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Technical Report
NREL/TP-7A40-60991
March 2014

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List of Abbreviations and Acronyms

AC	alternating current
ci	clearness index
cpi	clear power index
DC	direct current
DFI	diffuse irradiance
DNI	direct normal irradiance
GETCO	Gujarat Energy Transmission Corporation
GHI	global horizontal irradiance
GW	gigawatt
GW_{DC}	gigawatt direct current
km	kilometer
km^2	square kilometer
kWh	kilowatt hour
MW	megawatt
MW_{DC}	megawatt direct current
NLDC	National Load Dispatch Centre
NREL	National Renewable Energy Laboratory
PPA	power purchase agreement
PV	photovoltaics
REMC	Renewable Energy Management Centres
SCADA	supervisory control and data acquisition
SIA	sub-hour irradiance algorithm
SLDC	State Load Dispatch Centre

Executive Summary

India has ambitious goals for high utilization of variable renewable power from wind and solar, and deployment has been proceeding at a rapid pace. The western state of Gujarat currently has the largest amount of solar capacity of any Indian state, with over 855 megawatts direct current (MW_{DC})[1] among plants above 1 MW_{DC} in size. Combined with over 3,240 megawatts (MW) of wind, variable generation renewables comprise nearly 18% of the electric-generating capacity in the state. The Central Electricity Authority has projected these wind and solar capacities will more than double by 2017.[2]

With high penetration levels of wind and solar, system operators must have access to additional resources that can help balance the net-load variability (load minus wind and solar output) and carry adequate reserves to respond to the combination of load and variable generation forecast errors. To assess the adequacy of balancing resources, and to evaluate operational practices to access these resources, system operators and planners typically perform grid integration studies. Key to informative analysis is accurate representation—spatially and temporally—of the power variability and uncertainty of solar and wind generation. This report focuses on the solar characteristics needed for a grid integration analysis, which would also include information on load, wind, and conventional generation.

A new historic 10-kilometer (km) gridded solar radiation data set capturing hourly insolation values for 2002-2011 is available for India.[3] The authors apply an established method for downscaling hourly irradiance data to one-minute irradiance data at each photovoltaic (PV) power production location for one year—2006.[4] Using this data, the authors quantify solar production at locations reflecting six scenarios: baseline, totaling 1.9 gigawatts direct current [GW_{DC}]) and five possible expansion scenarios, each adding 500-1,000 MW of solar capacity, to yield a total installed solar capacity of 2.4 GW_{DC} and 2.9 GW_{DC}. The scenarios are:

1. Baseline: existing and planned solar generation, totaling 1.9 GW_{DC}
2. Charanka: expansion at an existing, single solar park; represents the most geographically concentrated scenario, 1.0 GW_{DC}
3. Seven utility PV locations: expansion at the seven best, developable sites, distributed throughout the state, 1.0 GW_{DC}
4. Kutchh: expansion in the Kutchh region of Gujarat, distributed across the region, 1.0 GW_{DC}

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[1] Direct current (DC) ratings refer to the capacity of the photovoltaic panels under standard conditions: 1,000 watts/square meter, 25°C. Alternate current (AC) ratings refer to the peak power output of the inverter, which includes system losses and DC to AC conversion losses.
[2] *Large-Scale Grid Integration of Renewable Energy Sources—Way Forward*. Central Electricity Authority, 2013. www.cea.nic.in/reports/powersystems/large_scale_grid_integ.pdf.
[3] "India Solar Resource Data: Hourly." National Renewable Energy Laboratory, 2013. http://www.nrel.gov/docs/fy14osti/61121.pdf, http://rredc.nrel.gov/solar/new_data/India/nearestcell.cgi.
[4] A single year of sub-hour data captures the seasonal and time of day variability; however multiple study years would be needed to understand the long-term economics of a PV plant at a particular location.

5. Narmada Canal: expansion above the canal, evenly distributed across its length 0.5 GW_{DC}
6. Sixteen Cities rooftop PV: expansion across rooftops in the 16 largest cities, evenly distributed across the cities; represents the most geographically diverse scenario, 1.0 GW_{DC}.

Three of the expansion scenarios (Charanka, Kutchh, and Narmada Canal) were suggested by the Gujarat Energy Transmission Corporation (GETCO). The other two scenarios were selected to reflect broader geographic diversity.

The objective of this report is to characterize and contrast the intra-hour variability of these six PV generation scenarios. The report statistically analyzes one year's worth of power variability data, applied to both the baseline and expansion scenarios, to evaluate diurnal and seasonal power fluctuations, different timescales of variability (e.g., from one to 15 minutes), the magnitude of variability (both total megawatts and relative to installed solar capacity), and the extent to which the variability can be anticipated in advance. The paper also examines how GETCO and the Gujarat State Load Dispatch Centre (SLDC) could make use of the solar variability profiles in operations and planning.

One factor inherent to grid balancing challenges associated with increased solar deployment is the ramp rate, which is the sustained rate of power increase or decrease over time.[5] Solar power ramps result from both the daily solar path and cloud patterns that decrease the incident solar radiation on the PV panels. Quantifying total MW per minute ramp rates allows system operators and planners to assess balancing options.

This analysis quantifies the relatively simple concept that the total magnitude of solar power ramping goes up with increased solar capacity. Simply put, total ramping in the baseline scenario of 1.9 GW_{DC} is less than total ramping in the baseline plus expansion scenario of 2.4 GW_{DC}, which is less than the four other baseline plus expansion scenarios totaling 2.9 GW_{DC}. The dominant cause of this correlation is ramping due to sunrise and sunset, which occurs over a short, predictable period of time. During the monsoon season, clouds reduce the sunrise and sunset ramp rates, and decrease the peak solar output by 20-35%. Figure ES-1, the aggregate power output from the baseline plus each expansion scenario in monsoon (left) and dry (right) seasons, illustrates these results.

[5] This change in power over time is typically expressed in MW over some time scale of interest, for example five minutes.

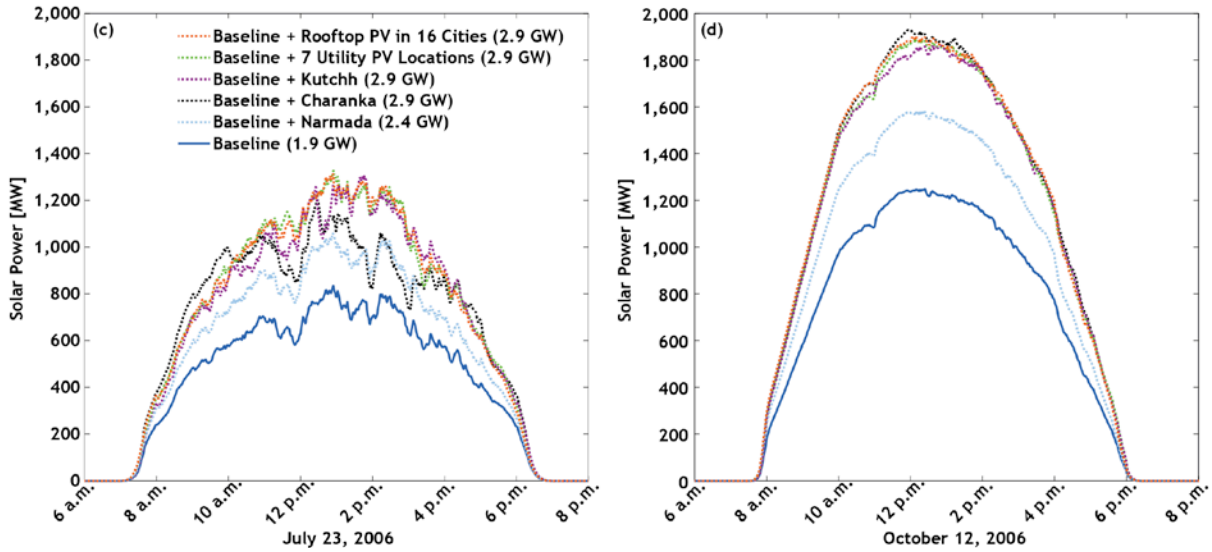

Figure ES-1. Aggregate power output of baseline plus expansion scenarios on July 23, 2006 (monsoon), and Oct. 12, 2006 (dry season)

This analysis also quantifies that aggregate power ramps from solar expansion scenarios are less dramatic as the geographic spread of deployment (spatial diversity) is increased. In contrast to using total magnitude ramp rates, illustrating the more complex effects of geographic diversity from alternative solar expansion scenarios is better assessed by normalizing ramp rates to the total nameplate rating.

As Figure ES-2a illustrates, the five-minute ramps normalized as a percentage of installed solar capacity are relatively constant across the baseline and expansion scenarios during the dry season, but vary based on time of day. The smallest ramps occur during the midday of the dry season, with the sun high in the sky and very few clouds. While observable, the ramp rate differences between scenarios are small because the East-West and North-South impacts on solar path are not large within Gujarat’s boundaries.

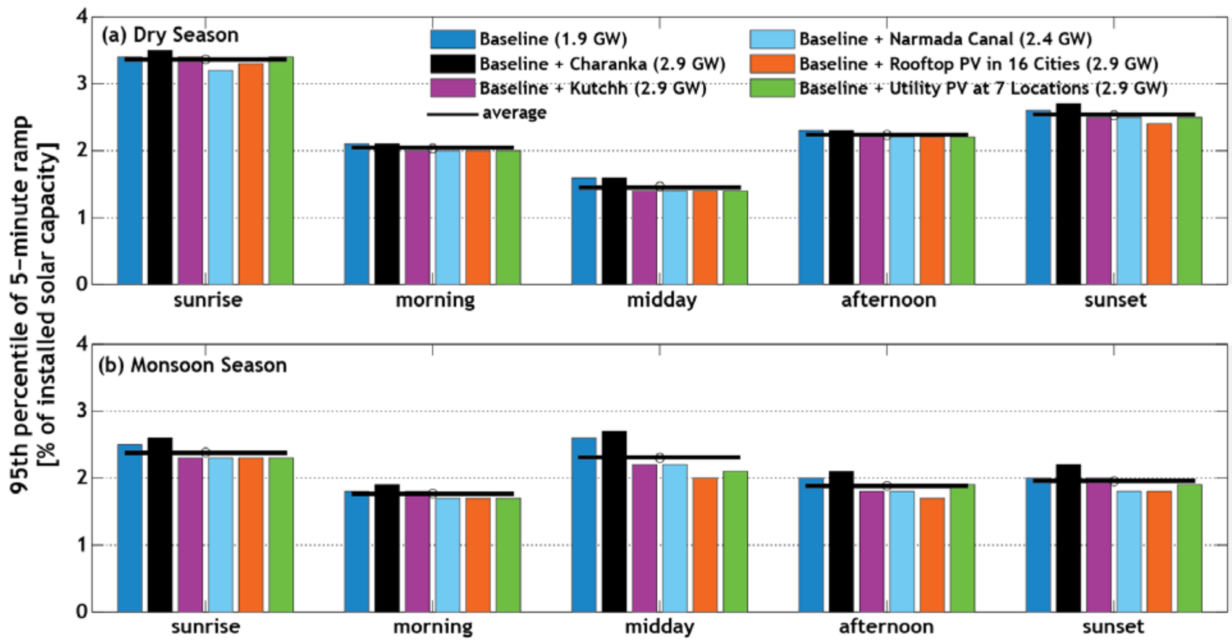

Figure ES-2. The dry season (a) and monsoon season (b) 95th-percentile five-minute ramp (percent of scenario installed DC solar capacity) during each time of day: sunrise, morning, midday, afternoon, and sunset

The monsoon season (Figure ES-2b) shows a different time of day pattern than the dry season—the largest ramps occur during midday, when there are many clouds that change the solar power production. The effect of geographic diversity becomes more noticeable when cloud coverage contributes to solar ramping. In this case, geographically diverse locations, such as baseline plus utility PV at seven locations or rooftop PV, experience lower absolute ramps than similarly sized scenarios. The baseline plus Charanka scenario (2.9 GW_{DC}), which concentrates new solar generation in a single location, has 30% and 7% greater ramps in the monsoon and dry seasons, respectively, over the baseline plus rooftop PV in 16 cities (2.9 GW_{DC}). These increases may be significant if added requirements for load and conventional generation to provide balancing services are costly.

The report also presents analysis showing the greatest difference between the monsoon and dry seasons is seen in the average unpredicted one-minute ramps, which demonstrates that dry season variability conditions driven by solar path alone persist for longer periods than monsoon season variability conditions where clouds impact solar output. In other words, it is harder to predict short-term variability in the monsoon season than in the dry season.

The impact of solar variability quantified in this study can be managed through targeted changes to system operations and planning. Because most of the solar ramping is based on known changes due to sunrise and sunset, the Gujarat SLDC may be able to schedule its resources accordingly. The greater periods of uncertainty stem from cloud-based variability. To address this impact, Gujarat, in coordination with the central government authorities, is in the process of assessing and strengthening its suite of tools to anticipate and mitigate this variability, which include stronger grids, advanced forecasting (day ahead and real-time), improved scheduling, and market reforms.

This work brings out several salient features that are important when evaluating potential future PV renewable generation and its potential grid integration impacts on the power system, including:

- The diurnal and seasonal power profiles and variability statistics for the existing and planned 1.9 gigawatts (GW) of solar are characterized using 2006 historic solar resource data. The geographic spread of this baseline is relatively broad. Power output is raised slightly if a portion of the plants is assumed to incorporate single-axis tracking, but the statistics of variability are largely unaffected by tracking.
- The expansion scenarios of 500 to 1,000 MW increase nearly proportionally the absolute magnitude of the solar variability. The differences in geographic density of the expansion scenarios affect variability, but when combined with the geographically diverse baseline scenario and normalized to the total nameplate DC capacity, the differences among scenarios are small.
- Results illustrate the power ramp rate differences between a single small plant, a very large plant, several spread out central plants, and rooftop distributed deployments. The least geographically diverse, baseline plus Charanka scenario, has 30% and 7% greater midday ramps in the monsoon and dry seasons, respectively, over the more geographically diverse baseline plus rooftop PV in 16 cities scenario.
- In evaluating expansion plans, system planners need to consider other factors related to location, such as access to uncongested transmission capacity, in addition to variability differences. If solar deployment across more Indian states is considered, and state-to-state grid cooperation is increased, the beneficial impacts of geographic diversity should be larger and would be worth re-evaluating.
- During the monsoon season, individual plant variability can be quite large due to cloud passage, but the aggregated power across all plants shows less volatility. Due to the broad and general nature of the storms, planning and operating the system using a derating of the solar capacity may help systems operations. Further research could assess whether this implication could be applicable to other regions of the world with similar monsoonal climatology and where solar power is being deployed or contemplated.
- The study shows that much of the diurnal solar variability is based on a known solar path, illustrating a large amount of the PV-imposed needs for grid flexibility are known in advance, which facilitates grid operational day-ahead scheduling.
- The variability shows strong seasonal characteristics. Generally, absolute variability is higher during dry seasons during known sunrise and sunset ramps. Variability relative to output is higher during the monsoon season at midday, when the region experiences a dramatic decrease in solar power output due to periodic (and relatively unpredictable) cloud passage.
- Diurnal and seasonal variability characteristics can be important to grid practices. Known variability implies ramping resources can be confidently quantified and potentially scheduled. Unpredictable variability statistics can also be quantified, but may require partially loaded quick ramp or quick start/stop resources to respond.

Finally, it is recognized that solar profiles are only part of the renewable energy integration study needs. The broader context calls for similar evaluation of wind power deployment scenario variability, which will be undertaken by the authors later in 2014. The results of this report should not be taken independently, as only studies of the full integrated electric system, including conventional generator capabilities, load variability, operational practice reform, and assessment of system-level mitigation measures will allow system planners and operators to examine and address challenges imparted by large-scale variable generation futures.

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1 Introduction

India has ambitious goals for high utilization of variable renewable power from wind and solar, and deployment has been proceeding at a rapid pace. The western state of Gujarat currently has the largest amount of solar capacity of any Indian state, with over 855 megawatts (MW) among plants above 1 MW in size. Combined with over 3,240 MW of wind, variable generation renewables are nearly 18% of the electric-generating capacity in the state.[6] The Central Electricity Authority has projected these wind and solar capacities will more than double by 2017.[7]

Worldwide, electric utilities and grid operators are concerned by the variable and uncertain nature of weather-driven renewable power sources—wind and solar generation output varies over time, and this output cannot be predicted with perfect accuracy. Grid operators routinely balance electric load (demand) with the suite of dispatchable conventional generators. With high penetration levels of wind and solar, system operators must have access to additional resources that can help balance the net-load variability (load minus wind and solar output) and carry adequate reserves to respond to the combination of load and variable generation forecast errors. A variety of approaches to both analyzing and mitigating impacts exist.[8,9]

India-specific challenges with variable generation are being discussed and addressed in the broader context of grid modernization through grid synchronization, strengthening of transmission ties, operator practice, and market design.[10] Previous collaboration between the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) and the Gujarat Energy Transmission Corporation (GETCO)[11] discusses the application of grid-operational modeling studies to examine challenges and mitigation measures for high future penetrations of renewable variable generation in Gujarat. The 2012 effort described the nature of a market-based integration study and how this approach, while new to Indian grid operation and planning, is necessary to understand how to operate and expand the grid to best accommodate the expansion of variable generation. The paper also discussed options in defining a study's scope, such as data granularity, generation modeling, and geographic scope. Finally, the paper explored how

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[6] Gujarat, like other Indian states, bears primary responsibility for generation-load balance within its boundaries, but is connected to the single, India-wide electrical interconnection.
[7] *Large-Scale Grid Integration of Renewable Energy Sources—Way Forward*. Central Electricity Authority, 2013. www.cea.nic.in/reports/powersystems/large_scale_grid_integ.pdf.
[8] See, for example, Holttinen, H. et al. *Design and Operation of Power Systems with Large Amounts of Wind Power*. VTT Technology, 2013. www.ieawind.org/task_25/PDF/T75.pdf.
[9] Cochran, J., L. Bird, et al. *Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience*. Golden, CO: National Renewable Energy Laboratory, 2012. www.nrel.gov/docs/fy12osti/53732.pdf.
[10] *Integrating Variable Renewable Energy with the Grid: Lessons from the Southern Region*. Mercados Energy Markets India PVT Ltd., November 2012. www.shaktifoundation.in/cms/uploadedImages/variable%20re%20grid%20integration.pdf.
[11] Stoltenberg, B. "Grid Integration Studies and India." Presented at the 2012 World Renewable Energy Forum. http://nrelpubs.nrel.gov/Webtop/ws/nich/www/public/Record?rpp=25&upp=0&m=1&w=NATIVE%28%27TITLE_V+ph+words+%27%27india+grid%27%27%27%29&order=native%28%27pubyear%2FDescend%27%29.

Gujarat's method of grid operation and current system reliability will affect how an integration study can be performed.

Market-based integration studies allow quantifiable evaluation of resources—and operational practices to access these resources—that are necessary to maintain reliability under various projections of wind and solar penetration. These studies evaluate characteristics and practices, such as unit commitment and dispatch; the flexibility of existing conventional generators; quantity and types of reserves; and cooperation between electrical balancing areas. Such studies can also examine the effects of modifications to historic practices, including market design, ancillary services, wind and solar power forecasts, and demand scheduling and control. Different future generation portfolios can be modeled to help guide resource acquisition, including storage acquisition, and value the provision of flexibility, such as the ability to increase output quickly or decrease output to low generation levels.

Key to all these informative analyses is accurate representation of the power variability and uncertainty of solar and wind generation. Individual plants show very rapid power changes due to cloud passage and wind speed variation. Simply scaling up output patterns from existing renewable plants to higher future deployment levels ignores deployment expansion geographic diversity effects and significantly overestimates fluctuations and mischaracterizes the magnitude and possible costs of the integration challenge.[12] Thus, spatial and temporal diversity must be accurately represented to capture renewable power ramps, which are the changes in generation output.

To represent spatial and temporal diversity, system planners typically examine multiple scenarios that include alternative plant locations, and use historic, time-synchronized load, wind, and solar patterns to capture weather-driven correlations between electric demand and renewable power delivery. Recent, advanced variable generation integration studies have highlighted the value of examining sub-hourly variability, which significantly increases the complexity in characterizing temporal variability.[13]

Development of these wind and solar resource databases is nontrivial. In the case of wind, large-scale, mesoscale weather models, calibrated with historic weather patterns, are used to predict wind speeds at potential generation sites. For solar, historic satellite photos of clouds can be used to determine ground insolation values. Recently, NREL completed a new historic hourly solar radiation data set capturing hourly insolation values for 2002-2011 for India.[14]

The objective of this report is to characterize the intra-hour variability of existing and planned solar generation in the state of Gujarat, and of multiple future scenarios of solar generation that reflect different plant locations. The authors apply an established method for downscaling hourly

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[12] Holttinen, H. et al. "Recommendations for Wind Integration." IEA Wind, October 2012. www.ieawind.org/task_25/PDF/WIW12_101_Task%2025_Recommendations_submitted.pdf .

[13] "Transmission Grid Integration: Western Wind and Solar Integration Study." National Renewable Energy Laboratory, 2013. www.nrel.gov/electricity/transmission/western_wind.html.

[14] "India Solar Resource Data: Hourly." National Renewable Energy Laboratory, undated. http://rredc.nrel.gov/solar/new_data/India/nearestcell.cgi.

irradiance data to one-minute irradiance data at each PV power production location for one year—2006. A single year of sub-hour data captures the seasonal and time of day variability; however, multiple study years would be needed to understand the long-term economics of a photovoltaic (PV) plant at a particular location. Following this introduction, Section 2 describes the scenarios that were generated for existing and expected solar installations, totaling 1.9 gigawatts (GW), and for five future scenarios with an additional 500-1,000 MW.

