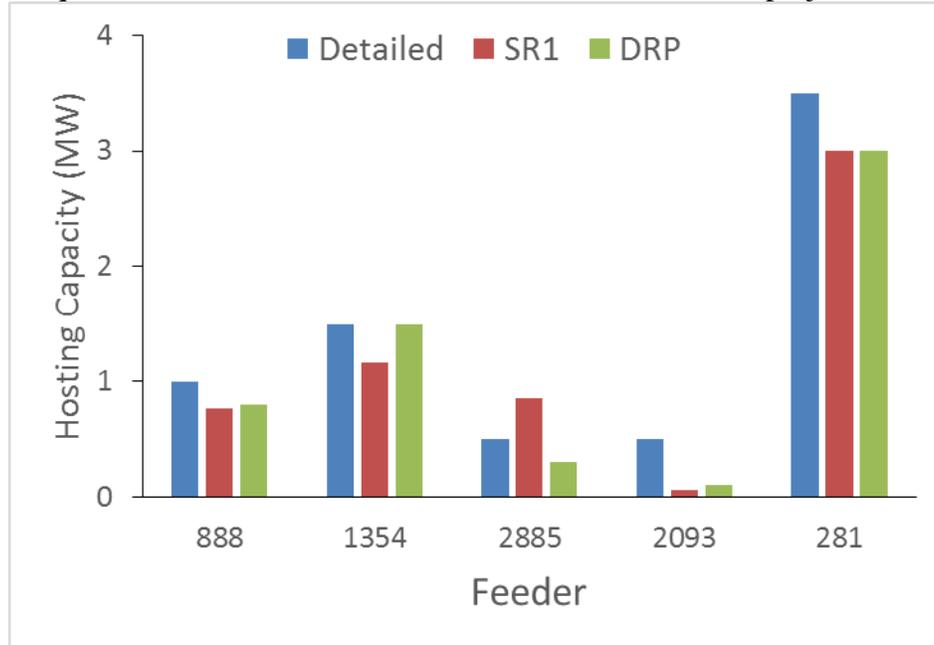

Figure 21. Improving Overvoltage Hosting Capacity Prediction with Distribution Resource Plan.

6.1 EPRI's Streamlined Hosting Capacity

The streamlined hosting capacity analysis has been created to better determine the system-wide ability to accommodate Distributed Energy Resources (DER) on the distribution system such as photovoltaics (PV) and energy storage. As described in Figure 22 detailed analysis would be more accurate but requires significantly longer analysis. Simple screens can be quick but are much less accurate. The streamlined analysis is a bridge between these two extremes and incorporates accuracy with speed.
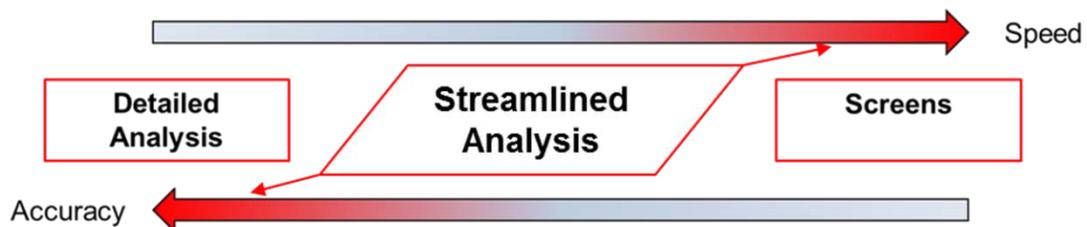
Figure 22. Streamlined Hosting Capacity Analysis Compared to Detailed Analysis and Screens.

The fundamental design of the streamlined analysis is outlined in Figure 23. The method is granular and can be applied to every distribution feeder which is necessary because each feeder is unique. The method is repeatable with automated scripts so that the analysis can be re-applied as the system changes. It is efficient such that it is scalable to analyze the entire system. The method is transparent and documented [15]. It is proven based on detailed feeder analysis conducted by EPRI over the past several years and also with 3rd party methods. And finally, the

method is in the process of becoming available in utility tools such as Cyme, Synergi, and Milsoft.

| Granular | • Capture unique feeder-specific responses |
Repeatable	• As distribution feeders change
Scalable	• System-wide assessment
Transparent	• Clear and open methods for analysis
Proven	• Validated techniques
Available	• Utilize readily available utility data and tools
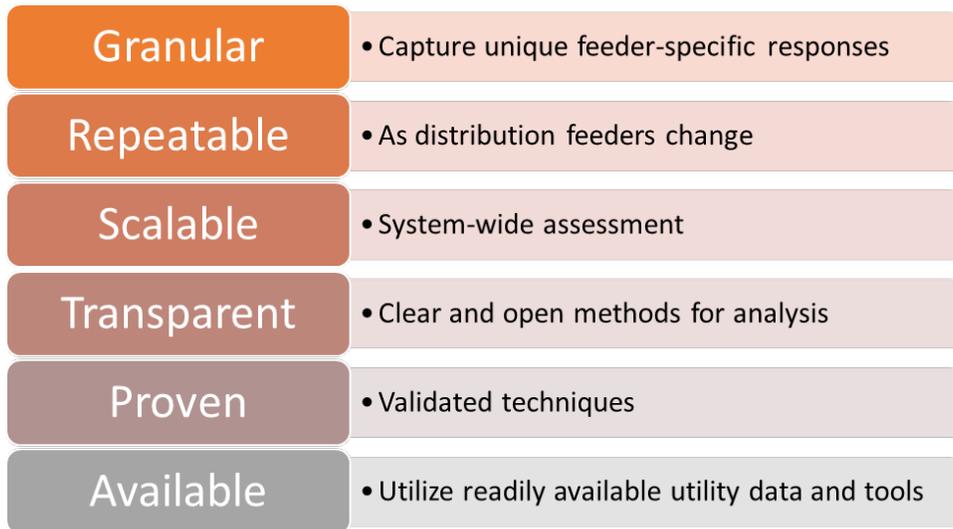
Figure 23. Design of the Streamlined Hosting Capacity Analysis.

