CONSULTANT REPORT

IDENTIFICATION OF LOW-IMPACT INTERCONNECTION SITES FOR WHOLESALE DISTRIBUTED PHOTOVOLTAIC GENERATION USING ENERGYNET POWER SYSTEM SIMULATION

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PREFACE

This study was performed for the California Energy Commission by New Power Technologies as a contractor to Aspen Environmental Group under Work Authorization WA-1910.014 under Standard Agreement No. 400-07-032 between the State Energy Resources Conservation and Development Commission and Aspen Environmental Group.

ABSTRACT

California's objective for more distributed renewable electric power sources strains existing processes to safely interconnect wholesale distributed resources to the grid. This study funded by the California Energy Commission demonstrates an approach using the Energynet® simulation, a regional power system model, to identify low-impact interconnection sites for wholesale photovoltaic systems on the grid. The model, which integrates transmission and distribution, employs a rich set of criteria that includes power system characteristics at a project's location and its potential power flow, loading, voltage, and power quality impacts, and includes direct simulation showing the project's local and regional impact — all in an evaluation requiring a few minutes. Criteria include assessment of conditions that vary for different interconnection points within the distribution circuit, including the system's resistance to voltage variation, or "strength." Nearly 80,000 potential distribution sites were evaluated, the impacts of more than 500 projects were individually simulated, and more than 11,000 low-impact sites within a regional power system were identified for wholesale distributed photovoltaic projects ranging from 500 kilowatts to 5 megawatts. Findings suggest that wholesale photovoltaic projects in this size range have low or manageable affects even at high penetrations without major system upgrades if their point of interconnection are at sufficiently strong network locations that consider upstream equipment ratings and avoid certain circuits with unusual sensitivity.

Keywords: Distributed generation, interconnection, high penetration, low impact, photovoltaic, PV, renewable, impact, wholesale, export, grid, power delivery, system, distribution, transmission, RPS

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EXECUTIVE SUMMARY

California leads the nation in adopting distributed renewable electric power generation. However, California investor-owned utilities report backlogs as long as seven years to process pending requests by project developers to interconnect renewable wholesale power generation projects to power distribution networks. Thus a conflict has emerged between the state's policies to promote renewable distributed generation and the utilities' need to ensure that interconnecting these projects will not adversely affect the power grid.

Ideally utilities would have the means to quickly assess the grid impacts of any proposed project interconnection. This rapid assessment would take into account the specific attributes of both the project and the power system at the proposed point of interconnection and consider the full range of potential grid impacts.

Such a tool would quickly and reliably identify low-impact interconnections. It would also quickly identify the specific issues of concern for high-impact interconnections. Such a tool could also be used to prepare and maintain an inventory of interconnection sites in a regional power system that are prescreened as low-impact sites for renewable wholesale generation projects of give size range. A utility could evaluate a developer's potential project locations against this inventory and even provide some detailed feedback on each location essentially instantly. Such information could help focus the efforts of stakeholders on low-grid-impact, high-probability projects, and avoid detailed studies that are unnecessary for low-impact projects. It could also guide and expedite more detailed system studies for those project interconnections with impacts that are still sought by applicants. This would promote greater use of distributed renewable generation without compromising grid performance and service to existing utility customers.

This study demonstrates an application of the Energynet® power system simulation, in this case for evaluating grid impacts of wholesale distributed photovoltaic project interconnections. As the Energynet simulation provides a high-definition view of a regional power system with detail to the distribution component level, it readily reveals the direct effects of power generation projects connected within the distribution system. This study used an existing, validated simulation model of Southern California Edison's "Hobby" system, the utility's largest regional power delivery system.

In this study the researchers used this Energynet application to pre-identify an inventory of more than 11,000 low-impact sites on 145 different distribution circuits for wholesale photovoltaic (PV) interconnections ranging from 500 kilowatts to 5 megawatts from nearly 80,000 candidate sites within the Hobby system. The researchers also performed simulations showing the direct voltage and power flow impacts on the grid of more than 500 hypothetical project interconnections.

In a Renewable Distributed Energy Collaborative workshop on March 4, 2011, the researchers demonstrated the Energynet application used for this study. The application assesses an individual interconnection in one click, and a simulation of the direct effect of the project on system voltage and power flow anywhere in the regional power system in less than a minute.

The Energynet application used in this project employs a rich set of criteria to identify low-impact interconnections. These criteria directly address the full range of potential impacts of distributed wholesale photovoltaic projects, including system voltage impacts associated with high photovoltaic penetrations and impacts arising from different system attributes at locations within circuits. The simulation results suggest that the application of these criteria does, in fact, predict low-impact interconnections.

These results suggest a relatively large and diverse set of low-impact interconnection sites for wholesale distribution-connected photovoltaic projects in the 500 kilowatt to 5 megawatt size range. While many circuits have some capability to accommodate such projects, the suitability of sites for wholesale photovoltaic interconnection varies greatly among circuits. More important, the suitability of sites for wholesale photovoltaic interconnection varies greatly *within* individual circuits. These results also suggest that wholesale photovoltaic projects interconnected at sufficiently strong network locations in a power system, with due consideration for the ratings of equipment lying between the interconnection point and primary system power source, and avoiding certain circuits with unusual sensitivity, have low or manageable impacts even at high penetrations without major system upgrades. These results also demonstrate that a utility using advanced power system simulation and analytical tools can gain detailed insight into the specific grid impacts of a particular requested interconnection within a few minutes.

This study did not address potential effects of wholesale photovoltaic in the distribution system on the operation of the transmission system or the entire regional power delivery system. It also did not address the effects of groups of distribution or transmission-connected projects that may be electrically interdependent. This study also did not address the assessment of impacts where the likelihood or timing of individual projects is uncertain. The Energynet simulation is a single regional model, incorporating both transmission and distribution that can characterize every proposed interconnection at once or in any combination. Therefore, it is well-suited for assessing these impacts.

CHAPTER 1: Introduction

Problem Statement

California utilities report backlogs as long as seven years[1] to process pending requests by project developers to interconnect generation projects to their power delivery networks. A significant portion of these requests is for wholesale renewable generation projects, promoted by California's Renewables Portfolio Standard that would connect at distribution system voltages. Utilities must accommodate these interconnection requests while ensuring that the safe, reliable operation of the power delivery system is maintained and that customer service quality is not compromised.

Utilities and project developers both would prefer to focus their attention on projects where interconnection would have minimal effect on the power delivery system — that is, projects requiring minimal detailed study and minimal system upgrades.

However, identifying such low-impact sites presents challenges. A particular project interconnected at a particular location within the power system in reality has a unique set of impacts on the power system. Further, power system conditions at a particular location within the power system not only change continuously with varying loads, but also periodically with ongoing system modifications and even other project interconnections.

Under existing interconnection processes, projects meeting certain "screening" criteria may be interconnected to the power system with essentially no study of project-specific grid impacts. An assumption of low levels of local generation as a share of load (or "penetration") allows these criteria to substitute for what would be time-consuming studies. However, this reliance on low penetration levels becomes an issue as California's policy promotes greater use of distribution-connected wholesale renewable generation.

Ideally utilities would have the means to quickly assess the project-specific grid impacts of proposed project interconnection. This rapid assessment would take into account the specific attributes of both the project and the power system at the proposed point of interconnection, and consider the full range of potential grid impacts. Such a tool would quickly and reliably identify low-impact interconnections. It would also quickly identify the specific issues of concern for those interconnections with impacts requiring mitigation or grid upgrades.

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1 Southern California Edison, *Amendments to Wholesale Distribution Access Tariff to Revise the Generator Interconnection Procedures*, page 7 of 43, March 1, 2011.

Rapid but comprehensive evaluation of individual project impacts would support project developer business objectives and reduce the risk to utilities of interconnecting these projects. A rapid evaluation tool could also be used to prepare and maintain an inventory of pre-identified low-impact interconnection sites in a regional power system. Such information could help focus the efforts of stakeholders on low-grid-impact, high-probability projects.

Project Objectives

This study demonstrates a particular application of the Energynet power system simulation, in this case as an approach to identifying low-impact interconnection sites for megawatt-class (MW) wholesale distributed photovoltaic (PV) projects. The initial objective of this study was to demonstrate how a utility could pre-identify an inventory of low-impact interconnection sites within a regional power delivery system for wholesale distributed PV projects ranging in size from 500 kilowatt (kW) to 5 megawatt (MW). The study would also demonstrate the use of the Energynet® application to rapidly evaluate large numbers of potential sites and individual wholesale PV interconnections.

An inventory of low-impact sites for wholesale PV interconnections within a regional power delivery system would not, of course, be a guarantee that a particular project will be found a low-impact interconnection. Further, the evaluation results for those locations *not* considered low-impact sites may be as valuable as a low-impact site inventory in that these results preview the shortcomings and nature of potential mitigations for any site. An inventory of low impact sites could be used to provide more refined, reliable guidance to the market, particularly where this inventory reflects differences in potential impacts at different sites within a circuit.

For an individual interconnection, the Energynet application used in this study would provide a rapid yet comprehensive assessment of the potential impacts and reliably identify interconnections having low grid impacts to avoid unnecessary detailed studies. The approach demonstrated in this study would not replace a full system impact study where one is required. However, where a project is found in the Energynet application to have grid impacts potentially requiring mitigation or system upgrades, these results would illuminate the nature and extent of the issues, guide potential project reconfiguration, and ease and expedite more detailed studies.

This study focuses on interconnections of MW-class PV, inverter-based generation projects connected to the electric power delivery system on “distribution” radials. Generation projects that connect at transmission voltages or in networked systems or that employ rotating machinery introduce additional issues that could be addressed using the tools of this study; however, such projects lie outside the scope of this particular study.

Innovations

The Wholesale Distribution Access Tariff (WDAT) "Fast Track" and Rule 21 "Simplified Interconnection" are legacy processes presently used by California utilities to identify low-impact projects that may be offered interconnection without detailed studies. The approach of this study departs from these processes in directly considering the following:

- Different power system characteristics *within* the circuit, evaluated at the project's specific point of interconnection
- Low load conditions on the project's circuit when the project may be operating
- The project's potential to overload components within the circuit
- The project's potential voltage and power quality impacts
- The project's direct voltage and power flow impacts on the system, evaluated by simulation of the proposed project as interconnected at the proposed location

This level of detail is possible due to the system visibility provided by the Energynet platform. Deployed for a given regional power system, the Energynet platform provides ready access to the details of the system and system loads and conditions at any point under any operating scenario. The simulation engine shows the direct impact of any system change, such as the addition to the system of a wholesale PV project at a particular location.

