Variability of Power from Large-Scale Solar Photovoltaic Scenarios in the State of Gujarat

Preprint

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Abstract

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 generation of any Indian state, with over 855 megawatts direct current (MW_{DC}) installed as of late 2013. Combined with over 3,240 megawatts (MW) of wind, variable generation renewables comprise nearly 18% of the electric-generating capacity in the state. A new 10-kilometer (km) gridded solar radiation data set capturing historic hourly insolation values for 2002-2011 is available for India. We apply an established method for downscaling hourly irradiance data to estimate one-minute irradiance values at potential photovoltaic (PV) power production locations for one year, 2006.

The objectives of this report are to characterize the intra-hour variability of existing and planned photovoltaic solar power generation in the state of Gujarat, and compare five possible expansion scenarios of solar generation that reflect a range of geographic diversity. Each expansion scenario postulates 500-1,000 MW of additional solar capacity, added to the 1.9 gigawatts of existing and planned baseline. The report statistically analyzes one year's worth of solar 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 Gujarat Energy Transmission Corporation (GETCO) and the Gujarat State Load Dispatch Centre (SLDC) could make use of the solar variability profiles in grid operations and planning.

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 MW_{DC}[1] among plants above 1 MW_{DC} in size. Combined with over 3,240 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 paper focuses on the solar characteristics needed for a grid integration analysis, which would also include information on load, wind, and conventional generation.

2 Solar Data

A new 10- km gridded solar radiation data set capturing historic hourly insolation values for 2002-2011 is available for India.[3] The data set containing global horizontal irradiance (GHI) and direct normal irradiance, is derived from satellite images from the Meteosat satellite using the semiempirical model developed by Perez et al.[4] 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 authors apply an established method for downscaling hourly irradiance data to one-minute estimated irradiance values. This study uses the sub-hour irradiance algorithm (SIA), developed for the U.S. Western Wind and Solar Integration Study Phase 2.[5] 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

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

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 Deployment Scenarios

The state of Gujarat has a high annual average solar resource of 5.5 to 6.0 kilowatt-hours (kWh)/square meter/day over the entire state. This uniformity implies solar power plants may be optimally located based on land use compatibility, proximity to load centers, and transmission lines.

3.1 Baseline Scenario

A “baseline” scenario totaling 1.9 gigawatts direct current GW_{DC} was defined to include existing and expected capacities and locations, based on information from GETCO (see Figures 1 and 2).[6]

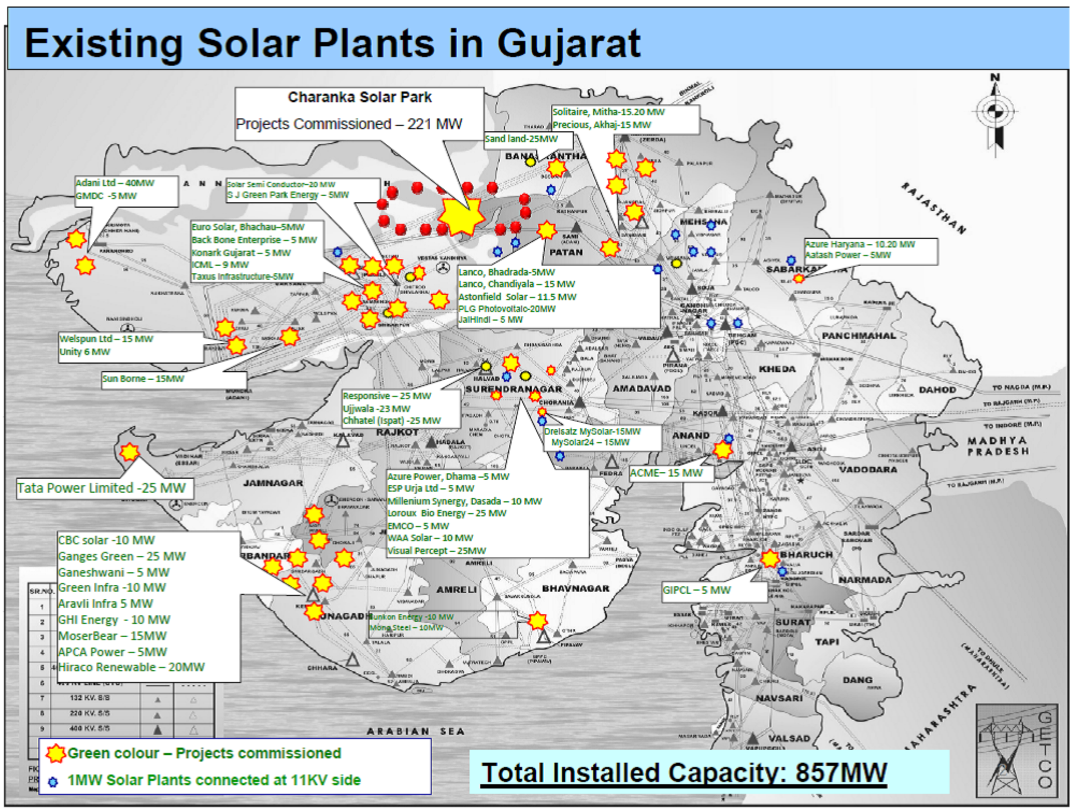

Figure 1. Existing solar plants in Gujarat

[6] All systems modeled for Gujarat, India, were assumed to be mounted at a 17° tilt and oriented due south (azimuth of 180°).

