



# Developing High PV Penetration Cases for Frequency Response Study of U.S. Western Interconnection

## Preprint

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# Developing High PV Penetration Cases for Frequency Response Study of U.S. Western Interconnection

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**Abstract**—Recent large penetrations of solar photovoltaic (PV) generation and the inertial characteristics of inverter-based generation technologies have caught the attention of those in the electric power industry in the United States. This paper presents a systematic approach to develop test cases of high penetrations of PV for the Western Interconnection. First, to examine the accuracy of the base case model, the Western Electricity Coordinating Council (WECC) model is validated by using measurement data from synchronized phasor measurement units. Based on the 2022 Light Spring case, we developed four high PV penetration cases for the WECC system that are of interest to the industry: 5% PV+15% wind, 25% PV+15% wind, 45% PV+15% wind, 65% PV+15% wind. Additionally, a method to project PV is proposed that is based on collected, realistic PV distribution information, including the current and future PV power plant locations and penetrations in the WECC system. Both the utility-scale PV plant and residential rooftop PV are included in this study.

**Keywords**—WECC; high PV penetration; PV projection; frequency response.

## I. INTRODUCTION

In recent years, solar power technologies have been experiencing rapid development in the United States. Most states have committed to high renewable portfolio standards (RPS) in the near future [1, 2]. For example, California is leading the goal to achieve 50% by 2030, and most other U.S. states have RPS that require approximately 10%–40% of their annual electricity sold. Solar will be a main contributor to RPS according to the latest data on renewable generation installation. For example, in 2015 solar was the largest source (69%) of RPS construction [1].

The SunShot Vision Study (DOE 2012) suggests that solar energy could satisfy approximately 14% of U.S. electricity demand by 2030 and 27% by 2050 [3]. To achieve these goals, significantly more installed capacity and instantaneous power penetration levels of solar should be considered for system operation because of solar generation's low capacity factor and high uncertainty.

Large-scale renewable deployment will bring challenges [4-8]; one is to ensure that the electric power system can operate reliably. Frequency response (FR)—the ability of the power system to stabilize and arrest frequency deviations following large, sudden mismatches between generation and

load—has always been an important operational concern. Recent studies have shown that frequency response has been declining in both the Eastern and Western interconnections during the past several years [9-12]. In the future, with a high penetrations of solar photovoltaic (PV), more synchronous generators may be replaced by utility-scale or distributed PV resources. This may further exacerbate the frequency response of the grid because current PV generation normally operates at its maximum power output without the capability to provide frequency support, which can be provided by conventional generators.

A number of previous studies have examined the effects of PV on distribution systems. Most research efforts have focused on distribution systems because the installed PV is assumed to be small enough to have little effect on a transmission system. In recent years [13], however, driven by the SunShot Vision Study, the impact of high penetrations of PV on transmission systems has caught the attention of industry and academics. These studies have examined the impacts of high penetrations of renewable generation on transmission systems. Ref. [7] studied the impact of increased penetrations of PV on the static performance and transient stability of a large power system. Ref. [4] presented a comparative investigation of the effect of PV on system stability in Ontario's power system at different penetration levels. Ref. [14] investigated the potential contributions of variable-speed wind generation on the Eastern Interconnection system frequency regulation. Ref. [15] focused on studying the frequency response of the Californian system under high wind and solar conditions. The base case in this study considered instantaneous penetrations of wind and solar at penetration levels as high as 17% in the Western Electricity Coordinating Council (WECC) and 37% in California.

Since 2010, the National Renewable Energy Laboratory (NREL) and General Electric (GE) have conducted phases of the Western Wind and Solar Integration Study with different focuses, including long-term operational and economic performance, frequency response and transient stability, and operation and control [16-18]. Ref. [16] investigated the WECC system's operation under scenarios of high wind, high solar, and a high mix. In this study, NREL's Regional Energy Deployment System (ReEDS) model [19] was used to site the wind and solar power plants for each scenario. Ref. [20] examined the Western Interconnection's transient stability and frequency response under high penetrations of

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instantaneous wind and solar. Based on the modified WECC 2022 Light Spring (2022LSP) power flow and dynamic simulation base case, a high renewable case and an extremely high renewable case were developed.