The Energynet Power System Simulation was demonstrated under a series of California Energy Commission Public Interest Energy Research (PIER) projects[2] as a potential utility tool to provide more granularity in power system and operations, particularly concerning the grid impacts of distribution-connected devices and resources. The present study represents one application or "use case" for utilities using such a tool.

2 Evans, P. (New Power Technologies), *Verification of Energynet Methodology,* California Energy Commission, PIER Energy Systems Integration Program, CEC-500-2010-021.

CHAPTER 2: Approach

Energynet Platform

The primary tool for conducting this study was an Energynet power system model and simulation of the Hobby system, Southern California Edison's (SCE) largest regional power delivery system.

The Energynet platform incorporates a power system model and simulation of the entire lines network of a regional power delivery system, incorporating regional transmission, local transmission, and distribution, including all distribution substations, circuits, and components. The model includes a representation of the relevant system element details, including individual line segment conductor ratings and configuration within every circuit, the presence and location of voltage control devices, and the proximity of existing distributed generation. The simulation can provide voltage and real and reactive power flow conditions at any point in the system under an actual system arrangement or under any hypothetical condition, such as with the addition of wholesale PV projects. The simulation can represent conditions as a static snapshot or in a series of snapshots reflecting quasi-dynamic behavior.

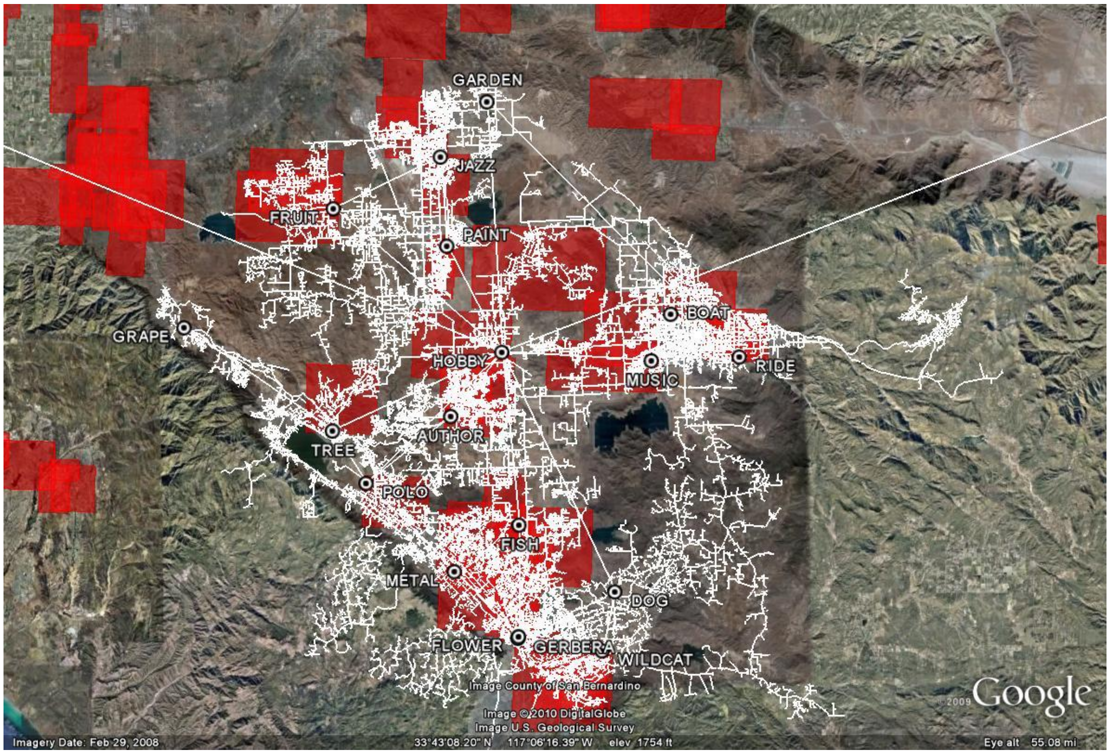
The Energynet platform is thus well-suited to reveal the impacts of wholesale PV projects connected at points in the distribution network on voltage and power flow at each project's point of interconnection, within the interconnecting circuit, on adjacent circuits and substations, and on the local and regional transmission system.

The Energynet model is generated with software using typical legacy system data, and can be updated as often as the underlying source data are updated.

For this study, an existing Energynet model of the SCE's "Hobby" system is shown in **Figure 1**. The Hobby system is a large, diverse regional electric power delivery network covering roughly 1,000 square miles and serving about 280,000 customers. The system consists of 58 substations and 246 distribution circuits ranging in voltage from 33 (kilovolt) kV to 2.4 kV.

The existing model used for this study characterizes the Hobby system with its actual layout and configuration from September 10, 2009, and with conditions simulated for individual hours during that day based on actual hourly loads, switch positions, and device status from supervisory control and data acquisition (SCADA) systems archives. New Power Technologies developed this simulation under a previous study (500-04-008) funded under the Energy Commission's PIER Program.

Figure 1: Hobby System Energynet Model/Opt.



Source: New Power Technologies.

Power Delivery System Map

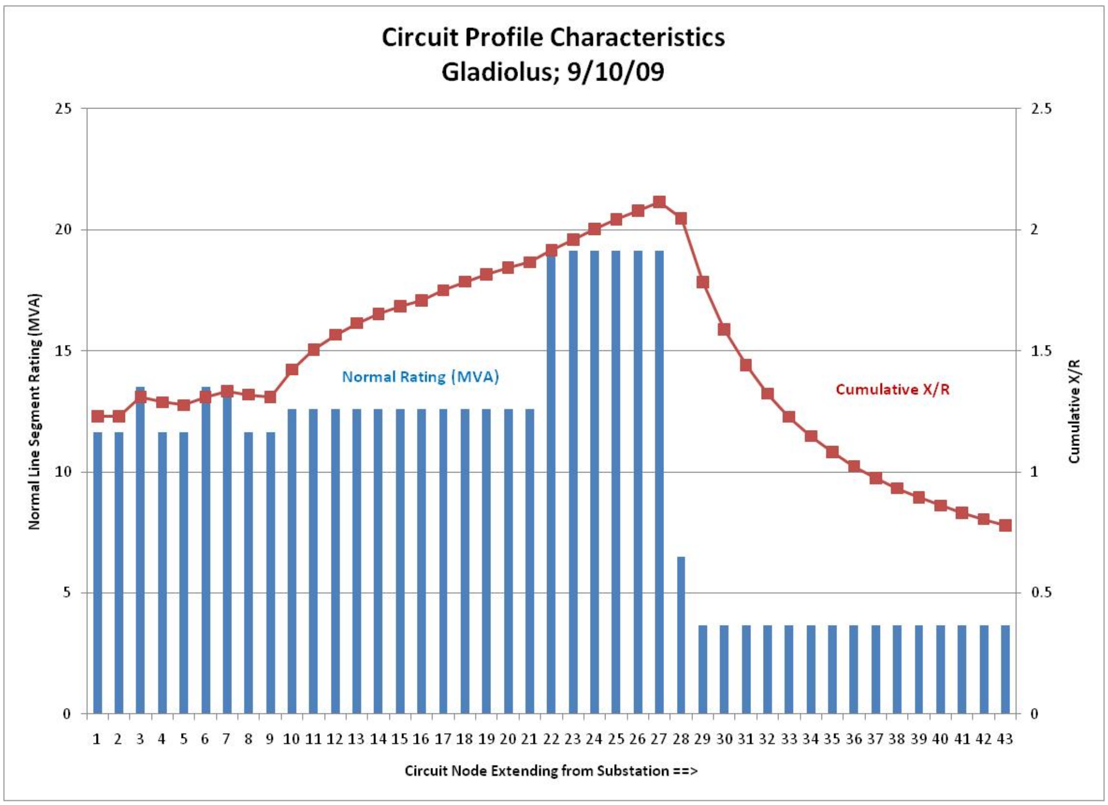
The impact of a given distributed generation project on a circuit varies depending on the interconnection location within the circuit. In other words, a wholesale PV project might have acceptable impact if connected at one location in a circuit, but may have significant impacts requiring mitigation or upgrades if connected at another location. One of the departures of this study from legacy low-impact project screens is to capture such differences.

To illustrate, **Figure 2** shows a profile or cross section of a particular distribution circuit as line segments and nodes extending from the substation. The normal line rating of each line segment is shown on the left axis, and the reactance (X) and resistance (R) of each line segment expressed as System (or Cumulative) X/R[3] at each point within the cross section is

3 X/R is the ratio of the cumulative system reactance (X) to cumulative system resistance (R) from the substation to the project's point of interconnection. A system's X/R is one measure of the power system's weakness, or resistance to voltage perturbations, at that location.

shown on the right axis. A 10 MW wholesale PV project connected near the substation, on the left side of the chart, could not cause power flow on the circuit that would exceed the normal megavolt amperes (MVA) rating of any line segment to the left or upstream, as those ratings range from about 12 MVA to 18 MVA. Further, the System X/R at those points ranges from about 1.25 to over 2.0, indicating that the system is "strong" or able to resist voltage changes from a sudden change in output of the project. Alternatively, a 10 MW project connected far from the substation, on the right side of the figure, could easily exceed the ratings of upstream lines. At points where X/R falls below 1.0, the system is "weak" — a sudden output change from the project connected at that point would cause a disproportionate system voltage change.

Figure 2: Location-Specific System Characteristics in a Circuit Profile



Source: New Power Technologies.

In the Energynet model each of the 246 circuits of the Hobby system is characterized in full detail from the substation to the individual customer service transformers. This detail allows the impacts of generation projects to be assessed as they differ at locations *within* a circuit.

Integrated Field Data

As part of the PIER study, the project team mapped more than 4,900 monitored data points from SCE's Energy Management System (EMS) and Distribution Control & Management System (DCMS) systems to individual physical devices and points within the Energynet power system model. These data points include strategically augmenting devices placed to achieve a uniform "monitoring density" within the Hobby system. This monitoring system provides to the Energynet platform continuous real and reactive load data for each circuit within the system. Thus for each Hobby circuit, not only is its actual peak load known, but also its actual minimum load and its minimum daytime load, the condition under which wholesale PV projects will have the greatest impact.

As noted above, for demonstrating the use of this method, existing cases simulating a single day's system loads and other conditions were used. Normally load patterns over the course of an entire year would be drawn from this field data to determine load conditions against which to evaluate PV project grid impacts.