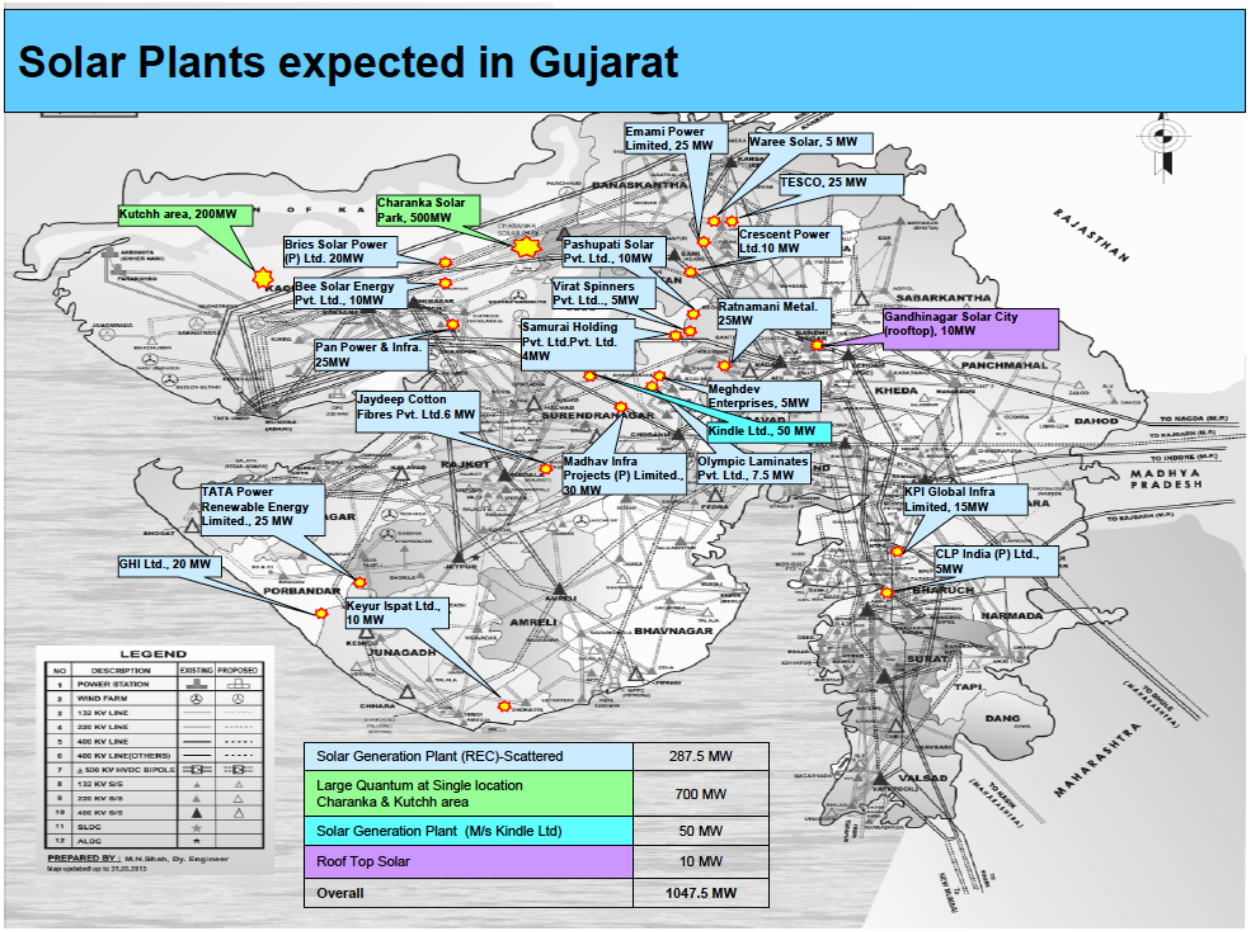

Figure 2. Expected solar plants in Gujarat

The modeled power outputs for a single 5-MW plant and the full baseline (existing plus expected plants) for two days during the monsoon (top) and dry (bottom) seasons, are plotted in Figure 3. These results illustrate why taking output from a single plant and simply scaling up power output to model larger deployment capacity values would misrepresent the variability by disregarding the smoothing value of geographic diversity.