Most of the aforementioned studies showed that high penetrations of renewables can have diverse effects on system frequency response and transient response. Note several key points: 1) some high PV cases for the WECC studies are not actual representations of a larger, interconnected power system [7]. 2) Wind power is the dominant resource in the aforementioned studies in the mixed wind and solar cases [9, 11]. 3) The method to locate PV sites throughout the large interconnection is either extremely simplified [7], [15] or based on the self-developed tool to which the public has no access [16, 18]. For example, in [7], PV is added to only a portion of the system, and there is a relatively large amount of conventional generation and export to other areas; [15] divides the WECC into the areas of California and non-California, and the increase in penetration level of PV is based on a rule of thumb. It is therefore necessary to generate more realistic PV penetration scenarios based on current publicly available data.

The first step is to comprehensively prepare the scenarios, evaluation metrics, power flow models, and dynamic models; these are also the keys to ensuring a reliable case study of a realistic electric grid. Therefore, this paper has two main contributions: 1) it explores a systematic approach to developing cases of high penetrations of PV for a realistic bulk electric grid—the Western Interconnection—based on publicly accessible data; and 2) it developed reasonable cases of high penetrations of PV, which include a case with 100% regional instantaneous penetration and a case of 80% renewable instantaneous penetration (65% PV+15% wind) in the Western Interconnection based on the detailed model. To the best of our knowledge, this is the highest PV penetration case developed for the Western Interconnection.

This paper is organized as follows. Section II provides an overview of the metrics used for the frequency response study. In Section III, the Western Interconnection model is validated by measurement data and analyzed. Section IV discusses the approach to developing the high PV penetration cases based on various databases, e.g., National Solar Radiation Data Base (NSRDB) data, Solar Energy Industries Association (SEIA) report, RPS data sheet. Section V shows the distribution results, and Section VI concludes.

## II. EVALUATION METRICS DEVELOPMENT

Setting a proper frequency response standard and metrics is essential for planning and operating an interconnection. To comprehensively investigate the frequency response of the U.S. interconnections, various frequency response metrics—which were adopted for the previous studies—have been summarized and extracted in this section. This work aligns with the objective of the North American Electric Reliability Corporation (NERC)’s Frequency Response Initiative to improve frequency response performance tracking by developing proper metrics and benchmarks [21].

The previous metrics can be roughly divided into three categories for different purposes: frequency evaluation

metrics under abnormal operation, frequency evaluation metrics under normal operation, and system-level metrics.

### A. Frequency Evaluation Metrics: Abnormal Operation

#### 1) Single-Event-Based Metrics

Since 2000, NERC and other industry experts have worked on defining consistent criteria to evaluate frequency response [22]. Fig. 1 shows a measured frequency excursion caused by a loss of a generation in the U.S. Western Interconnection.

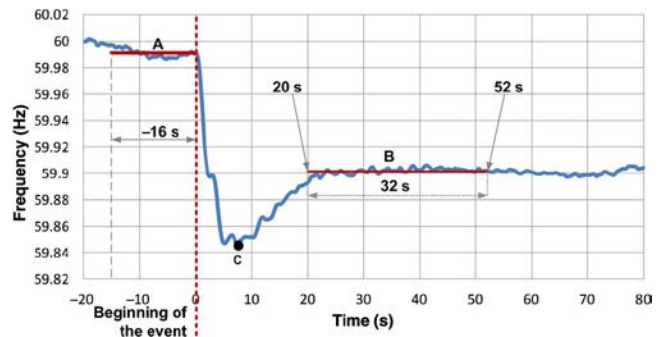


Figure 1. Description of BAL-003-1 frequency response metrics [9].