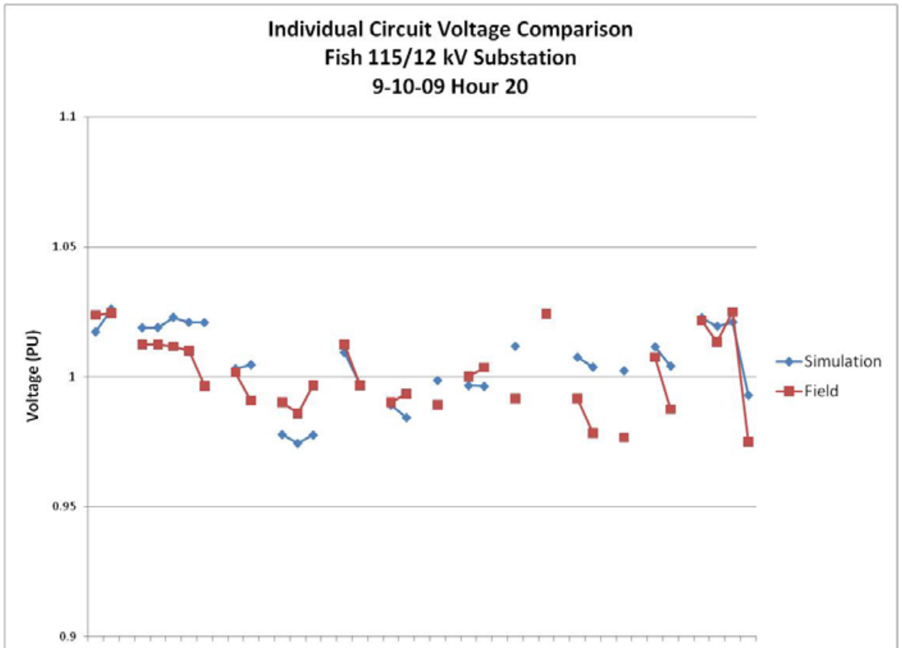
Validated Simulation Engine

In addition to the subcircuit detail noted above, the Energynet platform provides a simulation engine into which a model of a wholesale PV project at a particular location can be placed to observe its direct impacts.

In the earlier PIER study, the project team developed simulations of the Hobby system incorporating actual topology and recorded hourly loads and device status for specific hours of September 10, 2009. The team validated the simulation results with field-read values for voltage and power flow and found the simulation to be a statistically valid predictor of field conditions.

Figure 3 shows a comparison of field voltage reads and bus voltage values from the Energynet simulation corresponding to those line monitoring points on 14 distribution radials served from Hobby's Fish substation. Each cluster of linked data points represents the data for one circuit, with the data in topological order extending from the substation. For each circuit the simulation voltage values are well within 1–2 percent of the field values and even follow the voltage profiles of the individual circuits.

Figure 3: Comparison of Energynet Simulation and Field Voltage Values



Source: California Energy Commission PIER Report CEC-500-2010-021.

For this study, therefore, the team was able to "drop in" to the Energynet platform's simulation a model of a wholesale PV project of a given size interconnected in a specific location on any one of the system's circuits. The reconfigured simulation will show the project's direct grid impacts in terms of system voltage and power flow, and loading at the project site or at any other point in the system.

PV Project Characteristics

The focus of this study is a particular subcategory of distributed generation — PV wholesale distributed generation that is connected at distribution voltages, sunlight driven, inverter-based, and that is intended to export power from the project across the point of common coupling (PCC)[4]or the point where the project connects with the grid.

In other words, this study did not consider projects in larger or smaller sizes, projects using inductive or synchronous machines, projects that would connect directly to a substation bus or at transmission voltage, projects with a source of primary energy other than solar energy,

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4 Point of common coupling (PCC) is the point on the public (utility) electricity network at which a customer is, or could be, connected to received power.

or non-exporting projects whose output would be used entirely by the host. This study also did not consider single-phase project interconnections, and by extension did not consider impacts of such projects on shared secondary systems.

While this set of project characteristics is somewhat arbitrary, it arguably describes a market segment that may be expected to both (a) make a significant contribution to California's renewable power generation objectives and (b) seek interconnection at distribution voltages — that is, a market segment that sits at the intersection of California's policy objectives and their challenges for utility power delivery systems.

The team also assumed that all of the PV projects would use interconnection equipment that has met applicable California or Underwriters Laboratories certification requirements for the application, that incorporates anti-islanding features, and that is appropriate for the distribution system's primary line configuration at the point of interconnection. These assumptions are consistent with an active, commercially mature market segment.

In identifying low-impact interconnection opportunities, the team defined subject projects in tranches ranging in size from 500 kW to 5 MW in 500 kW increments — in effect, determining the largest project that would meet all of the applicable criteria in 500 kW increments from 500 kW to 5 MW.

Under present rules, interconnection of this study's subject PV projects to the investor-owned utilities' (IOU) power delivery systems (in this case SCE's Hobby system) would be evaluated under the utility's WDAT [5].

Project Grid Impact Evaluation Criteria

An effective set of distributed generation (DG) interconnection evaluation criteria should be sufficiently comprehensive to address the full range of grid impacts. It should also be sufficiently illuminating to both prompt detailed studies where warranted and avoid unnecessary studies.

The "Fast Track" criteria under the WDAT tariff are used to identify interconnections that are presumed to be low impact. While not strictly applicable at present for wholesale DG projects, a utility's Rule 21[6] Simplified Interconnection process also provides a set of screens used to identify presumably low-impact interconnections. The WDAT Fast Track and Rule 21 Simplified Interconnection processes each represent a set of criteria presently used to

5 Southern California Edison Company, *FERC Electric Tariff*, Second Revised Volume No. 5, from 20110301-5198 FERC PDF (unofficial), 03/01/2011.

6 Southern California Edison, *Rule 21 Generating Facility Interconnections*, Cal. PUC Sheet No. 36865-E *et seq*. Filed August 9, 2004.

identify low-impact projects that are in both cases offered interconnection without detailed studies.

In the most general terms, power generation on a distribution radial can have any of the following effects on the power delivery system:

- Potential to cause unintended post-fault energized island
- Potential overload of system components
- Potential impacts on system protection
- Potential impacts on system operating voltage
- Potential impacts on power quality

These impact categories are more fully explained and discussed in more detail below.

Table 1 provides a map of the WDAT Fast Track and Rule 21 Simplified Interconnection screens to the potential grid impacts noted above, along with the evaluation criteria applied in this study. "Line section" in **Table 1** refers to a portion of a power system bounded by an automatic sectionalizing device. For a radial distribution circuit with a single circuit breaker and no intermediate sectionalizing devices the line section and the circuit are effectively the same thing. The "circuit nonexport limit" in **Table 1** refers to the total DG on the circuit that would not exceed the circuit's minimum load while the DG is available to operate. So for PV, the circuit nonexport limit is the circuit's minimum daytime load less the output of any pre-existing DG in the circuit.

It is evident in **Table 1** that a wholesale PV project that met the screens for the Rule 21 Simplified Interconnection and WDAT Fast Track processes would not receive any direct evaluation for possible circuit overload, voltage, or power quality impacts that may arise. These factors might be indirectly addressed for such a project through the 15 percent of peak load DG limitation and the 2,000 kW overall project limitations applied under the SCE WDAT Fast Track provisions. Further, the 15 percent of peak load and 2,000 kW limitations themselves do not incorporate any project-specific considerations. So the operation of these screens has the potential to both allow impactful PV project interconnections to pass through without detailed studies and to subject low-impact PV project interconnections to detailed supplemental studies.

Table 1: Wholesale PV Grid Impacts and Evaluation Criteria

		SCE Rule 21 Simplified Interconnection	SCE WDAT Fast Track (< 2 MW)	Energynet DG Site Evaluation
Post-fault Island Potential				
	Generation relative to load	Individual project non-exporting (Screen #2); aggregate generation < 15% of line section peak load (Screen #4)	Aggregate generation < 15% of line section peak load (§6.5.2)	Generation < Circuit Non-export Limit
	Anti-islanding scheme	Certified as non-islanding (Screen #2)		All projects assumed certified as non-islanding
	Presence of fast reclosing scheme			
	Presence of mixed inverter and rotating DG within line section			
Potential overload of system components				
	Generation relative to upstream equipment ratings			Generation < Minimum Upstream Line Rating for PCC
Protection Impacts				
	EPS topology at PCC	PCC not on networked secondary (Screen #1)		Radial topology assumed
	Short circuit current contribution	Aggregate generation SCCCR < 0.1 at PCC (Screen #7)	Aggregate generation SCCCR < 0.1 at PCC (§6.5.4)	SCCCR assessment assumed
	Project protection features	SCC < 2.5% of interrupting rating (Screen #7)		
	Protection coordination		Short circuit current contribution from aggregate generation does not cause any protective device to exceed 87.5% of short circuit interrupting capability (§6.5.5)	Short circuit current assessment assumed
	Temporary over-voltage	Type of interconnection appropriate for primary distribution configuration (Screen #8); aggregate generation limited to 10% of peak load for 3? YG	Type of interconnection appropriate for primary distribution configuration (§6.5.6)	Primary distribution configuration at PCC identified (3 ? 3-wire / ? or 4-wire/YG)
Voltage Impacts				
	Circuit voltage regulation capability			Presence of substation bank LTC, # of line capacitors identified
	Impact on voltage regulating equipment operation			Project simulated max voltage impact (on 100% quasi-dynamic output change) at PCC < 2%
	Reverse flow at voltage regulating points			Generation < Circuit Non-export Limit; project simulated power flow impact
	System weakness or Stiffness Ratio at PCC			System X/R at PCC > 1.05
	Circuit voltage rise			Circuit voltage sensitivity, X/R @ PCC > 1.05, project simulated max voltage impact (on 100% quasi-dynamic output change) at PCC
Power Quality Impacts				
	Quasi-dynamic voltage impact			Circuit voltage sensitivity, X/R @ PCC > 1.05, project simulated max voltage impact (on 100% quasi-dynamic output change) at PCC < 2%
	Voltage Sag/Swell			Project simulated max voltage impact (on 100% quasi-dynamic output change) at PCC < 2%
	Flicker			Project simulated max voltage impact (on 100% quasi-dynamic output change) at PCC < 2%

Source: New Power Technologies.

This study sought to demonstrate a project evaluation approach that would identify truly low-impact interconnections quickly without allowing significant unknown grid impacts or risks to pass through. This approach is not intended to replace the detailed analysis required to interconnect projects known to have significant impacts, though its results would guide and expedite those more detailed studies.

Accordingly, the approach of this study departs from the Rule 21 Simplified Interconnection and WDAT Fast Track processes in several important ways. First, this approach incorporates not only the project's characteristics, but the characteristics of the power delivery system at the proposed point of interconnection — that is, not just the circuit characteristics, but the power system characteristics *within* the circuit at the relevant points. Second, the approach takes into account the range of loads a circuit would experience during periods when the proposed project is operating.