Section 3 documents the methods used to convert the hourly data set irradiation values to minute-to-minute power outputs. Section 4 presents the statistical analysis of one year's worth of power variability data on multiple timescales. Single-plant, regional, and state-wide aggregations will illustrate the smoothing effects of spatial diversity.

Section 5 places the analysis of solar power variability in the context of Gujarat electric grid operations and planning. The Gujarat State Load Dispatch Centre (SLDC) is ultimately responsible for maintaining the load-generation balance. Together with GETCO, the SLDC has taken many steps to accommodate and anticipate grid challenges caused by the variable and uncertain nature of solar and wind power. This section examines how GETCO and the SLDC could use the solar variability profiles in operations and planning.

Finally, as discussed in Section 6, it is recognized that solar profiles are only part of the renewable energy integration study needs. The broader context calls for similar evaluation of wind power deployment scenario variability. Only studies of the full, integrated electric system, including load variability, will allow system planners and operators to examine and address challenges imparted by large-scale variable generation futures.

2 Solar Power Scenarios

The PV solar power scenarios used in this analysis are divided into two groups: existing and expected locations, and expansion locations. The existing and expected locations include 1.9 GW of direct current (DC) capacity and are called the “baseline” scenario. The expansion locations add 500 to 1,000 MW of additional DC capacity. All scenarios are planned to meet a target DC installed capacity. The algorithm for transferring DC panel output to alternating current (AC) power output from the inverter is explained in Section 3.[15]

Figure 1 shows the average annual global horizontal irradiance (GHI) for India. The state of Gujarat has a high annual average solar resource of 5.5 to 6.0 kilowatt-hours (kWh)/square meters/day over the entire state. This uniformity allows solar power plants to be optimally located based on proximity to load centers and transmission lines.

[15] Direct current (DC) ratings refer the capacity of the photovoltaic panels under standard conditions: 1,000 watts/square meter, 25°C. Alternate current (AC) ratings refer the peak power output of the inverter, which includes system losses and DC to AC conversion losses.

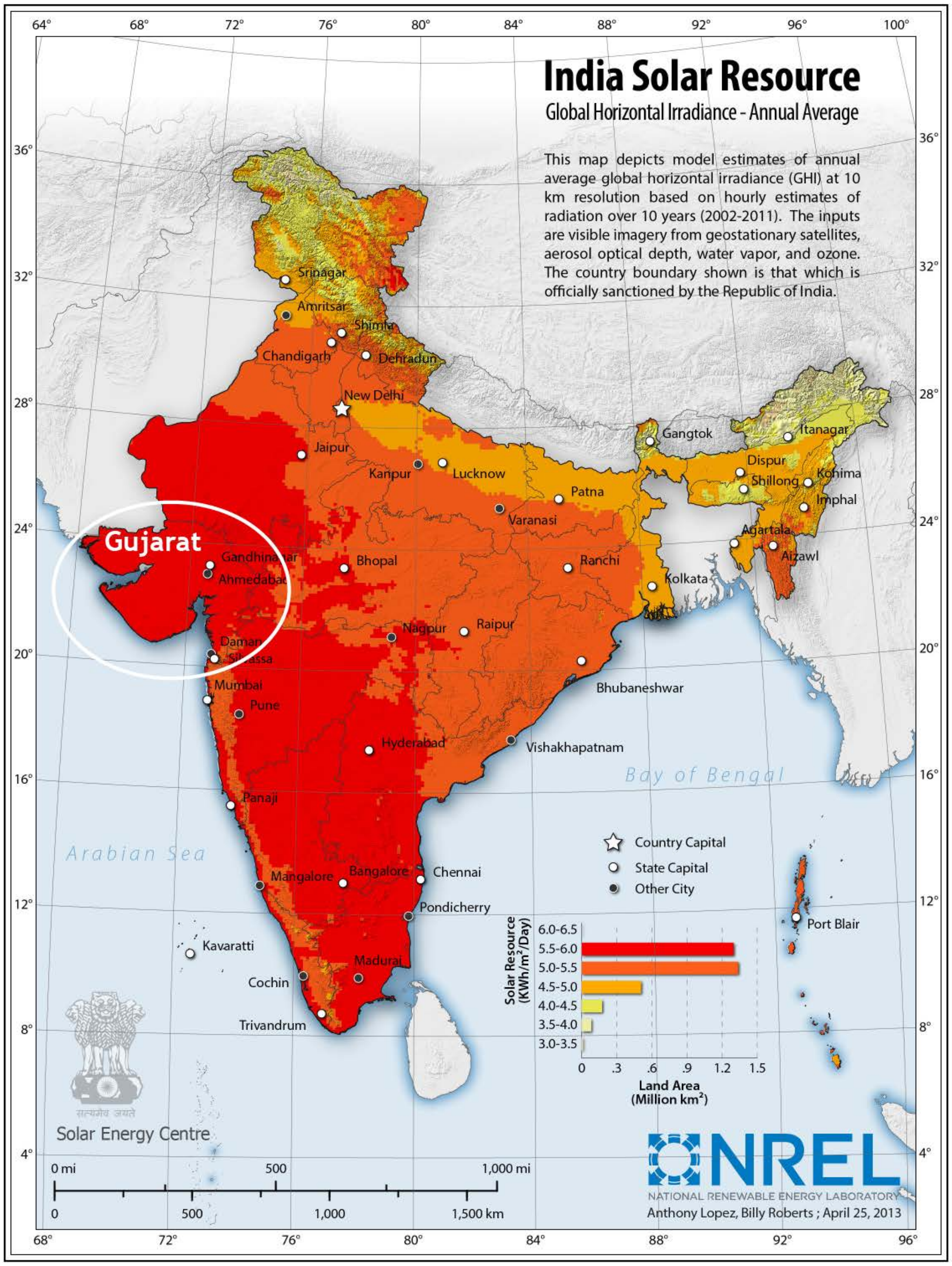

Figure 1. Annual average of GHI for India

2.1 Existing and Expected Locations

The existing and expected locations form the baseline scenario. This baseline scenario has three cases, which vary by extent of fixed-tilt versus tracking: 1) all locations have fixed-tilt PV plants, 2) 10% of the capacity is installed as single-axis tracking systems (with the remaining 90% installed as fixed-tilt systems), and 3) 25% of the capacity is installed as single-axis tracking systems (with the remaining 75% installed as fixed-tilt systems).[16] It is unknown what proportion of the existing and expected PV locations are or will be single-axis tracking plants. In the United States, approximately 30%-50% of new utility PV plant installations are single-axis tracking.[17] Figure 2 shows the grid cells (approximately 10 kilometers [km] by 10 km) where the PV plants in the 100% fixed-tilt baseline scenario are located. These locations are based on information from GETCO. The GETCO maps of existing (see Figure A-1) and expected (see Figure A-2) PV plant locations can be found in the appendix. The baseline scenarios with 10% and 25% single-axis tracking are shown in Figure 3a and 3b, respectively.

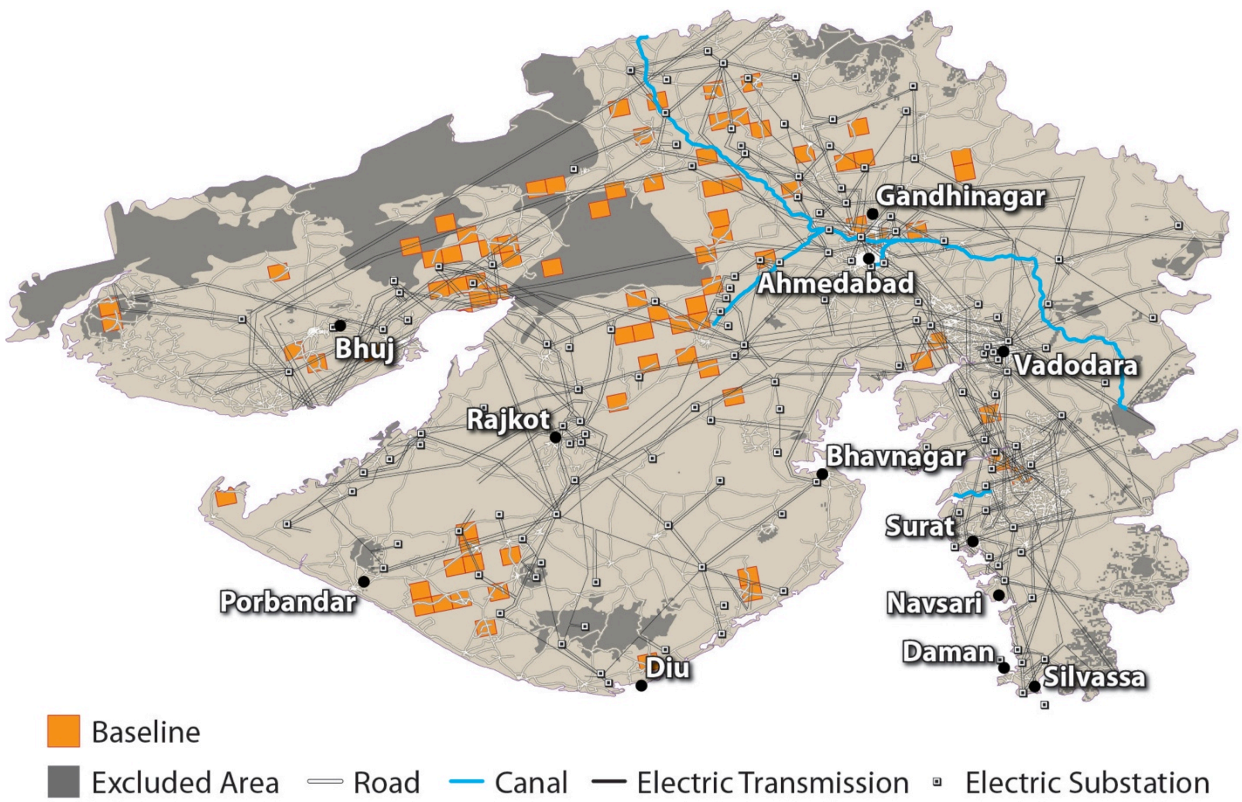

Figure 2. Baseline scenario PV plant locations in Gujarat, India[18,19]

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[16] All fixed-plate systems modeled for Gujarat, India, were assumed to be mounted at a 17° tilt and oriented due south (azimuth of 180°). Tracking systems were modeled as single-axis tracking systems with a tilt of 0° and oriented with a north-south pivot axis.
[17] Ong, S.; Campbell, C.; Denholm, P.; Margolis, R.; Heath, G. *Land-Use Requirements for Solar Power Plants in the United States.* NREL/TP-6A20-56290. Golden, CO: National Renewable Energy Laboratory, 2013. http://www.nrel.gov/docs/fy13osti/56290.pdf.
[18] The power map reflects infrastructure as of March 2013. More recent maps can be found at http://getco.co.in/getco_new/pages/power%20map.php.
[19] The excluded area is used to inform PV siting in one expansion scenario, and comprises forests, permanently flooded areas, regularly flooded areas, urban areas, water bodies, slope >5%, and protected areas.

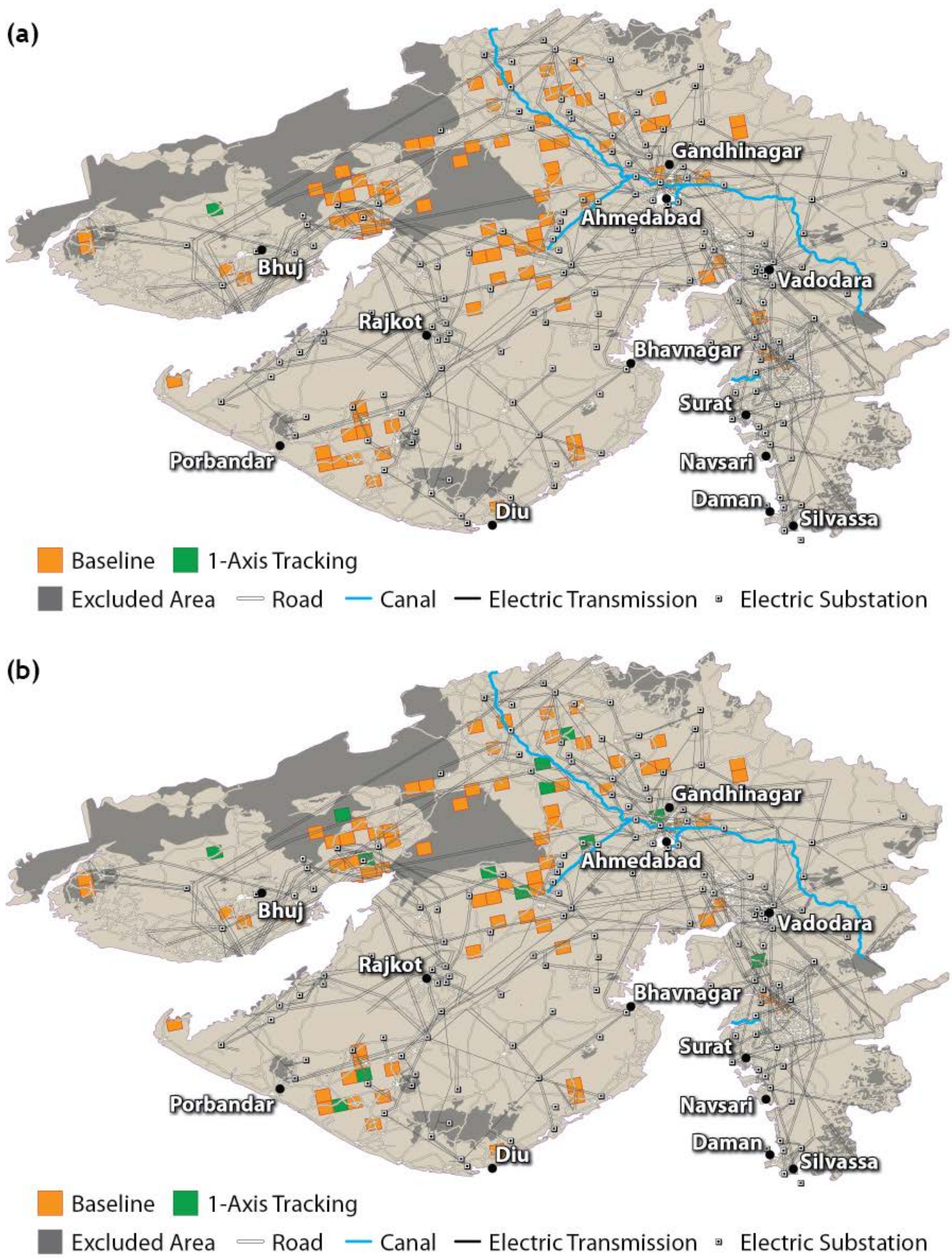

Figure 3. Baseline scenarios with approximately 200 MW of single-axis tracking (a) and approximately 450 MW of single-axis tracking (b)

2.2 Expansion Locations

To anticipate how variability might change if Gujarat continues to pursue renewable energy growth targets, the authors created solar profiles for five additional scenarios reflecting different locations for PV plants. Three of the sites for future scenarios (Charanka, Kutchh, and over the

Narmada Canal) were suggested by GETCO staff. The other two scenarios were selected to reflect broader geographic diversity: solar capacity allocations across seven central station locations throughout the state and a distributed rooftop scenario across 16 cities. The latter was selected to reflect the growing interest in India for rooftop PV.[20] Including the baseline, eight scenarios and their profiles were produced and analyzed. The remainder of this section will describe the five expansion scenarios in greater detail.

2.2.1 Charanka

The "Charanka" scenario expands the baseline scenario by adding 1,000 MW_{DC} at the Charanka Solar Park. One thousand MW requires about 25 square kilometers (km^2), which is one-quarter of a grid cell. Figure 4 shows the location of the Charanka scenario (yellow) on the baseline scenario map (orange). The Charanka Solar Park was initially started in 2010 and will be located on more than 20 km^2 near Charanka in the Patan district in north Gujarat. The solar park was envisioned to be the site of 500 MW_{DC} of installed solar capacity and is expected to be completed by the end of 2014. GETCO is supporting the project with infrastructure upgrades, including a 400-kilovolt transmission line, to evacuate the solar power produced.[21] This 500 MW_{DC} capacity is reflected in the baseline scenario. The addition of 1,000 MW_{DC} in the expansion scenario would result in a total of 1,500 MW_{DC} of solar capacity at the Charanka Solar Park.

This is the only scenario that includes solar expansion at an existing site. While future solar growth might occur at other existing sites, the Charanka scenario was chosen to capture the most centralized expansion and is useful in illustrating the impact of concentrated deployment on variability.

[20] "Gujarat prepares new solar rooftop policy." PV Magazine, Sept. 9, 2013. www.pv-magazine.com/news/details/beitrag/gujarat-prepares-new-solar-rooftop-policy_100012661/#axzz2t8RFTuNM.
[21] "Report on Green Energy Corridors: Transmission Plan for Envisaged Renewable Capacity." Power Grid Corporation of India Ltd., July 2012. www.forumofregulators.gov.in/Data/study/Report-Green-Energy-Tr.-corridor.pdf.

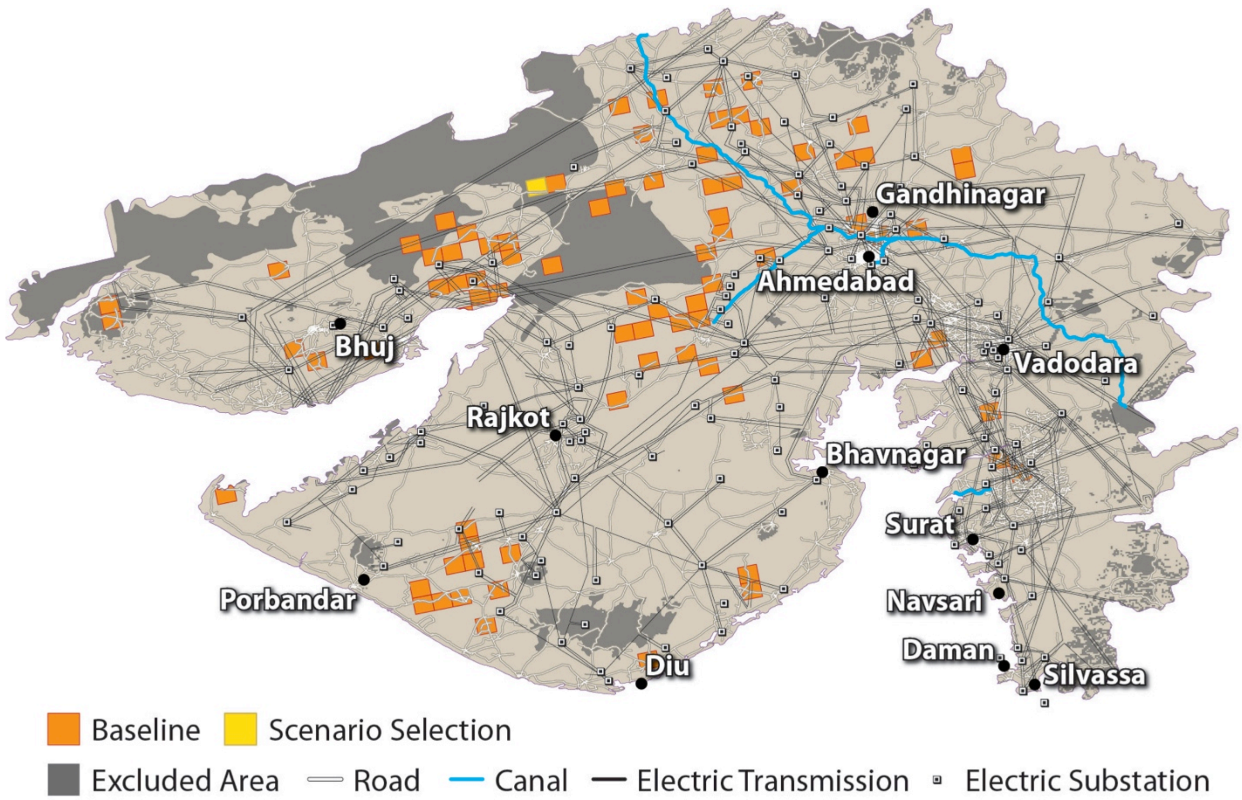

Figure 4. Charanka scenario is 1.0 GW of additional capacity at Charanka Solar Park (yellow) with the baseline scenario (orange)

2.2.2 Seven Utility Photovoltaic Locations

The “seven utility PV locations scenario” expands the baseline scenario by adding about 143 MW_{DC} at each of seven locations throughout western Gujarat. Figure 5 shows the locations of the seven PV plants. The seven locations are based on grid cells with the highest annual GHI intensity and at least 4 km^2 (using 40 MW_{DC}/km^2) of developable land. Developable land excludes forests, permanently flooded areas, regularly flooded areas, urban areas, water bodies,[22] slope >5%, and protected areas.[23] Developable land within grid cells is also tested for proximities, including: 5 km from roads[24] and 3 km from transmission.[25] If two adjacent grid-cells qualify, the next best grid cell is used in order to diversify the locations of the seven utility PV plants.

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[22] “Global Land Cover Characterization: Eurasia Version 1.” U.S. Geological Society, 2008. Version 1: http://edc2.usgs.gov/glcc/glcc.php.
[23] “ProtectedPlanet.net” United Nations Environment Programme and International Union for the Conservation of Nature, 2014. www.protectedplanet.net/.
[24] “OpenStreetMap.” OpenStreetMap contributors, undated. Accessed Jan. 7, 2013: http://www.openstreetmap.org/#map=5/51.500/-0.100.
[25] Shah, M.N. “Power Map of Gujarat” sent in personal communication to Stoltenberg, B., National Renewable Energy Laboratory. GETCO, May 27, 2013. The map was labeled as Updated March 31, 2013.