When an event happens, the inertia and primary frequency response of the system determines the lowest frequency ( $f_C$ ), which should be kept above the setting of the underfrequency load shedding (UFLS). The settling frequency ( $f_B$ ) is defined as the average frequency approximately from  $t=20$  seconds to  $t=52$  seconds after the event, which reflects the continued delivery of primary frequency response (PFR). The predisturbance frequency ( $f_A$ ) is defined as the average frequency approximately from  $t=-16$  second to  $t=0$  second, which is also a significant contributor to the variability of frequency response [21]. In 2011, Lawrence Berkeley National Laboratory (LBNL) proposed a metric called nadir-based frequency response (N-FR) to reflect the amount of generation needed to arrest the frequency and PFR to measure the power actually delivered by the primary frequency control at a specific time [23]. Based on previous technical studies during several decades, the discussion about the frequency response standard culminated in the approval of Standard BAL-003-1—Frequency Response and Frequency Bias Setting Reliability Standard in 2014 by FERC [24]. Other metrics are summarized in Table I.

TABLE I. SUMMARY OF THE FREQUENCY RESPONSE METRICS

	Symbol	Metric	Ref.	Definition
A1	$f_{nadir}$	Frequency nadir (Hz)	[9, 21, 23]	$f_C$
A2	$f_{pre}$	Predisturbance frequency	[21]	$f_A$
A3	ROCOF	Rate of change of frequency (mHz/s)	[9]	$\frac{f_A - f_C}{t_C - t_A}$
A4	$f_{settling}$	Settling frequency (Hz)	[9, 21]	$f_B$
A5	N-FR	Nadir-based frequency response (MW/0.1Hz)	[23]	$\frac{Power_{Lost}}{f_A - f_C}$
A6	FR	Frequency response (MW/Hz)	[25]	$\frac{Power_{Lost}}{f_A - f_B}$
A7	PFR	Primary frequency response at T1 (MW)	[23]	$Power_{deliver}(T_1)$

To eliminate the geographical dependency of the measurement, a way to measure the frequency is to use several measurements and then calculate the center of inertia (COI) frequency [26]. The system frequency was calculated from the frequency of each individual generator based on the concept of the COI frequency; the expression follows:

$$f_{\text{sys}} = \frac{\sum_{i=1}^N H_i \cdot f_i}{\sum_{i=1}^N H_i} = \frac{1}{H_T} \sum_{i=1}^N H_i \cdot f_i \quad (1)$$

where

$H_i$ : inertia constant of the  $i$ th synchronous generator

$f_i$ : the frequency of the  $i$ th synchronous generator.

### 2) Statistical-Analysis-Based Metrics

For the balancing authorities, frequency response performance is not a sufficient metric by which to judge compliance on a per-event basis. Normally, a minimum of 20–25 sample events are recommended to provide a stable measure of frequency response for an interconnection. A linear regression method is the preferred method for calculating the frequency response [21].

A minimum frequency performance criterion for each interconnection has been established as well; this is called the Interconnection Frequency Response Obligation (IFRO). The IFRO is designed to avoid the first stage of UFLS based on statistical analysis and an evaluation of historical field-trial data. For example, the IFRO of the Western Interconnection requires  $-840 \text{ MW}/0.1 \text{ Hz}$  [21].

### B. Frequency Evaluation Metrics: Normal Operation

During normal operation, standards and metrics are developed in BAL-003-1 for the balancing authority to evaluate the performance of managing the interchange power, area control error, and frequency during time frames of 1 minute or longer. The Control Performance Standard 1 requirement is based on 1-minute averages, and the Control Performance Standard 2 requirement is based on performance measured for 10 minutes. These averages are then further aggregated during the course of an entire year or month. Because this study mainly focuses on frequency response, descriptions about these metrics are omitted here.

### C. System-Level Metrics

The frequency response is determined by the amount and types of the generation and load on the grid. Table II shows the critical factors of generation and load as they relate to frequency performance [18, 25].