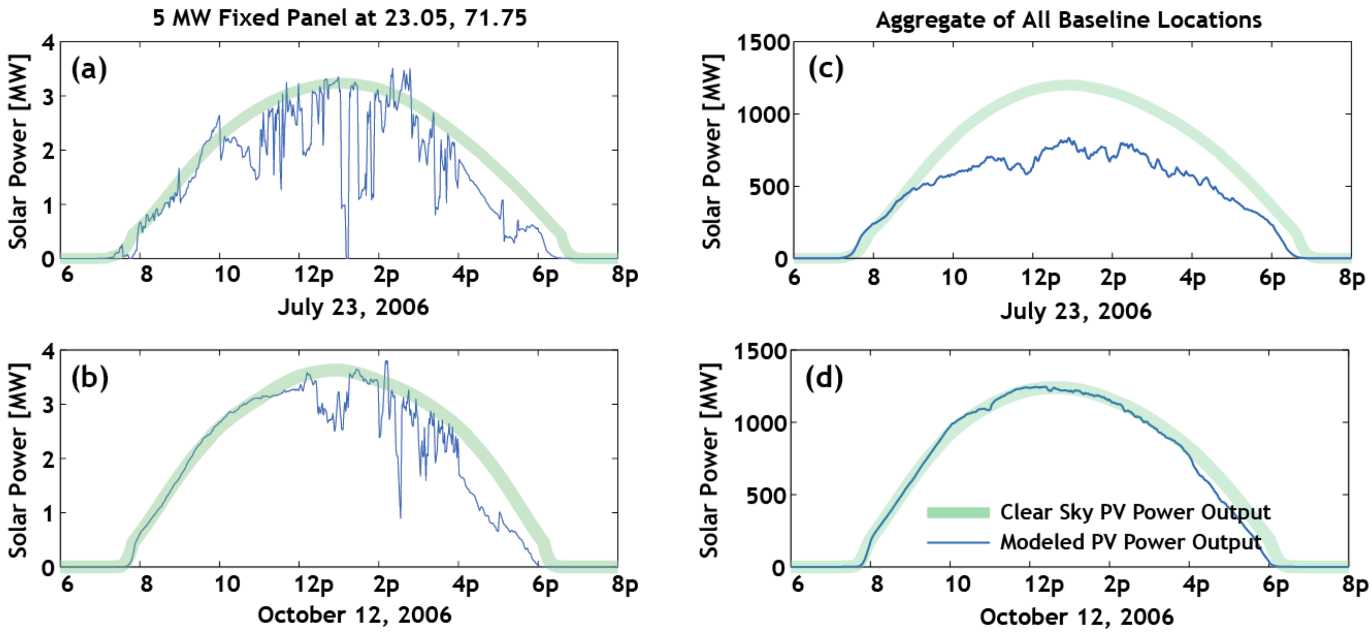

Figure 3. Clear sky and synthetic PV power output, one-minute resolution, for (left) single, randomly selected site from the baseline PV scenario, and (right) aggregation of all the baseline PV sites on July 23, 2006, and Oct. 12, 2006

To anticipate how variability might change if Gujarat continues to pursue renewable energy growth targets, the authors created solar profiles for five potential future expansion 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 examine and 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.[7] The remainder of this section will describe the five expansion scenarios in greater detail.

3.2 Charanka Expansion Scenario

The "Charanka" scenario expands the baseline scenario by adding 1,000 MW_{DC} at the Charanka Solar Park. Figure 4 shows the location of the Charanka scenario (yellow) along with the baseline (existing and expected) scenario (orange), overlayed on the Power Map of Gujarat.[8] The Charanka Solar Park was initially started in 2010 and will be located on more than 20 square-kilometers (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.[9] This 500 MW_{DC} capacity is reflected in the baseline scenario. The addition of 1,000 MW_{DC} in the

[7] "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.
[8] 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.
[9] "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.

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.

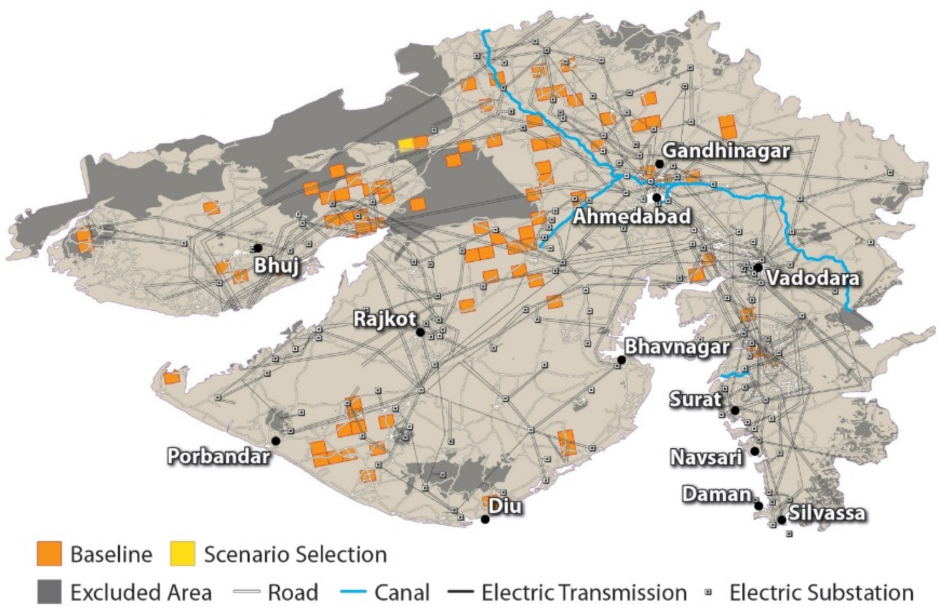

Figure 4. Charanka scenario is 1.0 gigawatts of additional capacity at Charanka Solar Park (yellow) with the baseline scenario (orange)

