CONSULTANT REPORT

INTEGRATED TRANSMISSION AND DISTRIBUTION MODEL FOR ASSESSMENT OF DISTRIBUTED WHOLESALE PHOTOVOLTAIC GENERATION

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Prepared by: New Power Technologies

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PREFACE

This study was performed for the California Energy Commission by New Power Technologies as a subcontractor to Aspen Environmental Group under Work Authorization WA1930.007 under Contract 1930-07 between the State Energy Resources Conservation and Development Commission and Aspen Environmental Group.

DISCLAIMER

Any results, findings, or conclusions included in this report relating to specific photovoltaic generation project interconnections should be viewed as illustrative. This study is intended to evaluate an approach to determine if it is feasible with available data and whether it can provide a new level of visibility that is useful for assessing regional impacts of photovoltaic generation at high penetrations relative to load. This study is not intended to provide conclusive interconnection results for the specific photovoltaic generation projects in question or to formally replace Pacific Gas and Electric Company's interconnection request review process. The interconnection points for the photovoltaic generation projects discussed herein have not been confirmed by Pacific Gas and Electric Company personnel. Consistent with the approved scope at this interim stage, New Power Technologies has not completed the full software integration of the subject study area source data, so the simulation model should not be viewed as fully checked or "final."

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 tool to assess the regional impacts of wholesale photovoltaic generation interconnected in large amounts relative to load. These interim results suggest that this integrated transmission and distribution model provides new visibility into the impacts of wholesale photovoltaic generation where combined output approaches or exceeds local load. Distribution feeder-level, substation-level, and transmission-level impacts derived in a common, unified analysis may reveal unexpected considerations that are not readily apparent in a decoupled distribution-only or transmission-only analysis, such as overloads in unexpected locations or very limited voltage impacts. Showing feeder-, substation-, and transmission-level impacts alongside one another may suggest new alternatives to addressing those impacts. A complete regional model with the transmission-, distribution feeder-, and device-level detail demonstrated in this project could provide a platform for rapid evaluation of many wholesale interconnections in different combinations and with different mitigation approaches, helping to identify low-cost interconnection solutions and easing the deployment of wholesale photovoltaic power generation.

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

The State of California has established an ambitious renewable power generation goal, a portion of which will be met with "wholesale" photovoltaic (PV) generation projects interconnected within the distribution system. Wholesale projects are intended to export power to the grid rather than serve on-site electrical load, even when connected to the distribution system. Further, developers may prefer rural sites, where local electrical loads are light. As a result, there is the possibility that wholesale PV generation may have cumulative effects on the regional transmission grid as well as local impacts within distribution.

The process under which these generation projects are connected to the grid generally considers the impacts of individual projects or, in some cases, clusters of projects within the distribution system. There has been little formal inquiry into how multiple, interconnected generation projects may affect the regional transmission grid. More importantly, the behavior and influence of distribution-connected generation projects on transmission are not well-represented in a traditional approach that decouples transmission and distribution analysis.

This project entails development and demonstration of a power delivery network simulation tool that integrates transmission and distribution in a single network model to address regional impacts of distribution-connected wholesale PV projects at high levels of output relative to local load, or "high penetration." Significantly, this approach allows modeling wholesale PV projects each at its appropriate location within a distribution circuit with the full characterization of the circuit, related circuits, and the distribution network, in a single model that also includes the substations and local, regional, and interstate transmission. No cumulative or weighted approximation of distribution circuits or distribution-connected generation at transmission buses is required. This approach enables a "coupled" analysis that shows impacts of a wholesale PV project or projects within distribution circuits, in substations, and in regional transmission.

The study area for this report covers a region in which there is substantial wholesale PV developer interest as evidenced by interconnection requests, where requests represent a mix of three types of transmission-level, substation-level, and distribution feeder-level interconnections, and where existing load is relatively light.

The project phase that is the subject of this report uses a portion of the study area as a sample to assess the feasibility of developing a model that integrates transmission and distribution, evaluates the availability and adequacy of system data for the study area, and provides initial working simulation models usable by California Energy Commission staff with existing, licensed software tools. This phase is also intended to assess whether this approach provides new visibility and potentially offers new insights. Subsequent work will provide a more complete view of the study area and the potential impacts of proposed wholesale PV projects.

These results show that an integrated transmission and distribution model providing a unified view of distribution, substations, and transmission provides enhanced visibility and increased transparency into the range of impacts of wholesale PV interconnections in high penetration. The integrated model results also provide real-world examples of instances where:

- Wholesale PV projects can affect operating conditions in either or both transmission and distribution.
- Identical projects connected in different locations can have very different network impacts.
- Modeling a distribution-connected project as transmission-connected can alter its perceived transmission impact.
- Voltage control features within a distribution feeder can reduce the tendency of generation connected within the feeder to affect feeder voltage.

These results also provide specific examples where large amounts of incremental wholesale generation can be incorporated in a power system without overloading lines, and with voltage impacts that lie well within the system's control capability (though in many cases substation transformers are overloaded). This prompts the question of what other impacts should be evaluated. Moreover, it suggests a need for a systematic approach to evaluating the addition of large amounts of renewable generation relative to load that is based on the demonstrated, direct network impacts of such additions, can objectively identify those impacts that are consequential, and can inform the mitigation of those impacts.

CHAPTER 1: Introduction

Problem Statement

Wholesale solar projects are intended to export power to the grid. Project developers often prefer rural sites due to the lower cost of land. Rural area typically have less electrical load. As a result, these projects may have aggregate effects on the regional transmission grid as well as local impacts within distribution.

The process under which these projects are connected to the grid generally considers the impacts of individual projects or, in some cases, clusters of projects within the distribution system. There has been little formal inquiry into how a large number of interconnected generation projects may affect the regional transmission grid. Moreover, the behavior and influence of distribution-connected generation projects on transmission are not well represented in transmission-only models. Thus, there is a need for studies and tools that capture the detail of distribution and distribution-connected generation with transmission for a unified regional view.

Contract 800-10-001 between the State Energy Resources Conservation and Development Commission and Aspen Environmental Group included technical support and training for electricity supply analysis, including, specifically, electricity system and infrastructure analysis (Task 2). Accordingly, the objectives of Work Authorization (WA) 1930.007 under Contract 800-10-001 were to:

- Develop models and datasets that represent the local and regional impacts of distribution-connected wholesale generation in a particular region of California's transmission system.
- Demonstrate the use of tools that capture the detail of distribution and distribution-connected generation in a regional or transmission-level view.
- Provide data sets and related tools and assistance to allow Energy Commission staff to perform analyses of regional and transmission impacts of distribution-connected generation.

Under the work authorization, contractor New Power Technologies would implement NPT's Energynet® platform and power system simulation as a systemwide model having distribution element-level detail.[1] This model can show the network impacts of individual distribution-level measures — including distribution-connected power generation — within the circuit at the level of individual distribution devices as well as wide-area impacts of multiple projects. The subject area of the regional delivery network for this simulation is a portion of the Pacific Gas and Electric (PG&E) system in which interconnection requests for wholesale generation exceed local load; accordingly, it is likely that the impact of these wholesale generation projects, if built, would be visible within the regional transmission system as well as within the distribution circuits.

The contractor's goals under the project were to:

- Develop integrated regional transmission and distribution model of the study area.
- Model the set of queued projects proposed for interconnection in the study area as an example of high penetration of distributed generation, and make this dataset available for Energy Commission staff use.
- Evaluate the potential individual impacts of queued projects proposed for interconnection.
- Establish an analytical tool that depicts the following in an integrated transmission and distribution model:
    - Local, subcircuit impacts of individual wholesale PV generation units
    - Circuit-level controls such as voltage regulation and step down transformer taps
    - Regional transmission
- Perform certain analyses relating to local and regional impacts of proposed distributed wholesale generation projects in the study area.
- Provide datasets for the use of Energy Commission staff.
- Provide guidance to Energy Commission staff for other analyses.

For this work authorization, New Power Technologies would use data provided to New Power Technologies by PG&E under a nondisclosure agreement. The deliverables under the WA disguise PG&E customer information and PG&E proprietary information, consistent with the nondisclosure agreement. Accordingly, the PG&E substation names used in this report are aliases, and the identifiers for wholesale PV projects are changed.

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1 The Energynet approach was initially demonstrated by New Power Technologies under PIER Contracts #500-01-039 and #500-04-008.

Innovations

The approach of this work authorization departs from conventional practice in its evaluation of distribution-connected wholesale generation using a single simulation incorporating both distribution and transmission portions of the subject power delivery network. Under this approach, a single analysis should illuminate project impacts at the point of interconnection, within the distribution radial, within the family of circuits served from the source substation, and within the local and regional transmission. More importantly, the simulation does not require the substantial power system delivery behavior approximations and loss of visibility required to represent distribution-connected projects as equivalents at transmission network buses. For example, a strong DG source at a weak point of interconnection in a power system will have a greater impact on the surrounding system.

CHAPTER 2: Approach

Study Area

For this project New Power Technologies refers to the study area as the "Vineyard" system. The study area for this project would incorporate the following PG&E distribution planning areas (DPAs):

- DPA incorporating Grasa Substation (Gamay DPA)
- DPA incorporating Sangiovese Substation (Madrasa DPA)
- DPA incorporating Aleatico Substation (Kadarka DPA)
- DPA incorporating Cereza Substation (Lumassina DPA)
- DPA incorporating Tibouren Substation (Bonarda DPA)

These DPAs serve an area of active developer interest for wholesale generation interconnections as well as relatively light existing network load. This area offers a real-world example of wholesale generation approaching or exceeding local load.

The scope of the present phase of the project is limited to a sample of two of the five DPAs named above. Based on a preliminary evaluation, the Energy Commission and New Power Technologies agreed to proceed with the Kadarka DPA and Bonarda DPA as the initial two DPAs. A preliminary review of the queued wholesale generation projects indicated both projects that would be directly connected to the substations and projects that would be connected out on the distribution radials. The selection of Kadarka and Bonarda was intended to provide a mix of such projects. PG&E did not object to this selection.

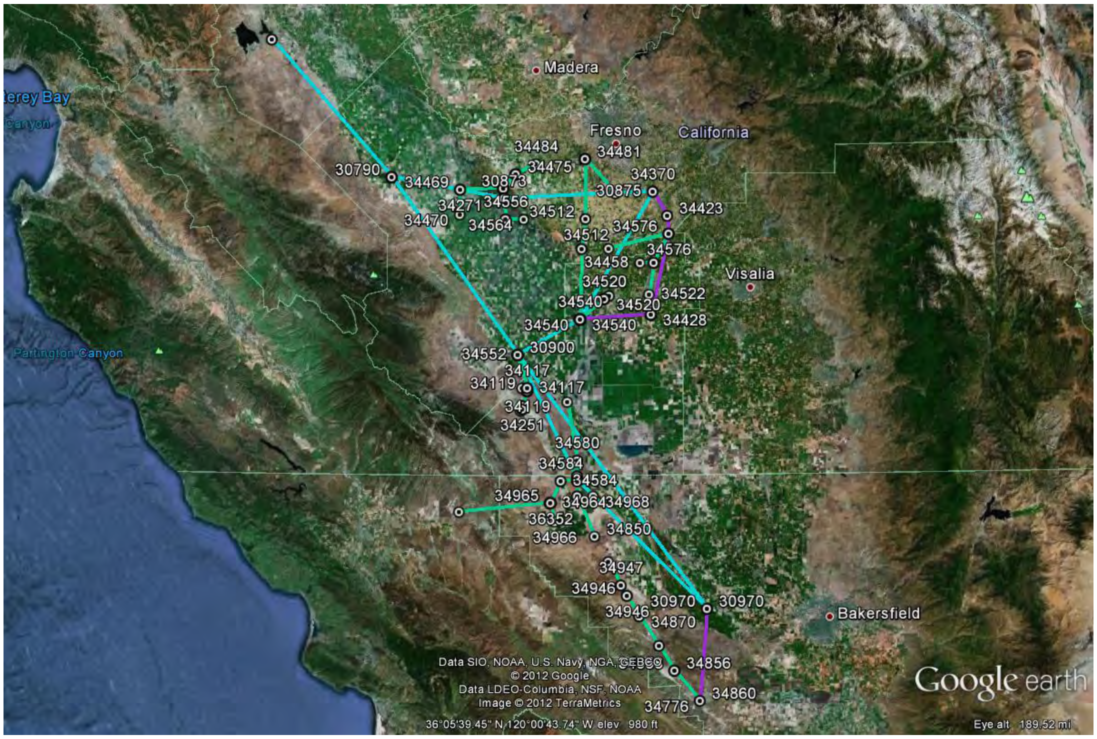
Each of these DPAs includes typically four substations, each of which serves typically 2-3 distribution feeders. Thus the selection of Kadarka and Bonarda DPAs incorporate the following:

- Kadarka Substation
  - Kadarka 1101 Circuit
  - Kadarka 2104 Circuit
- Aleatico Substation
  - Aleatico 2101 Circuit
- Dolcetto Substation

    - Dolcetto 1101 Circuit
    - Dolcetto 1102 Circuit
- Trepat Substation
    - Trepat 1104 Circuit
    - Trepat 1106 Circuit
    - Trepat 2108 Circuit
- Bonarda Substation
    - Bonarda 2101 Circuit
    - Bonarda 1102 Circuit
- Aragonez Substation
    - Aragonez 1101 Circuit
    - Aragonez 1102 Circuit
- Charbono Substation
    - Charbono 1102 Circuit
    - Charbono 1103 Circuit
- Tibouren Substation
    - Tibouren 1102 Circuit
    - Tibouren 2105 Circuit

With an integrated transmission and distribution model, the study area also includes the regional transmission network, which in this case includes 70 kilovolts (kV), 115 kV, and 230 kV, as well as the west wide transmission network, as shown in **Figure 1**. The colors depicted in Figure 1 indicate different voltage levels. Dark turquoise is 70 kV, purple is 115 kV, and turquoise is 230 kV.

Figure 1: Study Area – Central Valley



Source: New Power Technologies.

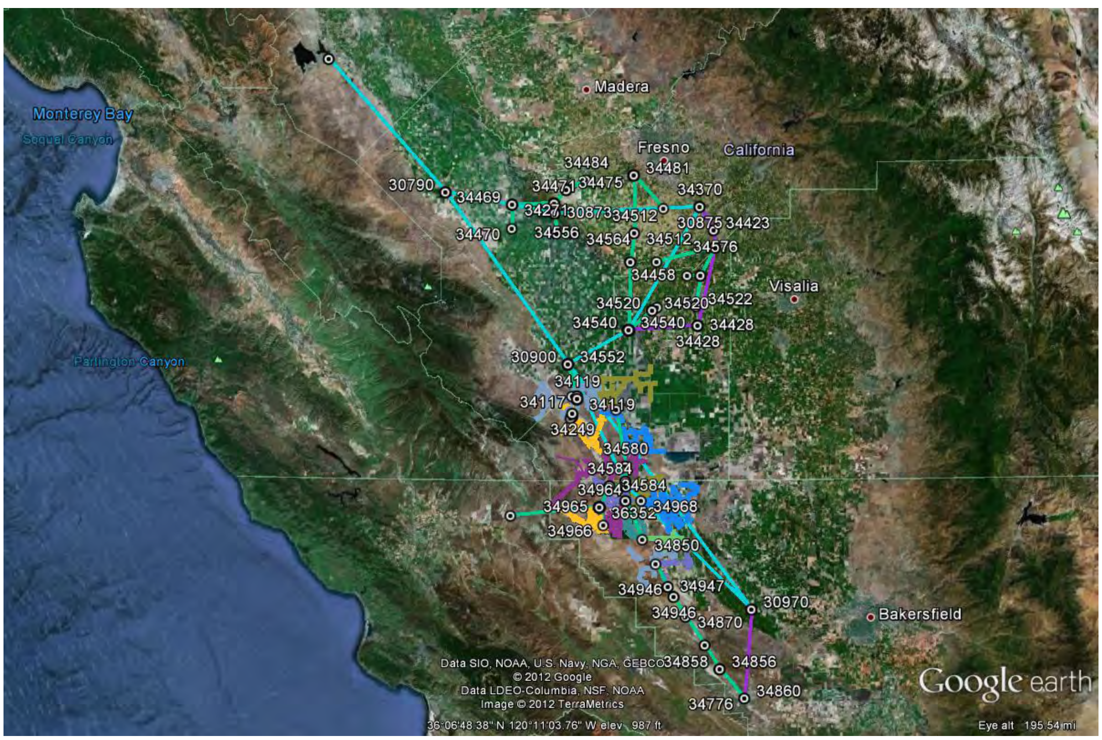
Energynet Platform

For this project, New Power Technologies developed an Energynet power system simulation for the Vineyard system, in this case incorporating the initial two DPAs. The Energynet simulation 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. New Power Technologies completed a partial integration of the Energynet software for this project, sufficient to assess the completeness and adequacy of the legacy source data.

To support this project, PG&E provided data extracted from legacy systems characterizing the individual distribution feeders within the study area as well as single line drawings for the relevant substations. All data sources were provided from their source systems "as-is," without any special handling or preprocessing for this project. The 8 substations and 16 distribution feeders that comprise the distribution portion of the integrated model for this phase are shown in **Figure 2** using various colors to indicate line segments. Energy Commission staff provided a dataset characterizing regional and westwide transmission — specifically the Western Electricity Coordinating Council (WECC), "12hs4a," a 2012 heavy summer operating case.

Figure 2: WA Study Area Energynet Model



Source: New Power Technologies.

Wholesale Photovoltaic Projects

The study area for this project is an area of active developer interest for wholesale photovoltaic generation projects. Based on a review of the Wholesale Distribution Access Tariff (WDAT) queue[2], the relevant projects are listed in **Table 1**. These projects are all solar PV projects. For this project, New Power Technologies included in the model projects shown as "withdrawn" in the queue.

Table 1: Queued Interconnection Requests in Kadarka and Bonarda DPAs

ID	Interconnecting Bus	Bus Number	Rated Output (kW)
gen_W1	ALEATICO	34546	20,000
gen_W2	21kV_OperatingBus	500500	10,000
gen_W3	ALEATICO	34546	19,000
gen_W4	21kV_OperatingBus	500500	20,000
gen_W5	ALEATICO	34546	100,000
gen_W6	21kV_OperatingBus	500500	20,000
gen_W9	12kV_MainBus	500501	20,000
gen_W10	12kV_MainBus	500501	20,000
gen_W7	Bus_F252731101_swt_21	700617	3,000
gen_W8	Bus_F252731101_ND1200027614	700660	3,000
gen_W9	Bus_F252951106_swt_6	702517	20,000
gen_W10	Bus_F252951106_ND1200027768	702596	20,000
gen_W11	12kV_MainBus	500503	20,000
gen_W12	12kV_MainBus	500503	20,000
gen_W23	Bus_F253451102_ND1300010673	701877	1,500
gen_W13	Bus_S2546812000_12kV_MainBus_D	500513	12,000
gen_W14	Bus_F254682101_ND1300248905	706073	12,000
gen_W22	Bus_F254681102_ND1300042518	705602	10,500
gen_W15	Bus_S2544012000_12kV_MainBus_D	500515	20,000
gen_W17	Bus_S2544012000_12kV_MainBus_D	500515	15,000
gen_W18	Bus_S2544012000_12kV_MainBus_E	500516	15,000
gen_W16	Bus_F254402105_ND1300019674	707139	1,500
gen_W19	Bus_F254402105_ND1300019674	707139	3,000
gen_W20	Bus_F254402105_ND1300019674	707139	3,000
gen_W21	Bus_S2520212000_12kV_MainBus	500509	10,500

Source: New Power Technologies.

2 PG&E's published queue of generator interconnection requests under its Wholesale Distribution Access Tariff (WDAT).
http://www.pge.com/b2b/newgenerator/wholesalegeneratorinterconnection/index.shtml

In total, these 23 projects represent 379 megawatts (MW). (W9 and W10 were evaluated at two locations and appear twice in **Table 1.**)

PG&E provided additional information on the project location or interconnection location for most of these projects. Where the actual interconnection point was not specified, New Power Technologies determined an interconnecting structure for this work based on the location of the project. **Figure 3** illustrates the placement of project W23 at nearby bus number 701877.[3] A bus is a network node or point in the network where lines and devices connect at a common voltage. In some cases this mapping resulted in large projects (> 10 MW) connected at locations within existing distribution feeders. These interconnections are included as they provide interesting results for evaluating the analytical approach of this study. However, PG&E's normal policy would generally require projects of this size to connect to the substation via a dedicated feeder.

For substation-connected projects, in most cases the interconnection queue specifies the high-voltage (transmission) side or low-voltage (distribution) side as the interconnection point. PG&E advised New Power Technologies that this selection is generally made by the project sponsor in the interconnection request. In practical terms, interconnection at transmission voltage could require some reconfiguration of the transmission beyond a direct tap (for example, a ring bus or breaker-and-a-half configuration), and connection at distribution voltage could require replacement of the substation transformer.

Each project is incorporated in the Energynet simulation as an individual generating project at the specified bus number, so the impact of each project on the power delivery network is appropriate for that project's size and location as well as the relevant attributes of power delivery network at the point of interconnection and nearby. The interconnection points include transmission-level network nodes, such as Aleatico Substation bus number 34546, distribution-level substation operating buses, and buses within individual distribution radials.

All of the projects listed in **Table 1** are identified in the interconnection queue as having a PV energy source. Accordingly, New Power Technologies assumed that each project would operate at a constant, unity power factor. New Power Technologies also assumed all generating projects would interconnect at 3-phase.

3 Bus numbers in this report refer to bus numbers in the Energynet dataset provided to Energy Commission staff.

Figure 3: W23 on Dolcetto 1102 Circuit

Source: New Power Technologies

Air photos from Google Earth revealed a large PV development near Aleatico substation, as shown in **Figure 4**. Further investigation by New Power Technologies confirmed that this is the 3-unit Aleatico Park development. New Power Technologies has assumed that this project is not represented among the queue projects listed in **Table 1**. The Aleatico Park development appears to have been provisionally incorporated in the WECC 2012hs4a operating case transmission data set provided by Energy Commission staff, with interconnection at the 70 kV transmission level, but with the units not in service. Press accounts indicate that this project is now operational, so for this work, New Power Technologies incorporated the project in the Energynet simulation as an operating project.

Figure 4: Aleatico Park Photovoltaic Project

Source: New Power Technologies.

Power Delivery Network

In addition to the assumption that the Aleatico Park project is operational, New Power Technologies made several other notable assumptions about the power delivery network. The modeled circuits contain a rich set of voltage regulation features, including substation tap changer under load transformers or bank voltage regulators, distribution line voltage regulators, and step-downs within the distribution feeders. New Power Technologies assumed all of these could function as active voltage-regulating devices. Further, New Power Technologies assumed that all of these would function properly when exposed to reverse flow due to interconnected generation.[4]

New Power Technologies also did not include any power generation other than existing distribution-connected generation included in the circuit data, existing transmission-

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4 Source data indicate that some of the line voltage regulators, in fact, have reverse power flow sensing, which could interpret a change in power flow due to distribution-connected generation as a change in strong source location.

connected generation included in the WECC dataset, and the WDAT generation described above as appropriate. One consequence of this is that no circuits with WDAT PV interconnections also have nearby rotating generation under normal grid operating conditions, particularly rotating generation providing reactive power. The importance of rotating reactive generation is because AC load has real and reactive components which must be matched by real and reactive generation. So the absence of reactive generation means even high-penetration PV can't sustain an unintended island. The inertia of rotating machinery can also help to sustain voltage in an unintended island.