Third, the approach directly considers the potential voltage and power quality impacts of a given project. Fourth, the approach incorporates a direct simulation with a validated model of the voltage and power flow impacts of the proposed project as interconnected at the proposed location, rather than an assumption of what those impacts might be.

DG projects have greater direct impacts on power flow and voltage when generation output is a greater share of nearby load. Accordingly, the loads on a circuit when a proposed project is likely to be operating, particularly low loads, are most relevant to evaluating project impacts. For PV projects that can operate only during the day, a circuit's night time minimum loads are not relevant. Also, a circuit's daytime peak load conditions may mask some impacts of these projects that occur at lower loads. So a fourth point of departure in this approach is to evaluate project impacts using actual hourly loads.

The Hobby system has hourly load reads on every circuit, and these data are continuously fed to the Energynet platform. While some augmenting instrumentation for the Hobby system was provided in the prior PIER project to achieve truly uniform monitoring density, the majority of the Hobby circuits already had some hourly load measurement. Ample basis for estimating the hourly loads where necessary existed and those estimates were confirmed in the simulation validation. It was never necessary to extrapolate relevant load levels from annual peaks (and introduce the associated error).

The criteria applied in this study, and the approach applied to each, are explained in more detail below. Notwithstanding the breadth of this study's demonstrated approach, the evaluation of an individual project can be completed in a few minutes, as appropriate for a rapid or preliminary evaluation. In addition, the entire population of a regional power system's possible interconnection locations can be assessed to create an inventory of sites at which projects could be interconnected while meeting a set of criteria indicative of low grid impacts and minimal required upgrades.

Unintended Island

Conventionally, a power system fault will cause breakers to open, "islanding" or separating the faulted area from the rest of the system, and de-energizing the island. This response allows service to continue for customers on the rest of the system, and the de-energized island is safe for crews to work on. Some power systems are designed to allow *intended* islands to continue to operate independently from the balance of the grid to support critical loads.

Electric power generation units within an island may continue to energize the separated portion of the power delivery system, resulting in an unintended, unplanned sustained energized island. An unintended energized island is a safety hazard for the utility crews seeking to identify and correct the fault, particularly if they believe the area is de-energized. Also, if the circuit has reclosing features, these reclosers may unknowingly attempt to reconnect an island that is energized and out-of-phase. This can cause significant equipment damage. Thus an unintended island is a hazard even if it lasts only a few minutes.

A study of the risk of unintended islands resulting from PV generation 5[7] concluded that real and reactive loads and sources within an island must be matched on a sustained basis to support the island even in a "quasi-stable" state (> 5 sec duration). Taking into account the simultaneous variation of both generation and load, and the exponential decay characteristics of an energized island, stable islands (> 60 sec duration) are unlikely to occur at all in practice. The study found no material additional risk of an energized island of >5 seconds duration due to PV generation on the circuit, even under high penetration scenarios where PV generation routinely *exceeds* pre-island load.

Inverter-based PV generation also often incorporates active anti-islanding features that trip the generating unit when a separation from the power delivery system's main (strong) source is detected. This feature further reduces the risk of an unintended island.

PV generation introducing the chance of an unstable (< 5 sec duration) island can be a concern where the distribution system incorporates rapid reclosing schemes. This can be addressed through reclose blocking or slower reclosing times.

For "low-impact" wholesale PV interconnections, the following criteria were applied to ensure these projects will not sustain a post-fault island:

- Aggregate circuit PV < 100 percent of circuit minimum daytime load less existing DG
- PV incorporates anti-island scheme

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7 Cullen, N., et al; *Risk Analysis of Islanding of Photovoltaic Power Systems Within Low Voltage Distribution Networks*; International Energy Agency, IEA PVPS T5-08:2002, March, 2002.

The first criterion effectively limits the total PV on a circuit to 100 percent of the circuit's minimum daytime load or less. This would make it very rare for PV generation at the time of a daytime fault to exceed prefault circuit load. According to a study by the International Energy Agency this is a triply conservative criterion as it relates to islanding risk – PV generation is very unlikely to exceed prefault load, it is unlikely to match prefault load, and PV provides no source of reactive power to sustain an energized island At the Re-DEC meeting on March 4, 2011, the Interstate Renewable Energy Council (IREC) proposed a PV penetration limit of 50 percent of the circuit's minimum daytime load,[8] even more conservative as it relates to islanding risk. For a circuit with minimum daytime load equal to 30 percent of its annual peak load, a limitation of aggregate PV generation on the circuit to 50 percent of the minimum daytime load is nominally equal to a limitation to 15 percent of the circuit's annual peak load.

The presence of synchronous or inductive DG on a distribution circuit with inverter-based PV generation introduces additional concerns over the possibility of a sustained post-fault island. In theory under fault conditions, the PV generation can provide a continuing source of excitation voltage, and the rotating DG can provide a continuing source of reactive power to sustain the island. Because there are few synchronous or inductive DG projects in the Hobby system, such an assessment was not incorporated in this study. More generally, an interconnection on a circuit with mixed generation from classification was excluded as a "low impact" interconnection.

Overload of System Components

DG on a distribution circuit displaces system power serving circuit load. However, if there is some loss of circuit load while the generation remains in service, the generators' full output will flow out of the circuit over upstream circuit components, potentially resulting in a thermal overload of those components. As explained above and in **Figure 2**, the operating rating of individual line segments or devices upstream of a particular point in the circuit may limit the capability of the circuit to handle the loading from a generator interconnected at that point.

For "low-impact" wholesale PV interconnections, the following criterion was applied to ensure these projects would not overload upstream distribution system equipment in such an event: project output < minimum upstream line rating at project site.

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8 Sheehan, Michael (IREC), *Updated Recommendations for the FERC Small Generator Interconnection Procedures*, Re-DEC, March 4, 2011, available at http://www.cpuc.ca.gov/PUC/energy/Renewables/Re-DEC.htm.

This is one of several criteria whose evaluation would change depending on the project's proposed interconnection location within the circuit.

Protection Impacts

DG on a distribution circuit represents an additional source of fault current, potentially affecting the short circuit duty of circuit components or requiring the resetting of protective relay setpoints or the redesign of the circuit's protection scheme. Because inverters are current limited, inverter-based generation represents a relatively small fault current source.

The WDAT Fast Track process contemplates a cursory evaluation of the impact of an interconnection on the short circuit current at relays and protective devices and its contribution to fault current. Often inverter-based generation is not significant in either evaluation, and this evaluation can be done by inspection. Such an evaluation was not explicitly incorporated in identification of "low-impact" interconnections, but the team did assume that such a cursory evaluation could and would be done for each project.

Significant reverse flow on a circuit could affect the function of fault detection equipment. Some relays may fail to accurately detect fault conditions under reverse flow.

For "low-impact" wholesale PV interconnections, the following criterion was applied to ensure these projects would cause reverse flow or power export out of the circuit on a sustained, everyday basis. This would avoid the need for a detailed study of the impact sustained reverse flow on system protection: aggregate circuit PV < 100 percent of circuit minimum daytime load less existing DG.

This criterion is the circuit's nonexport limit. This is the maximum wholesale PV project size a circuit could accommodate without sustained reverse flow.

The configuration of the 3-phase primary serving the project at the point of interconnection (for example, Delta or Wye[9]-Grounded) has a bearing on the potential for temporary over-voltage from the project under some fault conditions. Both Rule 21 Simplified Interconnection and WDAT Fast Track screens consider the suitability of the proposed interconnection for the circuit's primary-side configuration. In this approach to identifying "low-impact" sites, identification of the circuit's primary configuration was included at the point of interconnection to support such an evaluation. This is another factor whose evaluation would change depending on the proposed interconnection location within the circuit.

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9 Delta and Wye refer to two layouts in which different components on a circuit are connected. For a Wye type, three components are at the three points of a "Y" shape , connected in one center point; and for Delta, the three connected components become three points of a triangle .

Voltage Impacts

DG injects real power onto a circuit, which offsets the effects of circuit load. In doing so DG can increase the circuit's voltage. Similarly, if the output of the DG drops or ceases, the circuit's voltage can fall. Further, PV generation is subject to unpredictable swings in output due to changes in solar radiation. These changes can be quite rapid under partly cloudy conditions.

Studies of PV output variability for individual large-scale PV projects indicate short-duration output transients of up to 39 percent of the project's alternating current (AC) nameplate output over a period of one minute for 90 percent of days, and a maximum observed of 50 percent of output over one minute. Sustained transients, such as at sunrise and sunset, were observed at 10–21 percent of output over 15 minutes.[10] [11] Further, multiple PV projects may simultaneously experience output reductions due to a common factor such as a cloud passing or a system voltage deviation event. However, for short-duration transients (< 5 min), studies show a strong reduction in the variability of the combined output of multiple PV projects and no variability correlation for projects more than 3 kilometers apart.[12]

Some distribution circuits have features such as load tap changers (LTCs), voltage regulators, and automated capacitors that actively manage circuit voltage as conditions change. However, even for such circuits, if PV project(s) interconnected on a circuit have a significant enough impact, they may change circuit voltage more rapidly than electromechanical voltage regulation equipment can respond. The team defined such a change in conditions as a "quasi-dynamic" change; in practical terms it might be a change within less than 30–60 seconds. Significant reverse flow on a circuit could affect the function of voltage regulation equipment. Some voltage regulation equipment may fail to accurately detect conditions under reverse flow. Also, where voltage is regulated at the substation bus level via a single transformer load tap changer, one circuit backfeeding may complicate voltage regulation for the other circuits served from the same transformer.

The impact of a given swing in power injection on circuit voltage varies at points within the circuit. A project interconnected at a "weak" location within the circuit may have a comparatively greater impact on voltage. The ratio of the cumulative system reactance (X) to cumulative system resistance (R) from the substation to the project's point of

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10 Carl Lenox (SunPower), *Variability in a Large Scale PV Installation*, National Renewable Energy Laboratory, Utility-Scale PV Variability Workshop, Cedar Rapids, Iowa, October 7, 2009, http://www.nrel.gov/eis/pdfs/47514.pdf.

11 Jan Kleissl (UC San Diego), *How Geographic Smoothing and Forecasting RD&D Can Help High Penetrations of Distributed Generation*, California Energy Commission, 2011 IEPR Committee Workshop on Renewable Localized Generation, May 9, 2011.

12 Lave, Kleissl, et al, *High Frequency Irradiance Fluctuations and Geographic Smoothing*, August 31, 2011.

interconnection, or System X/R, is one measure of the power system's weakness, or resistance to voltage perturbations, at that location. As shown in **Figure 2**, the System X/R within a circuit varies significantly. Sites electrically distant from the substation can have very low System X/R; in these "weak" locations the variable output of a PV project of a given size can have a much more dramatic impact on circuit voltage.