3.3 Seven Utility Photovoltaic Locations Expansion Scenario

The "seven utility PV locations scenario" expands the baseline scenario by adding approximately 143 MW_{DC} at each of seven locations throughout western Gujarat. Figure 5 shows the locations of the seven PV plants, which 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.[10] Developable land within grid cells is also tested for proximities, including: 5 km from roads[11] and 3 km from transmission.[12] 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.

[10] The excluded area is used to inform PV siting in the expansion scenarios, and comprises forests, permanently flooded areas, regularly flooded areas, urban areas, water bodies, slope >5%, and protected areas as defined in "Global Land Cover Characterization: Eurasia Version 1." U.S. Geological Society, 2008. Version 1: http://edc2.usgs.gov/glcc/glcc.php and "ProtectedPlanet.net" United Nations Environment Programme and International Union for the Conservation of Nature, 2014. www.protectedplanet.net/.

[11] "OpenStreetMap." OpenStreetMap contributors, undated. Accessed Jan. 7, 2013: http://www.openstreetmap.org/#map=5/51.500/-0.100.

[12] 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.

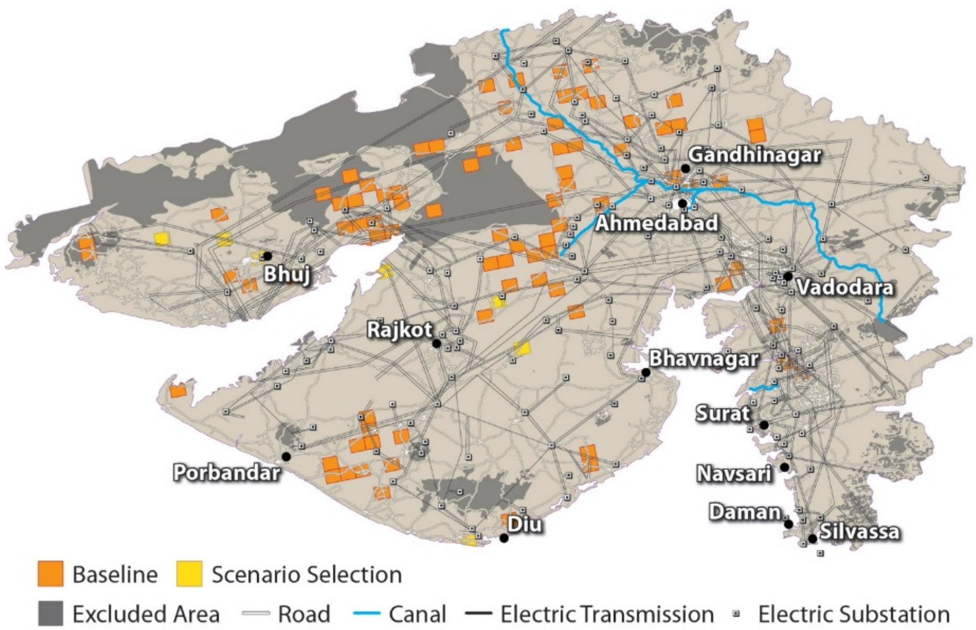

Figure 5. Seven utility PV locations scenario (yellow) each with 143 MW PV plants with the baseline scenario (orange)

3.4 Kutchh Region Expansion Scenario

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.[13] Grid cell selection within an area was performed using the same guidelines of annual GHI intensity and developable land use restrictions.