Project Grid Impact Evaluation Criteria

New Power Technologies evaluated distribution feeder-connected projects individually for the following factors. In each case, these factors are evaluated at the point of interconnection as appropriate:

- Potential circuit reverse flow
- Existing circuit voltage regulation capability
- Existing reclosing scheme
- Steady-state component overloads
- Steady-state voltage rise at interconnection bus
- Quasi-dynamic voltage impact due to output variation at interconnection bus
- Potential overload of upstream circuit components under loss-of-load conditions
- Weakness or stiffness ratio at the interconnection point

New Power Technologies did not look at the risk of an unintended island as a standalone criterion even in instances where PV generation exceeds local load. In a contingency event, where such an area separates from the main part of the grid, real and reactive load within the separated portion must precisely equal real and reactive generation within the separated portion at the moment of separation and beyond. In the case of these PV projects, there is no source of reactive power to match reactive load; even if real power load and generation did match, the island voltage would quickly collapse, the units would trip, and current would quickly decay.[5] Also, it is very likely that these PV units would all be equipped with active

5 Cullen, et al, *Risk Analysis of Islanding of Photovoltaic Power Systems within Low Voltage Distribution Networks*, International Energy Agency, Report IEA PVPS T5-08, 2002.

anti-islanding features (for example, direct transfer trip), which would trip the units upon a separation from the main grid.

New Power Technologies did identify any reclosers serving portions of the power system with PV projects. A recloser is a switch that will automatically reconnect the circuit following an interruption. One of the risks of generation close to or exceeding local load is if a breaker opens due to a fault and the isolated portion unexpectedly remains energized, if there is a recloser present it could attempt to reclose on an energized but now out-of-phase part of the grid, which is damaging and dangerous. There may be a risk that local generation could energize an island long enough for a reclosing attempt under a very rapid reclosing scheme. Identifying these affected reclosers is useful, as in practice the reclosing times for these reclosers might be reviewed and extended to a minimum of 30–60 seconds.

In addition to circuit reverse flow, New Power Technologies specifically identified voltage regulation points (substation or step-down transformers and line voltage regulators) that would be subject to reverse flow. While New Power Technologies assumed these devices would operate properly under reverse flow, a review of these devices would be required in practice to ensure that they would properly sense the strong source and continue to operate properly under reverse flow.

A full interconnection evaluation for projects of the type and size listed in **Table 1** would in practice normally also include a review of system protection and any changes to relays or set points appropriate with the connection of the generation project in question. New Power Technologies also did not look at "penetration" as a standalone criterion; the specific impacts of generation approaching or exceeding locally served load are captured in the criteria described in this section.

New Power Technologies employed two measures to capture the different impacts of interconnections due to differences in the power delivery network within the distribution circuit at the point of interconnection. These are the normal rating of the most limiting line segment upstream of the point of interconnection ("Minimum Upstream Rating") and the System X/R or stiffness ratio at the point of interconnection. The minimum upstream line rating will reveal a pinch point between the point of interconnection and the substation that increases the threat of an overload due to a generation interconnection at the proposed location. System X/R is a ratio of the total reactance divided by the total resistance of the power delivery system from the primary source (generally the substation) to the point where the DG project will connect to the system. It is an indicator of the ability of the system to resist voltage changes due to changes in the output of the DG. If the System X/R is low, changes in the output of the DG will cause system voltage to fluctuate more, eventually requiring mitigation. The System X/R or stiffness ratio indicates system "weakness" or disproportionate vulnerability of the system to voltage fluctuations arising from variation in the output of the project given the proposed point of interconnection

System X/R is defined as the sum of reactance divided by the sum of the resistance of the components between the point of interconnection and the substation. In *Identification of Low-Impact Interconnection Sites for Wholesale Distributed Photovoltaic Generation Using Energynet Power System Simulation,*[6] New Power Technologies postulated that System X/R < 1.05 might serve as an indicator of a "weak" interconnection point with a greater likelihood of voltage impacts. The system X/R metric alone does not take into account the size of the project relative to the strength of the system at the point of interconnection. Further, the PV projects evaluated in the referenced study were in a different size class, all under 5 MW.

Accordingly, for this project New Power Technologies also evaluated the points of interconnection for the distribution-connected projects for the short circuit duty attributable to the utility source at the point of interconnection and a "stiffness ratio" derived as:

(Utility Source SC duty as MVA + Generator SC duty as MVA) ÷ Generator SC duty.

New Power Technologies assumed the project output for inverter-based PV projects at unity power factor (MVA [mega volt-amperes] = MW) with short circuit duty equal to 120 percent of rated output. Where base voltage changes within the circuit, New Power Technologies converted fault current in amps to MVA at the base voltage at the project's point of interconnection.

The stiffness ratio takes into account the actual equivalent system impedance at the point of interconnection and the relative size of the generation source. It is intended only as a preliminary indicator of the potential impact of an individual project on the system voltage variability at its point of interconnection in light of the strength or weakness of the system at that point. A small ratio (lower than 9 or so based on the results presented here) indicates that the project individually represents a relatively large share of the total short circuit duty at the project site and, by inference, may have an outsized influence on voltage at that location.

This definition is consistent with "stiffness ratio," defined in the Institute of Electrical and Electronics Engineers standard 1547 (IEEE 1547) as an indicator of the ability of the power delivery system to resist voltage deviations caused by a distributed generation project.[7] Strictly speaking, the stiffness ratio would be evaluated with all sources of fault current

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6 CEC-200-2011-014. http://www.energy.ca.gov/2011publications/CEC-200-2011-014/CEC-200-2011-014.pdf

7 IEEE Std 1547.2-2008, "Application Guide for IEEE Std 1547™, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," Clause 3.1.7 and 3.1.8.

rather than just the utility source. For these projects, the only sources of fault current other than the utility are, in few cases, other PV inverters.

New Power Technologies also evaluated all projects individually for their maximum voltage impact in a simulation. The test scenario assumes an output change of 100 percent of the project's rated output evaluated "quasi-dynamically," or before any response from nearby voltage controls. Given the response time for electromechanical controls and programmed time delays for line voltage regulators, this quasi-dynamic period might range from 30 seconds to several minutes, in practical terms.

This set of assumptions — 100 percent output change with no system voltage control response — is a conservative scenario intended to put an upper bound on the voltage impact of an individual project. Research has confirmed that PV generation is subject to rapid output swings, but the maximum variation of a PV project in less than one minute is 50 percent of rated output.[8]

New Power Technologies grouped projects served from a common substation and evaluated the group for the following combined impacts on either transmission or distribution components:

- Lines with reverse flow
- Overloaded lines under steady-state conditions
- High-voltage buses under steady-state conditions

New Power Technologies has evaluated some groups of projects for these factors:

- Quasi-dynamic voltage impact due to coincident output variation
- Steady-state voltage impact due to coincident output variation

At this point in the study, New Power Technologies performed all of the simulations under peak loading conditions. Daytime low-load conditions should be more limiting in terms of PV impacts; in the absence of seasonal or hourly load data, New Power Technologies can approximate daytime minimum load conditions as 35 percent of peak load.

For the group output variation studies, New Power Technologies assumed a coincident change of 100 percent of the units' rated output. This is a very conservative assumption both

8 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.

in terms of the rapid change of one unit as noted above and the absence of any geographic smoothing, or flattening of load. Research has confirmed that while individual PV projects are subject to large, rapid fluctuations in output, groups of PV projects close to each other exhibit a significant "geographic smoothing" effect, damping the combined impact of the projects on the grid.[9]

For quasi-dynamic voltage impacts, New Power Technologies assumed the full output change with no response from circuit voltage controls. For steady-state voltage impacts, New Power Technologies allowed the taps to compensate, and in some cases allowed changes in the line capacitors as well. New Power Technologies treated all taps and line capacitors as variable.

9 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, http://www.energy.ca.gov/2011_energypolicy/documents/2011-05-09_workshop/presentations/08_PIER_Kleissl_5-9-11.pdf.

CHAPTER 3: Outcomes

Substation Groups

The following discussion considers the distribution and transmission impacts of the WDAT projects listed in **Table 1** individually and grouped according to the substation serving their interconnection circuit or where the project is to be interconnected. Four projects − W5, W6, W22 and W23 − are identified in the WDAT queue as part of a "cluster" study, while the other projects are part of "independent" studies. New Power Technologies considered W5 projects and W6 (with others) under the Aleatico substation evaluation; New Power Technologies considered project W22 (with others) with Bonarda substation and project W23 (with others) with Dolcetto substation. New Power Technologies did not take the WDAT "cluster" and "independent" annotations into consideration directly.

In addition to any grouping within the WDAT "clusters," there are certainly other groupings that make sense. In particular, several of the substation groupings affect the same transmission assets — a good example is the impact of the Kadarka and Aleatico projects on the 70 kV transmission system out of Gamay. The substation grouping presented in this draft is simply an initial grouping for purposes of demonstrating the approach. Evaluation is required before the potential impact of some projects on others begins to become apparent.

Kadarka

Kadarka substation serves two distribution feeders, 1101 and 2104. The operating voltage of Kadarka substation is 12 kV, though circuit 2104 operates primarily at 21 kV and circuit 1101 has a step-up to 21 kV.

New Power Technologies mapped two WDAT projects, W9 and W10, to the Kadarka substation 12 kV main bus and two projects, W7 and W8, to locations on Kadarka 1101 circuit. W9 and W10 are annotated in the queue as interconnecting at Kadarka substation, though the project locations themselves are closest to Trepat 1106 circuit. New Power Technologies evaluated W9 and W10 as connected at the 12kV main bus at Kadarka and at locations within Trepat 1106 circuit. W7 and W8 are identified in the queue by street address, and New Power Technologies mapped these to buses 700617 and 700660 (respectively) on circuit 1101. **Figure 5** shows Projects W7 and W8 in relation to these buses on the Kadarka 1101 circuit.

Figure 5: W7 and W8 in Kadarka 1101 Circuit

Source: New Power Technologies.

Table 2 lists the Kadarka WDAT projects and provides details concerning the distribution network at the point of interconnection of the two circuit-connected projects.

Table 2: Kadarka WDAT Projects – Distribution Network

ID	Interconnecting Bus	Bus Number	Rated Output (kW)	Minimum Upstream Rating (MVA)	System X/R	Utility Source SC (MVA)	Stiffness Ratio
gen_W9	12kV_MainBus	500501	20,000				
gen_W10	12kV_MainBus	500501	20,000				
gen_W7	Bus_F252731101_swt_21	700617	3,000	10.1	2.46	42.0	12.7
gen_W8	Bus_F252731101_ND1200027614	700660	3,000	10.1	2.46	40.9	12.3

Source: New Power Technologies.

The minimum upstream line rating, System X/R, and the stiffness ratio evaluated at the distribution feeder interconnection sites for W7 and W8 indicate that these are robust points within the distribution network. Individually, these two projects are not likely to result in equipment overloads or significant voltage variation. Kadarka circuit 1101 has extensive existing voltage regulation features, with three two-bank voltage regulators and a step-up transformer in addition to the tap in the substation. Further, the circuit 2104 step-up effectively provides the ability to manage voltage of the two Kadarka feeders independently. Under these operating conditions, neither project would individually cause reverse flow within the circuit beyond the point of interconnection.

While there are reclosers within circuit 1101, there are no reclosers between the point of interconnection of either of W7 or W8 and the substation, so neither project introduces a risk of the circuit reclosing into an energized island. Both project interconnection points are served by three-wire primary distribution. The Kadarka substation transformer is rated at 10.6 MVA, so either W9 or W10 individually would overload the substation transformer if the projects are connected at the low-voltage side of the substation.