The Rule 21 Simplified Interconnection and WDAT Fast Track screens lack any direct consideration of potential voltage impacts of proposed DG projects. These processes also lack consideration of the circuit's existing voltage regulation capability or the resistance of the circuit at the project's point of interconnection to voltage impacts from project output changes. These are significant shortcomings, particularly as they relate to evaluating wholesale PV projects.

For "low-impact" wholesale PV interconnections, the team applied the following criteria to ensure these projects would have minimal impact on circuit voltage:

- Circuit has voltage regulating capability (load tap changer or voltage regulator and automated line capacitors)
- System X/R > 1.0 at project site

These two criteria can be applied without the benefit of a power flow simulation. In this study, the team had the benefit of a power flow simulation to directly evaluate the actual voltage impact of a given project in a given location on voltage at the point of interconnection and elsewhere in the circuit.

For "low-impact" wholesale PV interconnections, the following power flow-based criteria for a 100 percent change in the project's output would be applied to ensure these projects would have minimal impact on circuit voltage:

- Quasi-dynamic voltage impact < 0.02 per unit (PU) at project site
- No capacitor redispatch or TCUL steps

This output change scenario of 100 percent of the PV project's rated output in a quasi-dynamic time frame is conservative compared to the maximum 39 percent to 50 percent of rated output change reported above for rapid transients.

Power flow simulations were performed for 535 PV projects interconnected on every circuit at sites otherwise meeting the non-power flow-based criteria above. These projects were configured in the simulations as large projects in weak locations expressly to stress-test each circuit. These simulations assessed whether projects at sites that meet the location-specific criteria of System X/R and minimum upstream line rating would, in a simulation, also meet the power flow-based voltage change criteria. Using these results, a few circuits were found whose voltage is unusually sensitive to output changes from wholesale PV projects, even where the location-based criteria are met.

Accordingly, for a wholesale PV interconnection to be considered "low-impact," the team added a criterion that the project not be interconnected on a circuit shown to have unusually high voltage sensitivity.

The choice of a minimum System X/R value of 1.0 began as somewhat arbitrary. In this study, the team also used these power flow simulation results to evaluate the ability of this measure to predict voltage impacts without a power flow simulation. As explained below, a strength criterion of System X/R > 1.05 predicted manageable project voltage impacts, and the final results reflect the revised criterion.

Power Quality Impacts

DG on a distribution circuit can contribute to rapid voltage fluctuations such as sags, swells, and flicker, as well as harmonic distortion.

Sags and swells are normally defined as voltage swings of greater than 0.10 PU (10 percent of nominal voltage). [13] Projects whose voltage impact for an output swing of 100 percent of rated is demonstrated to meet the 2 percent voltage impact criterion above are also incapable of inducing voltage swings that great.

Flicker is defined as a voltage change attributable to the DG project whose magnitude and frequency exceeds an established Borderline of Irritation Curve.[14] Projects whose voltage impact for an output swing of 100 percent of rated in a quasi-dynamic time frame is demonstrated to meet the 2 percent voltage impact criterion above may be close to this curve at a 30-second time frame. However, a more realistic project output change of 50 percent or less of rated would have a voltage impact below the flicker curve, and such a project is demonstrably unlikely to be a source of flicker.

The use of certified interconnection equipment should ensure that the project will not cause unacceptable harmonic distortion. Accordingly, the team did not apply any additional criteria for low-impact projects to address power quality impacts.

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13 IEEE 1547.2-2008 Annex G.

14 IEEE 1547-2003 4.3.2; IEEE 519-1992. Borderline of Irritation Curve plots change in voltage and its frequency on dimming of lights and the level at which resulting flicker becomes noticeable and irritable.

The criteria applied to identify low-impact interconnections are listed in summary below:

- Project will not sustain a post-fault island:
  - Aggregate circuit PV < 100 percent of circuit minimum daytime load less existing DG
  - PV incorporates anti-island scheme
- Project cannot overload upstream distribution system equipment:
  - Project output < minimum upstream line rating at project site
- Project will have minimal impact on system protection:
  - Project will not cause reverse flow at protection devices (aggregate circuit PV < 100 percent of circuit minimum daytime load less existing DG)
  - Short Circuit Current Contribution Ratio and Short Circuit Current evaluation per WDAT Fast Track process
  - Primary distribution configuration (Delta or Wye-Grounded) identified
- Project will have minimal impact on circuit voltage:
  - Circuit has voltage regulating capability (LTC or voltage regulator and automated line capacitors)
  - Project will not cause reverse flow at voltage regulating points (aggregate circuit PV < 100 percent of circuit minimum daytime load less existing DG)
  - System X/R > 1.05 at project site
  - Project is not on a circuit with unusually high voltage sensitivity
  - Power flow: 100 percent quasi-dynamic output change voltage impact < 0.02 PU at project site

A PV project interconnection meeting *all* of these criteria was identified as “low impact.”

Candidate Sites

Any physical structure within the Hobby system was considered as a candidate site to interconnect a PV project. In other words, nodes representing line segment junctions only were excluded. Substation operating buses and network locations that host main radial circuit breakers, reclosers, and voltage regulators were also excluded. All the candidate sites within the Hobby system were evaluated against the criteria listed above.

CHAPTER 3: Outcomes

This study incorporated an Energynet platform application that can rapidly evaluate a site in a modeled regional power system under the criteria above for its suitability to interconnect a distributed generation project having given characteristics. The application identified for the Hobby system an areawide inventory of low-impact interconnection sites for wholesale PV in the 500 kW to 5 MW size range. The research team performed simulations of the grid voltage and power flow impacts of more than 500 individual hypothetical PV projects in the Hobby system.

In evaluating an individual interconnection using the Energynet platform, a project simulation to assess the project's direct voltage and power flow impacts would normally be included as an inherent capability of the tool. In the context of the Hobby system low-impact site inventory, the simulations the team performed provided particular perspectives. First, they revealed a small number of individual circuits with unusual voltage sensitivity to these PV projects. The team concluded that sites on these circuits should not be considered low-impact interconnection sites. Second, the simulations validated the predictive value of the nonsimulation-based low-impact site criteria. Most important, these simulations demonstrated the practicality of assessing grid impacts via power flow simulation for hundreds of potential projects using the Energynet platform.

Identification of Low-Impact Wholesale Distributed PV Interconnection Sites

Within the Hobby system, 78,468 network nodes in the 246 circuits representing physical structures were identified. Rather than just identifying the low-impact sites, every site was evaluated. The low-impact site inventory aside, identifying the particular criterion (or criteria) under which interconnection at one of the remaining sites may have impacts is arguably more valuable. With this information, if a project sponsor seeks to interconnect at such a location, both the applicant and the utility have an indication of what the issues are, what type of detailed studies should be performed, and the nature of the mitigation that may be required.

Sites for 3-Phase PV Generation

Of the 78,468 sites representing physical structures, 24,816 3-phase[15] sites are also not substations or main circuit breakers, and do not support voltage regulators or reclosers.

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15 *Three-Phase* refers to the manner in which alternate current is transmitted and serves a specific load. A residential load is generally served by single-phase current. A phase refers to the shape of the

More specifically, 52,906 sites would not be considered low-impact sites for the wholesale PV projects in this study because they are not served at 3-phase and thus would not support 3-phase wholesale PV generation projects. An additional 746 sites would not be considered low-impact sites because they are unsuitable interconnection points due to the system equipment at those locations.

"Strong" Sites

The team also applied the system strength criterion of System X/R > 1.0 described above to all of the candidate project sites. Of the 24,816 sites not eliminated above, 17,362 sites had System X/R 1.0 or greater. In other words, 7,454 sites would not be considered low-impact sites for wholesale PV projects due to the system's weakness at that particular location within the circuit as indicated by the System X/R ratio.

Sites Equipped to Manage PV-Related Voltage Variation

According to these criteria, low-impact interconnection sites for MW-scale wholesale PV projects would lie only in distribution circuits with existing voltage regulation features. These features would allow the power delivery system operator to manage potential voltage impacts of such projects interconnected in those circuits. Of the 17,362 sites meeting the 3 phase and system strength criteria, 3,574 sites would not be considered low-impact sites because they are on circuits that lack existing voltage regulation capability, leaving 13,788 sites.

Sites Unlikely to Cause Sustained PV-Related Reverse Flow

Using hourly load data for each circuit, the team evaluated the minimum daytime load of each of the 246 Hobby system circuits. There are 227 circuits with minimum daytime loads of 500 kVA or greater that could support a wholesale PV project of at least 500 kW in that the output of the project is unlikely to exceed the circuit's daytime load and induce reverse flow into the substation. There are also 19 circuits whose minimum daytime load (less any previously sited generation) is less than 500 kVA. Sites on these circuits would not be considered low-impact interconnection sites under this criteria for a wholesale PV project of 500 kW or larger due to the likelihood of sustained reverse flow. None of the 13,788 sites meeting the other criteria above is situated on any of these low-load circuits.

In the Energynet platform application, the circuit minimum daytime load less any existing circuit generation is the circuit's nonexport limit for wholesale PV projects. This is also the

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sine curve as both current and voltage rise and ebb. A 3-phase is commonly used for large motors/loads.

largest single project the circuit can host without experiencing sustained reverse flow and export from the circuit. Under these criteria, low-impact sites for wholesale PV projects of 500 kW or more would be on circuits whose nonexport limit is no less than 500 kVA.