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

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

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

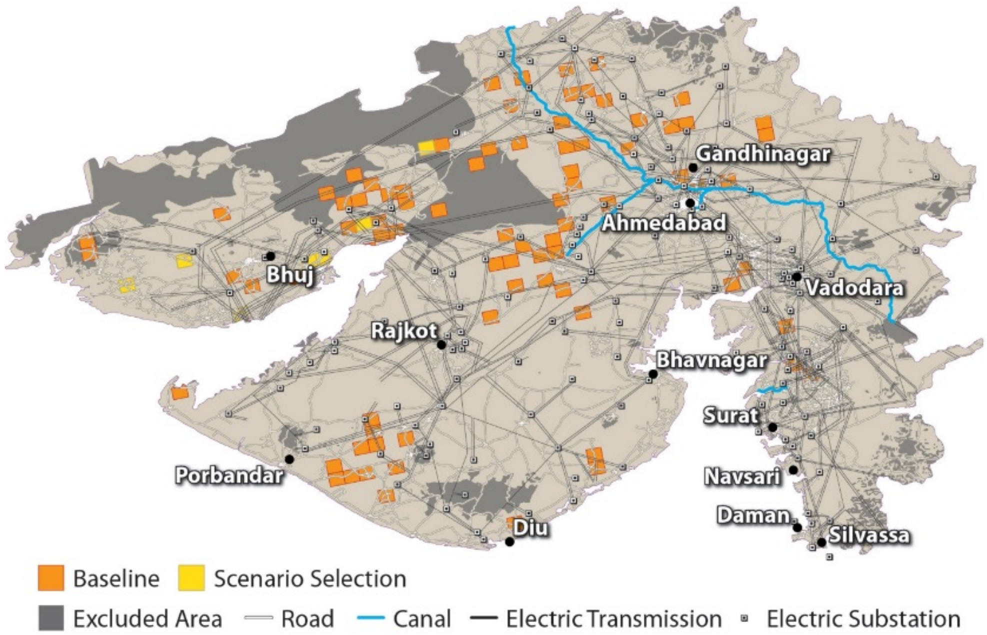

Figure 6. Kutchh scenario (yellow) consists of six utility PV plants ranging from 100 to 200 MW with the baseline scenario (orange)

3.5 Narmada Canal Expansion Scenario

The "Narmada Canal" scenario is based on recent reports that fixed PV panels are being mounted over the canal.[14] 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 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.

[14] "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.

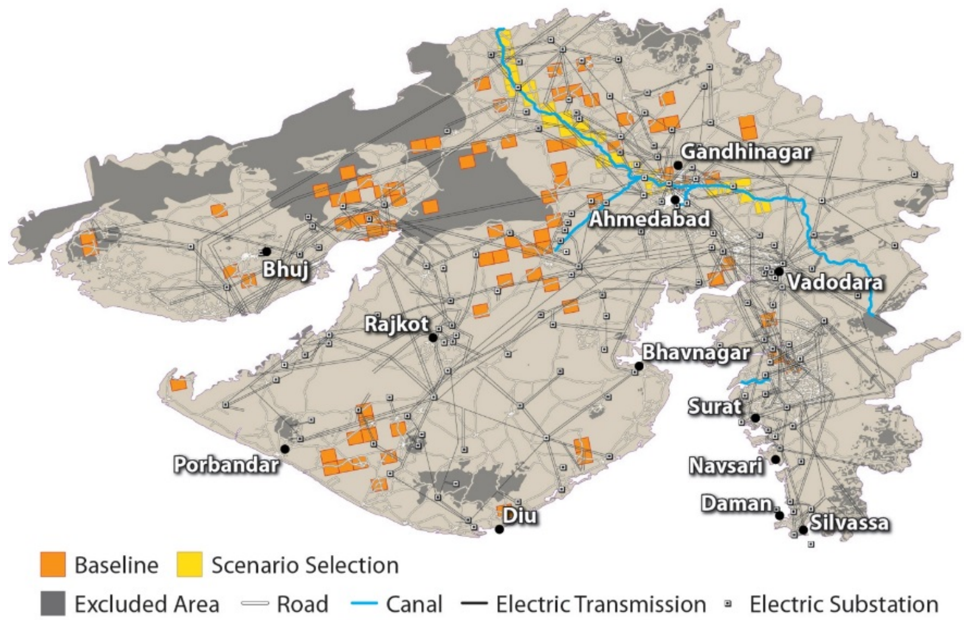

Figure 7. Narmada Canal scenario (yellow) with 500 MW distributed along the Narmada Canal in Gujarat with the baseline scenario (orange)

3.6 Sixteen Cities: Rooftop PV Expansion Scenario

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 that identified large cities.[15] 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.

[15] "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/.

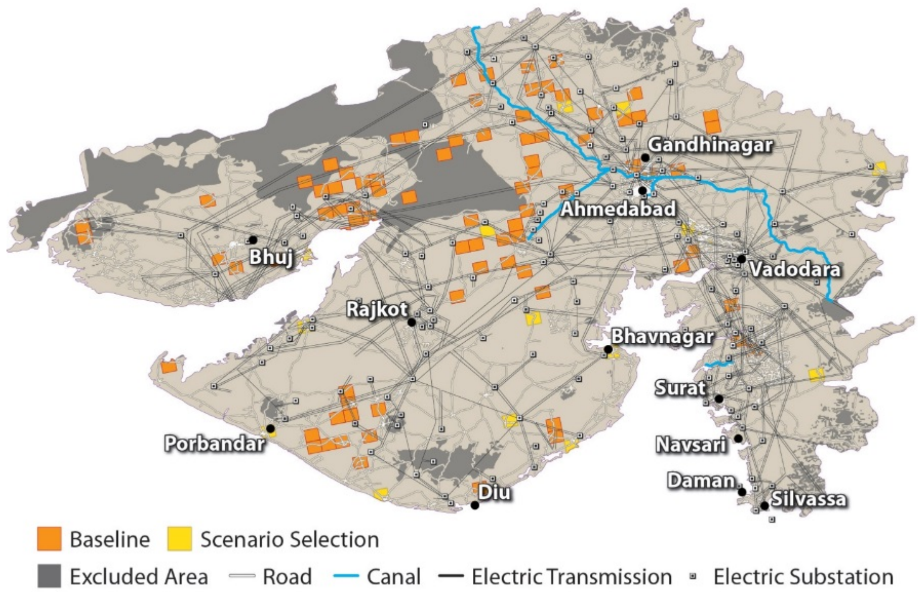

Figure 8. Sixteen cities: rooftop PV scenario (yellow) consists of 62.5 MW in each of 16 cities with the baseline scenario (orange)