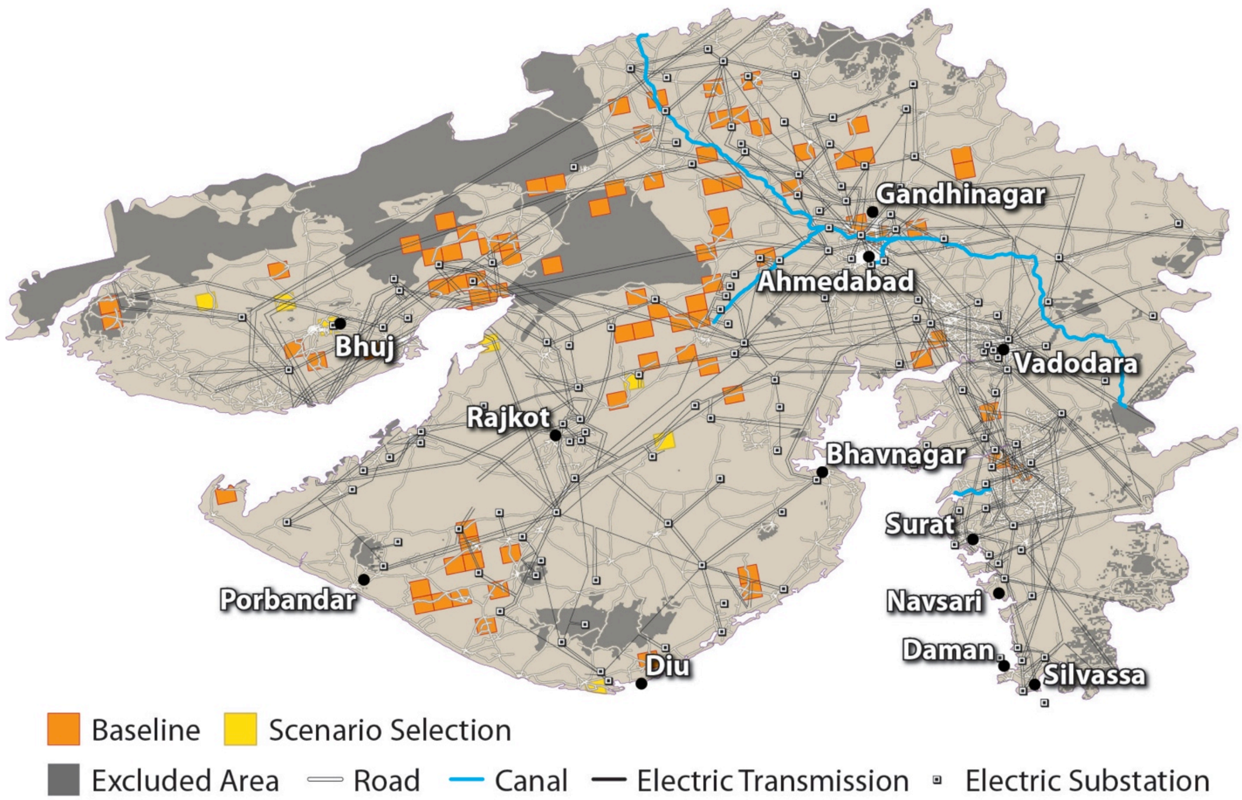

Figure 5. Seven utility PV locations scenario (yellow) each with 143 MW PV plants with the baseline scenario (orange)

2.2.3 Kutchh Region

The "Kutchh region" scenario is six utility PV plants spread through the Kutchh region, as shown in Table 1. The allocation of capacity throughout Kutchh was performed under the guidance of GETCO.[26] Grid cell selection within an area was performed using the same guidelines of annual GHI intensity and developable land use restriction outlined in Section 2.2.2.

Table 1. Allocation of Capacity for Utility PV Plants in the Kutchh Region

Area	Capacity (MW_{DC})
Bhachau and Shivlakha	200
Anjar	200
Varsana	200
Nakhatrana	150
Abdasa	150
Nani Khakhar	100

Figure 6 shows the grid cells selected for the Kutchh scenario and the baseline scenario.

[26] Kalsaria JE, D.H. Email to Stoltenberg, B., National Renewable Energy Laboratory. GETCO, Sept. 30, 2013.

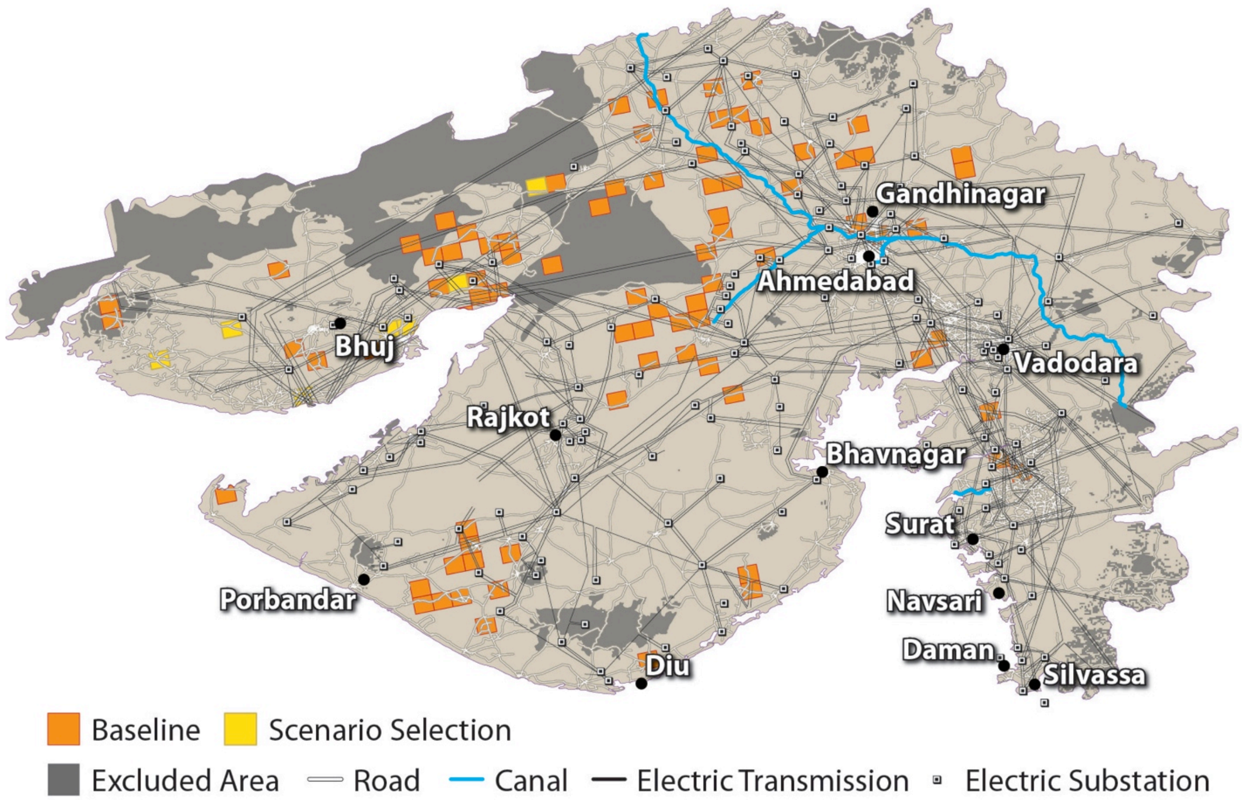

Figure 6. Kutchh scenario (yellow) consists of six utility PV plants ranging from 100 to 200 MW with the baseline scenario (orange)

2.2.4 Narmada Canal

The "Narmada Canal" scenario is based on recent reports that fixed PV panels are being mounted over the canal.[27,28] The selection of grid cells for this scenario was formed by finding the grid cells that spatially intersect the canal and calculating the PV capacity available within each grid cell, assuming 1.3 MW_{DC} per kilometer of canal. The grid cells are sorted by annual GHI intensity, and the grid cells are selected in order of highest resource quality until the cumulative sum is 500 MW_{DC}.

Figure 7 shows the grid cells selected along the Narmada Canal. The average DC capacity per grid cell is 31 MW.

[27] "Gujarat's canal-top solar power plant: 10 must-know facts." *The Economic Times*, April 10, 2013. http://economictimes.indiatimes.com/slideshows/infrastructure/gujarats-canal-top-solar-power-plant-10-must-know-facts/slideshow/19472958.cms.

[28] "Gujarat lights up canal with 10 MW project." PV Magazine, Aug. 14, 2013. www.pv-magazine.com/news/details/beitrag/gujarat-lights-up-canal-with-10-mw-project_100012392/#axzz2ojoILPCO.

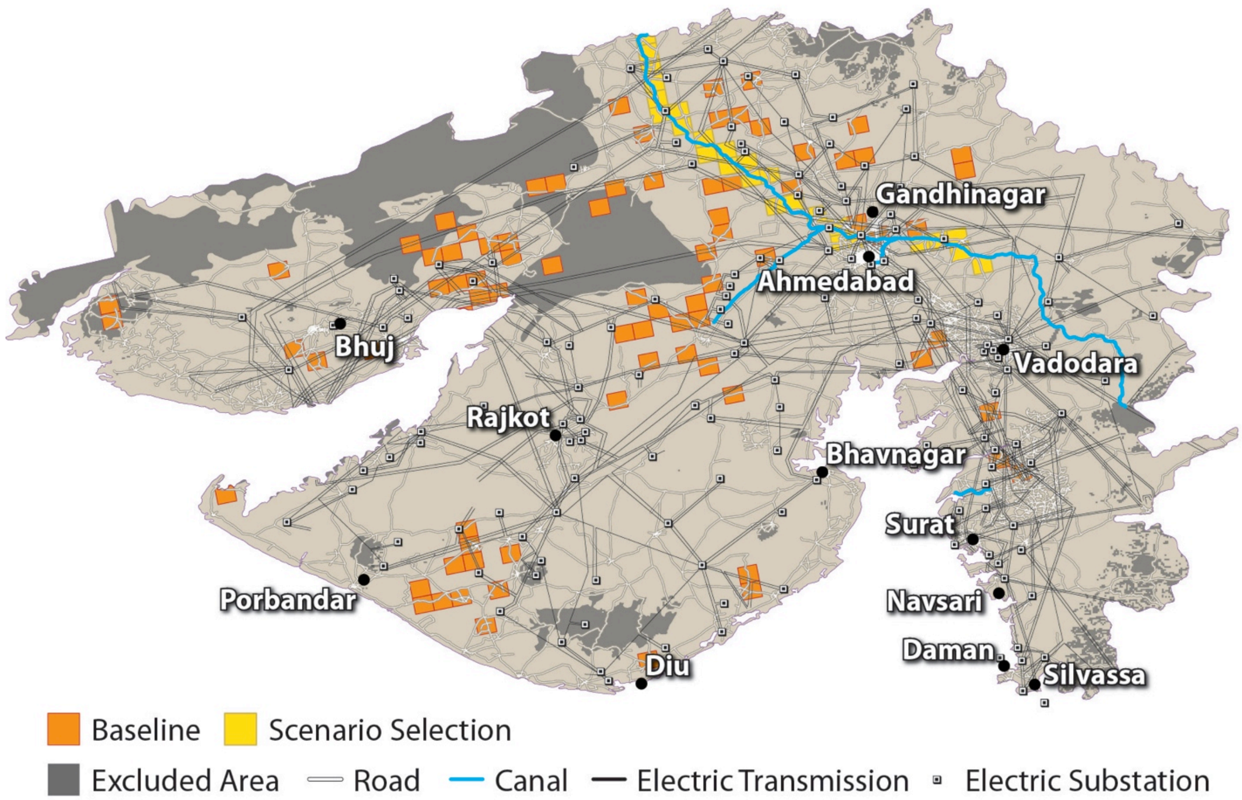

Figure 7. Narmada Canal scenario (yellow) with 500 MW distributed along the Narmada Canal in Gujarat with the baseline scenario (orange)

2.2.5 Sixteen Cities: Rooftop PV

The "16 cities: rooftop PV" scenario consists of 62.5 MW_{DC} of rooftop PV in 16 large cities in Gujarat, for a total of 1,000 MW_{DC}. The cities are randomly selected from a spatial data set[29] that identified large cities. Rooftop PV is assumed to be evenly distributed over the entire grid cell. Figure 8 shows the locations of the 16 cities on top of the baseline scenario. Grid issues for rooftop deployment include distribution system concerns related to safety and electric effects. Specific local feeder impacts depend on interconnection voltage, protection schemes, inverter characteristics, and other factors of feeder system design. For the purpose of this paper, only the aggregate power ramping effects are examined, with the view of characterizing changes in the bulk electric system operational needs. This scenario captures the impact of the most widely dispersed geographic deployment.

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[29] "ESRI Data and Maps 9.3: World Populated Places." ESRI, 2005. Cities: Vadodara, Dhrangadhra, Patan, Visnagar, Gandhi Dam, Dahod, Nadiad, Anand, Jamnagar, Botad, Bhavnagar, Porbandar, Kundla, Ukal, Mahuva, and Veraval. www.esri.com/.

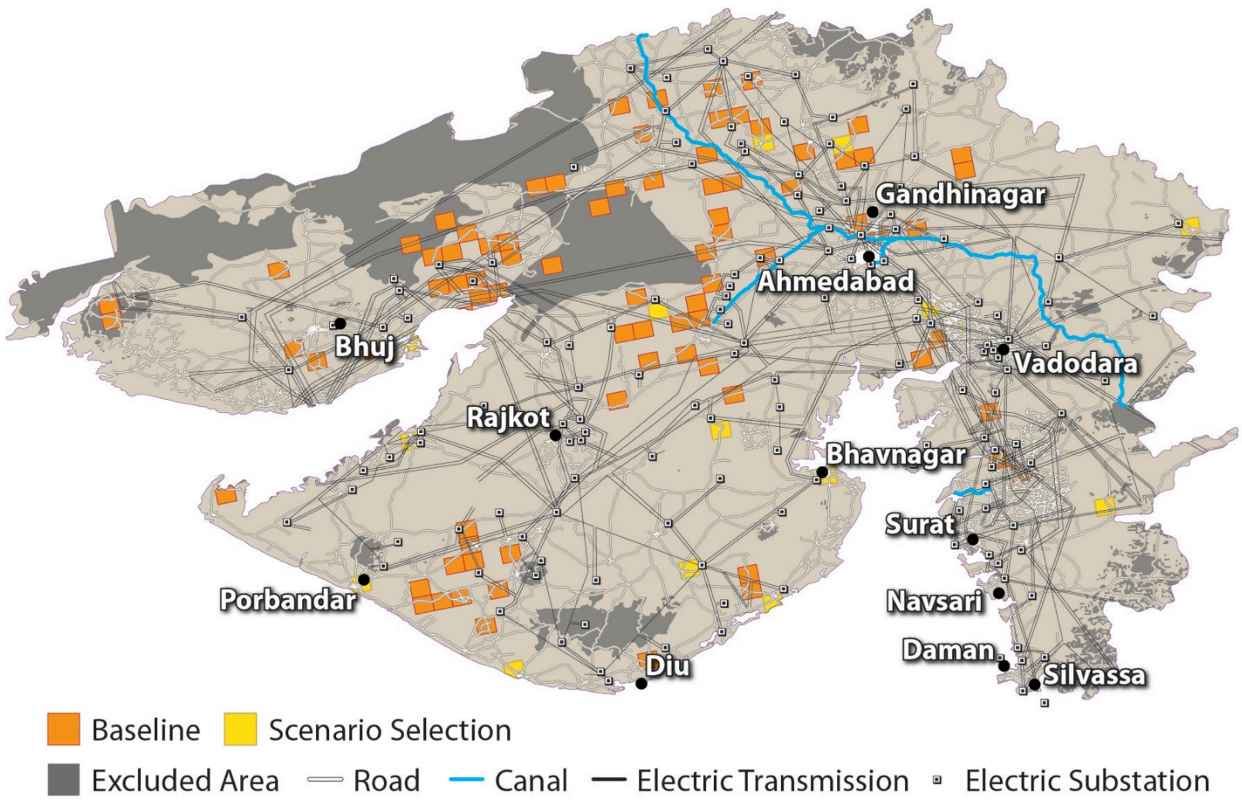

Figure 8. Sixteen cities: rooftop PV scenario (yellow) consists of 62.5 MW in each of 16 cities with the baseline scenario (orange)

2.3 Summary of Scenarios

Table 2 summarizes the capacity, number of locations, geographic area encompassing all locations, and scenario density for the baseline scenarios and each of the expansion scenarios, independent of the baseline scenario. The geographic area and the scenario density serve as a proxy for estimating the geographic diversity. In addition, the densities of the baseline plus each expansion scenario were computed.

Table 2. Capacity, Area, and Density of the Baseline and Expansion Scenarios for Gujarat

Scenario	Capacity of Baseline or Expansion (MW_{DC})	Number of Plant Locations	Scenario Area (km^2)	Scenario Density (MW_{DC}/km^2)	Baseline plus Expansion Scenario Density (MW_{DC}/km^2)
Baseline (all scenarios)	1905	84	72604	0.026	-
Charanka	1000	1	1000	1.000	0.040
Seven utility PV plants	1000	7	28652	0.035	0.039
Kutchh region	1000	6	3884	0.257	0.040
Narmada Canal	497	16	7199	0.069	0.032
16 cities: rooftop PV	1000	16	62813	0.016	0.032

3 Sub-Hour Solar Power Data

Rapid changes in PV power output at a single location are observable in the time series shown in Figure 9, an example from Boulder, Colorado. These rapid changes in solar power output may impact the operation of other generators and the economics of operating the grid reliably.[30] Solar power production data with high temporal and spatial resolution is needed in order to study the effect of different solar capacity expansion scenarios. The qualities of the data set, most relevant to an integration study, include:[31]

- Solar power data must be time synchronized to the weather conditions during each time step and at each geographic location.
- Solar power data must have sufficient temporal resolution to capture site-specific solar power output ramps.
- Solar power data must have appropriate spatial-temporal correlations to capture intra-plant and plant-to-plant ramping correlations.
- Solar power data must have sufficient geographic resolution to represent the relative solar power injection into the power system at each location.

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[30] Lew, D. et al. *How do Wind and Solar Power Affect Grid Operations: The Western Wind and Solar Integration Study*. Proceedings of the 8th International Workshop on Large-Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms, Bremen, Germany, Oct. 14–15, 2009. NREL/CP-5500-54684.

[31] Hummon, et al. *Sub-Hour Solar Data for Power System Modeling From Static Spatial Variability Analysis, Preprint.* Proceedings of the 2nd International Workshop on Solar Power in Power Systems, Nov. 12-13, 2012. NREL/CP-6A20-60548.

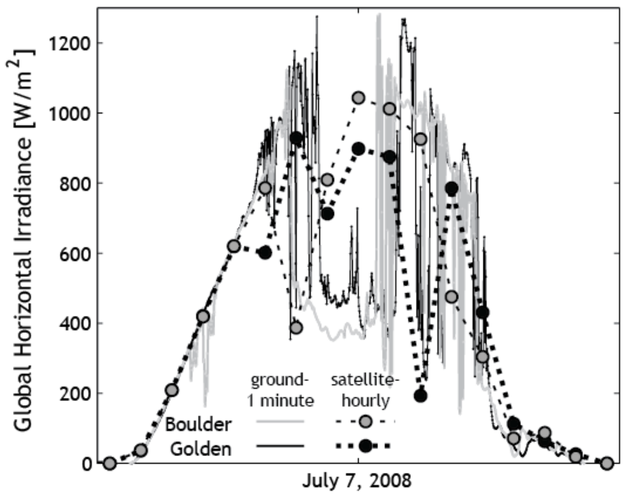

Figure 9. Simultaneous irradiance measurements from two sites 70.4 km apart at two time scales: t_{step} = 1 minute (line) and satellite irradiance values, t_{step} = 60 minutes (dotted line with circles). The site near Boulder, Colorado, is located at 39.911_N -105.235_W (gray), and the site near Golden, Colorado, is located at 39.742_N -105.180_W (black).[32]

The following subsections describe the source of the hourly irradiance and meteorological data for Gujarat, summarize the method for downscaling hourly irradiance data to one-minute irradiance data, and describe the conversion of the irradiance and meteorological data to power output from the solar plant.

3.1 Satellite Irradiance and Meteorological Data

The new historic 10-km solar radiation data set for India capturing hourly insolation values for 2002-2011, including GHI and direct normal irradiance (DNI), is derived from satellite images from the Meteosat satellite using the semiempirical model developed by Perez et al.[33] The data set captures impacts of earth/solar geometry and localized atmospheric effects, including clouds, aerosols, humidity, and decreased visibility. The data is mapped into a 10 km by 10 km grid on the Earth's surface. The irradiance data is shifted from Greenwich Mean Time to local standard time.[34] The hours listed in Table 3 replicated the same value over the entire region. During these hours, the sub-hour irradiance algorithm, which analyzes and categorizes the spatial variability, did not perform as expected because the standard deviation of the identical spatial data is undefined.[35]

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[32] Hummon, et al. *Sub-Hour Solar Data for Power System Modeling From Static Spatial Variability Analysis, Preprint.* Proceedings of the 2nd International Workshop on Solar Power in Power Systems, Nov. 12-13, 2012. NREL/CP-6A20-60548.

[33] Perez, R. et al.. "A New Operational Satellite-to-Irradiance Model." *Solar Energy* (73:5), 2012; pp. 307-317.

[34] Wilcox, S. M. *National Solar Radiation Database 1991-2010 Update: User's Manual*. NREL/TP-5500-54824. Golden, CO: National Renewable Energy Laboratory, 2012. www.nrel.gov/docs/fy12osti/54824.pdf.

[35] These hours were not included in the statistical variability analysis in Section 4.