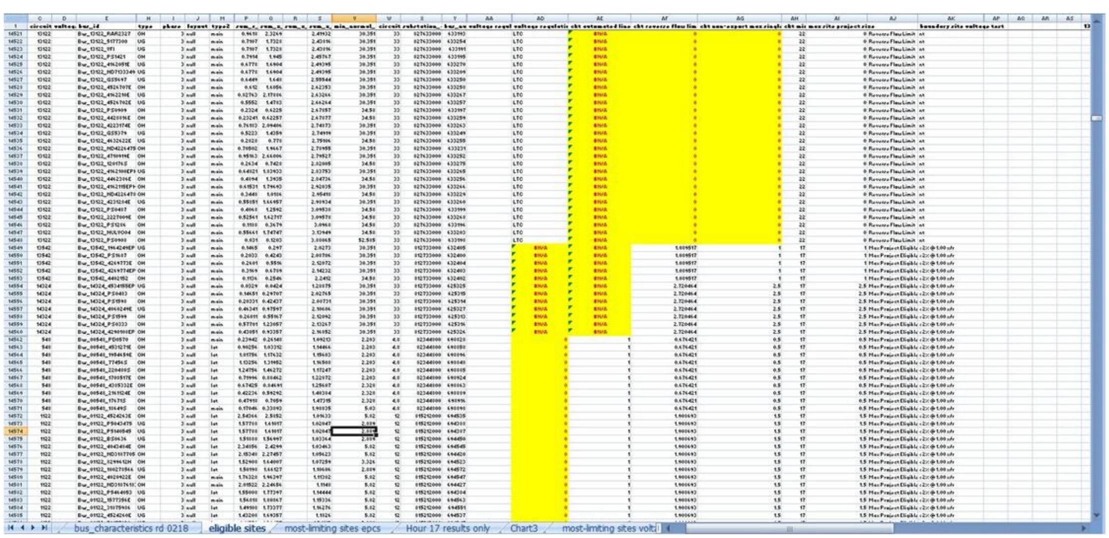
Sites Unlikely to Cause PV-Related Circuit Overloads

The maximum size of the low-impact PV project that could be accommodated at each of these sites may be limited by the circuit's nonexport limit as above. It could also be limited by the most limiting rating of upstream equipment within the circuit. In the event of a loss of circuit load, the circuit must be capable of delivering the project's output from the point of interconnection to the balance of the system over the upstream equipment. The team found that of these 13,788 sites, 3,993 sites would limit the largest low-impact project to less than the circuit's nonexport limit due to limitations on equipment upstream of the project site.

Through the foregoing process, the team identified 13,788 sites capable of interconnecting a PV project of at least 500 kW while meeting *all* of the foregoing criteria. These sites lie on 169 circuits with nominal circuit voltages ranging from 33 kV to 4.8 kV.

For the remaining 64,680 sites representing physical power delivery system structures, the team identified the individual criterion or criteria under which each fell short to be classified as a low-impact site. **Figure 4** shows sample output for a portion of the Hobby sites. While the individual values are not readable, **Figure 4** shows that the findings under each criterion are presented for each individual site, with highlighting of the one or more specific criteria these particular sites failed to meet. These sites could conceivably support a wholesale PV interconnection of the type considered in this study, but would require additional study focused on these identified shortcomings and possibly mitigation.

Figure 4: Hobby System Low-Impact Site Prescreening Results



Source: New Power Technologies.

Direct Evaluation of PV Voltage Impacts Using Energynet Simulation

With the simulation features of the Energynet model, the team was able to simulate and directly assess the voltage and power flow impacts of individual PV projects. Under the nonpower flow-based criteria each simulated project would have been evaluated previously for the system strength at the project's point of interconnection, and for the voltage control features of that circuit. Each project would also have been evaluated for the maximum low-impact project size at the project's point of interconnection, whether established by the circuit's nonexport limit or the most-limiting rating of equipment or lines upstream of the project's location.

By actually simulating the voltage impact for a sample of projects that would otherwise qualify as low-impact interconnections, the voltage sensitivity of each circuit could be evaluated. This allows identification of those provisionally "low-impact" PV project sites that in practice might still have unacceptable voltage impacts without mitigation due to unusual voltage sensitivity in the circuit. The team developed models and performed full power flow simulations for 535 PV projects of different sizes and interconnected at different sites throughout the Hobby system. The simulations mimicked the conditions under which the largest number of circuits are at their daytime minimum loads, which for the cases used in this study was Hour 17 (or the 10:00 p.m. hour, Pacific Daylight Time) of the date used for this study, September 10, 2009.

The projects simulated that would nominally meet the low-impact criteria were purposefully configured to stress those criteria — that is, they were relatively large projects in relatively weak locations. Further, to test the predictive value of the low-impact site criteria impacts of projects that did not strictly meet the low-impact criteria were simulated. These included projects too large for their location under these criteria in light of upstream constraints and projects at sites that do not meet the system weakness criterion the team applied.

The team tested and recorded the "maximum voltage impact" of each simulated project as the voltage change at the project site with project in and out of the system with all voltage controls held static. These simulations represent an effective ramp of 100 percent of the project's output. With voltage controls held constant, these simulations are in effect quasi-dynamic, or before any response from voltage controls. So the simulation scenario is, in effect, 100 percent of output change in the project's output within 30 seconds to 1 minute. The voltage change read at the project site is where the voltage impact would be greatest, without any attenuating factors.

Studies suggest that the maximum observed subminute change in output for a large-scale PV project is around 50 percent of rated output, so at 100 percent of rated output change these simulations may be considered worse than "worst case." These are also not true dynamic simulations; however, it is unlikely that an operational dynamic transient would yield a greater output change and voltage change in the power system. These are also not simulations of fault conditions.

The voltage change at the point of interconnection indicates the maximum voltage rise anywhere in the system the project would cause while operating and the maximum voltage drop the project would cause due to output variability or a unit trip. The simulation results can also tell observers the voltage change at the nearest voltage regulation point, at the nearest customer site, at the substation, and so forth.

Circuit Voltage Sensitivity

The team found that for most circuits, given a project sited at a location meeting the system strength criterion and sized to meet the nonexport and upstream equipment overload criteria, the project's maximum voltage impact in simulation is less than 0.02 PU (2 percent of nominal voltage). In fact, with a slight increase in the minimum system strength criterion from System X/R > 1.0 to System X/R > 1.05, nominally low-impact projects in 86 percent of the 169 circuits with low-impact sites showed maximum voltage impacts of 0.02 PU or less in simulation.

However, 14 of the 169 circuits were moderately sensitive to voltage impacts of PV projects. In these circuits, low-impact projects at sites meeting an elevated strength criterion of System X/R > 1.05 showed maximum voltage impacts in simulation of up to 0.035 PU.

Ten of these 169 circuits were quite sensitive to voltage impacts of interconnected generation. In these circuits, even projects at sites meeting the more restrictive System X/R > 1.05 weakness criterion had maximum voltage impacts greater than 0.035 PU.

This suggests that a system strength criterion may not be a reliable predictor of acceptable voltage impacts on all circuits. Accordingly, for purposes of the Hobby area low-impact site inventory, the team excluded sites located on the 10 circuits shown to have high voltage sensitivity to interconnected generation. Of the 13,788 sites identified above as low-impact for a PV interconnection of 500 kW or more, 1,044 lie on such circuits.

A wholesale PV project with a maximum voltage impact at the project site of 0.02 PU or less would also meet the criterion for no impacts on voltage controls. These controls often operate with a 2 percent dead band, and a 2 percent voltage impact from the PV project at the project site will be further attenuated at any voltage control points by the electrical distance to these devices.

Because the projects simulated were configured as large interconnections in weak locations, the voltage response observed for the simulations on each circuit is indicative of that circuit's voltage response for less extreme interconnections elsewhere in the circuit. Accordingly, circuits shown capable of holding these sample projects, at locations meeting a System X/R > 1.05, to voltage impact of 0.02 PU or less could support low-impact interconnections meeting the strength criterion with acceptable voltage impacts. Similarly, for circuits in which simulated projects meeting the System X/R > 1.05 strength criterion had a voltage impact of greater than 0.02 PU, the team could not be confident that projects at sites meeting that strength criterion would have acceptable voltage impacts. Sites on such circuits would not be considered low-impact interconnection sites.

With sites on 24 circuits with unusually high voltage sensitivity excluded, an inventory of 11,666 low-impact interconnection sites on 145 circuits remained in the Hobby system for 500 kW to 5 MW wholesale PV projects.

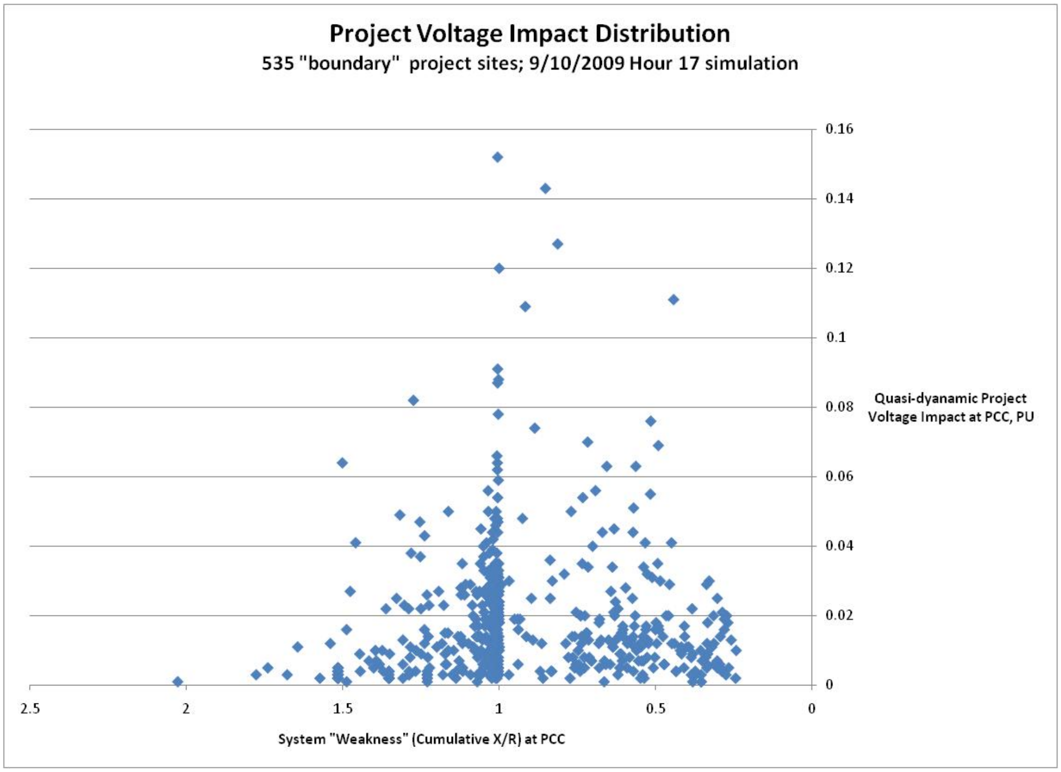
Voltage Impact Predictive Capability

Performing an individual power flow simulation of a proposed generation project placed at its proposed point of interconnection is always preferable, as this provides insight into the project's voltage impacts at a variety of key points in the system and power flow and loading impacts as well. Nonetheless, the team used the simulations described above — PV projects in a range of sizes at locations having a range of system strengths — to evaluate the system strength criterion as a possible predictor of projects having "low" voltage impacts without a power flow simulation.

Figure 5 shows the distribution of simulated project voltage impacts by system strength (System X/R) at the project site. The team evaluated a mix of projects, including some in locations that did not meet the System X/R > 1.0 weakness criterion. Projects in very "strong" locations were not simulated.