4 Solar Power Variability Results

The primary objective of this analysis is to characterize and contrast the intra-hour variability of these six PV generation scenarios. The report statistically analyzes power production based on 2006 irradiance data,[16] 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 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.[17] 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 megawatts 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

[16] 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.
[17] This change in power over time is typically expressed in MW over some time scale of interest, for example five minutes.

sunset ramp rates, and decrease the peak solar output by 20%-35%. Figure 9 illustrates these results by showing the aggregate power output from the baseline plus each expansion scenario in monsoon (left) and dry (right) seasons..This analysis also demonstrates that aggregate power ramps from solar expansion scenarios are less dramatic as the geographic spread of deployment (spatial diversity) is increased.

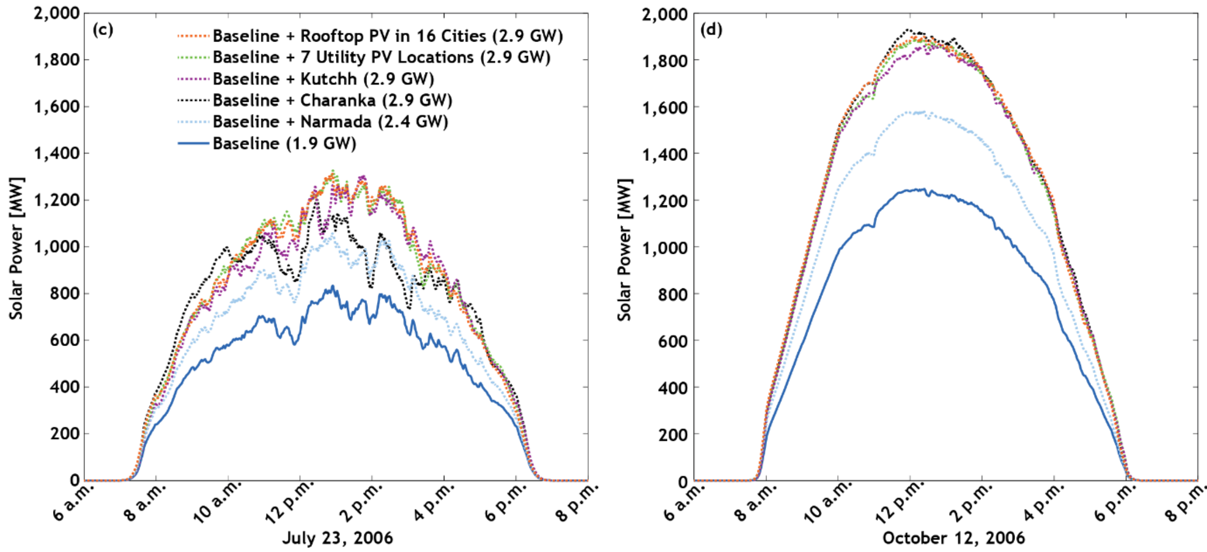

Figure 9. Aggregate power output of baseline plus expansion scenarios on July 23, 2006 (monsoon), and Oct. 12, 2006 (dry season)

The more complex effects of geographic diversity from alternative solar expansion scenarios are better assessed by *normalizing* ramp rates to the total nameplate rating. As Figure 10a 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.