Table 3 provides voltage impacts of the Kadarka WDAT projects individually as directly estimated in a power flow simulation. These results confirm the outcomes suggested by the System X/R and stiffness ratio — that variation in the output of these projects would not result in significant circuit voltage variation. Each of the projects has individual quasi-dynamic[10] voltage impact of less than 0.03 PU (3 percent voltage change).[11]

Table 3: Kadarka WDAT Projects – Voltage Impacts

				Individual Project @ Interconnection Bus	
ID	**Interconnecting Bus**	**Bus Number**	**Rated Output (kW)**	**Steady State Voltage Impact**	**Quasi-dynamic Voltage Impact**
gen_W9	12kV_MainBus	500501	20,000		0.012
gen_W10	12kV_MainBus	500501	20,000		0.012
gen_W7	Bus_F252731101_swt_21	700617	3,000		0.028
gen_W8	Bus_F252731101_ND1200027614	700660	3,000		0.029

Source: New Power Technologies.

New Power Technologies also evaluated the impacts of these projects as a group. The steady state voltage rise impact of W7 and W8 within Circuit 1101 can be managed with the existing voltage regulation capability within the circuit, and there are no distribution buses

10 100 percent change in project output before any changes in taps or SVDs.

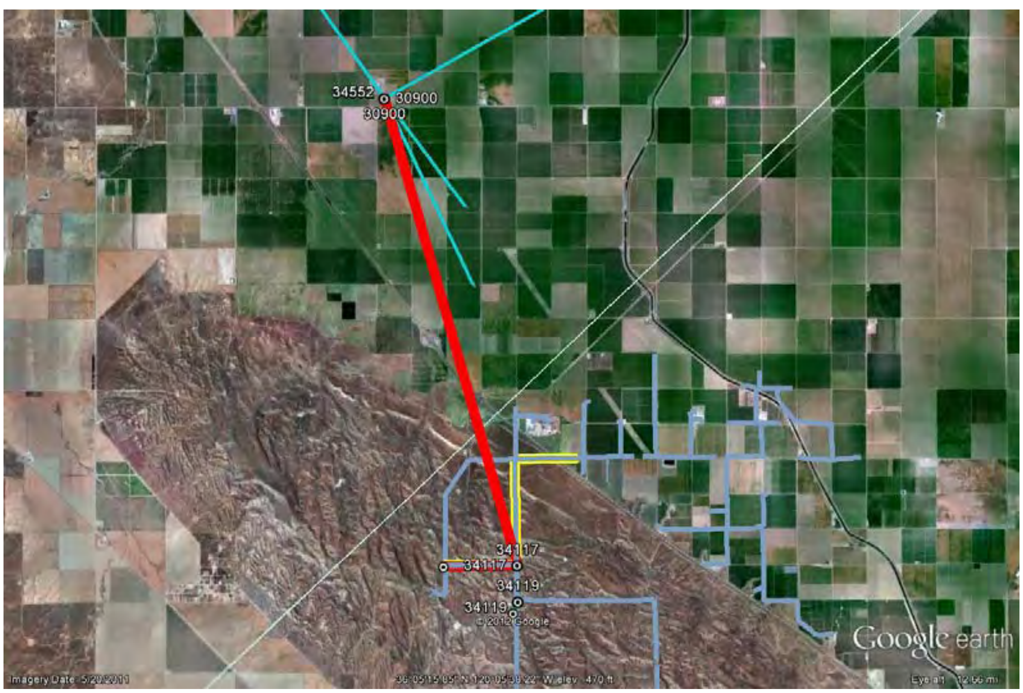
11 For context, delivery networks should maintain voltage variation where power is delivered to customers within 0.95 to 1.05 per unit (PU), or ± 5 percent of nominal voltage, consistent with the normal customer voltage variation allowed under CPUC Electric Rule 2. Many distribution voltage control schemes operate with an "acceptable" voltage variation dead band of 2 percent at the point of measurement.

over 1.05 PU with the group of projects operating. Similarly, the output of W9 and W10 leaves the voltage at the 12 kV and 70 kV buses at Kadarka substation well under 1.05 PU.

Figure 6 shows the combined power flow impacts of these four projects. While neither project induces reverse flow individually, W7 and W8 together induce reverse flow within Circuit 1101 (shown in yellow). However, there is no modeled overload; moreover, the combined output of the two distribution-connected projects is less than the most-limiting upstream line rating, so it is not possible for these projects to overload the circuit under any load conditions. There is also no reverse flow at any of the voltage-regulating devices within Circuit 1101.

The combined output of the two distribution-connected projects and the two 12 kV operating bus-connected projects induces reverse flow in the Kadarka substation transformer. These projects together also far exceed the capability of the transformer. In addition, the combined output of the four projects added to the existing output of the Aleatico Park development overloads the 70 kV transmission line from Kadarka to Gamay (shown in red). **Figure 6** shows that under these operating conditions the flow impact of these projects is absorbed at Gamay Substation and reversals or overloads (shown in red) do not extend to the rest of the regional 70 kV network. The blue and purple lines indicate nearby circuit line and circuit numbers.

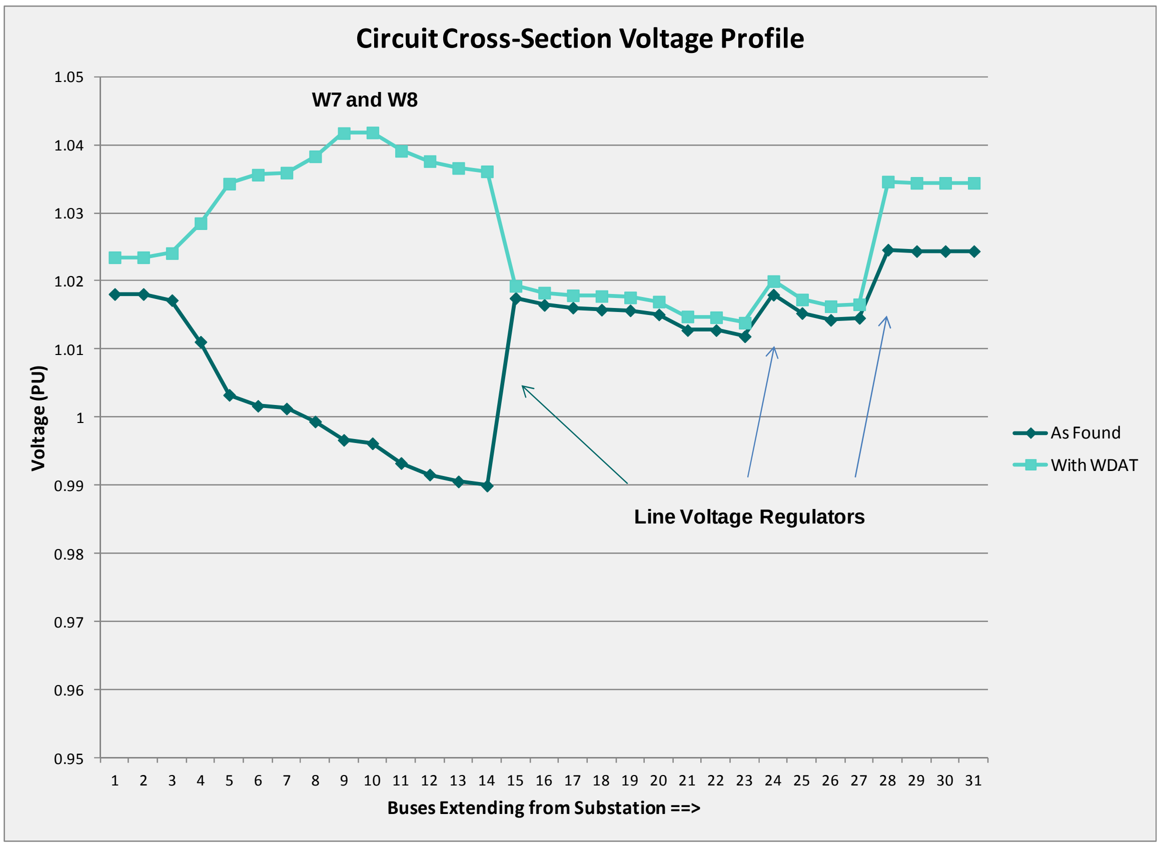
Figure 6: Kadarka Project Flow and Loading Impacts



Source: New Power Technologies.

Within Circuit 1101, the points of interconnection of W7 and W8 lie between the substation and the first line voltage regulator. Accordingly, as noted, these projects do not induce reverse flow in the circuit's line voltage regulators. As shown in **Figure 7**, under existing conditions there is a 3–4 percent voltage drop from the substation to the first voltage regulator, which this first voltage regulator is likely intended to overcome. The output of the two generators boosts the source-side voltage at the first regulator from 0.99 PU to 1.036 PU. With the PV units operating, the first regulator maintains the load-side voltage at its 1.02 PU setpoint by regulating the voltage down. The second and third voltage regulators maintain the voltage downstream as in the as-found case. So while a voltage rise of nearly 4 percent from these projects might normally be a cause for concern, the detailed analysis reveals that the overall voltage profile of Circuit 1101 is arguably improved by the PV units.

Figure 7: Kadarka Voltage Profile and Project Impact



Source: New Power Technologies

Aleatico

Aleatico substation serves one distribution feeder, Circuit 2101. The WDAT queue identifies six projects, W1- W6, all annotated in the queue as connecting at either the 21 kV operating bus or the 70 kV transmission bus of Aleatico substation. In addition to these projects, the Aleatico Park development is incorporated in the model interconnected in the 70 kV transmission system between Aleatico Substation and Kadarka substation. **Table 4** lists the Aleatico WDAT projects.

Table 4: Aleatico WDAT Projects – Distribution Network

ID	Interconnecting Bus	Bus Number	Rated Output (kW)
gen_W1	ALEATICO	34546	20,000
gen_W2	21kV_OperatingBus	500500	10,000
gen_W3	ALEATICO	34546	19,000
gen_W4	21kV_OperatingBus	500500	20,000
gen_W5	ALEATICO	34546	100,000
gen_W6	21kV_OperatingBus	500500	20,000

Source: New Power Technologies.

The Aleatico substation transformer is rated at 15.8 MVA, so either W4 or W6 individually would overload the substation transformer. **Table 5** shows the power flow simulation results for the voltage impacts of the individual projects. Other than W5 at 100 MW, each of the projects has individual quasi-dynamic voltage impact of less than 0.03 PU (3 percent voltage change).

Table 5: Aleatico WDAT Projects – Voltage Impacts

				Individual Project @ Interconnection Bus	
ID	Interconnecting Bus	Bus Number	Rated Output (kW)	Steady State Voltage Impact	Quasi-dynamic Voltage Impact
gen_W1	ALEATICO	34546	20,000		0.010
gen_W2	21kV_OperatingBus	500500	10,000		0.008
gen_W3	ALEATICO	34546	19,000		0.010
gen_W4	21kV_OperatingBus	500500	20,000		0.012
gen_W5	ALEATICO	34546	100,000		0.037
gen_W6	21kV_OperatingBus	500500	20,000		0.012

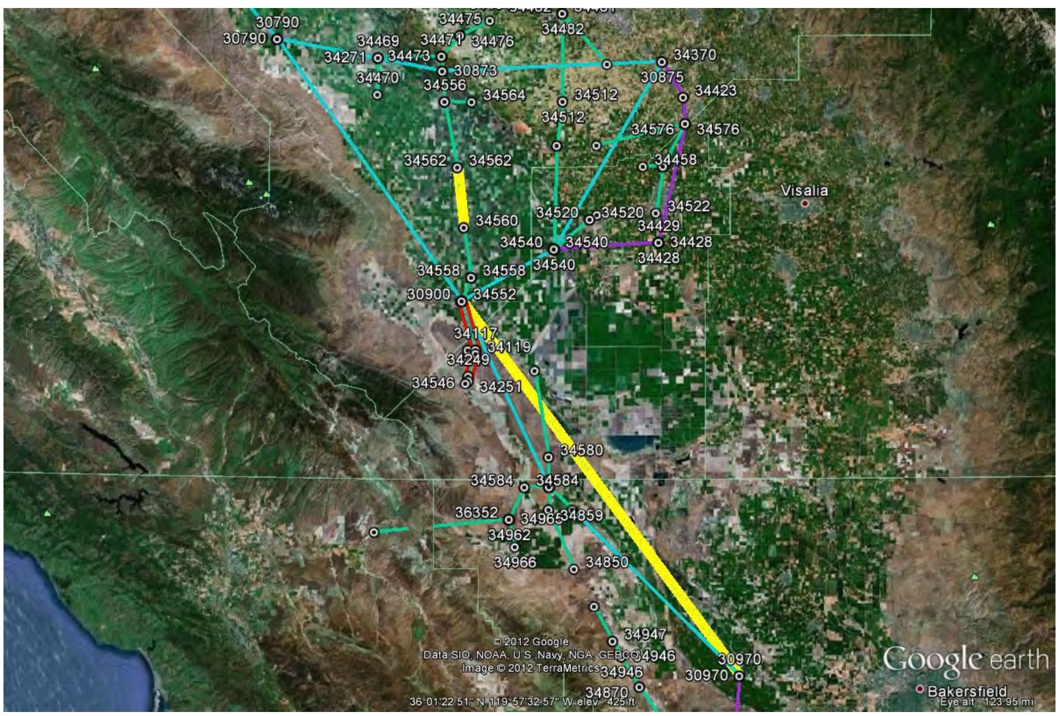
Source: New Power Technologies.