These results show that for the most part even projects in "weak" locations, with System X/R < 1.0, have modest voltage impacts. However, there are some examples where projects at weak sites do have very large voltage impacts. The results also show, as discussed above, that there are some projects at sites that nominally meet the strength criteria (System X/R > 1.0) and still have large voltage impacts. Pending further investigation, the team noted those circuits as having unusual voltage sensitivity and excluded them from consideration as hosting low-impact sites.

Figure 5: PV Project Voltage Impact by System Strength



Source: New Power Technologies.

The overarching finding is that, for projects at sites with a System X/R > 1.05, simulations show greater than 95 percent have a maximum voltage impact at the project site of less than 0.035 PU. Given that the project output change scenario used is itself conservative, this suggests that the likely voltage impacts of these projects would be well under 0.035 PU, thus manageable by circuit voltage controls.

A slightly enhanced strength criterion of System X/R > 1.05 is reasonably predictive of readily manageable voltage impacts indicative of a low-impact project. While it is preferable to perform a simulation to assess the voltage impacts of a given project, such a criterion could be applied instead, particularly if any circuits with unusual voltage sensitivity have already been identified.

Applying this enhanced strength criterion of System X/R > 1.05 leaves an inventory of 11,121 sites on 145 circuits.

Low-Impact Interconnection Site Inventory

At the end of the screening process described above, 11,121 interconnection sites on 145 circuits remained within the Hobby system. Each of these sites would support the interconnection of a PV project of a particular size in the range from 500 kW to 5 MW while meeting all of the criteria stated above. Again, while the team did not simulate the voltage impact of all 11,121 potential interconnections, simulations were performed for each circuit of relatively large projects at relatively weak locations and excluded from the low-impact site inventory sites on those circuits that demonstrated moderate to high voltage sensitivity.

Table 2 represents this set of sites in terms of the largest individual project size and the number of circuits that would support a project of that size. Table 2 shows 145 circuits that would support "no" projects. This group includes circuits whose sites were disqualified as low-impact sites under one or more criteria as well as circuits with nominally qualifying low-impact sites that would not support a project as large as 500 kW.

Table 2: Circuits Supporting Low-Impact Interconnections by Project Size

Maximum Single Project Size	Number of Circuits
5 MW	45
4.5 MW	18
4 MW	11
3.5 MW	17
3 MW	15
2.5 MW	11
2 MW	9
1.5 MW	6
1 MW	8
500 kW	5
Circuits Failing Criteria for Any Size	145

Source: New Power Technologies.

This study considered Hobby system operating conditions of a single day and did not include a review of annual load data to identify what would be a more-limiting light daytime load operating condition. In practice, a study such as this one should include such a review.

Lower circuit loads would affect this inventory in two ways. First, the nonexport/reverse-flow criterion would be more limiting — for many circuits the nonexport limit would be lower. Thus there would likely be fewer sites capable of carrying the larger project sizes in **Table 2** while meeting all of the low-impact site criteria. Second, it is possible the lighter loads could reveal in simulation greater voltage impacts of otherwise low-impact projects. However, the system strength criterion, as applied, would not change with lower circuit loads. Further, because lighter loads would limit project sizes through the nonexport limit criterion, nominally low-impact projects meeting all of the applicable criteria may not necessarily show greater voltage impacts when simulated under lighter load conditions.

CHAPTER 4: Discussion and Conclusions

A Tool to Address Interconnection Backlog

This study demonstrates that the Energynet Power System Simulation model is a tool suited to the scale of the California IOUs interconnection study backlog, presently numbering in hundreds of requests. During this study, the team performed preliminary siting assessments for MW-class PV project interconnections at nearly 80,000 sites. An inventory of more than 11,000 "low-impact" sites on 145 of the distribution circuits within the Hobby system was identified. The team demonstrated (under the system conditions of the study) that each of these sites is capable of interconnecting a PV project ranging in size from 500 kW to 5 MW while meeting criteria that support the following conclusions:

- Project will not sustain a post-fault island.
- Project cannot overload upstream distribution system equipment.
- Project will not cause reverse flow at substation bus or voltage regulation point.
- Project will have minimal impact on circuit voltage.

The team also performed individual power flow simulations of 535 PV project interconnections, assessing the direct voltage and power flow impact of each project.

As of late March 2011, Pacific Gas and Electric (PG&E) and SCE had, respectively, 191 and 231 WDAT interconnection requests pending. SCE at that time estimated that it would take as long as six to seven years to complete the studies for the small generator interconnections in its queue.

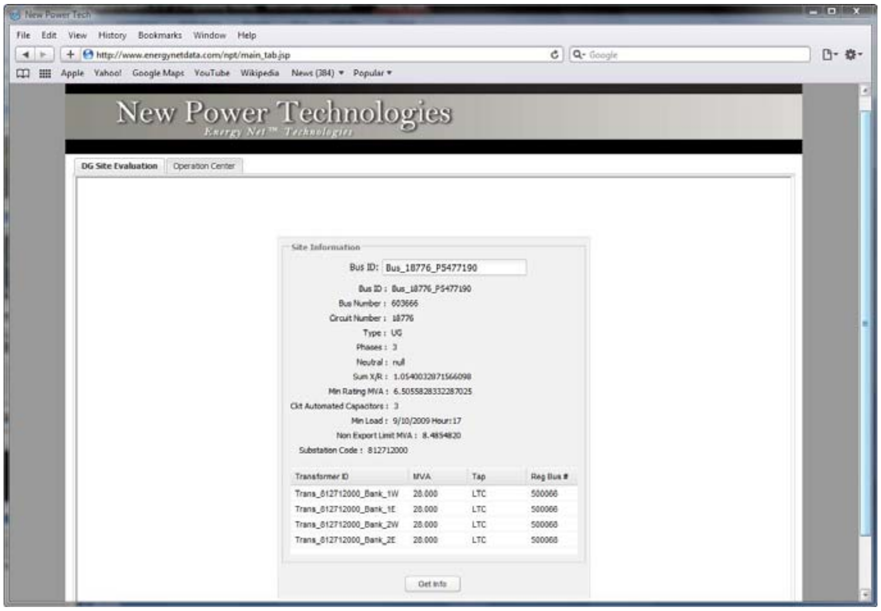
In a Renewable Distributed Energy Collaborative workshop on March 4, 2011, the team demonstrated the Energynet application used for this study. Even applying a robust set of criteria compared to the Rule 21 Simplified Interconnection and WDAT Fast Track processes, the Energynet platform assesses an individual interconnection site under those criteria in one click, as shown in the screenshot in **Figure 6** and as demonstrated at the workshop.

The Energynet application also produces a project model that can be dropped into the power flow simulation engine supporting the Energynet simulation – in this case Generator "1" in GE PSLF[16] shown in **Figure 7** – enabling an evaluation of the direct impact of the project on system voltage and power flow anywhere in the regional power system, with any

16 General Electric's Power System Load Flow model.

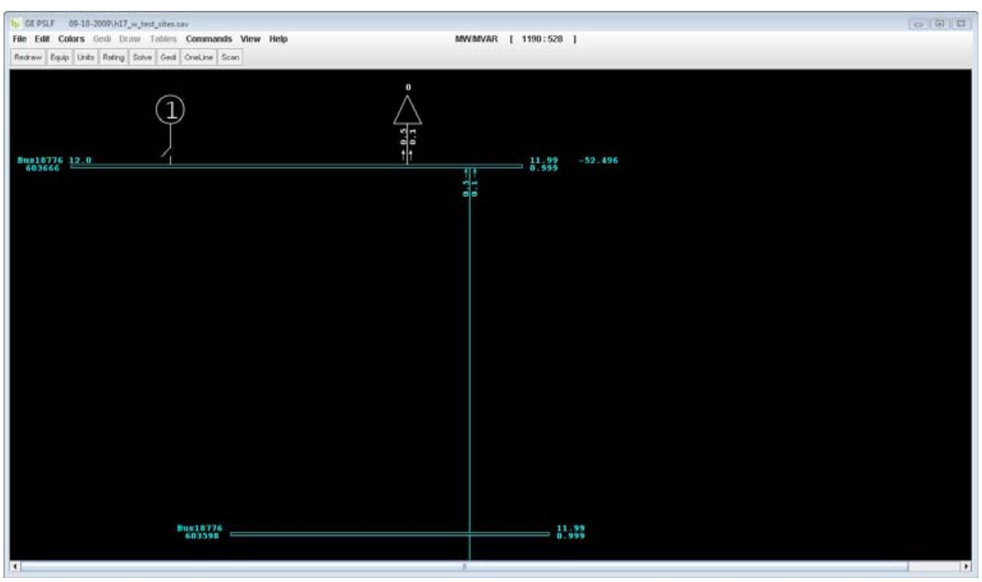
other combination of other projects or alternative system arrangements. The result is an assessment of the direct impacts of a particular project interconnection, of a particular size, in a particular location, under a broad set of measures, with a full simulation, in less than a minute.

Figure 6: Energynet DG Site Evaluation Application Screenshot



Source: New Power Technologies.

Figure 7: Energynet DG Site Evaluation Application Screenshot



Source: New Power Technologies.

The data requirements and burden of creating and maintaining a tool such as the Energynet platform are valid concerns. The results of PIER Project 500-04-008 demonstrated that the Energynet model can be developed using routinely maintained utility system and field monitoring data, that once deployed a new system model can be developed in less than a month. An existing model can be updated in less than a day, with minimal burden on utility personnel.

Identifying "Low-Impact" Interconnections Is a Key Opportunity

This study demonstrates an approach that a utility could use to identify low-impact interconnection sites for wholesale PV projects within a regional power system early, even on a pre-identified basis, and provide a rapid but comprehensive assessment of the grid impacts of an individual proposed interconnection. This information available early in a project interconnection process could help divert utility and developer resources from high-impact, low-probability projects to high-probability projects that also have low impacts on the utility's system. It could help avoid unnecessary studies and arbitrary barriers to projects that really are low impact.

There is nothing unusual about the Hobby system to suggest that the findings of this study are not generally relevant. The Hobby system is a very large, diverse regional power delivery system comprised of hundreds of distribution circuits and hundreds of thousands of line segments and devices. The team calculated the system "strength", or System X/R ratio, at nearly 80,000 individual locations in the Hobby system; these ratios range from a very weak 0.12 to a very strong 3.88, with an average of just over 1.0. The Hobby system defies any general categorization as "weak" or "strong."

As described above, the low-impact site evaluation criteria applied included identification of circuits with light loads, in which large PV projects might introduce sustained reverse flow. In addition, the team identified locations *within* circuits where an upstream pinch point should limit the size of an interconnected project and where system weakness should preclude placement of a large wholesale PV project. The team also used a large number of simulations to identify circuits with unusual voltage sensitivity. All of these conditions existed within the Hobby system. Every power system is different. This study demonstrates that this approach is capable of identifying these conditions for individual interconnections and the inventory of low-impact sites demonstrably avoids them.