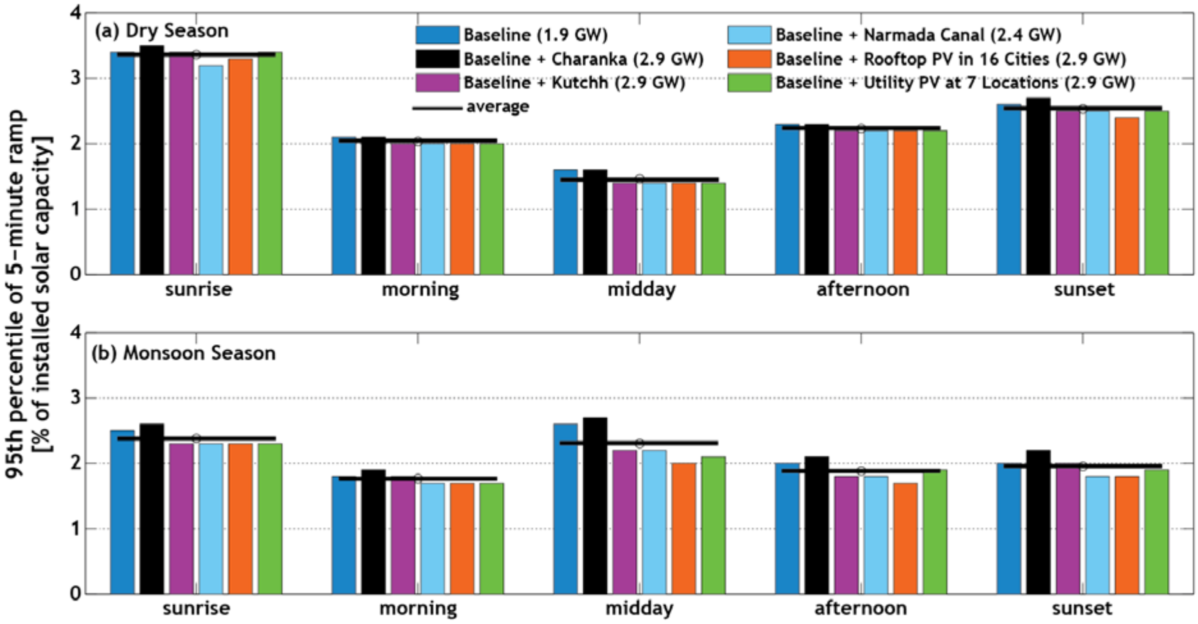

Figure 10. The dry season (a) and monsoon season (b) 95th-percentile five-minute ramp (percent of scenario installed DC solar capacity) during each time of day: sunrise, morning, midday, afternoon, and sunset

The monsoon season (Figure 10b) 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.

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 11. The "unpredicted" ramp is the difference between the projected and actual one-minute solar power data (Steps 2 and 3 of Figure 11).[18] This is calculated in the clear power index (cpi) 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 11).

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

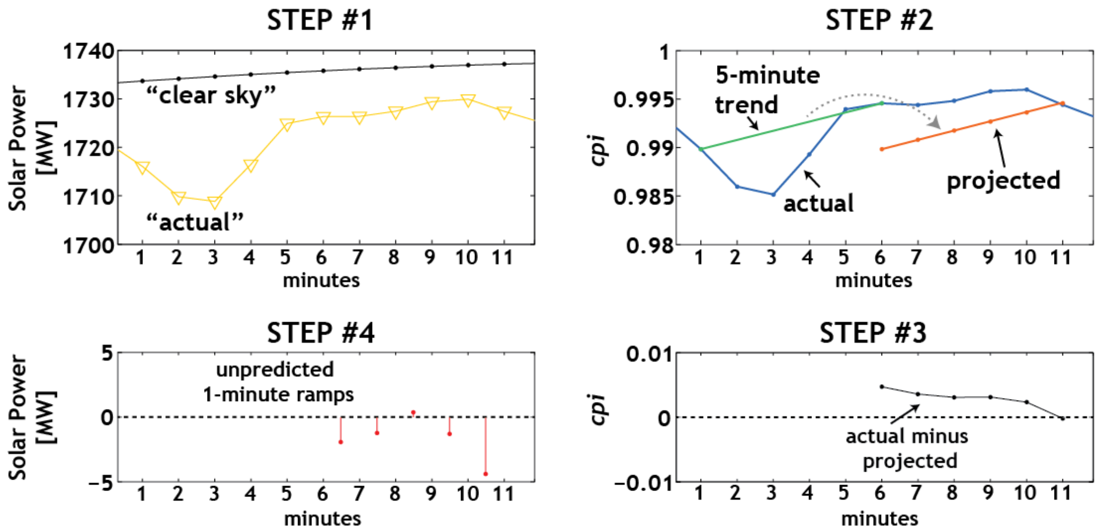

Figure 11. Illustration of the calculation of unpredicted one-minute solar power variability

The average unpredicted down (decrease in solar power) and up (increase in solar power) one-minute ramps are shown in Figure 12. 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 seem to be driven more by total installed capacity than geographic diversity. These results also demonstrate 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 NREL report titled *Variability of Photovoltaic Power in the State of Gujarat Using High Resolution Solar Data* (http://www.nrel.gov/docs/fy14osti/60991.pdf) contains additional analysis of interest to grid operators, including comparisons of the large relative variability from single solar power plants to the lower relative variability for broader, larger megawatt deployment scenarios (further illustrating the geographic diversity smoothing effect), a comparison of five-minute and 15-minute ramp distributions (which could be useful for informing ancillary service duration needs), and further “heat map” and distributional representations of the diurnal and seasonal variability characteristics for the baseline and expansion scenarios. Interested readers are directed to the full report.