Table 3. Hours of Missing Meteosat Satellite Data

Day	Hours (local time)
Dec. 8, 2006	3 p.m.
Dec. 11, 2006	3 p.m.
Dec. 14, 2006	2 p.m.
Dec. 16, 2006	2 p.m., 3 p.m.
Dec. 24, 2006	4 p.m.
Dec. 30, 2006	2 p.m.
Dec. 31, 2006	3 p.m.

Meteorological data, including dry bulb temperature and wind speed, necessary to calculate the power output from a PV module is from the National Aeronautics and Space Administration Modern-Era Retrospective Analysis for Research and Applications data set.[36] The data set is available to the public through NREL at http://rredc.nrel.gov/solar/new_data/India/nearestcell.new.cgi.

3.2 Sub-Hour Irradiance Algorithm

This study uses the sub-hour irradiance algorithm (SIA), developed for the U.S. Western Wind and Solar Integration Study Phase 2.[37] The algorithm generates synthetic GHI values at an interval of one minute, for a specific location, using satellite-derived, hourly irradiance values for the nearest grid cell to that location and grid cells within 40 km. The input to SIA, spatial irradiance data surrounding the location of interest, make the output of SIA dependent on the specific location, season, and time of day by classifying the likely temporal variability from the spatial distribution of irradiance variability. During each hour, the observed GHI value for the grid cell of interest and the surrounding grid cells is related, via probability distributions, to one of five temporal cloud coverage classifications. An algorithm for each cloud coverage classification was designed to reproduce the variability statistics of that class in the form of a time series with one-minute time steps.

3.2.1 Spatial and Temporal Variability Relationship

The algorithm predicts the temporal variability from a spatial "patch" of satellite data points. The GHI values are converted to a fraction of the clear sky irradiance value, called the clearness index (ci), to remove the diurnal effects of the solar zenith angle. Figure 10a shows the measured GHI from a ground sensor and the predicted clear sky GHI. Dividing the measured GHI by the clear sky GHI results in a number between zero and one, where one is clear sky conditions and zero is no visible irradiance, as shown in Figure 10b. Clearness index values greater than one occur both due to cloud-focusing events, where irradiance is reflected off of the edge of a cloud, and thus, the total irradiance at the earth's surface is greater than the clear sky transmittance path, and where the clear sky irradiance estimate is underestimated.

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[36] For more information, see: http://rredc.nrel.gov/solar/new_data/India/about.html.
[37] Lew, D. et al. *Western Wind and Solar Integration Study Phase 2*. NREL/ TP-5500-55588. Golden, CO: National Renewable Energy Laboratory, 2013. www.nrel.gov/docs/fy13osti/55588.pdf.

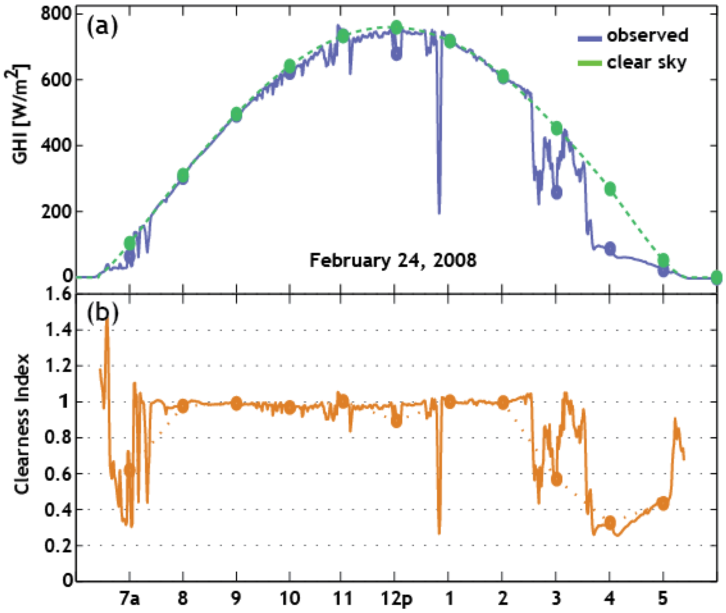

Figure 10. GHI for the ground-measured data and calculated for the clear sky on Feb. 24, 2008, at NREL's Solar Research Radiation Laboratory in Golden, Colorado (a). Dividing the observed GHI by the clear sky GHI results in the clearness index (b).

The satellite hourly data provide a snapshot of the sky at that location. The single snapshot of irradiance has a correlation coefficient of 0.669 with the mean ci of the next 60 minutes of measured, ground data, while the distance-weighted mean of satellite ci data from approximately 40 nearby locations have a correlation coefficient of 0.736. This set of time-synchronized ci satellite data representing an area of approximately 4,500 km^2 is called a "patch." Figure 11 shows an example of the patch data on the left of each pair of figures and the measured ci time series on the right from the location marked on the patch. At hour 13, the spatial data plot shows a fairly clear sky, and the time series hovers near a ci of one, with three brief clouds depressing the ci to 0.3. By hour 16, the spatial data is much darker (average ci of 0.42), and the time series hovers near 0.5 with three to four brief periods of clear sky. Measures of the variance (σ), mean (μ), and statistical distribution of ci values in each patch, characterized at each hour, form the basis for the probability statistics relating patch data and temporal data.

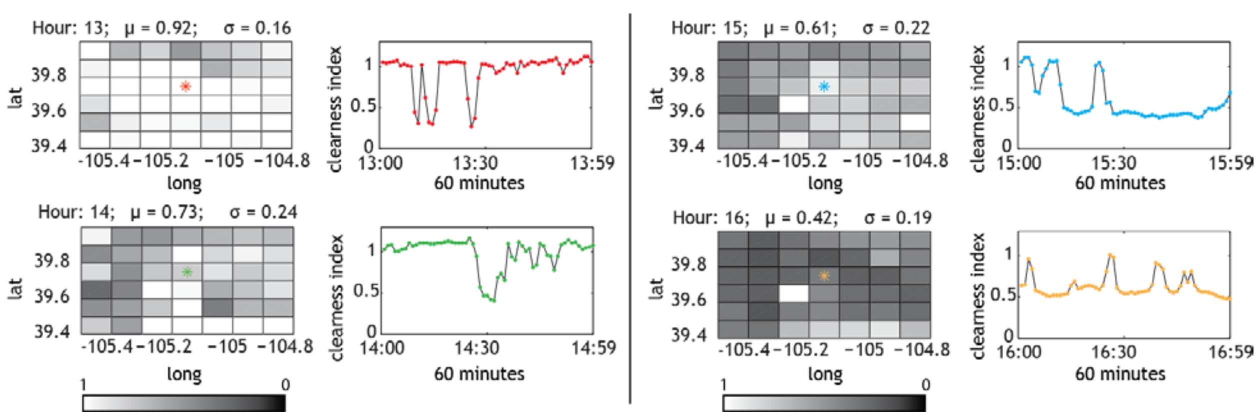

Figure 11. Spatial clearness index patch (a) and time series measured at the starred location for the same hour of time (b). Data shown are from the Measurement and Data Instrumentation Center at NREL, in Golden, Colorado.

The one-minute ci data is categorized into five classifications of cloud cover (Classes I-V). Visual inspection of 60 consecutive one-minute values of ci, grouped by the mean and standard deviation of the clearness index over that period, yielded classification of irradiance variability into one of five classes, as shown in Figure 12. Classes I, II, and III show relatively low variability, with less than 0.02%, 0.87%, and 4.53% of one-minute ramps exceeding 0.1 ci, respectively. Classes IV and V demonstrate distinct, sharp shifts in ci with greater than 20% of one-minute ramps exceeding 0.1 ci. Class V irradiance variability is distinct from Class IV not by the magnitude of ramps (in fact, the portion of Class IV ramps between 0.05 and 0.2 exceeds Class V), but by the physical interpretation of the temporal data. Class V represents clear sky conditions with intermittent clouds, while Class IV irradiance variability is characterized by multiple ci states. The temporal classification scheme is based on inferential statistics. By grouping the 60-minute periods by mean and variance, an inductive inference from a subset of observations is able to be made to the parameters of the whole group.

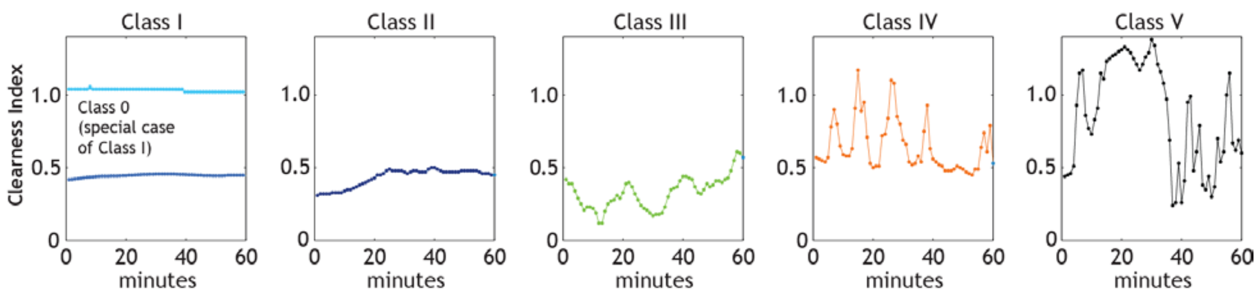

Figure 12. Classes of temporal variability (from SIA)

3.2.2 Modeling the Temporal Variability Classes

The steps in producing synthetic temporal variability ci values are outlined in Figure 13. First, the clear sky GHI is calculated for every location within 40 km of the location of interest. The set of locations surrounding the site of interest is called a patch. Second, the mean and standard deviation of the patch data, for a given hour, selects a temporal classification probability distribution.

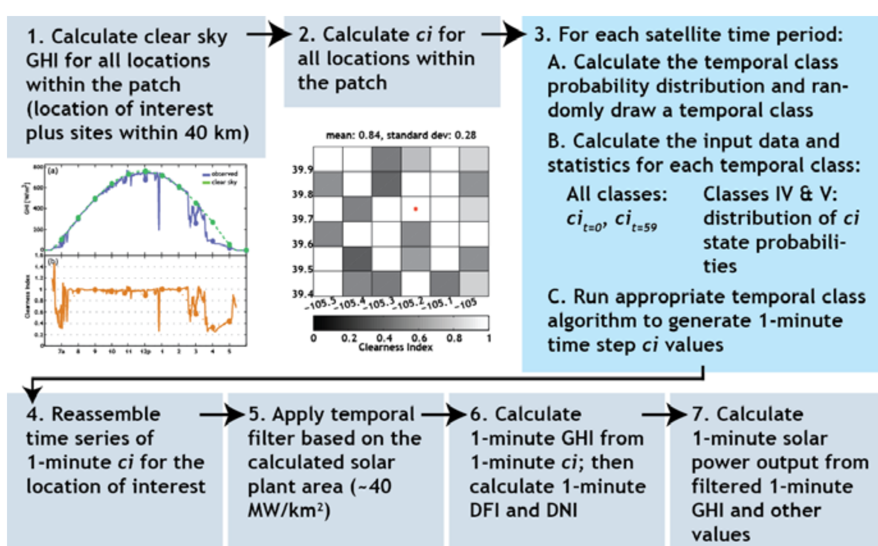

Figure 13. Workflow for producing modeled ci values at a single location

Figure 14 shows three examples of patches and the temporal variability classification probability distribution, which is selected based on the weighted mean and standard deviation of the ci values in the patch.

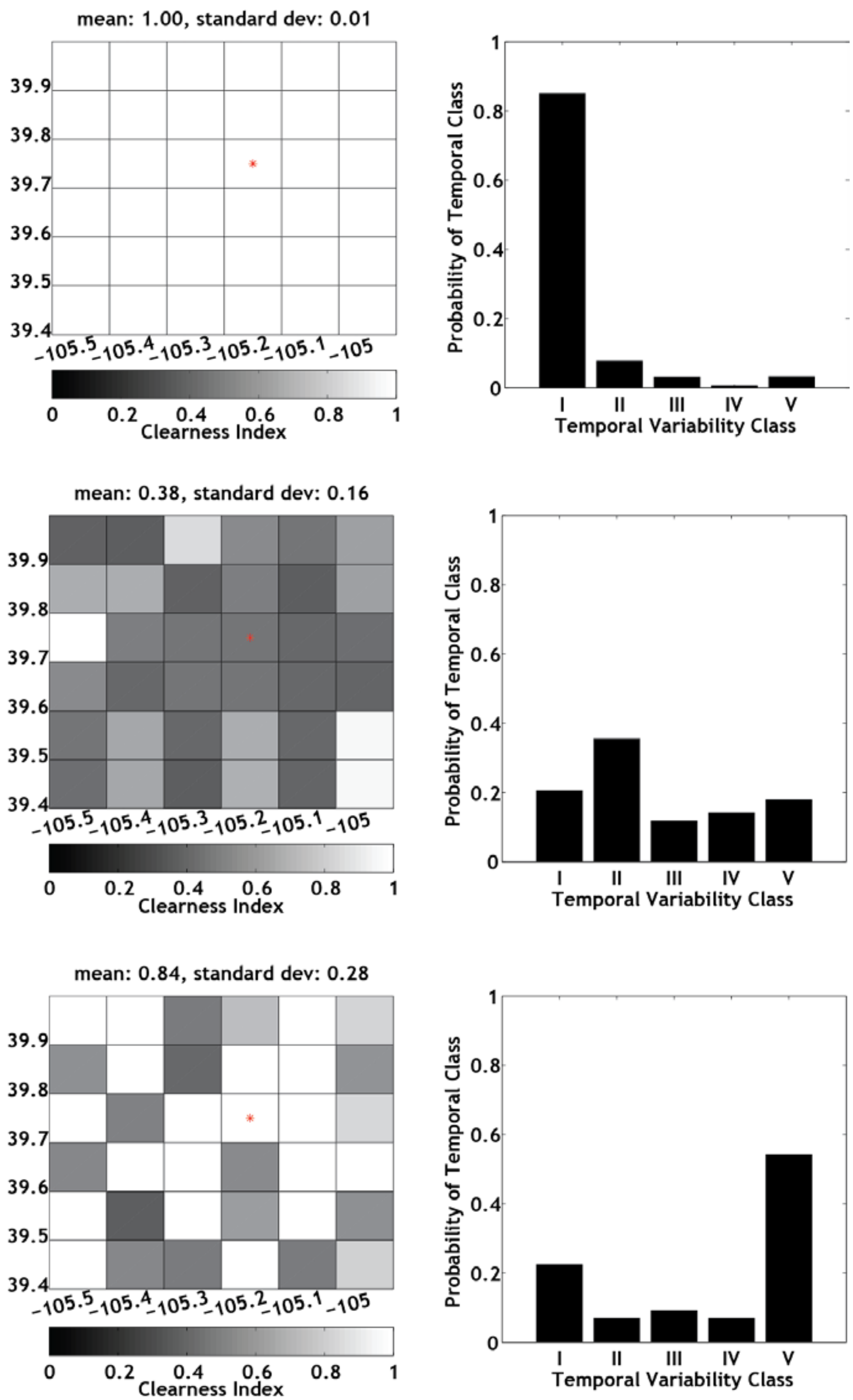

Figure 14. Weighted mean and standard deviation of the patch ci values determines the probability distribution of temporal classifications for that patch

A random number draw against the probability distribution for temporal variability class determines which algorithm is run to model the one-minute interval ci values. The algorithms for Classes I, II, and III are similar in method, only differing in the distribution of ramps (see Figure 15) used to generate the sequential values of modeled ci. Classes I, II, III, and Class 0 have a slowly changing ci, where the change in ci from one minute to the next is independent of the mean ci. For these classes, 60 random draws from the ci ramp distribution are cumulatively summed from the ci value at the beginning of the hour. A slope is applied to the time series determined by the mean slope between the ci value at the beginning of the hour and the ci value at the beginning of the next hour.

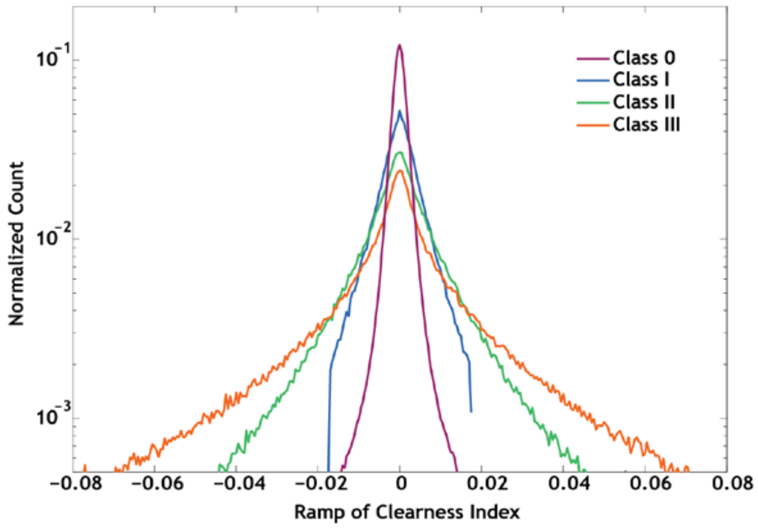

Figure 15. Clearness index ramp distributions for measured data with temporal variability classification of Class 0, I, II, and III

The algorithms for Classes IV and V are similar in concept, though they are based on different qualities of the patch data set. Classes IV and V are modeled on the basis that the cloud cover in the sky and the resulting ci classification can be characterized as a system undergoing transitions between states. The states represent different opacities of cloud cover, and the transition probabilities represent cloud movement over the area. Class IV is modeled as a system with the probability of transitioning between six ci states defined as the range of ci: 0.01-0.3, 0.31-0.45, 0.46-0.6, 0.61-0.75, 0.76-0.9, and 0.91-1.1. The probability of the state is determined by the distance-weighted proportion of the ci values from surrounding sites in that ci state. The state duration is determined by a random draw from a distribution of state durations, which were derived through empirical analysis of state durations in measured data.

Class V is a simpler system, consisting of just two states: clear (ci >0.9) and cloudy (ci <0.75). The cloudy or clear state ci value is determined by finding the distance-weighted mean of ci values, such that ci <0.9 or ci >0.9, respectively. The transition probability of moving from a clear to cloudy state is determined by the distance-weighted proportion of sites that are cloudy compared to the total number of distance-weighted sites. The transition probability of returning to a clear state is determined by drawing a random cloudy state duration from empirical analysis, similar to Class IV.

The algorithms for each temporal class act on one-hour intervals to produce one-minute synthetic ci values. Before steps five through seven are executed (see Figure 13), the one-hour sets of ci values are concatenated into one-time series. The remaining subsections describe the reduction in variability with increasing PV plant area and the conversion of irradiance to AC power output.

3.2.3 Reduction in Variability with Increasing Photovoltaic Plant Area

Power output from large PV plants may be less variable, relative to the installed capacity, than a small PV plant because the power output from a PV plant is the average of the power output of all the modules. Modules that are spread out over a large area do not necessarily experience the same power output variability (e.g., cloud movement) at the same time. The synthetic one-minute GHI values from SIA represent the variability of a single photosensor, about 1 square centimeter in area. To model the variability of a real PV plant, a technique developed by Marcos et al.[38] was used, which represents the reduction in variability as a low-pass filter with a cut-off frequency dependent on the spatial area of the PV plant. Figure 16 shows the time series representing a point source and the filtered time series for a PV plant with an area of 2.6 km^2. Figure 17 shows the cut-off frequency, displayed as the cut-off time, below which the variability is reduced as a function of the (a) PV plant area and the (b) DC capacity, assuming the packing density is 40 MW per square kilometer. For instance, a 1-km^2 PV plant has a reduction in variability below eight minutes, while a 4-km^2 plant shows a reduction in variability below 15 minutes.

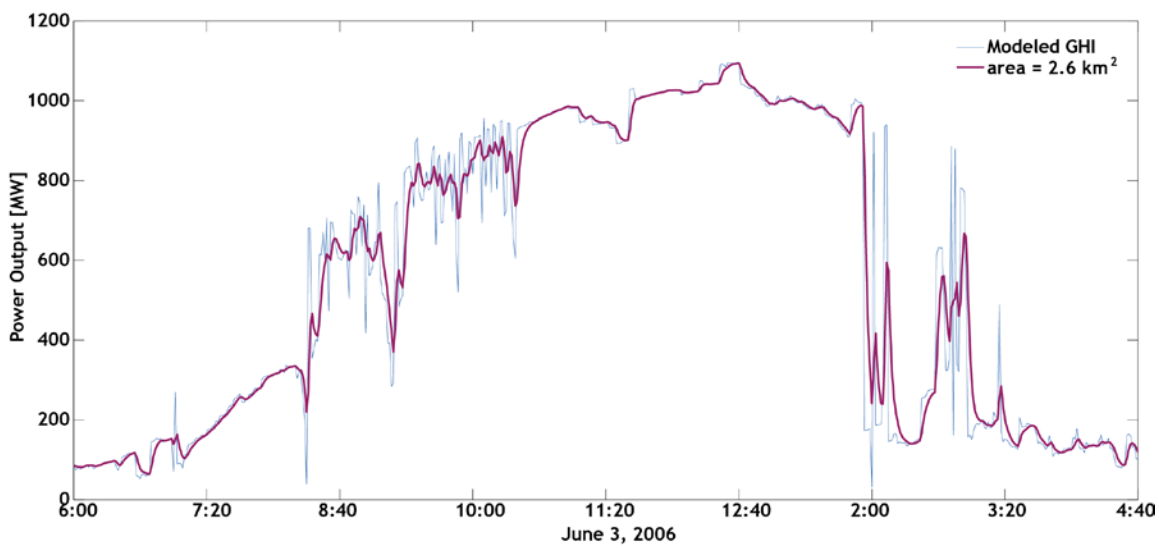

Figure 16. Time series of one-minute GHI before and after applying the low-pass filter for a plant area of 2.6 km^2

[38] Marcos, J. et al. "From irradiance to output power fluctuations: the PV plant as a low pass filter." *Progress in Photovoltaics* (19:5), 2011; pp. 505–510. http://onlinelibrary.wiley.com/doi/10.1002/pip.1063/pdf.