As a group, these projects have additional impacts. These projects together represent a significant amount of incremental generation at one location. The three projects on the low-voltage substation bus reverse flow at the Aleatico substation transformer and cause power flow exceeding the transformer's normal rating. Under the regional configuration in the 2012 WECC case, Aleatico substation is essentially the end of a radial 70 kV line from Gamay via Kadarka, with the tie to Trepat not in service (open). Accordingly, the combined output of the existing Aleatico Park development and the Aleatico WDAT projects pushes power flow back to Gamay and beyond.

Figure 8 shows the power flow impacts of the Aleatico projects in total. These projects overload the 70 kV transmission lines between Aleatico and Gamay, as shown in red. They also move the null point within the 70 kV network between Sangiovese and Gamay toward Sangiovese, reversing the flow in the Cortese-Semillon line, and reverse the flow shown in yellow on the 230 kV Gamay-Malbec line.

The steady-state voltage rise impact of these projects is modest. With adjustment of the taps at Aleatico substation, the 21 kV bus voltage is held at under 1.05 PU. The 70 kV bus voltage at Aleatico is elevated to 1.055 PU, but the high-voltage effect dissipates within one or two substations between Aleatico and Gamay. The blue and purple segments are nearby circuits.

Figure 8: Aleatico Project Flow and Loading Impacts



Source: New Power Technologies.

Bonarda

Bonarda substation serves two distribution circuits, 1102 and 2101. The operating voltage of Bonarda substation is 12 kV, though Circuit 2101 operates primarily at 21 kV. New Power Technologies mapped three WDAT projects to Bonarda substation, W13, W14, and W22. W13 is annotated in the queue as interconnecting at the 12 kV bus at Bonarda Substation. The plans of interconnection for W14 and W22 are not noted in the WDAT queue. New Power Technologies mapped W14 to bus 706073 within Bonarda 2101 based on the project's location identified in the queue. New Power Technologies mapped W22 to bus 705602 in Bonarda 1102 based on a guess at the project's location. This mapping results in distribution feeder-connected projects that exceed 10 MVA. As noted, projects of this size would normally require a dedicated feeder, but these interconnections are included here for illustration purposes.

Table 6 lists the Bonarda WDAT projects and provides details concerning the distribution network at the point of interconnection of the two feeder-connected projects.

Table 6: Bonarda WDAT Projects – Distribution Network

ID	Interconnecting Bus	Bus Number	Rated Output (kW)	Minimum Upstream Rating (MVA)	System X/R	Utility Source SC (MVA)	Stiffness Ratio
gen_W13	Bus_S2546812000_12kV_MainBus_D	500513	12,000				
gen_W14	Bus_F254682101_ND1300248905	706073	12,000	11.9	1.44	49.2	4.4
gen_W22	Bus_F254681102_ND1300042518	705602	10,500	2.6	1.00	15.0	2.2

Source: New Power Technologies.

The minimum upstream line rating, System X/R, and the stiffness ratio evaluated at the distribution feeder interconnection sites for W14 and W22 indicate that these are relatively weak sites within the network for projects of this size. Both projects have rated output that would exceed the rating of the most limiting upstream line segment, creating the possibility of an overload. The System X/R for W14 is moderately strong, and the System X/R for W22 is weak. The stiffness ratios evaluated at the two project sites are low, particularly for W22. These suggest voltage impacts that may be unacceptable, particularly for W22. In reality, the sites for W14 and W22 are even weaker than they appear here as the calculated equivalent impedance excludes a step-up transformer upstream of W14 and a voltage regulator upstream of W22.

The interconnection point of W14 in Circuit 2101 is served by 3-wire distribution primary. There are no reclosers between the point of interconnection and the substation. The interconnection point of W22 in Circuit 1102 is served by 3-wire distribution primary. There is a recloser between the point of interconnection of W22 and the substation.

Bonarda circuits 1102 and 2101 have extensive existing voltage regulation features. Circuit 1102 has three line voltage regulators, including one between the W22 interconnection point and the substation. The Circuit 2101 step-up lies between the W14 interconnection point and the substation. These features provide some ability to manage voltage of the two Bonarda radials independently and to directly compensate for the voltage impact of the two generating projects. W14 would cause reverse flow at the Circuit 2101 step-up, and W22 would cause reverse flow at the line voltage regulator in Circuit 1102 upstream of the project's point of interconnection.

The Bonarda substation transformer is rated at 12.5 MVA, so while none of these projects individually would overload the transformer, each comes close. **Table 7** provides voltage impacts of the Bonarda WDAT projects individually as directly estimated in a power flow simulation. These results confirm the outcomes suggested by the System X/R and stiffness ratio.

Table 7: Bonarda WDAT Projects – Voltage Impacts

				Individual Project @ Interconnection Bus	
ID	Interconnecting Bus	Bus Number	Rated Output (kW)	Steady State Voltage Impact	Quasi-dynamic Voltage Impact
gen_W13	Bus_S2546812000_12kV_MainBus_D	500513	12,000	0.008	0.023
gen_W14	Bus_F254682101_ND1300248905	706073	12,000	0.035	0.043
gen_W22	Bus_F254681102_ND1300042518	705602	10,500	0.209	0.251

Source: New Power Technologies.

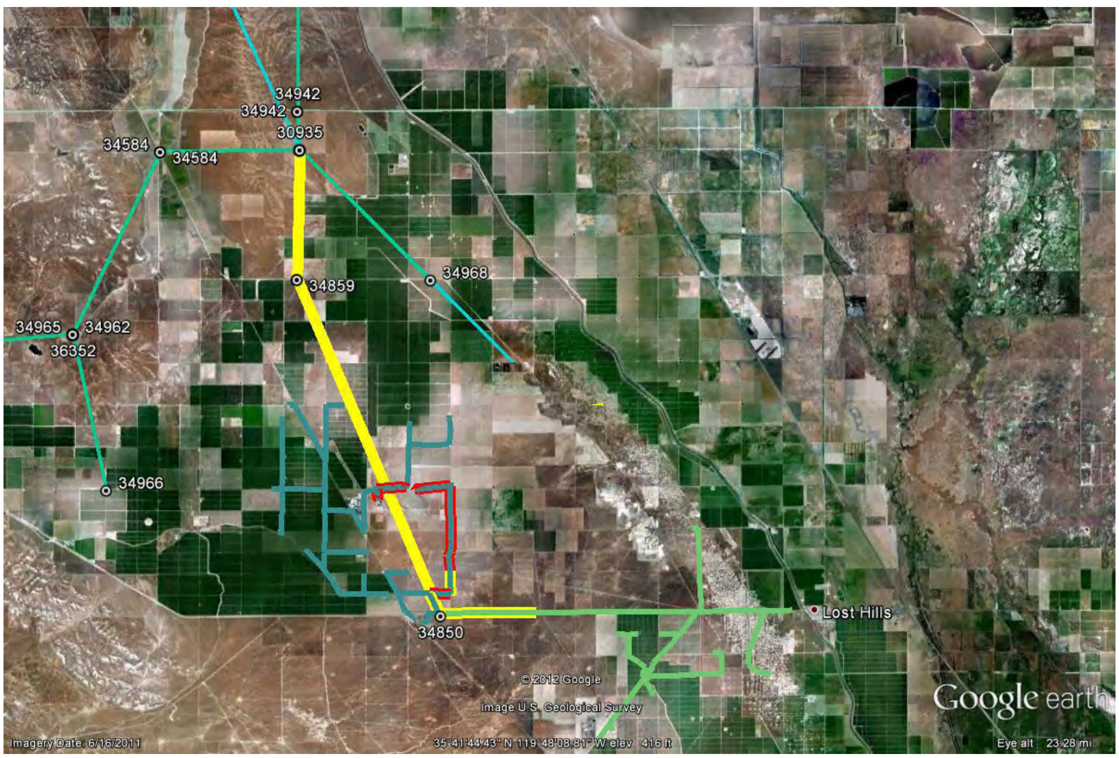
W22 has a very significant quasi-dynamic voltage impact of 0.251 PU (25.1 percent voltage change), indicative of an interconnection point that is far too weak for a project of this size without some mitigation. The quasi-dynamic voltage impact of W14 is also relatively large at 0.043 PU (4.3 percent voltage change). The steady state voltage impact of each project is markedly less. In the case of each project, the point of interconnection lies downstream of a line voltage regulation device. W22 causes very high steady-state voltage in some parts of Circuit 1102, but the voltage rise is contained within the circuit, and the voltage at the 12 kV bus of the substation remains under the 1.03 PU high target.

The Bonarda projects represent a good example of three nominally similar projects having vastly different impacts due to the different characteristics of the network at the point of interconnection for each project. Also, the interconnection point analyzed for W22, while included here for illustration as noted, only revealed its unsuitability through the analysis. Interestingly, the distribution circuit interconnection point for W14, also included for illustrative purposes, almost works in terms of voltage and loading impacts.

New Power Technologies also evaluated impacts of the Bonarda projects as a group. With the reconfiguration of the 70 kV transmission system reflected in the 2012 WECC case, Bonarda substation is served radially from Acolon substation and the connection to Charbono substation to the south is open (with Charbono served from Malbec).

Figure 9 shows in red reverse flow and overloaded lines introduced by project W22 within Circuit 1102 between the project site and Bonarda substation. Project W14 introduces reverse flow within Circuit 2101 but no overload, as shown in yellow. The three projects together introduce reverse flow through the Bonarda substation transformer and in the radial 70 kV lines back to Acolon substation; at that point, the output of the projects is absorbed. The three projects operating would also overload the Bonarda substation transformer.