The streamlined hosting capacity method and analysis has been developed through multiple years of research on distributed PV impact studies. The evolution of the methodology is shown in Figure 24. The method analyzed millions of potential PV deployments across more than 30 feeders while examining the impact to multiple issues. The simulations and impacts observed on specific feeders have been beneficial in determining how PV can impact the distribution system as well as providing the utility a screening criterion.

Develop Detailed Hosting Capacity Method → Apply Detailed Hosting Methodology to Broad Set of Feeders → Correlation Assessment → Develop Streamlined Hosting Capacity Analysis
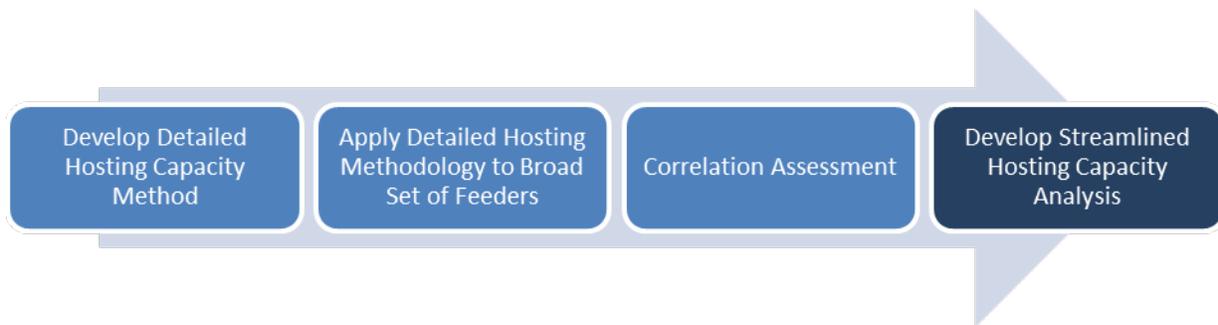
Figure 24. Evolution of Hosting Capacity Analysis.

The question that often arose during the detailed analysis is how the hosting capacity analysis on several test feeders could be extrapolated to the additional thousands of feeders within a service territory. Unfortunately, the response of each feeder is unique and the time and effort involved in the detailed study is too great to replicate on thousands of additional feeders. Therefore, the impact results found in the detailed study cannot be mapped directly to other feeders.

Although the results cannot be mapped to other feeders, there are correlations in the feeder response. These correlations allow the key characteristics to be derived and support the development of faster and easier methods to arrive at similar solutions. The overarching observation is that the location of PV matters and the feeder impact cannot be decoupled from the full range in characteristics/detail included in a feeder model.