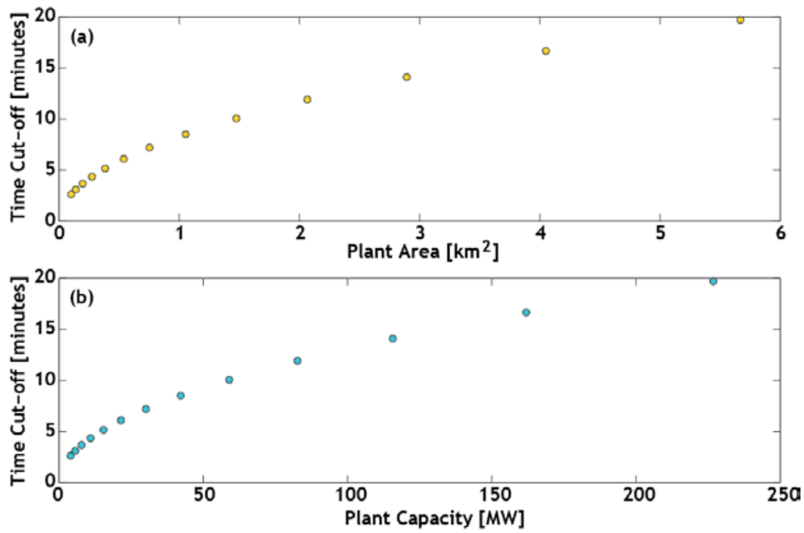

Figure 17. Cut-off time below which there is reduced variability due to the geographic area of the plant

3.2.4 Converting Irradiance Data to Alternate Current Power Output

A one-minute power time series is calculated from the synthesized one-minute solar irradiance data (GHI, diffuse irradiance [DFI], and DNI) using the PVWatts program.[39] PVWatts models PV solar power generation by modeling the sun position, plane of array irradiance, module cover, thermal effects, and inverters. The inputs to the program are time, DNI, DFI, wind speed at 10 meters above the surface, temperature, system DC capacity, derate, the tracking mode (fixed, single–axis, double–axis), and tilt and azimuth angle of the installed PV. PVWatts outputs are the incident plane of array irradiance, transmitted plane of array irradiance, the output DC power, and the output AC power. All fixed-plate systems modeled for Gujarat were assumed to be mounted at a 17° tilt and oriented due south (azimuth of 180°). Tracking systems were modeled as single-axis tracking systems with a tilt of 0° and oriented with a north-south pivot axis. The modeled derate is 0.81 and is a single number that "represents losses in the system due to nameplate direct current (DC) ratings, inverter efficiency at maximum power, mismatch, diodes and connections, DC wiring, alternating current (AC) wiring, soiling, system availability, shading, tracking error, and aging."[40] An inverter efficiency curve reduces the AC power output at sub-maximum DC power from the photovoltaic panel. While different PV panel technologies have different conversion efficiencies, the authors chose to use an efficiency equivalent to crystalline silicon modules for all locations.[41] The authors did not attempt to capture differing efficiencies for either existing/planned locations or postulated future installations.

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[39] Dobos, A. P. *PVWatts Version 1 Technical Reference*. NREL/ TP-6A20-60272. Golden, CO: National Renewable Energy Laboratory, 2013. www.nrel.gov/docs/fy14osti/60272.pdf.

[40] Dobos, A. P. *PVWatts Version 1 Technical Reference*. NREL/ TP-6A20-60272. Golden, CO: National Renewable Energy Laboratory, 2013. www.nrel.gov/docs/fy14osti/60272.pdf.

[41] Ref. Dobos 2013 describes the module efficiency in terms of a reference module output at 1,000 watts/square meter with -0.5% coefficient for each degree of cell temperature deviation from the reference cell temperature of 25°C.

3.3 Summary

The authors synthesized one-minute interval solar power output for locations in Gujarat based on the spatial variability observed in the satellite data for 2006. The PV plant characteristics include installed DC capacity, tracking and panel orientation, as well as a general derate that encompasses losses due to wiring, shading, and aging, and a DC to AC conversion efficiency curve. Modeled data reflect installation characteristics, including utility-scale PV plants based on land-use requirements and rooftop PV panels that cover wide areas. The power production and variability of the scenarios is evaluated in Section 4.

4 Solar Power Variability

The addition of new solar in Gujarat would affect system operations, for example, in how much conventional generation must increase or reduce supply to match changes in electric load and solar output, such as from sunrise and cloud coverage. Nevertheless, the Gujarat SLDC can prepare for these impacts by analyzing the likely power fluctuations of solar, including: diurnal and seasonal power fluctuations; timescales of change (e.g., from one to 30 minutes); magnitude of change (both total megawatts and relative to installed capacity); and extent to which the changes can be anticipated in advance. A single year of sub-hour data captures the seasonal and time of day variability; however, multiple study years would be needed to understand the long-term economics of a PV plant at a particular location. This section describes such an analysis, applied to both the baseline and expansion scenarios, as well as the sum of the baseline (all fixed panel) plus the expansion scenarios. This section first reviews the absolute power production, followed by variability at 15-minute, five-minute, and one-minute intervals.

4.1 Scenario Power Production and Capacity

The baseline scenarios include both existing and planned PV plants. The study developed three scenarios, all with a total nameplate capacity (DC) of 1.9 GW: 100% fixed-axis, flat-panel PV modules; 90%/10% fixed-axis/single-axis tracking PV modules; and 75%/25% fixed-axis/single-axis tracking PV modules (see Section 2).

Table 4 summarizes the capacity, annual generation, and capacity factor for the three baseline scenarios. The substitution of 10% or 25% of the nameplate capacity of fixed-axis PV plants with single-axis tracking increases the annual power output by 2% and 5%, respectively, which increases the capacity factor as well. Each of the baseline scenarios has 84 PV plant locations, with an average nameplate capacity of 22.7 MW. The smallest plant is 1 MW, and the largest plant is 500 MW. Table 4 also shows the AC capacity and AC capacity factor for each scenario. The AC capacity was determined by taking the sum of the peak AC power output of each 84 PV plants, under clear sky conditions.[42] The AC capacity factor increases from 24.3% for the baseline scenario with all fixed-PV systems to 25.5% for the baseline scenario with 25% single-axis tracking.

[42] There is no established method for determining the rated AC capacity. One possible method is to use the AC rating of the inverter; however, the power transfer function used in this study, PVWatts, uses the full DC rating of the panel as the inverter rating and then applies a derate to the DC power output that encompasses system losses and an inverter efficiency curve. This study used the peak AC power output from the clear sky simulation to estimate the maximum AC capacity capable by the system.

Table 4. Installed Capacity, Annual Power Output, and Capacity Factor for the Expected Location Scenarios[a]

Scenario	Annual Power Output (MWh)	AC Capacity (MW)	AC Capacity Factor	DC Capacity (MW)	DC Capacity Factor
Baseline	2,834,226	1330	24.3%	1905	17.0%
Baseline with 10% single-axis tracking	2,897,073	1335	24.8%	1905	17.4%
Baseline with 25% single-axis tracking	2,984,858	1337	25.5%	1905	17.9%

[a] Insolation data is from 2006.

Figure 18 shows the power output for a PV plant in the Kutchh region (200 MW_{DC}) configured as either a fixed-axis system with a tilt of 17° or a single-axis tracking system with a tilt of 0° on Jan. 23-24, 2006. January is close to the winter solstice (late December), when the sun appears to be furthest south. During midday, the fixed system has a higher power production because the panel's tilt of 17° off the horizontal reduces the angle of incidence between the sun's rays and the surface of the PV panel. The single-axis tracking system has steeper sunrise and sunset slopes because the tracking panel decreases the angle of incidence at these extreme zenith angles and therefore produces more power. The baseline scenarios with 10% and 25% tracking capacity show a moderate increase in sunrise and sunset ramps (see Section 4.2).

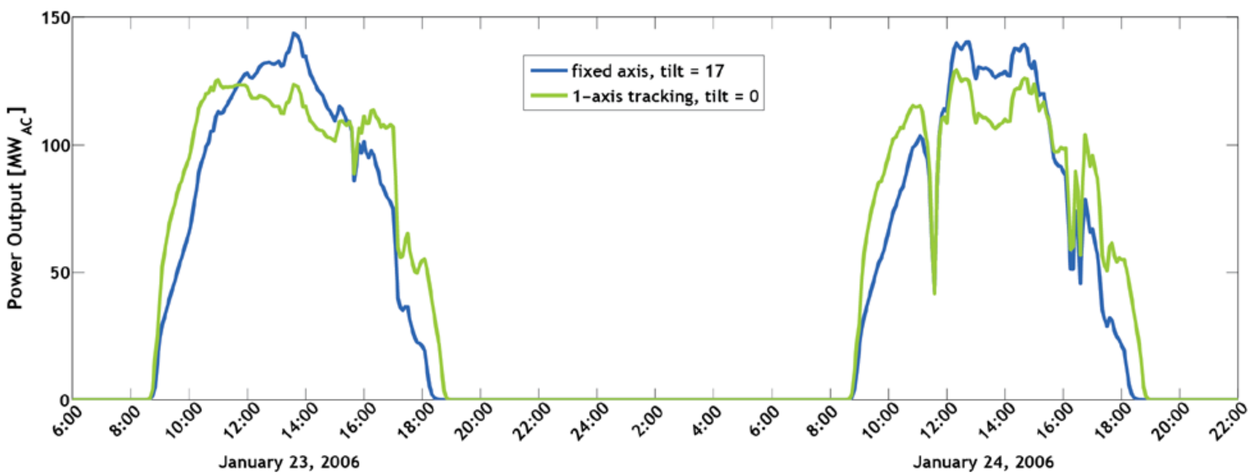

Figure 18. Power output for a 200 MW_{DC} PV plant with either fixed panel at 17° tilt or a single-axis tracking panel with no tilt, on Jan. 23-24, 2006, at 23.65° N, 69.55° E in the Kutchh region.

The "expansion" scenarios include new PV plants that may or may not be proposed or planned. The five scenarios include (1) adding 1.0 GW_{DC} at the Charanka Solar Park, (2) adding seven utility-scale PV plants with a total installed capacity of 1.0 GW_{DC}, (3) adding 1.0 GW_{DC} in the Kutchh region, (4) siting 500 MW_{DC} of fixed-panel PV over the Narmada canal, and (5) adding rooftop PV in 16 cities with a total installed capacity of 1.0 GW_{DC}. Results are presented for both the expansion scenarios, independently, as well as the sum of each expansion scenario with the baseline scenario with all fixed-axis panels. The expansion scenarios have a very similar DC and AC capacity factor to the baseline scenarios. When the expansion scenarios are combined with the baseline scenario of all fixed-plate PV plants, the AC capacity factor ranges from 24.2% to 24.5%. These capacity factors are more indicative of the meteorological conditions in Gujarat in 2006 than of the particular scenarios. Ten or more years of data (daily or hourly insolation) is typically used by developers and financiers to estimate the long-term expected performance of a PV plant.

Table 5. Installed Capacity, Annual Power Output, and Capacity Factor for the Expansion Scenarios and the Baseline Scenario (all fixed-axis) Plus Each Expansion Scenario[a]

Scenario	Annual Power Output (MWh)	AC Capacity (MW)	AC Capacity Factor	DC Capacity (MW)	DC Capacity Factor
Charanka	1,454,356	670	24.8%	1,000	16.6%
Utility PV at 7 Locations	1,519,665	702	24.7%	1,000	17.3%
Kutchh	1,514,560	702	24.6%	1,000	17.3%
Narmada Canal	737,452	353	23.8%	497	16.9%
Rooftop PV in 16 Cities	1,498,158	716	23.9%	1,008	17.1%
Baseline + Charanka	4,288,582	2,000	24.5%	2,905	16.9%
Baseline + Utility PV at Seven Locations	4,353,891	2,032	24.5%	2,905	17.1%
Baseline + Kutchh	4,348,786	2,032	24.4%	2,905	17.1%
Baseline + Narmada Canal	3,571,678	1,683	24.2%	2,402	17.0%
Baseline + Rooftop PV in 16 Cities	4,332,384	2,046	24.2%	2,905	17.0%

[a] Insolation data is from 2006.

Figure 19 shows the time series for a single site (left column) and the aggregate of all baseline scenarios (right column) for two days, July 23, 2006, and Oct. 12, 2006 (top row and bottom row, respectively). The clear-sky PV power output is shown as a reference for the expected PV power output from the PV plant if there were no clouds in the sky. In July (see Figure 19a), the monsoon season, the time series from individual PV sites often show characteristics of clouds in the sky—rapid changes in power output due to clouds obstructing the irradiance path from the sun to the PV module. Actual PV power output can exceed the clear sky PV power output during intermittent conditions due to cloud focusing. The clear sky PV power output is drawn as a band because the expected PV power output when there are no visible clouds present varies from day to day and site to site due to different densities of aerosols and water vapor in the atmosphere.[43] The calculation of clear sky values for the sub-hour irradiance algorithm can be found in Hummon et al.[44] The aggregate time series on July 23 (Figure 19c) shows significant reduction

[43] The clear sky estimate accounts for multi-day reduced visibility from air pollution.
[44] Hummon et al.[44] *Sub-Hour Solar Data for Power System Modeling From Static Spatial Variability Analysis, Preprint.* Prepared for 2nd International Workshop on Solar Power in Power Systems, Nov. 12-13, 2012. NREL/CP-6A20-56204. Golden, CO: National Renewable Energy Laboratory, 2012. www.nrel.gov/docs/fy13osti/56204.pdf.

in total power output compared to the clear sky conditions, as well as a decrease in the rapid changes in power output due to the geographic diversity of the baseline scenario.

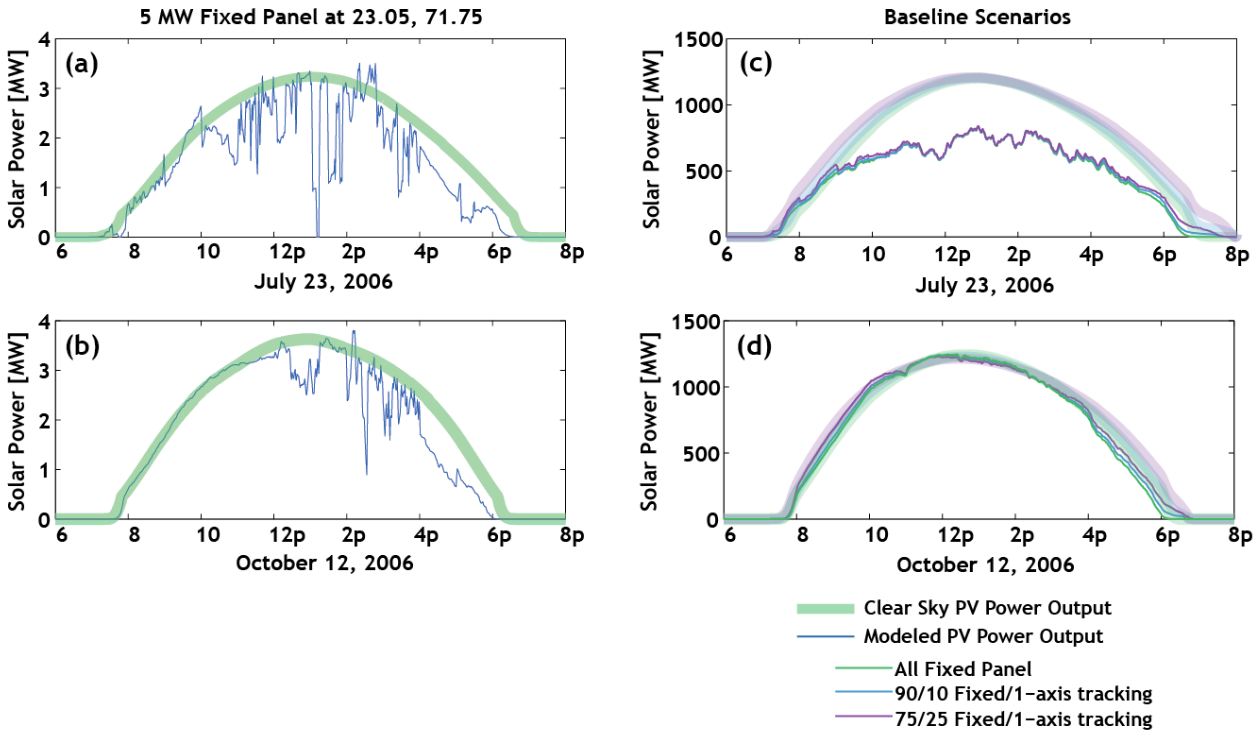

Figure 19. Clear sky and synthetic PV power output, one-minute resolution, for (left) single, randomly selected site from the baseline PV scenario, and (right) aggregation of all of the baseline PV sites on July 23, 2006, and Oct. 12, 2006

In October, the aggregate time series power nearly matches the clear sky power output in all of the baseline scenarios. Single locations can have significant midday variability (Figure 19b); however, the variability of a 5-MW_{DC} PV plant has little effect on the aggregate performance of 1,905 MW_{DC} plants spread over a 72,000 km^2 area.

The aggregate power output from the baseline scenario, each expansion scenario (separate from the baseline), and the baseline scenario plus each of the expansion scenarios are shown in Figure 20 for both July 23, 2006 (monsoon season), and Oct. 12, 2006 (dry season). Figure 20 (top left) demonstrates that during the monsoon season the largest variability in solar power output among the expansion scenarios is from the Charanka scenario, in which PV is concentrated at a single location. Three expansion scenarios (rooftop PV in 16 cities, seven utility PV locations, and Kutchh region), when combined with the baseline scenario, all show a decrease in the relative magnitude of unpredicted ramps on July 23 due to an increase in the total geographic diversity (the aggregate magnitudes are of course most important to grid systems operation). During the dry season, geographic diversity is not as important because there are “clear skies” over nearly all of Gujarat.

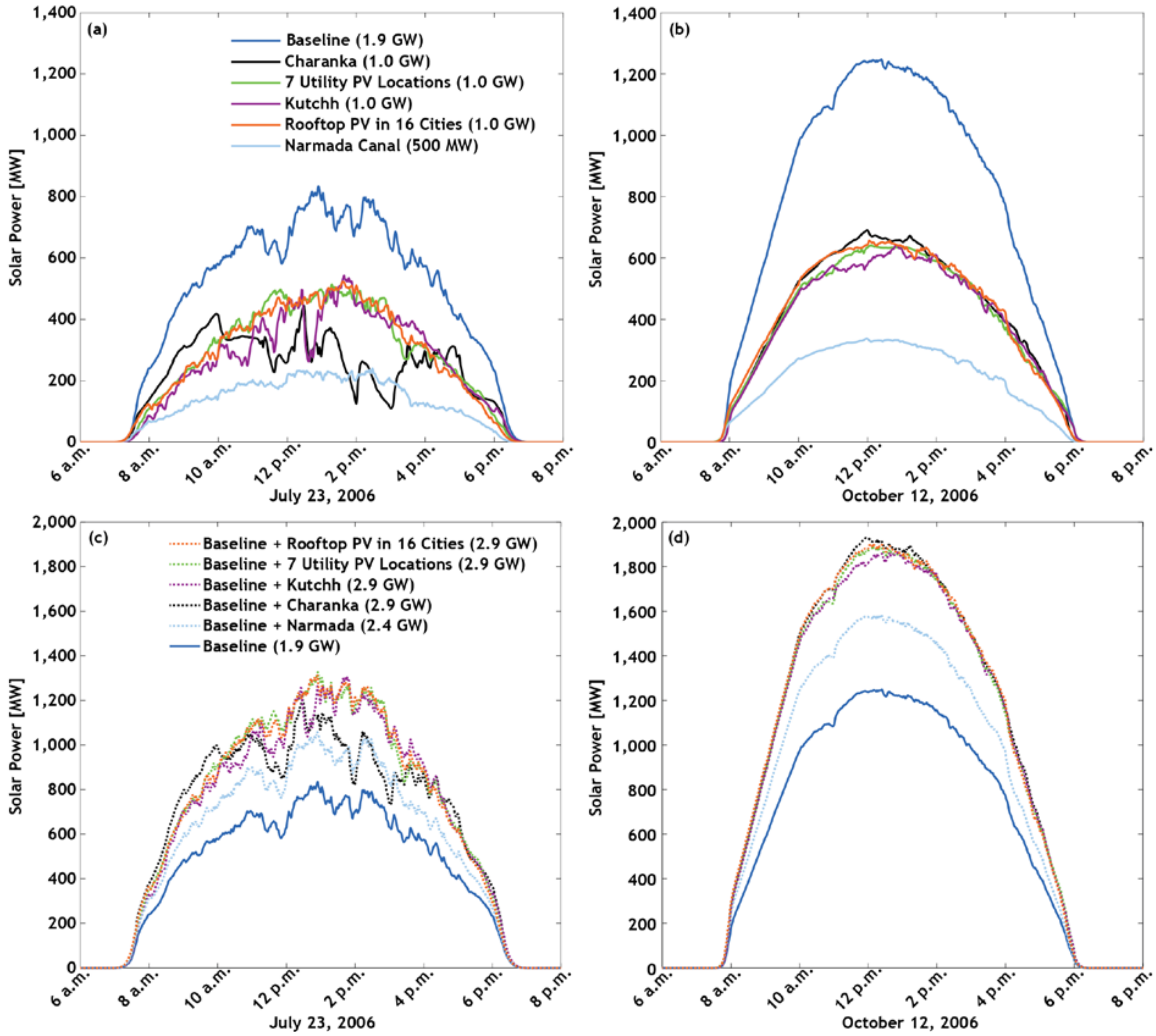

Figure 20. Aggregate power output in the baseline and expansion scenarios, separately (top) and combined (bottom), on July 23, 2006 (left) and Oct. 12, 2006 (right)

The contrast of the time series between July and October is apparent in Figure 21, which shows the power production from the baseline (all fixed panel) scenario by time of day and day of year. The data has been averaged to 15 minutes on the vertical axis and three days on the horizontal axis. Peak power production is at 1:00 p.m. local time on average, with the highest months of power production being March through May. Monsoon season is visible in June, July, and August, with a decrease in power production of approximately 25% to 50%.