The studies required to interconnect a high-impact project with appropriate system facilities are legitimately time-consuming and require tools beyond those used for this study. However, identifying the issues associated with such a project early on may avoid this additional effort entirely.

Implied Hierarchy of Project Evaluation Criteria

Simply identifying “low-impact” PV project sites is no solution to accommodating PV projects if those sites are unworkable from a PV project standpoint. The criteria applied in this study to identify those sites suggest a hierarchy of issues at play in potential project interconnection at a site that is not “low-impact.” A site that fails under some criteria may inevitably require costly mitigation, while a site that fails under other criteria may still be workable, or even require no mitigation.

For example, a project site that is shown to be “weak” in terms of System X/R or constrained by an upstream pinch point might be improved by reconfiguring the host circuit, but most likely would require costly reconductoring of some portion of the circuit. On the other hand, a circuit lacking existing voltage controls nominally may have no “low impact” sites. Providing voltage controls could have an acceptable cost.

Notably in the Hobby system, 33 kV circuits serving lower voltage substations have very strong System X/R ratios at every site. From a power system standpoint, these would be attractive sites for large wholesale generation projects. However, for the most part, these circuits lack voltage controls, so their sites do not appear in the inventory of low-impact sites. Given the system strength on these circuits, the voltage impact of even a large wholesale PV project may be so small that voltage controls are unwarranted.

In other words, knowing why a project site is not “low impact” is as valuable as identifying “low-impact” sites.

Project Evaluation Criteria

This study sought to demonstrate a project evaluation approach that would identify truly low-impact interconnections quickly but without allowing significant unknown grid impacts or risks to pass through.

As shown in **Table 1**, the team applied criteria that departed from the Rule 21 Simplified Interconnection and WDAT Fast Track processes in several important ways. The characteristics of the power delivery system at the proposed point of interconnection— that is, system characteristics *within* the circuit at the relevant points- were incorporated in the evaluation.

The study also took into account the range of loads that a circuit would actually experience during periods when the proposed project would operate, in this case derived from recorded hourly data. As the majority of Hobby circuits had hourly load monitoring, and for those that did not there was ample data from which to estimate variable loads, the team found it unnecessary to extrapolate the load levels relevant to the impact analysis from annual peak loads (and introduce the associated error). The team also directly considered the potential voltage and power quality impacts of a given project. Last, a direct simulation of the voltage and power flow impacts of the proposed project were included.

One set of reviewers stated that it is “very unlikely” that a project meeting all the criteria we applied would be shown later, under detailed system impact studies, to have adverse system impacts requiring mitigation.[17]

The impacts of any wholesale DG project should be evaluated using a simulation; however, a strength criterion provides useful guidance to identify a project with manageable voltage impacts without performing a power flow analysis. The system strength criterion employed here, particularly the enhanced System X/R > 1.05 criterion, was shown to effectively identify those interconnections where PV project voltage impacts would nearly always fall within the range of circuit voltage controls. It is possible this criterion may be further improved if stated in terms that also incorporate the project’s strength relative to the system strength, such as “stiffness ratio.”[18]

Simply applying such a criterion to an individual project cannot identify those sites on circuits with unusual voltage sensitivity. In this study, the power flow simulations revealed that there were such circuits in the Hobby system and identified those specific circuits. Modeling potential PV interconnections in a power flow simulation rather than relying on such criteria must be the preferred approach.

Voltage Impacts of MW-Scale PV Projects

The voltage impacts of “exporting” PV projects connected to the distribution system, particularly where aggregate generation is large relative to load (“high-penetration”), are the subject of active discussion within the industry and prominent topics in IEEE 1547 standards working groups. This study’s results include full simulations of the impacts of more than 500 wholesale distributed PV projects in MW-class sizes at a wide variety of interconnection sites in a diverse regional power delivery system. The projects modeled are the largest individual projects the circuit could accommodate under the parameters of this study, and the interconnection sites were intentionally chosen as relatively weak but viable. The projects themselves were simulated without any measures to reduce their voltage impact, and the system voltage controls were frozen to show the maximum voltage impact.

These results show that for MW-class PV projects connected to distribution circuits at the maximum site size supportable by the circuit and even at relatively weak locations, the

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17 K. Brunkenhoefer et al, Oncor, Personal Communication, March 2011.

18 System plus project fault current at project site ÷ project fault current; see IEEE 1547.2-2008 Clause 3.1.8.

maximum voltage impact of individual projects is nearly always less than 0.04-0.06 PU. These results are meaningful within the predictive capabilities of the Energynet simulation, which was shown in validation studies to predict field voltage values within 0.02 PU (2 percent) or better of field measured values.

The simulations performed in this study represent what is essentially a maximum theoretical "ramp" of the PV project as they reflect 100 percent change in output in a time frame before circuit voltage controls can respond — roughly 30 seconds to one minute. Observations of actual large-scale PV projects indicate variable output changes in that period with a maximum of 50 percent.[19]

To put these findings in some context, voltage "sags" and "swells" are normally defined as voltage swings of plus or minus 0.10 PU or greater.[20] The CPUC Re-DEC workplan prepared by Black & Veatch includes a provision for installation of LTCs or fast-acting capacitor banks on circuits as a mitigant for DG voltage impacts where needed to maintain voltage within a range of 0.10 PU.[21] The results of this study suggest that it would be rare for a wholesale PV project as modeled in this study to cause a voltage swing of 0.10 PU. Such a voltage variation might be limited to particularly sensitive circuits and/or very weak network locations.

For further context, San Diego Gas & Electric has shown recorded voltage impacts of a particular distributed PV project's variability within a five minute period as great as 0.078 PU.[22] Again, the results of this study suggest that such a voltage impact would be very rare. While the SDG&E observations are likely valid, the project itself may be interconnected in a particularly weak location in the network. This underscores the importance of considering conditions in interconnection evaluations that vary within a circuit, particularly system weakness at the project's point of interconnection.

This study's results suggest that if MW-class PV projects are sited in modestly "strong" locations within the grid and adhere only to circuit nonexport limits, the voltage impacts of such projects may be fairly small and readily managed under conventional voltage management schemes.

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19 Carl Lenox (SunPower), *Variability in a Large Scale PV Installation*, National Renewable Energy Laboratory, Utility-Scale PV Variability Workshop, Cedar Rapids, Iowa, October 7, 2009, http://www.nrel.gov/eis/pdfs/47514.pdf.

20 IEEE 1547.2-2008 Annex G.

21 Black & Veatch, *Draft Re-DEC Work Plan*, California Public Utilities Commission, May 2010, Section 2.2.4.

22 Bill Torre (SDG&E), *R&D Involving Distributed Generation*, California IEPR Committee Workshop, May 9, 2011.

Under German power quality rules, which accommodate very high penetrations of PV projects, a project-related voltage change of more than 0.02–0.03 PU could require mitigation or a change in the point of interconnection.[23] The simulations performed in this study show 90 percent of the interconnections at moderately "strong" points (System X/R > 1.05) having voltage impacts of 0.035 PU or less, even with a conservative assumption for the possible output change. This further supports the conclusion that PV interconnections meeting system strength and circuit nonexport limits will have manageable voltage impacts.

This study did not evaluate the possible interactions of multiple wholesale PV interconnections and their potential group impact on circuit voltage. However, as the projects simulated in this study are at the maximum size supportable by the circuit at each location, they present greater impacts than would multiple, smaller projects with greater timing diversity. More important, research suggests that there is a significant "geographic smoothing" effect on the variability of aggregate project output (and concomitant voltage impacts) experienced by the power system in a system with multiple interconnections.[24]

This study did reveal a small number of circuits in which even projects meeting the system strength criterion had large voltage impacts. This finding follows the pattern of other area-wide studies performed by study team members, in which a small percentage of study-area circuits are uncovered that exhibit outlier behavior relative to a particular factor.[25] In this study, the potential interconnection sites on these circuits showing unusual voltage sensitivity were excluded from consideration as "low-impact" PV project sites. Further study of those circuits could reveal that the unusual voltage sensitivity was characteristic only of the particular site the team chose, or could reveal some of the reasons for the voltage sensitivity. Again, this underscores the limitations of any preliminary project impact assessment that does not take into account both the individual project and its individual interconnection point in the power system, ideally with a power flow simulation.

This study demonstrates the availability of power network analysis tools that can provide a rapid, comprehensive assessment of the grid impacts of potential wholesale PV interconnections. It also demonstrates the feasibility of evaluating interconnections under a robust set of criteria that considers power system characteristics at a project's location and the project's potential power flow, loading, voltage, and power quality impacts, and

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23 KEMA, *European Experience Integrating Large Amounts of DG Renewables*, California Energy Commission IEPR Committee Workshop, May 9, 2011.

24 Jan Kleissl (UC San Diego), *How Geographic Smoothing and Forecasting RD&D Can Help High Penetrations of Distributed Generation*, California Energy Commission, 2011 IEPR Committee Workshop on Renewable Localized Generation, May 9, 2011.

25 Evans, P.B. et al, *Impacts of Plug-in Vehicles and Distributed Storage on Electric Power Delivery Networks,* IEEE Vehicle Power and Propulsion Conference, 2009, VPPC '09. IEEE, pp 838-846, 7-10 Sept. 2009, doi 10.1109/VPPC.2009.5289761.

includes direct simulation showing the project's local and regional impact, all in an evaluation requiring a few minutes. It illustrates direct consideration of conditions that vary for different interconnection points within a distribution circuit, including the system's resistance to voltage variation, or "strength."All of this can serve to reduce system impact risks associated with high penetrations of wholesale distributed PV. To that end, the findings of this study suggest that wholesale PV projects interconnected at sufficiently strong network locations with due consideration for upstream equipment ratings and avoiding certain circuits with unusual sensitivity have low or manageable impacts even at high penetrations without major system upgrades.

ACRONYMS

AC	Alternating current
CPUC	California Public Utilities Commission
DCMS	Distribution control and management system
DG	Distributed generation
EMS	Emergency Management System
IEA	International Energy Agency
IEEE	Institute for Electrical and Electronics Engineering
IOUs	Investor owned utilities
IREC	Interstate Renewable Energy Council
kV	Kilovolts
kW	Kilowatts
LTC	Load tap changer
MVA	Megavolt amperes
MW	Megawatt
PCC	Point of common coupling
PSLF	Power system load flow
PU	Per unit, or percent or nominal
PV	Photovoltaic
REDEC	Renewable distribution
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
TCUL	Tap changer under load
WDAT	Wholesale Distribution Application Tariff