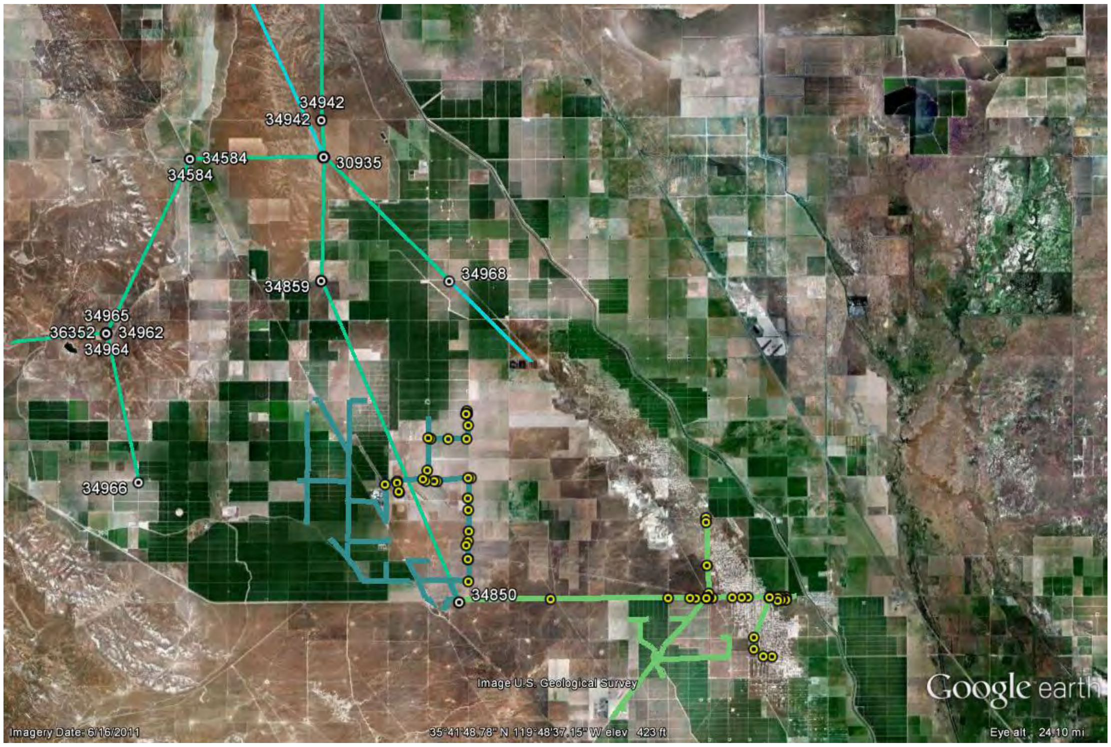
Figure 9: Bonarda Project Flow and Loading Impacts



Source: New Power Technologies.

With all three Bonarda projects operating under steady state conditions there are very high voltage buses in Circuit 1102 and moderately high voltage buses in Circuit 1101, shown as yellow placemarks in **Figure 9**. However, the voltage at the 12 kV operating bus at Bonarda substation can be maintained within the acceptable range at 1.027 PU. While not readily visible in **Figure 10**, voltage at the 70 kV Bonarda substation bus (#34850) rises to 1.07 PU (7 percent above nominal). However, beyond bus #34859 the high voltage dissipates in the network and the 70 kV bus at Acolon substation remains within the acceptable range at under 1.04 PU.

Figure 10: Bonarda Project Voltage Impacts



Source: New Power Technologies.

Tibouren

Tibouren substation serves two distribution feeders, 1102 and 2105. The operating voltage of Tibouren substation is 12 kV, though Circuit 2105 operates primarily at 21 kV. New Power Technologies mapped three WDAT projects, W15, W17, and W18 to one of the two sections of the Tibouren 12 kV operating bus, consistent with the annotation in the WDAT queue. New Power Technologies also mapped three projects, W16, W19, and W20 to a location on Circuit 2105. W16, W19, and W20 appear to belong to a family of projects, with the location of one identified in the WDAT queue. For this analysis, New Power Technologies assumed they are colocated with a common interconnection point at bus 707139 in Circuit 2105.

Table 8 lists the Tibouren WDAT projects and provides details concerning the distribution network at the point of interconnection of the three circuit-connected projects.

Table 8: Tibouren WDAT Projects

ID	Interconnecting Bus	Bus Number	Rated Output (kW)	Minimum Upstream Rating (MVA)	System X/R	Utility Source SC (MVA)	Stiffness Ratio
gen_W15	Bus_S2544012000_12kV_MainBus_D	500515	20,000				
gen_W17	Bus_S2544012000_12kV_MainBus_D	500515	15,000				
gen_W18	Bus_S2544012000_12kV_MainBus_E	500516	15,000				
gen_W16	Bus_F254402105_ND1300019674	707139	1,500	4.6	1.69	14.9	9.3
gen_W19	Bus_F254402105_ND1300019674	707139	3,000	4.6	1.69	14.9	5.1
gen_W20	Bus_F254402105_ND1300019674	707139	3,000	4.6	1.69	14.9	5.1

Source: New Power Technologies.

The minimum upstream line rating, System X/R, and the stiffness ratio all evaluated at the distribution feeder interconnection site for W16, W19, and W20 indicate that this is a fairly robust point within the network. Considered individually, none of these projects is likely to result in equipment overloads or significant voltage variation. The interconnection site for W16, W19, and W20 also lies downstream of the Circuit 2105 step-up transformer, which offers single-circuit voltage regulation capability.

The interconnection point for W16, W19, and W20 is served with 3-wire primary distribution. There is also a recloser between substation and the point of interconnection.

The Tibouren substation has two main transformer banks rated at 16 MVA each. So any one of W15, W17, or W18 could overload or nearly overload one bank if the 12 kV operating buses are separated in operation.

Table 9 provides voltage impacts of the Tibouren WDAT projects individually as directly estimated in a power flow simulation. These results confirm the outcomes suggested by the System X/R and stiffness ratio –variation in the output of these projects would not result in significant circuit voltage variation. Each of the projects has individual quasi-dynamic voltage impact of less than 0.03 PU (3 percent voltage change).

Table 9: Tibouren WDAT Projects Voltage Impacts

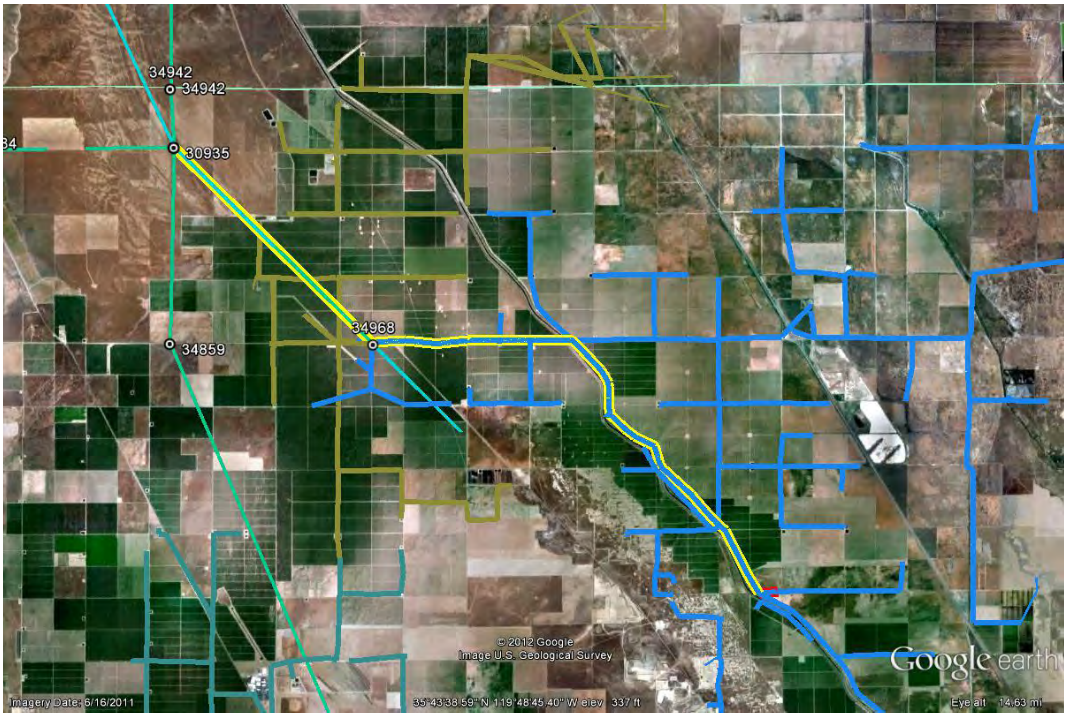
				Individual Project @ Interconnection Bus	
ID	Interconnecting Bus	Bus Number	Rated Output (kW)	Steady State Voltage Impact	Quasi-dynamic Voltage Impact
gen_W15	Bus_S2544012000_12kV_MainBus_D	500515	20,000	0.008	0.010
gen_W17	Bus_S2544012000_12kV_MainBus_D	500515	15,000	0.008	0.009
gen_W18	Bus_S2544012000_12kV_MainBus_E	500516	15,000	0.004	0.005
gen_W16	Bus_F254402105_ND1300019674	707139	1,500	0.014	0.014
gen_W19	Bus_F254402105_ND1300019674	707139	3,000	0.027	0.026
gen_W20	Bus_F254402105_ND1300019674	707139	3,000	0.027	0.026

Source: New Power Technologies.

As a group, these projects have additional impacts. Energizing all three distribution feeder-connected projects in Circuit 2105 elevates the steady-state voltage at the point of interconnection to 1.09 PU, well over the 1.05 PU desired maximum. However, manipulating the voltage regulation setpoints within the circuit reduces the voltage at the point of interconnection to near or below 1.05 PU. These three projects together would induce reverse flow at the Circuit 2105 step-up transformer. With all six projects operating, the voltage at the Tibouren substation 12 kV operating bus is 1.007 PU and at the Tibouren 70 kV main bus is 1.035 PU, all within the acceptable range. So apart from the substation bank itself, at least under these load conditions and steady state, the voltage management features of the Tibouren substation and circuits can accommodate these projects.

Figure 11 shows the combined power flow impacts of these six projects. Concerning W16, W19, and W20 within Circuit 2105, the most limiting line segment is actually immediately at the project site. Accordingly, the three projects introduce an overload at that point, as shown in the small segment of red in the lower right corner. The balance of the circuit experiences reverse flow, which with output of the three projects at the substation, extends through the substation transformers and the 70 kV transmission to Acolon substation. The projects together would also overload either or both substation transformers, depending on the alignment of the substation 12 kV main bus sections.

Figure 11: Tibouren Project Flow and Loading Impacts



Source: New Power Technologies.

For the Tibouren projects, New Power Technologies also evaluated the quasi-dynamic impact of coincident output variation of the projects as a group. All six projects can operate at full output under steady-state conditions with voltage within range and no overloads except at the W16/W19/W20 project site. If the output of all six projects were to drop by 100 percent simultaneously, with no regulation changes, the voltage at the 12 kV bus in the substation falls by 0.012 PU to 0.995 PU, and the voltage at the W16/W19/W20 project site falls by 0.065 PU to 0.981 PU. The voltage at some of the voltage regulation points within Circuit 2105 falls as low as 0.957 PU. So the immediate (quasi-dynamic) voltage impact is significant with a 6.5 percent voltage drop at the point of interconnection, but no "low" voltage (under 0.95 PU) within the circuit results. Once the taps adjust, the voltage at the regulation points within Circuit 2105 returns to close to nominal with the generation still off line. So under these load conditions a simultaneous swing of 100 percent of output for the six WDAT projects together lies within the voltage regulation capability of the Tibouren substation and circuits.

Dolcetto

Dolcetto substation serves two distribution feeders, 1101 and 1102. The operating voltage of Dolcetto substation is 12 kV.

New Power Technologies mapped two WDAT projects, W11 and W12, to the Dolcetto substation 12 kV main bus and one project, W23, to a site on Dolcetto 1102 Circuit. W11 and W12 are annotated in the queue as interconnecting at Dolcetto Bank #1. W23 is identified in the queue by location and as connecting with Dolcetto 1102 Circuit, but is also annotated as associated with Tibouren substation. For this analysis, New Power Technologies treated W23 as within the Dolcetto substation project group. Based on the physical location of W23 noted in the queue , New Power Technologies mapped the project to bus 701877 on Circuit 1102, as shown in **Figure 12**.

Figure 12: W23 in Dolcetto 1102 Circuit

Source: New Power Technologies.

Table 10 lists the Dolcetto WDAT projects and provides details concerning the distribution network at the point of interconnection of the circuit-connected project, W23. W23 is a relatively small project when compared to the others evaluated in this study. The project's output is well under the most limiting upstream line rating and a fraction of the utility source fault duty at the point of interconnection. However, the System X/R indicates that this is a weak location, while the stiffness ratio at the project point of interconnection does not provide a strong indication. Further, the location for W23 is even weaker than suggested by the values in **Table 10** due to the impedance of an upstream line voltage regulator. This suggests that W23 could have an outsized voltage impact for a project of its size, though the line voltage regulator also provides a means to directly manage that impact.