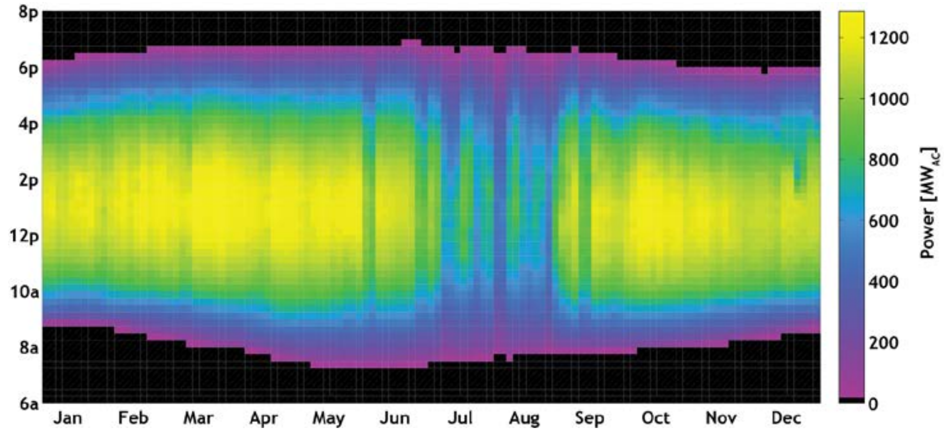

Figure 21. Color map of power production from the baseline scenario by time of day (vertical axis) and time of year (horizontal axis)

4.2 Variability of the Scenarios

The magnitude of solar power generation variability will depend on the penetration of solar, geospatial diversity, and weather patterns in the region. Figure 22, which shows the distribution of five-minute clear power index ramps, shows how geographic diversity of a PV scenario can decrease the relative variability. The clear power index is the synthetic five-minute solar power output divided by the clear sky five-minute power output. The baseline scenarios, with differing percentages of single-axis tracking, do not change the distribution of five-minute clear power index ramps appreciably. The expansion scenarios with the lowest variability are the rooftop PV in 16 cities and the Narmada Canal. These two scenarios have high geographic diversity and high resource quality, both of which decrease the frequency of solar power ramping events. Section 4.2 presents multiple measures of solar power variability, including the absolute solar power ramps, clear power index ramp, and unpredicted short duration ramps.

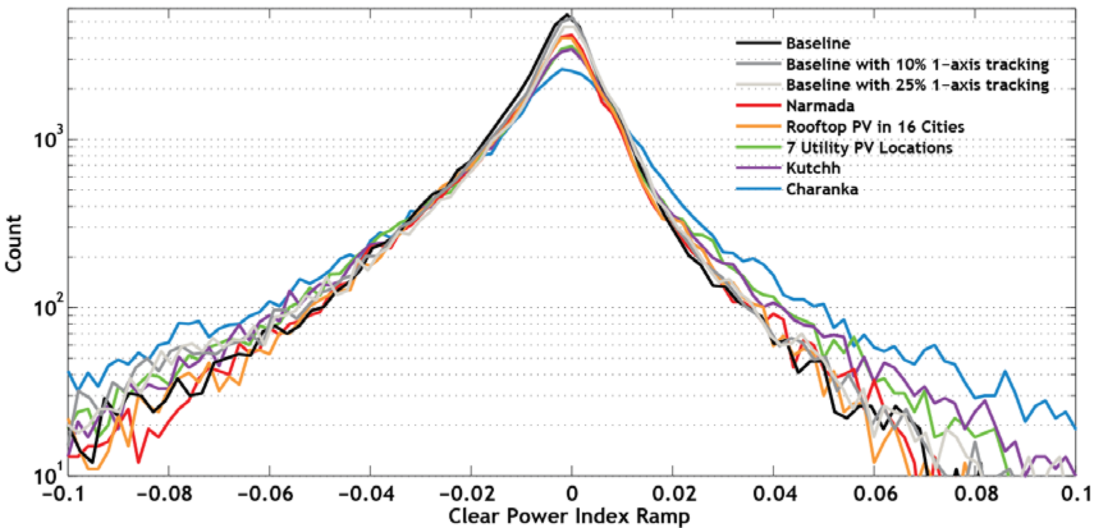

Figure 22. Five-minute clear power index ramp distribution for each baseline scenario and each expansion scenario (separate from the baseline). The "count" axis is on a log scale.[45]

The frequency of a particular "larger ramp magnitude" increases with increasing PV penetration, while the number of smaller ramps decreases. This is seen in Figure 23a, where the number of ramps in the 35 to 50 MW per five-minute range is nearly two times greater for the baseline plus expansion scenarios (mean count = 1,337 across scenarios), with a total installed capacity of 2.9 GW_{DC} compared to the baseline scenario alone (count = 638). The same is true for 15-minute ramps (see Figure 23b). The baseline plus Narmada scenario is slightly smaller (2.4 GW_{DC}), and thus, the increase in frequency of larger ramps, from 970 to 1,517 counts, is limited to 35 to 40 MW per five-minute range. The other baseline plus expansion scenarios show an increase in the frequency of ramps of 60 MW per five minutes. The frequency of ramps greater than 88 MW per five minutes is less than 0.10% for all scenarios.[46] That threshold is reached at 80 MW per five minutes for the rooftop PV and seven utility PV location scenarios.

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[45] The clear power index (cpi) is the ratio of the power production to the power production that was expected in the absence of any clouds (clear sky conditions). This is similar to the clearness index that was introduced in Section 3 (see Figure 10). The five-minute cpi ramp is the difference between the cpi at time t = 00:10:00 and the cpi at time t = 00:05:00.

[46] 0.10% is equivalent to less than 100 intervals of five minutes.

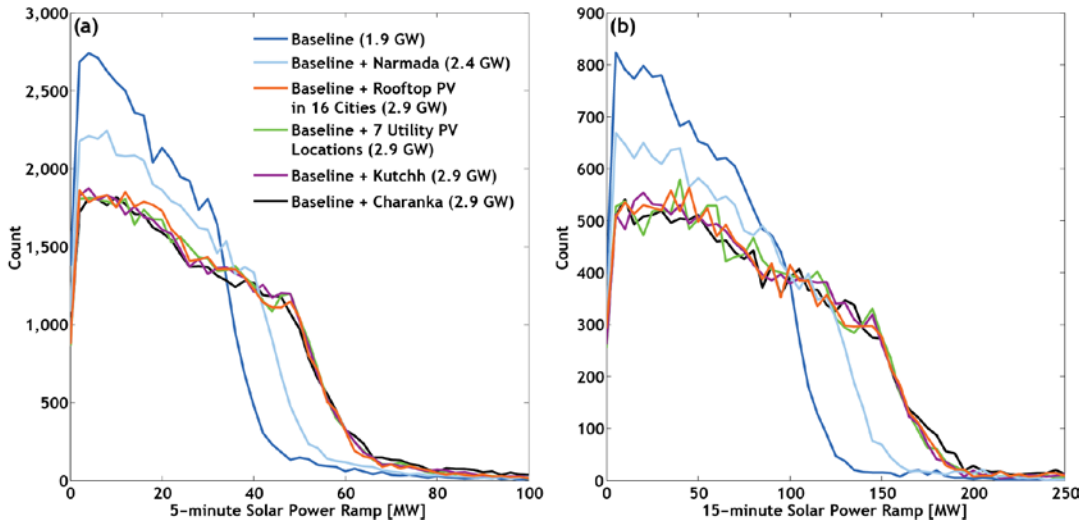

Figure 23. Absolute five-minute (a) and 15-minute (b) solar power ramp distribution for the baseline scenario and the baseline scenario plus each of the five expansion scenarios (daytime analysis)

The distribution of clear power index ramp values is shown in Figure 24 for a single site from the baseline scenario located near Bhabhar, Gujarat, and for the aggregate of the baseline scenario and the baseline plus each expansion scenario. The baseline scenarios show a significant reduction in the number of ramps that are greater than 5% of the clear power production compared to the single site.

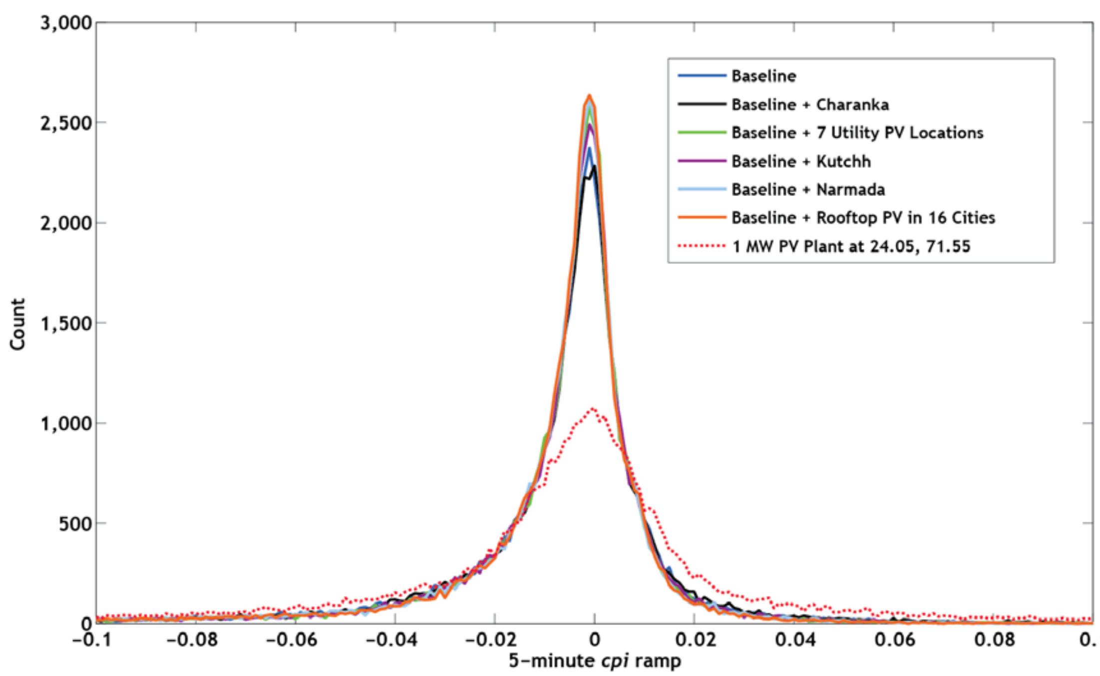

Figure 24. Distribution of five-minute clear power index ramps for the baseline scenario, baseline plus expansion scenarios, and a randomly selected site from the baseline scenario (1 MW fixed-PV plant located at 24.05°, 71.55°)

Figure 25 shows the five-minute clear power index ramp as a function of both time of day (vertical) and day of year (horizontal) for the expansion scenarios of (a) Charanka and (b) rooftop PV in 16 cities (these do not include the baseline scenario). The higher variability in Charanka, throughout the rest of the year, is due to the lack of geographic diversity of the Charanka scenario. When the baseline scenario is summed with the expansion scenarios, the variability is greatly reduced (see Figure 24c and 24d), though baseline plus Charanka still appears to have more variability during the monsoon season than the baseline plus rooftop PV in 16 cities.

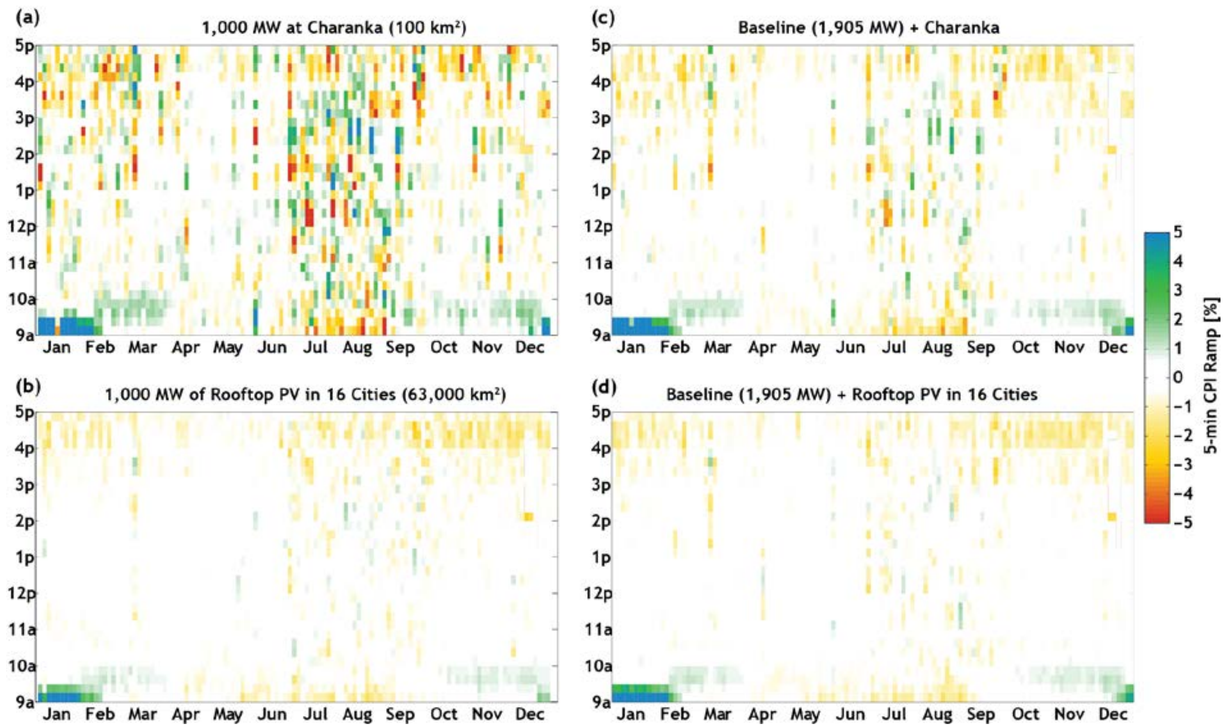

Figure 25. Comparison of the daytime variability of three scenarios: baseline, Charanka, and rooftop PV in 16 cities

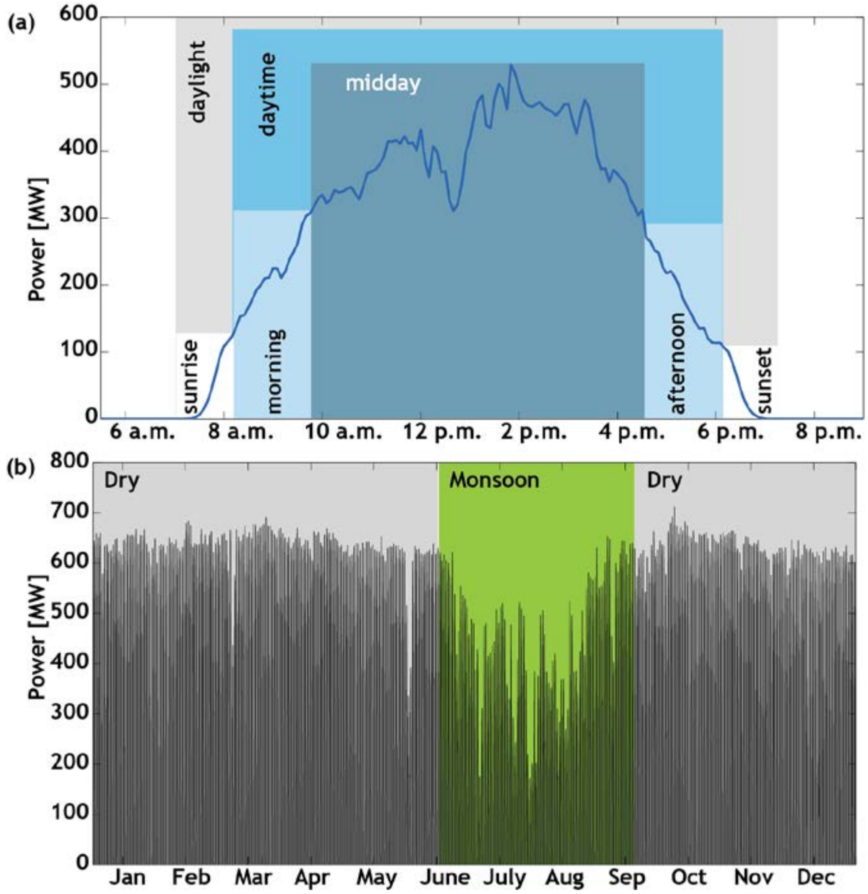

Figure 26. Definitions for (a) time of day and (b) season for five-minute ramp analysis

To explore the seasonal and time of day changes in solar power variability, the authors use Figure 26 to define the time of day analysis (Figure 26a) and the dry and monsoon season analysis (Figure 26b). Distributions of five-minute ramps are studied to determine trends in variability over time and scenario. There are six measures of five-minute ramps used in this analysis. The first three are the median absolute value ramp (50^{th} percentile) for a scenario by season and time of day, and that ramp is expressed as a percent of installed DC capacity or as a percentage of the clear power ramp. The second three are the 95^{th} percentile absolute value ramp for a scenario by season and time of day, and again, that ramp scaled by capacity and clear sky ramp. For example, Figure 27a shows the distribution of absolute value five-minute ramps for the baseline scenario during sunrise and midday. The median (50^{th}) and 95^{th} percentile ramp are marked on each distribution. Figure 27b shows the same ramps, scaled by the installed capacity (1,900 MW_{DC} for the baseline scenario and 2,900 MW_{DC} for the baseline plus Charanka scenario) so that the ramp is now expressed as a percentage of installed capacity. Lastly, Figure 27c shows the five-minute clear power index ramp for the baseline scenario during midday for the dry and monsoon seasons.

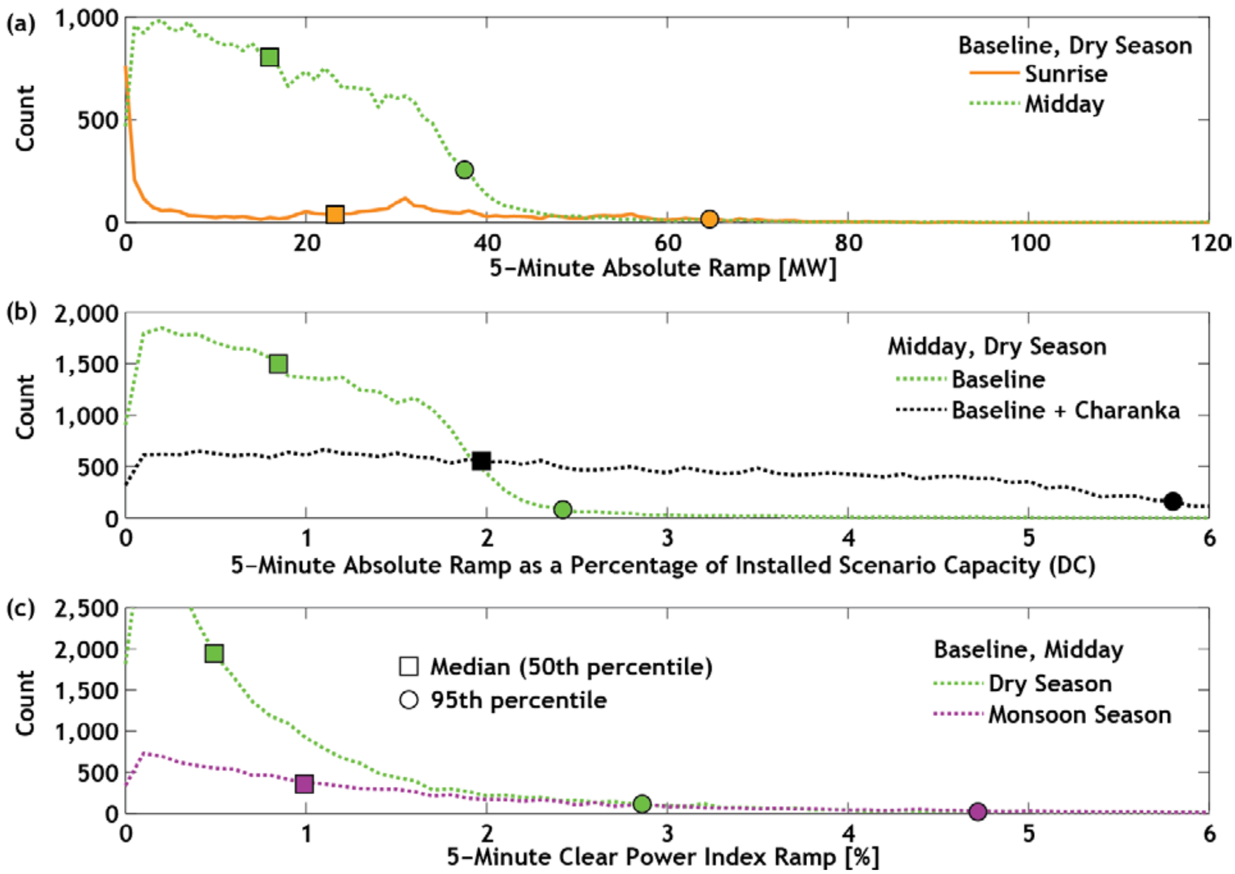

Figure 27. Example of the distribution of five-minute ramps and the identification of the 50th and 95th percentile: (a) the baseline scenario, in the dry season, for the distributions of five-minute absolute ramps for the sunrise and midday "time of day" periods, (b) the distributions of five-minute absolute ramps scaled by the installed capacity for the baseline and baseline plus Charanka scenarios during midday of the dry season, and (c) the baseline scenario during midday, for the dry and monsoon seasons, expressed as a percentage of the clear sky five-minute ramp.