The hosting capacity's ultimate dependency on the actual feeder model is the driving force to develop EPRI's streamlined method. Thus the streamlined method is rooted in the details and takes into consideration the full range in feeder characteristics by examining the model's power flow solution and short-circuit response. These two key data streams provide input to the overall method, and combined with a characterization of the feeder topology, form the basis of the streamlined hosting capacity methodology. The application of the EPRI's Streamlined Hosting Capacity Analysis applied to an entire system is shown in Figure 25.
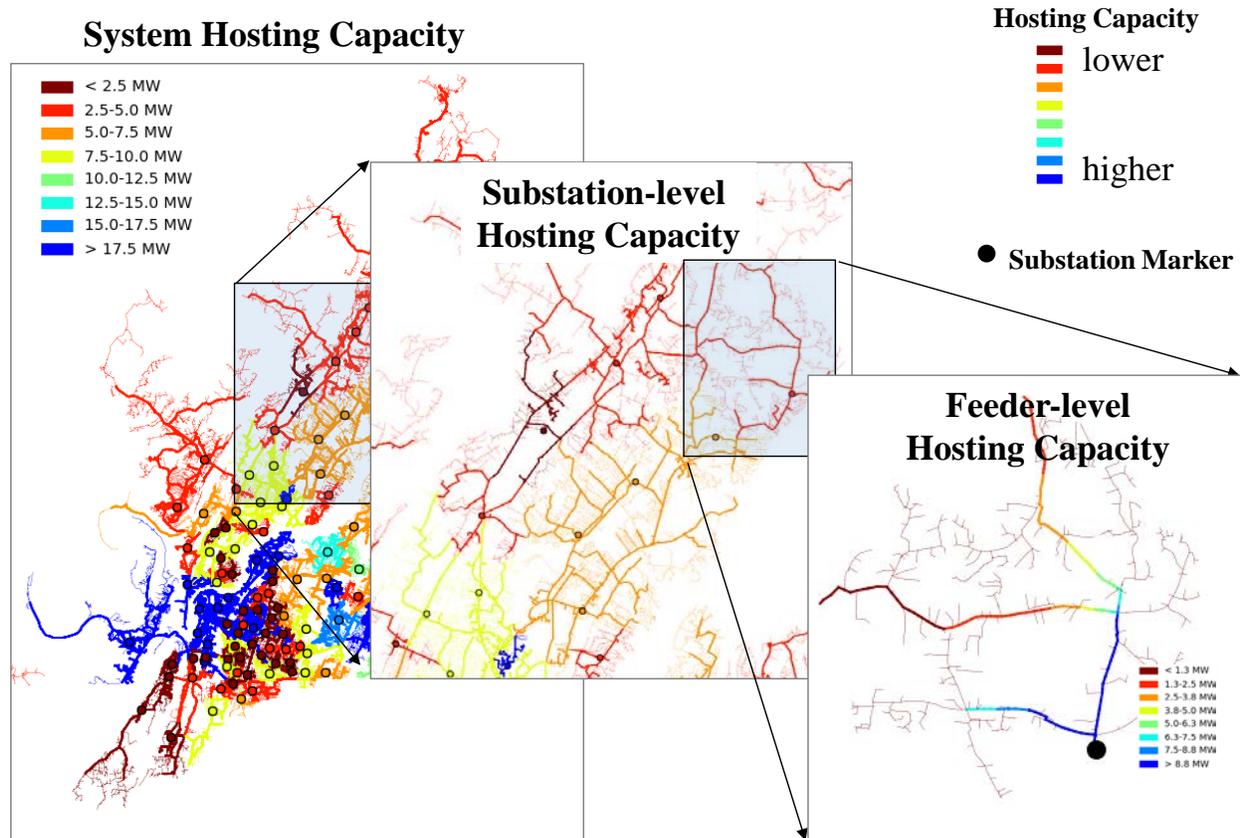

Figure 25. Sample Results from System-Wide Analysis.

7. CONCLUSIONS

Rule 21 is an interconnection procedure for California utilities to follow for distributed generation application reviews. Utilities have the opportunity to go above and beyond where necessary but at minimum must consider the screening methods in the rule. The interpretation and application of Rule 21 screens are based on planning procedures and the ability to conduct certain analyses. Most CA utilities have commented that even though the screening process can take well longer than the allotted time if supplemental and detailed review are necessary, their proficiency in the review process is considerably better than most due to the number of interconnection requests encountered to date.

Each task of this project helped progress to the final goal of improving CA Rule 21 as penetration levels and interconnection requests continue to increase. The bulk of the project consisted of selecting the feeders for detailed analysis as well as performing that analysis, suggesting updates to Rule 21, and validating those updated methods.

The selection of the utility feeders is based on the results of a comprehensive clustering analysis where each feeder from the three CA investor owned utilities is characterized and grouped into representative sets. The representative sets are not suggesting all feeders within the set will have a similar response to distributed generation, but the sets allow selection of several feeders, one from each set, that will have considerably different characteristics. These representative feeders from each utility are placed into two groups. One set of 16 for detailed analysis and another set of 6 for validation.

A detailed feeder model is developed for each of the selected feeders. The models are based on the utility planning model and converted into the OpenDSS distribution software. The OpenDSS distribution software is used so that detailed analysis can be performed similarly across the different utilities even though the original models come from different software platforms.

The analysis of the models is conducted with PV as the distributed resource. Rule 21 is inclusive of all distributed resources, but this project specifically analyzes distributed PV. The hosting capacity analysis determines the amount of PV that can be accommodated on a distribution feeder without impacts exceeding predefined utility guided thresholds. The hosting capacity for each feeder is unique for voltage and protection issues.

The detailed feeder impact analysis performed identifies when potential issues from aggregate distributed generation are not properly identified and also when a feeder is capable of accommodating considerably higher levels of distributed generation. The "Alternatives to the 15% Rule" found in this project more properly address the impacts from distributed generation and are not dependent on load level alone. The improvements suggested to Rule 21 include:

- Add an Initial Review screen that addresses if the feeder has line regulators

- Modify the Initial Review to always address aggregate generation

- Add Supplemental Review equations to be used as a guideline to address the voltage and protection impacts from aggregate generation

These improvements are based on the detailed analysis of 16 study feeders that span a wide range in characteristics. The modified screens are then applied to a separate set of 6 validation

feeders to observe and verify the new recommendations. The application of the modified screens show that the aggregate impact can be better screened for the issues analyzed.

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Electric Power Research Institute
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Knoxville, TN 37902

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Electric Power Research Institute
942 Corridor Park Boulevard
Knoxville, TN 37902

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National Renewable Energy Laboratory
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National Renewable Energy Laboratory
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