Table 10: Dolcetto WDAT Projects

ID	Interconnecting Bus	Bus Number	Rated Output (kW)	Minimum Upstream Rating (MVA)	System X/R	Utility Source SC (MVA)	Stiffness Ratio
gen_W11	12kV_MainBus	500503	20,000				
gen_W12	12kV_MainBus	500503	20,000				
gen_W23	Bus_F253451102_ND1300010673	701877	1,500	2.3	0.72	11.9	7.6

Source: New Power Technologies.

Dolcetto 1102 has limited voltage regulation features; however Dolcetto 1101 has three line voltage regulators, which may provide some ability to manage the voltage of the two circuits independently.

The Dolcetto substation transformer is rated at 5.2 MVA, so either W11 or W12 would dramatically overload the substation transformer.

Table 11 provides voltage impacts of the Dolcetto WDAT projects individually as directly estimated a power flow simulation. The power flow simulation of the individual projects confirms the voltage impact suggested by the evaluation of the point of interconnection of W23 — W23 does have a large quasi-dynamic voltage impact, at 0.062 PU (6.2 percent voltage change). Under steady-state conditions where the line voltage regulator can compensate, the project varies voltage at the project site by 0.03 PU (3 percent voltage change).

Table 11: Dolcetto WDAT Projects Voltage Impacts

				Individual Project @ Interconnection Bus	
ID	Interconnecting Bus	Bus Number	Rated Output (kW)	Steady State Voltage Impact	Quasi-dynamic Voltage Impact
gen_W11	12kV_MainBus	500503	20,000		0.024
gen_W12	12kV_MainBus	500503	20,000		0.024
gen_W23	Bus_F253451102_ND1300010673	701877	1,500	0.03	0.062

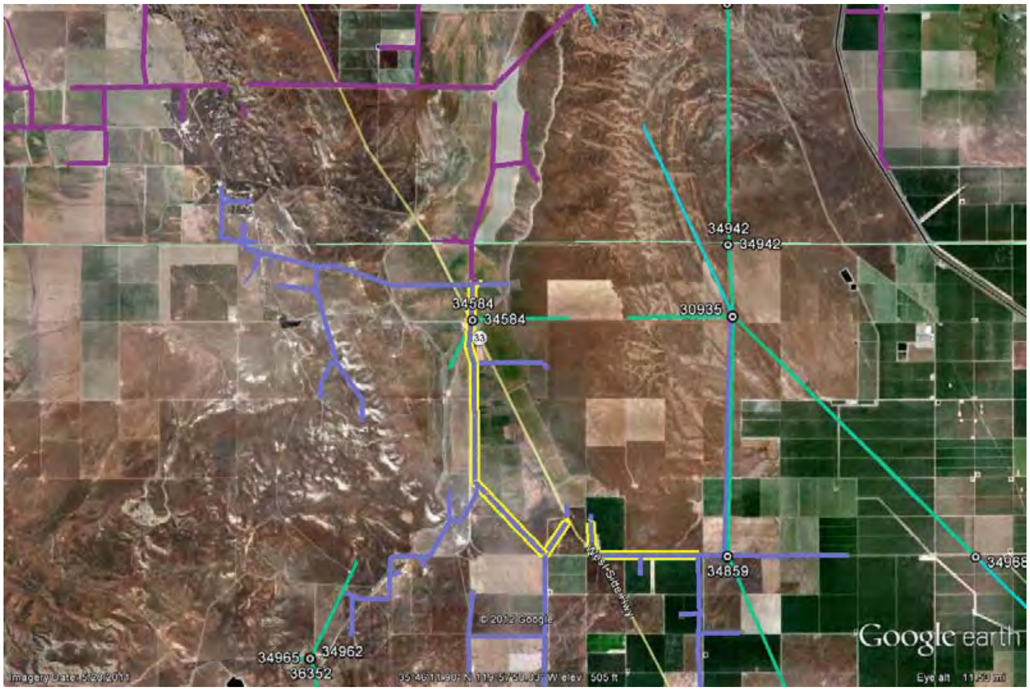
Source: New Power Technologies.

As a group, these projects have additional impacts. With W23 and one of W11 or W12, operating flow is reversed within Circuit 1102, as shown in **Figure 13** in yellow. Under these conditions, there is no reverse flow within the transmission system. Within the 70 kV transmission system at this location and the 2012 configuration, Dolcetto lies between Acolon and several large pumping plants. The addition of 21.5 MW of generation at Dolcetto displaces the power flow from Acolon to the pumping plants but does not reverse the flow. The Acolon-Dolcetto 70 kV line is rated at 53 MVA. This suggests that, without the pumping plant load, the generation at Dolcetto would backfeed but not overload this line.

With W23 and one of W11 or W12 operating, voltage at the Dolcetto 12 kV and 70 kV buses and at Acolon remains under 1.05 PU. W23 causes very limited steady-state over-voltage within Circuit 1102.

As of this point in the study, New Power Technologies has not been able to achieve a power flow solution with the full output of both W11 and W12.

Figure 13: Dolcetto Project Flow and Loading Impacts



Source: New Power Technologies.

Aragonez

Aragonez substation serves two distribution feeders, 1101 and 1102. The operating voltage of Aragonez substation is 12 kV.

New Power Technologies mapped one WDAT project, W21, to the Aragonez substation 12 kV main bus based on the annotation in the WDAT queue, with no distribution-connected projects.

Table 12 lists the details of the Aragonez WDAT project. The Aragonez substation transformer is rated at 10.5 MVA, so W21 would essentially overload the substation transformer with no circuit load.

Table 12: Aragonez WDAT Projects

ID	Interconnecting Bus	Bus Number	Rated Output (kW)
gen_W21	Bus_S2520212000_12kV_MainBus	500509	10,500

Source: New Power Technologies.

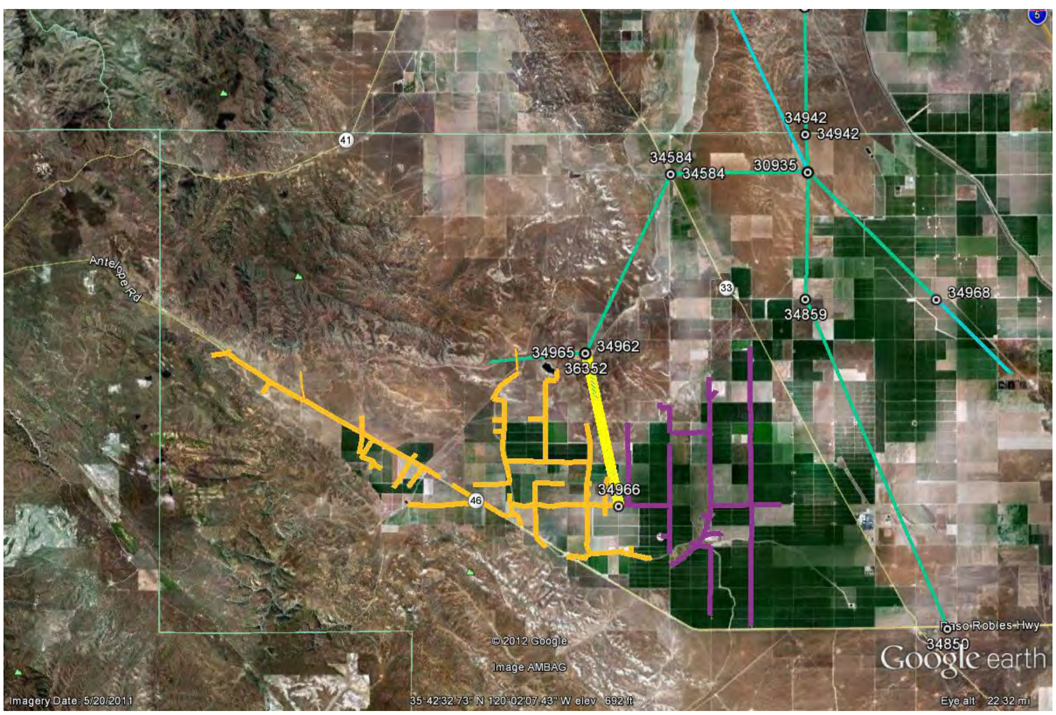
Table 13 shows the voltage impact of W21 interconnected at the Aragonez 12 kV main bus with no tap adjustments. Under the peak load conditions analyzed here, Aragonez substation serves about 3.4 MW, so W21 would reverse flow in the 70 kV system to Aragonez Junction (as shown with the thick yellow line in **Figure 14**) and reduce but not reverse flow from Dolcetto. With tap adjustments, there is no change to the Aragonez 12 kV bus voltage; the Aragonez substation 70 kV bus rises by 0.014 PU but remains under 1.05 PU. With the loss of pumping plant load, the output of W21 would cause a slight voltage elevation to 1.054 PU at some 70 kV buses.

Table 13: Aragonez WDAT Projects Voltage Impacts

				Individual Project @ Interconnection Bus	
ID	**Interconnecting Bus**	**Bus Number**	**Rated Output (kW)**	**Steady State Voltage Impact**	**Quasi-dynamic Voltage Impact**
gen_W21	Bus_S2520212000_12kV_MainBus	500509	10,500	0	0.014

Source: New Power Technologies.

Figure 14: Aragonez Project Flow and Loading Impacts



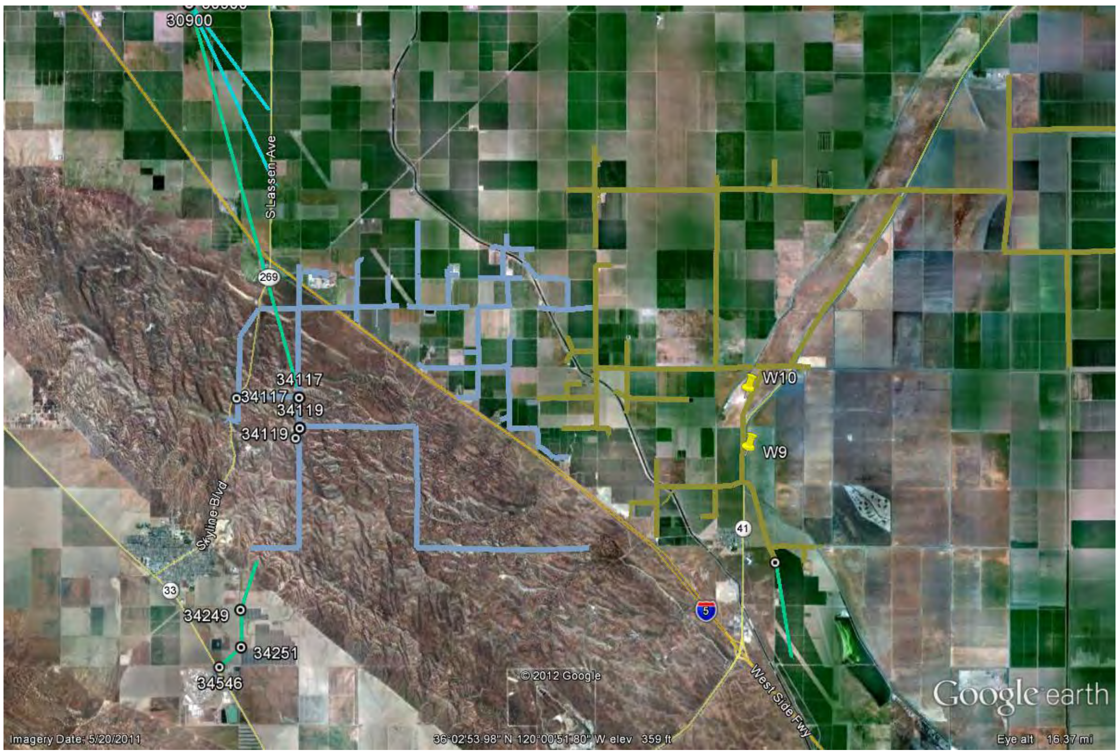
Source: New Power Technologies.