Table 6. The Median (a) and 95th Percentile (b) Five-Minute Ramp (absolute magnitude, percent of DC solar capacity, and clear power index) by Season

(a) Median Five-Minute Ramp (daytime hours, excluding sunrise and sunset; see definition of daytime in Figure 26)

	Monsoon Season			Dry Season		
Scenario	**Ramp (MW)**	**Ramp (% of DC Capacity)**	**CPI Ramp (%)**	**Ramp (MW)**	**Ramp (% of DC Capacity)**	**CPI Ramp (%)**
Baseline (1.9 GW)	14.9	0.8	1.0	16.0	0.8	0.5
Baseline with 10% Tracking (1.9 GW)	14.6	0.8	1.0	15.4	0.8	0.5
Baseline with 25% Tracking (1.9 GW)	14.1	0.7	1.0	13.9	0.7	0.5
Baseline + Charanka (2.9 GW)	22.7	0.8	1.0	24.2	0.8	0.5
Baseline + Kutchh (2.9 GW)	22.2	0.8	0.9	24.0	0.8	0.5
Baseline + Narmada Canal (2.4 GW)	17.9	0.7	0.9	19.9	0.8	0.4
Baseline + Rooftop PV in 16 Cities (2.9 GW)	21.2	0.7	0.9	24.0	0.8	0.4
Baseline + Utility PV at 7 Locations (2.9 GW)	22.6	0.8	0.9	24.1	0.8	0.4

(b) 95th Percentile Five-Minute Ramp (daytime hours, excluding sunrise and sunset; see definition of daytime in Figure 26)

	Monsoon Season			Dry Season		
Scenario	**Ramp (MW)**	**Ramp (% of DC Capacity)**	**CPI Ramp (%)**	**Ramp (MW)**	**Ramp (% of DC Capacity)**	**CPI Ramp (%)**
Baseline (1.9 GW)	43.6	2.3	4.7	37.6	2.0	2.9
Baseline with 10% Tracking (1.9 GW)	45.3	2.4	5.3	38.4	2.0	3.3
Baseline with 25% Tracking (1.9 GW)	45.3	2.4	4.7	38.0	2.0	3.2
Baseline + Charanka (2.9 GW)	71.8	2.5	5.1	58.0	2.0	3.0
Baseline + Kutchh (2.9 GW)	59.1	2.0	4.1	55.7	1.9	2.5
Baseline + Narmada Canal (2.4 GW)	47.8	2.0	4.0	45.9	1.9	2.6
Baseline + Rooftop PV in 16 Cities (2.9 GW)	53.8	1.9	3.8	55.3	1.9	2.4
Baseline + Utility PV at 7 Locations (2.9 GW)	57.5	2.0	3.9	55.6	1.9	2.5

Table 6 tabulates all of the measures of five-minute ramps for each baseline scenario and the baseline (all fixed axis) plus each expansion scenario that are illustrated in Figure 27. The ramps in Table 6 do not include sunrise and sunset (see Figure 26 for the definition of time of day). The 95th percentile ramp represents the largest change in the solar power production that a system operator can expect during 95% of the five-minute periods. The substitution of fixed-axis plants for single-axis tracking plants increases the size of the 95th percentile ramp during both the monsoon and dry seasons, while decreasing the size of the median ramp. The largest absolute magnitude five-minute ramps are found in the baseline plus Charanka scenario because it has both a larger installed DC capacity and a higher geographic density than the baseline scenario. The magnitude of the ramps scaled by the installed DC capacity shows the Charanka scenario (without the baseline scenario) has 64% and 55% greater 95th percentile ramp magnitude than the baseline scenario during the monsoon and dry seasons, respectively. This is because the Charanka scenario is a single location, while the baseline scenario has PV plants spread across an area greater than 72,000 km^2. The five-minute ramps in the monsoon season expressed as a percentage of the clear power ramp are about twice that of the dry season measured at both the 50th and 95th percentiles.

Figure 28 shows the 95th percentile ramps relative to the installed capacity of the scenario as a function of time of day and season. During the dry season (Figure 28a), across all scenarios, the largest ramps occur during sunrise and sunset. The peak solar output is 25% to 50% greater in the dry season than in the monsoon season and that peak is reached over a very short period of time; hence the largest ramps occur during sunrise and sunset. The sunrise ramp is exacerbated in the baseline scenarios with single-axis tracking (not shown). The baseline with 25% tracking scenario has a 95th percentile five-minute ramp, as a percentage of installed capacity, of 4%.

The smallest ramps occur during the midday of the dry season, when there are very few clouds. The monsoon season (Figure 28b) shows a different time of day pattern than the dry season—the largest ramps occur during the midday, when there are many clouds that change the solar power production. The baseline plus Charanka scenario stands out as being distinctly more variable in the monsoon season than the other baseline plus expansion scenarios.

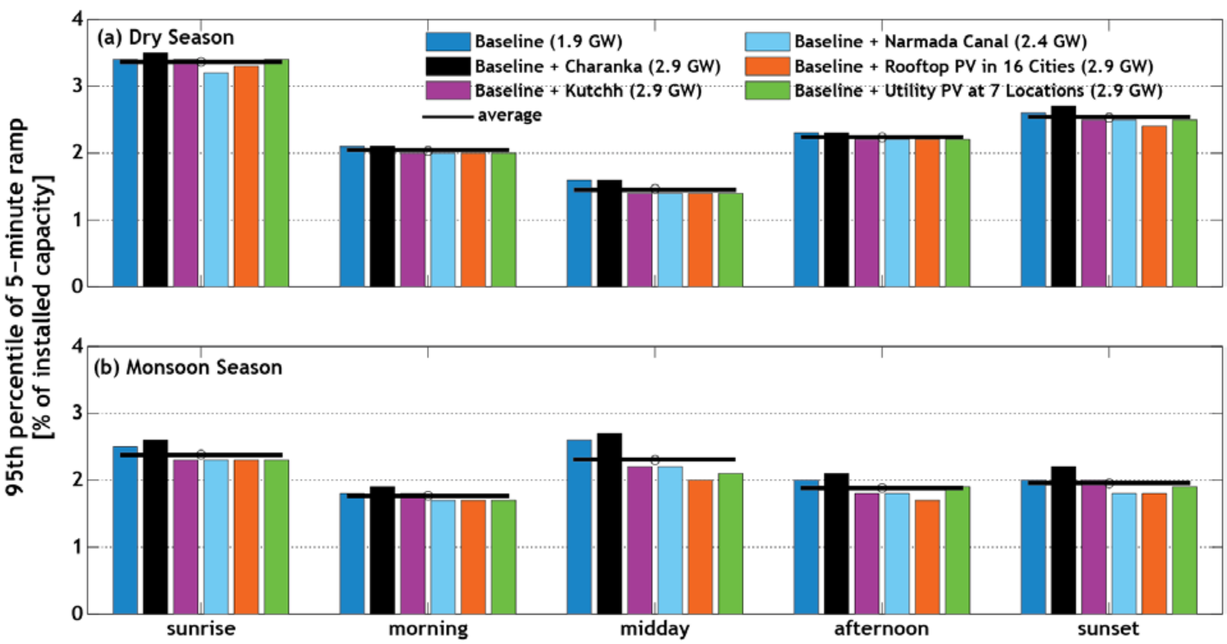

Figure 28. The (a) dry season and (b) monsoon season 95th percentile five-minute ramp (percent of scenario installed DC solar capacity) during each time of day: sunrise, morning, midday, afternoon, and sunset

In contrast to the 95th percentile five-minute ramps, which present the extreme ramps over five minutes, the average "unpredicted" one-minute ramp is characterized by how similar the system is from one five-minute period to the next. The calculation of "unpredicted" one-minute ramps used is illustrated in Figure 29. The "unpredicted" ramp is the difference between the projected and actual one-minute solar power data (Steps 2 and 3 of Figure 29).[47] This is calculated in the clear power index space to minimize the effect of the zenith angle of the sun. The unpredicted ramps are expressed as a change in solar power megawatts per minute (Step 4 in Figure 29).

The average unpredicted down (decrease in solar power) and up (increase in solar power) 1-minute ramps are shown in Figure 30. The data is divided into dry and monsoon seasons because the monsoon season has nearly twice the absolute magnitude of unpredicted one-minute solar power ramps. The baseline scenario is shown on the far left, and the incremental addition of ramps from the expansion scenario is shown as a darker set of blocks below/above the baseline down/up ramps. The Narmada Canal scenario has a smaller magnitude of one-minute ramps because the expansion scenario is 500 MW, compared to the 1,000 MW in the other expansion scenarios. Across all of the remaining baseline plus expansion scenarios, the additional unpredicted one-minute ramps seems to be driven more by total installed capacity than geographic diversity.

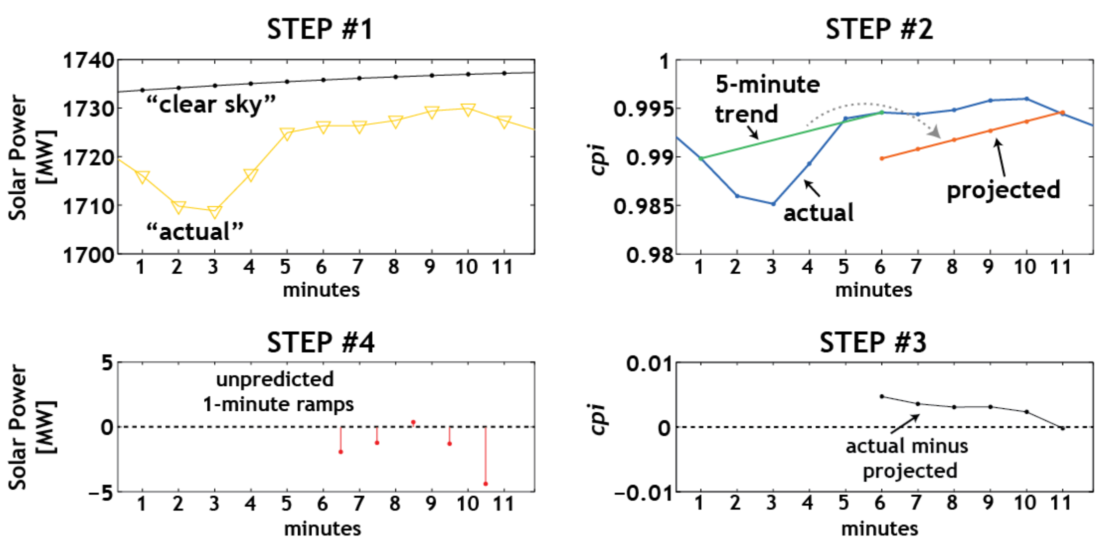

Figure 29. Illustration of the calculation of unpredicted one-minute solar power variability

[47] The calculation and interpretation of unpredicted one-minute ramps is the subject of ongoing research.

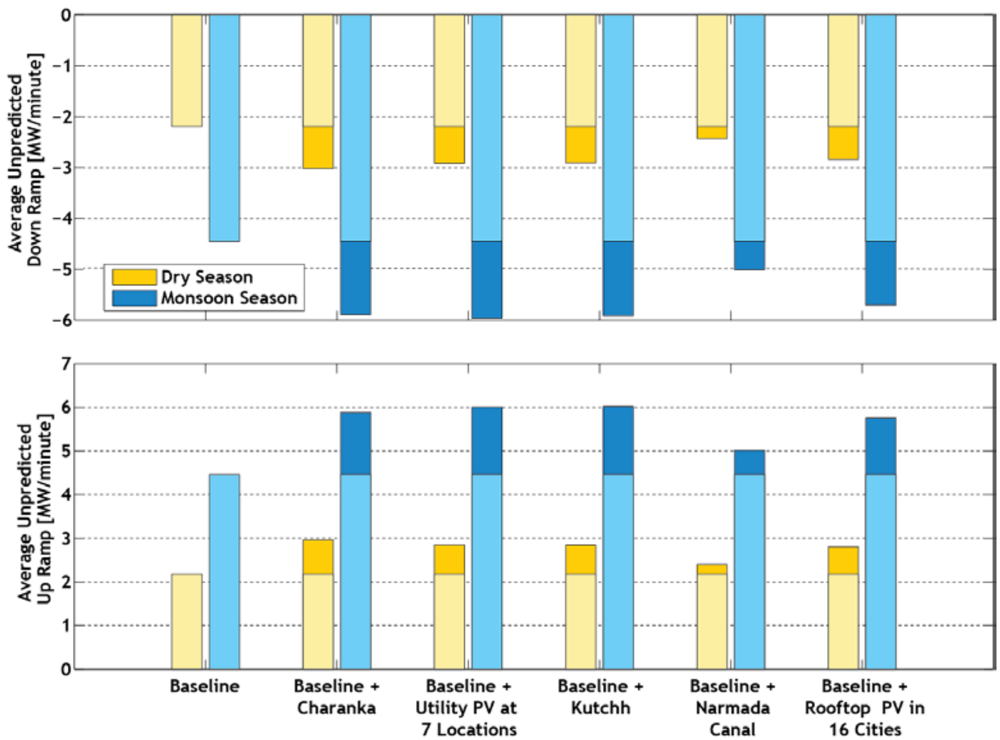

Figure 30. Average minute-to-minute change in solar production, normalized by expected clear sky solar production for the baseline scenario plus each expansion scenario. Darker tones reflect the incremental addition of ramps from the expansion scenarios.

4.3 Summary

Section 4 explores the absolute power production and variability of the baseline scenario (all fixed axis), each expansion scenario, and the baseline plus each expansion scenario. The analysis demonstrates that ramping increases with solar capacity, dominating any difference due to geographic diversity—baseline (1.9 GW_{DC}) ramping is less than baseline plus Narmada Canal (2.4 GW_{DC}) ramping, which is less than the ramping in other baseline plus expansion scenarios (2.9 GW_{DC}). As Figure 27a illustrates, the five-minute ramps as a percentage of installed DC solar capacity are relatively constant across the baseline and expansion scenarios during the dry season, but vary based on time of day.

The effect of geographic diversity becomes significant when cloud coverage contributes to solar ramping. In this case, geographically diverse locations, such as baseline plus utility PV at seven locations or rooftop PV, which are represented by relatively low power densities, experience lower absolute ramps than similarly sized scenarios. The baseline plus Charanka scenario has 30% and 7% greater daytime ramps in the monsoon and dry seasons, respectively, over the baseline plus rooftop PV in 16 cities.

The greatest difference between the monsoon and dry seasons are seen in the average unpredicted one-minute ramps, which demonstrates that persistence predictions in the dry season are more accurate than in the monsoon season.

These measurements of variability, relative to the installed capacity, clear sky ramps, and absolute magnitude of ramps, give system planners and operators a better understanding of how each expansion scenario will impact system operations.

5 Actions to Address the Variability of Solar Generation

The variability of solar generation, as described in the previous section, can be managed through changes to system operations and planning, a number of which are already being adopted in Gujarat. The changes most relevant to Gujarat span the areas of grid reinforcement, system operations, and market reforms.

5.1 Grid Reinforcement

One potential constraint to increasing solar generation is the capacity of the grid. A strong grid serves two key purposes:

- Power can be physically evacuated from areas with high solar resources to where the electricity is needed
- System operators can access a broader range of flexible resources, including conventional generation, to balance the variability of net load (which is electricity demand minus the electricity supplied by wind and solar).

To identify grid infrastructure priorities necessary to meet renewable energy targets in the 12th five-year plan, the central transmission utility, the Power Grid Corporation of India Ltd., conducted a "green corridors" study.[48] The engineering study optimizes inter- and intrastate transmission capacity expansion based on likely areas of renewable energy development as identified by state agencies in seven states, including Gujarat, with input from central agencies, such as the Ministry of New and Renewable Energy, Central Electricity Regulatory Commission, Central Electricity Authority, and Power System Operation Corporation. The proposed infrastructure is designed to both move electricity between states and help resource-rich states better absorb renewable energy within the state, while maintaining both frequency and voltage stability.[49]

The green corridors report identified several infrastructure improvements for Gujarat, including increased interstate transmission capacity to better connect with the northern region and evacuate power from the Charanka Solar Park, intrastate lines to better integrate wind and solar generation internally, and dynamic volt-ampere reactive compensators and other equipment needed to maintain voltage. This transmission will facilitate access to solar power for out-of-state customers, currently a critical constraint for renewable energy capacity expansion. System operators will also be able to better manage solar ramping, as identified in the previous section, with additional transmission capacity to resources that can help balance (provided mechanisms exist to enable resources, especially from out-of-state, to respond to this variability).

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[48] "Report on Green Energy Corridors: Transmission Plan for Envisaged Renewable Capacity." Power Grid Corporation of India Ltd., July 2012. www.forumofregulators.gov.in/Data/study/Report-Green-Energy-Tr.-corridor.pdf.

[49] Although the transmission corridors are being planned, commercial arrangements to secure the grid upgrades have yet to be implemented.

Potential follow-on analysis to this paper, as part of a larger grid integration study for Gujarat, includes evaluating the impact of grid upgrades on the ability of Gujarat SLDC to manage solar ramps. Such an analysis would support an optimized cost-benefit assessment of transmission and generation investments to better evaluate scenario expansion options explored in this paper.

5.2 System Operations

In addition to increased transmission capacity, changes to system operations—through advanced forecasting, improved scheduling, and ancillary services—can also help manage the variability of solar generation. Many of these changes will be implemented as part of the new Renewable Energy Management Centres (REMC), the first of which is under construction in Gujarat. The green corridor report proposed the REMCs, to be colocated in load dispatch centers, address some of the challenges to system operators in managing variable resources.

Challenge	REMC Functions
Low visibility of renewable energy forecasting, especially for solar	Forecast renewable energy generation at timescales ranging from hour-ahead to month-ahead, including at solar power generation plants
Low availability of real-time generation data	Provide real-time tracking of renewable energy generation and system conditions, including geospatial visualization
Limited ability to automatically control generation output, such as through a supervisory control and data acquisition (SCADA) system or automatic generation control	Automated coordination with load dispatch centers to manage variability of generators to control output, when necessary

5.2.1 Advanced Forecasting

The load dispatch center in Gujarat receives forecasting data (day ahead and real time) for all solar plants 5 MW and above, and for wind generators that are 10 MW or greater and connected to a pooling station.[50] The REMC in Gujarat will allow the creation of forecasts based on weather sensors being installed at wind locations of at least 50 MW, which will provide data on speed, direction of wind flow, and temperature, among other factors. Because persistence forecasts for the next 15-minute time period are fairly accurate (for wind generally, and for solar in the dry season), this real-time power production data will be particularly helpful to the SLDC in evaluating upcoming scheduling requirements.

With better visibility of forecasted and real renewable energy generation, system operators will be better equipped to manage ramping. For example, in the baseline plus Charanka scenario, the modeling in this study shows how solar variability changes over the course of a year, and that the

[50] Wind plants commissioned on or after May 3, 2010, and covered under the Renewable Regulatory Fund also must provide forecasting data.

monsoon months of June through August, with its cloud coverage, create the greatest variability in solar ramps. The REMC will be designed to predict specific storm events, allowing system operators to prepare for sudden changes in output. Section 4 demonstrates that dry season variability conditions (one-minute interval changes in solar power output) persist for longer periods than monsoon season variability conditions. In other words, it is harder to predict short-term variability in the monsoon season than in the dry season. Although the practice and science of very short-term solar forecasting is evolving, the forecasting objective of the REMC will likely not address the unpredicted one-minute ramps. An ancillary service, such as automatic generation control, would likely offer the most value to the SLDC in managing unexpected ramping.

Nevertheless, improved forecasting will allow system operators to better anticipate periods of ramping and adjust the quantity of operating reserves based on expected system conditions. This paper illustrates two components of solar variability. The first is determined by the solar path, and plant location and configuration. The associated morning ramp-up and evening ramp-down power changes are known in advance, and can therefore be anticipated in day-ahead scheduling. The second, cloud-driven component of variability becomes better anticipated through forecasting, and is diminished by the geographic diversity of broad deployment scenarios. For example, this study shows that reserves needed to manage midday solar variability are likely to be minimal in October, when skies are largely clear, and greatest in July, when solar variability is less predictable.

5.2.2 Improved Scheduling

Unlike some other states in India, Gujarat has a strong base of resources to meet demand and hold reserves. The adequacy of resources provides Gujarat more in-state options to balance wind and solar variability. Access to this flexibility, however, is limited if schedules are fixed day-ahead and offer little ability to make intraday adjustments based on improved forecasts.

One mechanism to access flexibility is exercising direct control. Under the Energy Act of 2003, the SLDC functioned primarily as a coordinator rather than a controller of resources. The Indian Electricity Grid Code of 2010 now permits direct management of identified resources through automatic generation controls. However, in practice, in Gujarat and all other Indian states, use of governors has been limited, in part due to the prevalence of large frequency swings. With the progressive narrowing of the frequency band, the use of automatic generation controls has become a possibility. As noted in the description of the REMC functions, the REMC will be designed to feed forecast and generation information into the SLDC scheduling system. This allows the SLDC to use real-time telemetry, such as through software like SCADA, which is used to transfer data and control equipment remotely, to directly control the output of wind and solar generators.

Thermal plants offer another source of flexibility—elsewhere, coal has demonstrated the ability to cycle on and off up to twice a day.[51] Coal-based generators in India—both publicly and privately owned—are wary of schedule revisions, given the maintenance requirements and wear and tear associated with cycling. However, these costs (e.g., wear and tear while ramping and providing ancillary services), along with information on operating parameters (e.g., fuel availability, ramp rate, minimum generation point), can be incorporated in economic dispatch when revising intraday schedules. Gujarat is already using coal as a source of flexibility to help balance variability. The state has secured agreement from NTPC Ltd. to vary coal generation under Gujarat's contractual control (500 MW), from 60% to 100% of unit capacity.[52] Expanding the use of thermal plants to meet intraday scheduling revisions will provide greater options for Gujarat to balance variability and address uncertainty.