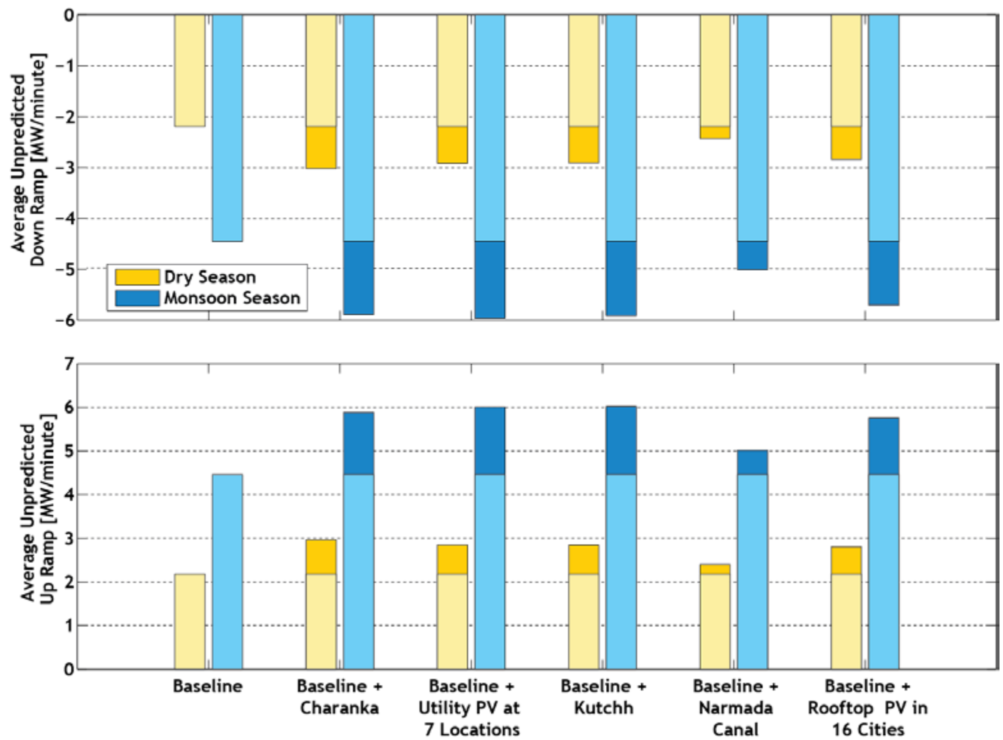

Figure 12. Average minute-to-minute change in solar production, normalized by expected clear sky solar production for the baseline scenario plus each expansion scenario. Darker tones reflect the incremental addition of ramps from the expansion scenarios.

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: 1) power can be physically evacuated from areas with high solar resources to where the electricity is needed and 2) 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.[19] The engineering study optimizes inter- and intra-state 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,

[19] "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.

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.[20]

The green corridors report identifie*d several infrastructure improvements for Gujarat, including increased interstate transmission capacity to b*etter 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. Additional transmission capacity connecting to flexible resources will also assist system operators with managing solar ramping.

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 Systems 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 be colocated in load dispatch centers in order to address some of the challenges to system operators in managing variable resources. Table 2 summarizes challenges to wind and solar integration that the proposed REMC would address.

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 system or automatic generation control	Automated coordination with load dispatch centers to manage variability of generators to control output, when necessary

Table 2. Challenges to renewable energy grid integration addressed by the proposed REMCs

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

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.[21,22] 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 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. The analysis in this paper 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

[21] Wind plants commissioned on or after May 3, 2010, and covered under the Renewable Regulatory Fund also must provide forecasting data.
[22] Forecasting protocols in India continue to evolve. For example, in March 2014, the CERC temporarily suspended penalties for failing to provide an accurate wind forecast, citing feedback from industry on the difficulty of predicting within the required 30 percent band for day ahead (www.bloomberg.com/news/2014-03-07/india-puts-wind-forecasting-on-hold-on-inaccurate-results.html).

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 a supervisory control and data acquisition system, 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.[23] 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.[24] 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 under consideration by the

[23] 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.
[24] *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.

Central Electricity Regulatory Commission,[25] and would likely replace system operators' existing tool for balancing—the unscheduled interchange mechanism.[26] 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.[27]

The type, magnitude, and timing of ancillary services can be tailored to meet the projected variability and uncertainty of renewable energy. The analysis in Section 4 illustrates the 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 ranges, 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 Indian rupees 3.56/kWh or near 6 U.S cents/kWh in June 2012) and must balance excess supply by backing down cheaper generation (Indian rupees 2.50-2.70/kWh, near 4 U.S. cents/kWh).[28] Other states may be deterred from purchasing Gujarat's renewable energy, for a number of reasons:

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[25] "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.

[26] 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.

[27] *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.

[28] *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.

- 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.

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),[29] and increased availability to revise interstate schedules.

5.4 Actions to Address the Variability of Solar Generation—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.

[29] 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

This work brings out several salient features that are important when evaluating potential future PV 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.
- 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 direct current capacity, the differences among scenarios are small.
- Results illustrate the power ramp rate differences between 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 reevaluating.
- 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 system 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.

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 subhourly wind variability and different potential future wind power generation scenarios are needed to more fully understand the challenges of increasing grid-connected renewable energy. The broader context calls for similar evaluation of wind power deployment scenario variability, which will be undertaken by the authors later in 2014.

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, and 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 to a grid with high penetration levels of variable 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; and balancing mechanisms and associated ancillary service and reserve procedures could be further analyzed.

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:[30,31]

- 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 REMC 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.

[30] 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.

[31] 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.