Trepat

Trepat substation serves three distribution feeders, 1104, 1106, and 2108. The operating voltage of Trepat substation is 12 kV, though most of Circuit 2108 operates at 21 kV.

As noted, projects W9 and W10 are identified in the WDAT queue as interconnected at the Kadarka substation, and the impacts of the two projects interconnected at that location are included in the Kadarka discussion. **Figure 15** shows that projects W9 and W10 are actually located near Trepat 1106 circuit (the yellow-green colored lines on right side of page) and not near Kadarka substation or Kadarka 1101 circuit (blue).

Figure 15: W9 and W10 Project Locations



Source: New Power Technologies.

As an exercise, New Power Technologies also evaluated W9 and W10 as interconnected at the nearest structure within Trepat 1106 circuit, as shown in **Figure 16;** accordingly, W9 is mapped to bus 702517, and W10 is mapped to bus 702596. This mapping results in distribution feeder-connected projects that exceed 10 MVA. As noted, projects of this size would normally require a dedicated feeder, but these interconnections are included here for illustration.

Figure 16: W9 and W10 Project Locations

Source: New Power Technologies.

Table 14 lists the Trepat WDAT projects and provides details concerning the distribution network at the point of interconnection each project. These two projects would be by far the largest distribution feeder-connected projects evaluated in this study. The minimum upstream line rating applicable to each project location indicates that either project would overload the circuit under loss of circuit load conditions and normal peak loading as well. System X/R at either location is moderately strong, though the stiffness ratios are somewhat weak. Both sites lie within the main backbone of the circuit, relatively close to Trepat substation, although the W10 site is electrically farther away and the equivalent system impedance is greater (and stiffness ratio lower).

Table 14: Trepat WDAT Projects

ID	Interconnecting Bus	Bus Number	Rated Output (kW)	Minimum Upstream Rating (MVA)	System X/R	Utility Source SC (MVA)	Stiffness Ratio
gen_W9	Bus_F252951106_swt_6	702517	20,000	7.9	1.72	78.1	4.3
gen_W10	Bus_F252951106_ND1200027768	702596	20,000	7.9	1.72	45.8	2.9

Source: New Power Technologies.

Trepat 1106 circuit has three line voltage regulators; however, none is located between the point of interconnection for W9 or W10 and the substation. Further, Trepat 1104 has no line voltage regulators, so Circuits 1104 and 1106 have very limited capability for independent voltage regulation. The step-up for Circuit 2108 effectively permits voltage management of that circuit independently of 1104 and 1106.

The Trepat substation transformer is rated at 10.6 MVA, so either W9 or W10 individually would overload the substation transformer.

Table 15 provides voltage impacts of the Trepat WDAT projects individually as directly estimated a power flow simulation. The power flow simulation of the individual projects indicates voltage variation that would not be acceptable without mitigation; however, these projects do not have the greatest voltage impact of the distribution-connected projects New Power Technologies evaluated, owing to the relative strength of the interconnection locations.

Table 15: Trepat WDAT Projects Voltage Impact

				Individual Project @ Interconnection Bus	
ID	**Interconnecting Bus**	**Bus Number**	**Rated Output (kW)**	**Steady State Voltage Impact**	**Quasi-dynamic Voltage Impact**
gen_W9	Bus_F252951106_swt_6	702517	20,000		0.090
gen_W10	Bus_F252951106_ND1200027768	702596	20,000		0.114

Source: New Power Technologies.

This is a good example of the limitations of System X/R as a stand-alone measure of the system's “weakness” at a proposed interconnection site. As the conductor serving both sites is the same, the System X/R evaluated at each site is identical. However, the equivalent system impedance at the site for W10 is in fact greater, the location is less “stiff,” and the individual voltage impact of an identical project is shown to be greater in a simulation.

Under the 2012 WECC configuration Trepat is not connected to Kadarka or Henrietta substations within the 70 kV network and is served radially from Bellone, Limnio, and Acolon. Under steady-state conditions, the addition of the output of both projects causes, in addition to reverse flow and overload within the circuit and the substation, reverse flow in the 70 kV system from Trepat through Bellone to Limnio substation, and overvoltage at Trepat, Bellone, Limnio, and Acolon substation 70 kV buses. Under these conditions the reverse flow loading of the Trepat-Bellone 70 kV line is near the line's normal rating but nominally not an overload.

CHAPTER 4: Discussion and Conclusions

The project's intent was to demonstrate and evaluate an approach that departs from conventional practices currently in use by utilities. Using the Energynet platform to model integrating distribution and transmission, the project evaluated the potential regional grid impacts of wholesale PV projects in high penetration. New Power Technologies wishes to reiterate that this study is not intended to conclusively determine the suitability of interconnection of any of the WDAT projects, prescribe necessary mitigation, or supplant the established interconnection process and study effort underway by PG&E.

Several conclusions were apparent:

- Integrated, or "coupled," transmission and distribution analysis provides new visibility.
- All interconnections are different.
- High penetrations of distribution-connected generation projects affect regional transmission.
- Distribution-connected projects are different from transmission-connected projects.
- Distribution-connected projects are different from each other.
- Related projects are hard to define by observation.
- The full definition of "meaningful" regional impacts remains.

A "Coupled" Transmission and Distribution Analysis Provides New Visibility

These interim results indicate that this approach provides a new level of visibility into the impacts of these WDAT projects, particularly in groups, and as those impacts extend beyond distribution through the substations and into the transmission system. The report enumerates direct impacts of individual projects and groups of projects in detail, covering loading, steady-state and quasi-dynamic voltage, and impacts on individual devices and lines, in distribution, within the substations, and in transmission.

This additional visibility may reveal considerations that were previously not readily apparent and may be unexpected. Some interesting examples include the Kadarka, projects that overload transmission but not distribution, the pervasiveness of distribution transformer overloads, and the relative absence of significant or far-reaching voltage impacts.

Further, by showing the distribution, substation, and transmission impacts directly alongside one another, this approach may suggest new alternatives to addressing those impacts. The pervasive substation transformer overloads noted above suggest consideration of transmission-level interconnections. The transmission impacts of the distribution-connected Trepat projects (W9 and W10) suggest reconfiguration of the 70 kV transmission as an impact mitigation strategy.

If the model demonstrated in this phase of the project is extended to the full set of regional distribution planning areas, it provides a platform for easy evaluation of the impacts of many regional wholesale PV project interconnections, alternative interconnection schemes for those projects, different project grouping or ordering, and different configurations of the regional power delivery system to address various impacts. This should help identify low-cost interconnection solutions and speed interconnection evaluations, facilitating the deployment of wholesale PV projects.

All Interconnections Are Different

This set of results includes individual evaluations of a common class of distributed generation (wholesale PV), but beyond that a wide variety of projects in terms of their size, type of interconnection (feeder, substation high-voltage bus, substation low-voltage bus), system characteristics, and system features at the point of interconnection. Accordingly, the individual impacts of each project range across a broad spectrum. These results show that it is difficult to generalize or guess at impacts. Terms like "high" penetration, "moderately sensitive" delivery network environment, or even "small" or "large" generation project provide little rigorous guidance. Best practices suggest that projects warrant individual attention.

These results also show that a regional power system simulation with integrated distribution detail readily shows many of the direct impacts of PV projects proposed within the region, individually and in groups. This suggests that evaluating large numbers of potential projects under different interconnection schemes, in different groupings, or under different regional network configurations could become a straightforward task that could be completed quickly and whenever needed to inform and guide developer decisions.

High Penetrations of Distribution-Connected Generation Projects Affect Regional Transmission

Every project group that included distribution-connected generation was shown to have impacts at the circuit level, the substation level, and at the transmission level. In the case of the Aleatico projects, the impact extended through the 70 kV transmission system to the higher-level 230 kV system, with impacts extending over 60 miles away. New Power Technologies did not attempt to identify and evaluate all relevant groupings of projects, although the super-groupings of projects affecting the Gamay and Acolon substations warrant further evaluation. These results are sufficient to show that, at least in this part of the power delivery network, a decoupled evaluation of the proposed interconnections that considers only distribution impacts or only transmission impacts of a given project or projects reveals a partial picture.

Distribution-Connected Projects Are Different From Transmission-Connected Projects

These results clearly show that to equivalize a group of proposed PV projects and simulate them as a single transmission-level interconnection can misrepresent their impacts. The Tibouren projects as a group have a relatively benign impact on transmission with reverse flow to Acolon substation. Modeling these projects at their individual points of interconnection in the substation or out on the distribution feeder reveals their overloads of the substation transformer and line segments within the circuit. Similarly, modeling the two distribution circuit-connected Kadarka projects at their appropriate points within the circuit shows how their voltage impact at the point of interconnection essentially disappears as seen by the transmission system.

Distribution-Connected Projects Are Different From Each Other

The distribution-connected projects associated with Bonarda and Kadarka substation provide an excellent example of the differences in impacts of similar projects in different locations. W7 and W8 within Kadarka are in strong locations and have modest impacts. W14 and W22 in Bonarda are similar in size to each other but have very different impacts compared to each other. They are also both in weaker locations (and are larger) and have much greater impacts than projects W7 and W8. Project W23 in Devils Den is a good example of a small project with a big impact due to the system weakness at the interconnection location. There is not one "rule of thumb" assumption that fairly characterizes the potential impacts of such projects. They must be evaluated individually, taking into account the attributes of their actual point of interconnection within the circuit as appropriate.

Related Projects Are Hard to Define by Observation

New Power Technologies evaluated projects in groups based on the substation through which they connect to the power delivery system. Detailed, accurate distribution feeder maps would have been required to determine these groupings even for an analysis not intended to distribution detail — for example, Project W23 began the study assigned to a different substation. With detailed, accurate distribution feeder topology incorporated in the integrated regional model, grouping by substation is an easy, reasonable first pass.

With the analysis performed at this stage, other relevant groupings become visible. The Kadarka and Aleatico substation projects represent a clear example of projects that are electrically interdependent. Analysis shows that both sets of projects can affect the 70 kV transmission system between Gamay and Aleatico, and because of the presently modeled alignment of the 70 kV system with the tie to Trepat open, their impacts are largely additive. The analysis also shows that the Bonarda and Tibouren substation projects both have effects visible at Acolon substation, even though they affect different parts of the down stream 70 kV system. It would take further analysis to determine if the Trepat, Devils Den, and Aragonez projects could have overlapping impacts in the transmission system, or if taken together their meaningful influence could extend to Acolon substation.

As an example, Charbono and Bonarda substations are administratively related within the Bonarda DPA. Their circuits are also physically close to each other. The detailed Energynet system characterization shows that under the present 70 kV alignment, as long as the distribution feeders in Bonarda DPA are operated radially with open inter-circuit ties, there would be essentially no electrical connection between wholesale projects connected on circuits served from those two substations.

The Full Definition of “Meaningful” Regional Impacts Remains

In these results, New Power Technologies applied an approach for evaluating individual project impacts demonstrated in prior studies and refined here. The approach for evaluating the aggregate impacts of project groups of projects having high penetration emerged during the course of this phase and will be refined with further work and peer review.

Under this evolving rubric, these results provide several examples where large amounts of incremental generation can be accommodated without unacceptable voltage rise, with manageable voltage variability, and without overloading transmission or distribution lines (substation transformers are overloaded in most instances). At the transmission level, in many cases voltage rise appears confined to one or two substations, and flow impacts are often limited to reversed direction within a networked system. A stepwise approach to evaluating impacts of these projects was useful throughout the study.

This suggests an opportunity to develop a more systematic approach and set of considerations to evaluate system impacts from groups of wholesale generation with high-penetration.

Acronyms

Acronym	Definition
DPA	Distribution Planning Areas
Energy Commission	California Energy Commission
kV	Kilovolt
MVA	Mega Volt-Amperes
MW	Megawatt
PG&E	Pacific Gas and Electric Company
PU	Per unit
PV	Photovoltaic
TCUL	Tap changer under load
WA	Work Authorization
WDAT	Wholesale Distribution Access Tariff
WECC	Western Electricity Coordinating Council