Automation of scheduling at state load dispatch centers will also help system operators balance ramp events. Currently, many scheduling transactions are not automated—SLDCs can require several hours to clear requests from state distribution utilities and over a day from captive (industry-owned) power plants. This manual process, in turn, impacts the speed of scheduling at regional and national load dispatch centers. Once all scheduling is conducted online, as already occurs in Gujarat, state-level clearance can be automated, which in turn, will increase for all states the liquidity and access to resources to help balance net load.

5.2.3 Ancillary Services

The development of ancillary services would be one of the most significant changes to system operations, with significant potential to improve options and reduce the costs of managing variability and uncertainty. Ancillary services would compensate for the provision of reserves, tailored to different time scales, and voltage control. This package is in consideration by the Central Electricity Regulatory Commission,[53] and would likely replace system operators' existing tool for balancing—the unscheduled interchange mechanism.[54] Although Gujarat has a greater reserve margin for peak demand relative to other states (500-1,000 MW, provided by conventional generation), ancillary services could be structured to ensure adequate spinning (hot) reserves, which are currently in insufficient supply.[55]

The type, magnitude, and timing of ancillary services can be tailored to meet the projected variability, and its uncertainty, of renewable energy. The analysis in Section 4 illustrates the

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[51] Cochran, J.; Lew, D.; Kumar, N. "Flexible Coal: Evolution from Baseload to Peaking Plant." 21st Century Power Partnership. NREL/BR-6A20-60575. Golden, CO: National Renewable Energy Laboratory, 2013. http://www.nrel.gov/docs/fy14osti/60575.pdf.

[52] *Large-Scale Grid Integration of Renewable Energy Sources—Way Forward*. Central Electricity Authority, 2013. www.cea.nic.in/reports/powersystems/large_scale_grid_integ.pdf.

[53] "Introduction to Ancillary Services in Indian Electricity Market." Central Electricity Regulatory Commission (CERC), April 10, 2013. www.cercind.gov.in/2013/whatsnew/SP13.pdf. Note CERC staff is currently revising this paper to evaluate a wider range of options, beyond markets, for SLDCs to procure ancillary services.

[54] The unscheduled interchange mechanism prices deviations from schedule such that there is a financial incentive to maintain grid frequency. The mechanism limits how much schedules are allowed to deviate.

[55] *Integrating Variable Renewable Energy with the Grid: Lessons from the Southern Region.* Mercados Energy Markets India PVT Ltd., November 2012. www.shaktifoundation.in/cms/uploadedImages/variable%20re%20grid%20integration.pdf.

types of ancillary services of most importance to solar variability. For example, in the monsoon season, automatic generation control would be valuable to address the unexpected minute-to-minute variations due to cloud coverage. The analysis in Section 4 also illustrates potential magnitudes, for example, in the magnitude of solar output change over five-minute periods. The study finds that greater than 88 MW ramps per five minutes occurs less than 0.10% of the time for all scenarios—this type of information could serve as input for reserve capacity calculations.

Varying the timing of ancillary services—such as dynamic reserves that are targeted to ramping needs specific to time of day and year—can reduce the cost of integrating variable renewable energy. This paper demonstrates the change in variability and uncertainty over the course of the day and across a year. When solar variability is combined with wind and load data, including forecast errors for all three, the net variability can be calculated, and an evaluation can be made on how to define and schedule reserves, and whether the capacity to provide these reserves is sufficient among existing generators.

Finally, this paper also demonstrates the impact of geographic diversity on reserve management, and quantifies the differences in cloud-driven ramping between extremely centralized deployment (Charanka), alternative widely distributed central plants (utility PV at seven locations), and even broader distributed rooftop scenarios (rooftop PV in 16 cities). Rooftop PV would require fewer reserves to manage solar ramping compared to other expansion scenarios.

5.3 Market Reforms

Commercial impediments to renewable generation sales remain one of the greatest challenges in Gujarat for scaling up renewable energy. As with other states, utilities in Gujarat must pay a feed-in tariff for wind and solar production (average of rupees 3.56/kWh in June 2012), and must balance excess supply by backing down cheaper generation (rupees 2.50-2.70/kWh).[56] Other states may be deterred from purchasing Gujarat's renewable energy, for a number of reasons:

- States have limited options to balance variability. The state purchasing solar through a power purchase agreement (PPA) is also purchasing the balancing requirement.
- Energy purchased through the unscheduled interchange during periods of supply excess, such as during the windy monsoon months, is cheaper than establishing PPAs.
- Obligations for other states to meet renewable energy targets are not enforced.

Changes to market design and participation, such as development of a robust spot market, would increase the options for system operators to address solar ramping, providing a centralized exchange to balance wind and solar variability. Also, contracts for all generators (e.g., to provide compensation for part load, flexible operations, and ancillary services) will likely require renegotiation to align with evolving operating and market structures. Wholesale market designs for energy and ancillary services can help integrate and make efficient the provision of these services, and serve as a framework for contract renegotiation.

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[56] *Large-Scale Grid Integration of Renewable Energy Sources—Way Forward*. Central Electricity Authority, 2013. www.cea.nic.in/reports/powersystems/large_scale_grid_integ.pdf.

Short of having a robust market, improving cooperation across balancing areas can help expand access to resources needed for balancing, although this is less of an issue for Gujarat, which has adequate in-state resources for balancing. Typically in India, the process for revising the day-ahead interstate schedules is inflexible. As forecasts for generation and load increase with accuracy close to real-time power delivery, system operators have limited options to revise schedules. For example, an intraday market on the power exchanges exists, but with too little participation to offer liquidity. The SLDCs have limited options to revise intraday, interstate schedules with the regional load dispatch center, for example, to accommodate a bilateral trade necessary for balancing. Therefore, SLDCs have three primary options to balance their system in real time: adjust schedules of in- and out-of-state resources (such as conventional generation based on merit order), shed load (in Gujarat, agricultural feeders are scheduled to be curtailed first), and purchase or sell power through the unscheduled interchange mechanism).

Options to improve interstate trade could include improved intraday market liquidity, sharing of reserves (such as under development in the Western U.S. energy imbalance market),[57] and increased availability to revise interstate schedules.

5.4 Summary

Targeted changes to system operations and planning can account for anticipated impacts on grid operations introduced by increased amounts of solar generation, across all scenarios analyzed. Because most of the solar ramping is based on known changes due to sunrise and sunset, the Gujarat SLDC can schedule its resources accordingly. The greater periods of uncertainty stem from cloud-based variability. To address this impact, Gujarat is in the process of strengthening its suite of tools to anticipate and mitigate this variability, including stronger grids, geographic diversity of PV locations, advanced forecasting (day ahead and real time), improved scheduling, introduction of ancillary services, and strengthened markets across balancing areas.

[57] Milligan, M.; Clark, K.; King, J.; Kirby, B.; Guo, T.; Liu, G. *Examination of Potential Benefits of an Energy Imbalance Market in the Western Interconnection.* NREL/TP-5500-57115. Golden, CO: National Renewable Energy Laboratory, 2013. www.nrel.gov/docs/fy13osti/57115.pdf.

6 Summary, Implications, and Next Steps

Higher penetration levels of wind and solar add variability and uncertainty to power system operations. To assess the adequacy of balancing resources, and to evaluate operational practices to access these resources, system operators and planners typically perform grid integration studies. Key to informative analysis is accurate representation—spatially and temporally—of the power variability and uncertainty of solar and wind generation. This report focuses on one element of a grid integration study—solar variability.

This paper demonstrates the use of a new Indian solar radiation data set and a method to develop sub-hourly power variations. The insolation profiles are used to derive potential PV power generation profiles for additional deployment locations in the state of Gujarat. This work brings out several salient features that are important when evaluating potential future PV renewable generation and its potential grid integration impacts on the power system, including:

- The diurnal and seasonal power profiles and variability statistics for the existing and planned 1.9 gigawatts (GW) of solar are characterized using 2006 historic solar resource data. The geographic spread of this baseline is relatively broad. Power output is raised slightly if a portion of the plants is assumed to incorporate single-axis tracking, but the statistics of variability are largely unaffected by tracking.
- The expansion scenarios of 500 to 1,000 MW increase nearly proportionally the absolute magnitude of the solar variability. The differences in geographic density of the expansion scenarios affect variability, but when combined with the geographically diverse baseline scenario and normalized to the total nameplate DC capacity, the differences among scenarios are small.
- Results illustrate the power ramp rate differences between a single small plant, a very large plant, several spread out central plants, and rooftop distributed deployments. The least geographically diverse, baseline plus Charanka scenario has 30% and 7% greater midday ramps in the monsoon and dry seasons, respectively, over the more geographically diverse baseline plus rooftop PV in 16 cities scenario.
- In evaluating expansion plans, system planners need to consider other factors related to location, such as access to uncongested transmission capacity, in addition to variability differences. If solar deployment across more Indian states is considered, and state-to-state grid cooperation is increased, the beneficial impacts of geographic diversity should be larger and would be worth re-evaluating.
- During the monsoon season, individual plant variability can be quite large due to cloud passage, but the aggregated power across all plants shows less volatility. Due to the broad and general nature of the storms, planning and operating the system using a derating of the solar capacity may help systems operations. Further research could assess whether this implication could be applicable to other regions of the world with similar monsoonal climatology and where solar power is being deployed or contemplated.
- The study shows that much of the diurnal solar variability is based on a known solar path, illustrating a large amount of the PV-imposed needs for grid flexibility are known in advance, which facilitates grid operational day-ahead scheduling.

- The variability shows strong seasonal characteristics. Generally, absolute variability is higher during dry seasons during known sunrise and sunset ramps. Variability relative to output is higher during the monsoon season at midday, when the region experiences a dramatic decrease in solar power output due to periodic (and relatively unpredictable) cloud passage.
- Diurnal and seasonal variability characteristics can be important to grid practices. Known variability implies ramping resources can be confidently quantified and potentially scheduled. Unpredictable variability statistics can also be quantified, but may require partially loaded quick ramp or quick start/stop resources to respond.

These results inform grid operations and planning processes with realistic solar variability characteristics applicable to various futures in Gujarat. With data, one can assess the impacts of increases in solar deployment and formulate approaches to address challenges.

6.1 The Need for Similar Wind Resource and Power Profiles

The availability of the new historic solar data set for India was key to motivating this PV variability analysis. However, wind power is currently posing more challenges to the Gujarat SLDC. During 2012-2013, when Gujarat's installed wind capacity reached over 3 GW, wind power fluctuated more than 500 MW within 69% of the days, while fluctuating more than 1,000 MW on 16% of the days.

Like the solar variability analyzed in this paper, similar analyses of sub-hourly wind variability and different potential future wind power generation scenarios are needed to more fully understand the challenges of increasing grid-connected renewable energy.

Compared with solar, generating historic weather-year resource models for wind is more difficult, requiring use of complex mesoscale representation of the atmospheric flows. While models are available, they are computationally intensive, require often hard-to-find measurement data for calibration, and necessitate skilled parametric tuning to capture hub-height phenomena. The *U.S-India Energy Dialog Work Plan: Joint Action Plan*[58] intends to address this gap. As part of this, the Centre for Wind Energy Technology and NREL will calibrate wind data, and NREL will complete the mesoscale model development in the first half of this year (2014).

Once this model is available, development of scenario-specific wind power profiles using data from the historic weather year 2006 is anticipated. Wind results will be matched with the solar profiles developed in this study. Such contiguous weather-year PV and wind power profiles will provide a key element needed for grid integration operational and planning analyses, and complement inputs based on load profiles and conventional generator characteristics. For example, such an analysis could address whether system operators can maintain reliability during the monsoon season, when wind output is strong, the uncertainty of solar variability is highest,

[58] *U.S.-India Energy Dialog Work Plan: Joint Action Plan*, *2013*. New Technology and Renewable Energy Working Group, December 2012. http://scholar.google.com/scholar_url?hl=en&q=http://asiasolarenergyforum.org/wp-content/uploads/sp-client-document-manager/2/2013-03-04-ntre-action-plan---draft-final--dec-2012.docx&sa=X&scisig=AAGBfm1PpebStYrcxbRbsA378sW4CgqT1Q&oi=scholaralrt.

and many sources of system flexibility are constrained (e.g., hydro storage is full, coal capacity is offline or at part load). Such analyses can then be used to anticipate future variable renewable challenges and evaluate possible solutions.

6.2 Uses of Renewable Power Variability Profiles

Integration studies of the full integrated electric system, including conventional generator capabilities, load variability, operational practice reform, and assessment of system-level mitigation measures will allow system planners and operators to examine and address challenges imparted by large-scale variable generation futures.

Realistic wind and solar power profiles corresponding to potential future deployment scenarios help characterize some of the integration challenges. Without these evaluations, vagueness and anxiety might otherwise hold back development. With the power profiles, many types of analyses can be performed, including:

- Intra- and interregional transmission load flow and transmission expansion planning studies
- Evaluation of reactive power requirements and harmonics
- Production cost operational modeling of the integrated grid
- Resource adequacy-based reliability assessments, including wind and solar capacity credit determinations.

Performing these types of investigations leads to a better understanding of the challenges of a grid with high penetration levels of renewable energy. Through production cost modeling, both physical and institutional features of the grid can be examined, for example:

- Ramp capabilities of conventional generators and possible maintenance cost increases due to increased cycling
- Market structure and dispatch practices
- Balancing mechanisms and associated ancillary service and reserve procedures

A holistic approach to grid integration analysis will recognize that each element might be important for further planning and could serve as the basis to support technology innovation, new procurement rules, new transmission interties, among other strategies to integrate wind and solar. Operational evaluations have often led to creative solutions.

Once the flexibility needs are quantified, a wide variety of mitigation approaches can be evaluated. Some effective approaches based on international experience include: [59] [60]

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[59] See, for example, Holttinen, H. et al. *Design and Operation of Power Systems with Large Amounts of Wind Power*. VTT Technology, 2013. www.ieawind.org/task_25/PDF/T75.pdf.

- Improving forecasting in appropriate time frames through better data gathering and analysis
- Shortening unit commitment and dispatch intervals and gate closures
- Alternative market structures and balancing mechanisms (ancillary services and reserves)
- Utilizing smart-grid modernization to improve situational awareness, data flow, and improved access to demand control measures (such as is being developed through the Renewable Energy Management Centre in Gujarat)
- Increased balancing area cooperation through shared imbalances, reserves, and load/resource diversity (for India this includes national-to-state and state-to-state cooperation)
- Steering future generation additions to encourage increased geographic dispersion of renewables and more flexible conventional generation
- State-of-the-art active power control capabilities on wind and solar plants, such as ramp rate control, inertial response, and automatic generation control.

These types of analyses and evaluations of solutions are predicated on realistic, quantified wind and solar power variability profiles, such as what is illustrated in this paper for solar PV generation in the state of Gujarat.

[60] Cochran, J., L. Bird, et al. *Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience*. Golden, CO, National Renewable Energy Laboratory, 2012. www.nrel.gov/docs/fy12osti/53732.pdf.

Appendix: Solar Plant Diagrams

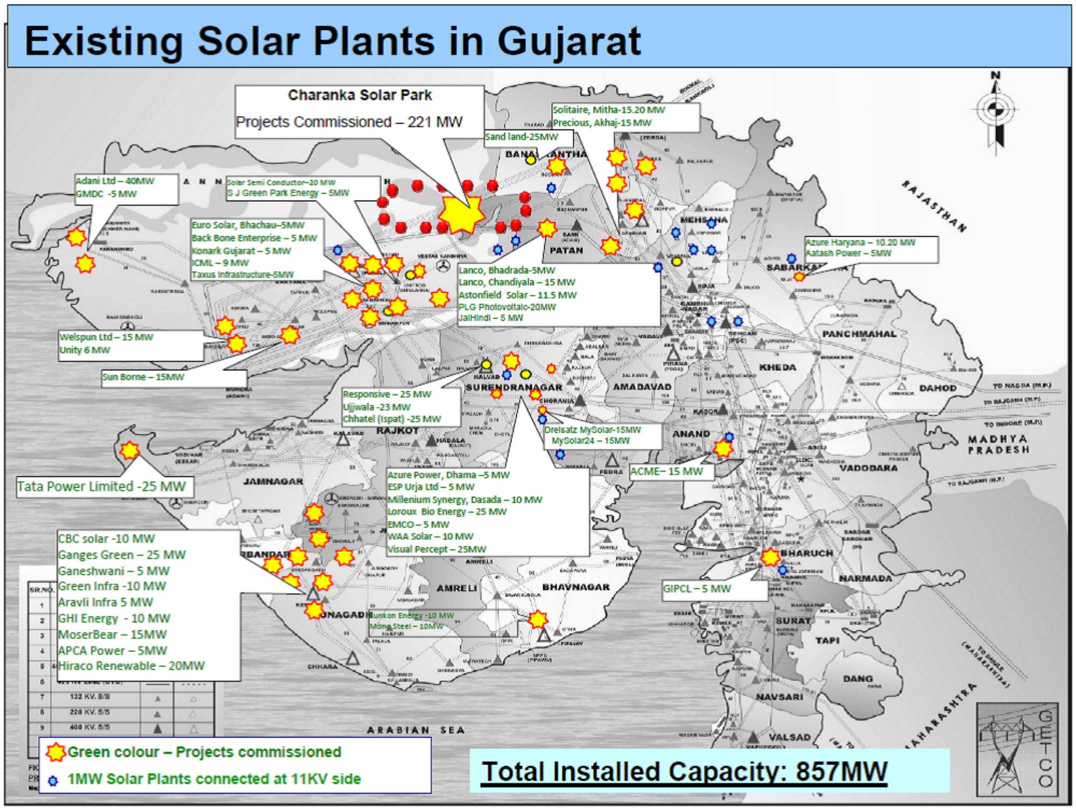

Figure A-1. Existing solar plants in Gujarat

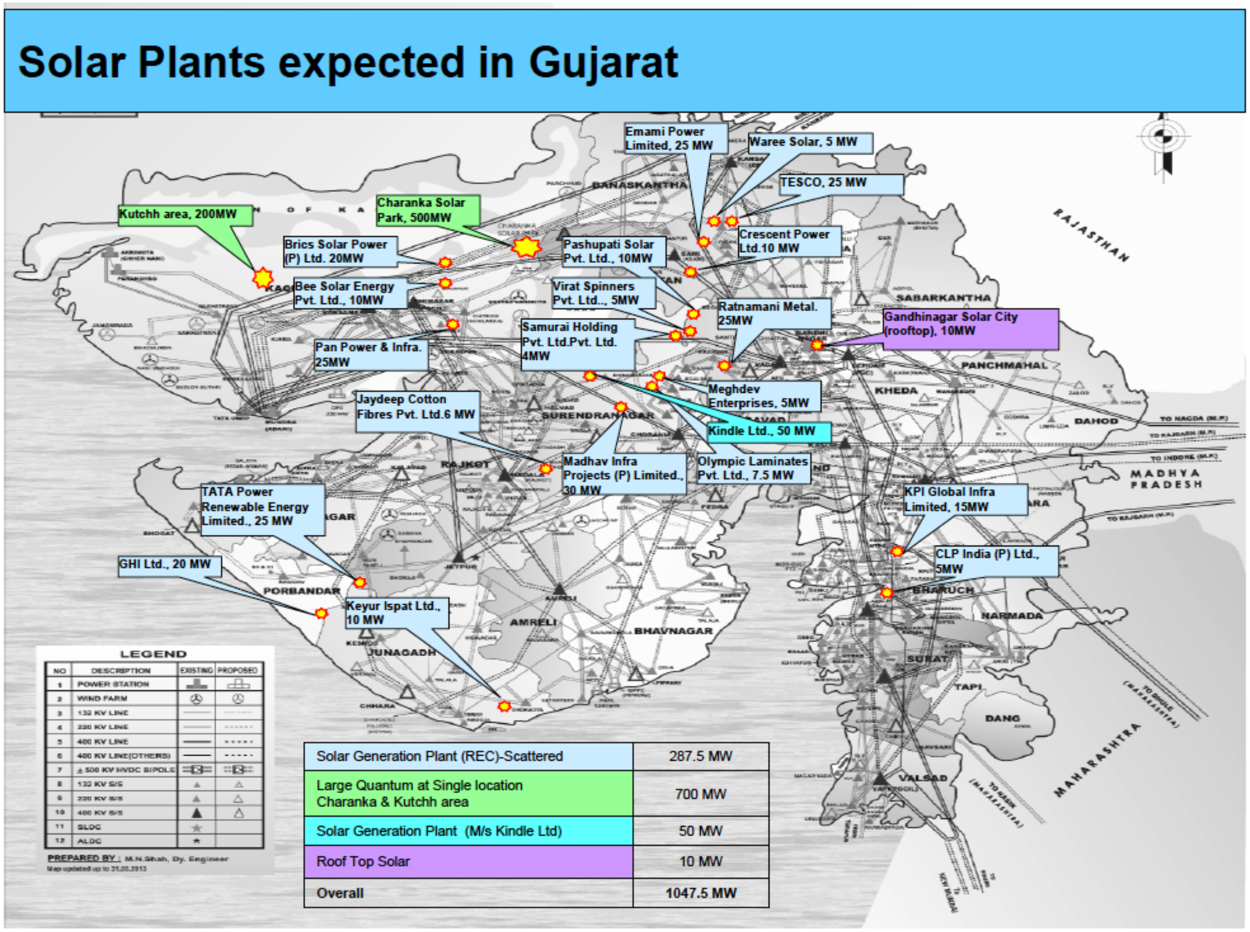

Figure A-2. Expected solar plants in Gujarat