TABLE II. CASE SUMMARY METRICS

	Symbol	Metric Description
C1	$P_{\text{gen}}$	System generation (GW)
C2	$P_{\text{GR}}$	Generation of units with governor (GW)
C3	$P_{\text{mc}}$	Capacity of the units with governor (GW)
C4	$P_{\text{hr}}$	Headroom of units with governor (GW)
C5	$P_{\text{px}}$	Generation of units without governor (GW)
C6	$P_{\text{wind}}$	Power generation of wind (GW)
C7	$P_{\text{solar}}$	Power generation of solar (GW)
C8	$P_{\text{load}}$	System load (GW)
C9	Kt (%)	Ratio of governor-responsive generation to total
C10	$H_{\text{sys}}$	Equivalent system inertia (s)

The increased variable renewable generation will affect the efficacy of frequency control actions from several aspects: 1) reduce the system inertia, which can be reflected by  $H_{\text{sys}}$ ; 2) potentially displace the synchronous generator with the governor, which can be reflected by  $P_{\text{GR}}$ ; 3) potentially reduce the frequency control reserve, which can be reflected by  $P_{\text{hr}}$ ; (4) affect the location of the primary frequency control reserves, which can be reflected by the interchange power of the tie-line.

In 2010, LBNL introduced a ratio as the metric Kt [27]: the lower the Kt, the smaller the fraction of generation that will respond. The exact definition of Kt is not standardized, but a reasonable definition according to industry discussions is still warranted. In this paper, it is defined as follows:

$$\text{Kt}(\%) = \frac{P_{\text{mc}}}{P_{\text{mc}} + P_{\text{px}} + P_{\text{wind}} + P_{\text{solar}}} \times 100 \quad (2)$$

The equivalent system inertia is:

$$H_{\text{sys}} = \frac{K.E.}{\text{SUM}(VA_{\text{base}})} \quad (3)$$

where:

$$K.E. = \sum_{i=1}^n H_i \times VA_{\text{base}_i} \quad (4)$$

$H_i$ : inertia constant of the  $i$ th synchronous generator [s]

$VA_{\text{base}_i}$ : rating of the  $i$ th synchronous generator [MVA]

$VA_{\text{base}}$ : total online rating of the grid [MVA]

$K.E.$ : kinetic energy at the rated speed [MW·s].

The metrics introduced here are developed to provide a tool to guide and gauge the impact of renewables on frequency response and operation of the grid. Different metrics can be flexibly chosen, adjusted, and added according to the different purposes of the study.

## III. MODEL VALIDATION AND DEVELOPMENT

Accurate dynamic modeling is important for power system dynamic simulations and frequency response analysis. Following the 1996 blackouts in the western United States, WECC updated, validated, and calibrated its operation and planning models. WECC base cases have been recognized for their consistency and accuracy in general.

Because this paper focuses on developing future scenarios of high penetrations of solar for a frequency response study in WECC, a base case with a significant amount of planned renewable generators as well as low loading levels is an ideal benchmark for this development. The WECC 2022 Light Spring case was used as the base case for multiple studies of high renewable penetration levels and has the most current available renewable generation in the low-load system [8]; therefore, this case is used as the base case for the WECC study in this paper.

### A. Model Validation Using Synchrophasor Frequency Measurement

To ensure the accuracy of the dynamic model of the base case, a sanity check is suggested to be applied by comparing the dynamic frequency response of the adopted WECC model to the FNET/GridEye frequency measurement data [28]. Although it is impossible to check the accuracy of the

future scenario model by using current year measurements, it is reasonable to compare light spring cases in recent years to the FNET/GridEye recording for accuracy with the knowledge that the future planning cases are based on current system structures.

Four generation trip events that occurred in spring 2015 are used for the validation; these are shown in Table III.

TABLE III. EVENTS AND ESTIMATED AMOUNT

Event	Date	Time (UTC)	Estimated Generation Trip (MW)
A	03/03/2015	22:24:50	783.5
B	04/05/2015	19:57:52	805.0
C	04/26/2015	17:53:23	605.0
D	05/06/2015	02:00:23	715.0

Because WECC did not publish the 2015 light spring case, the simulations are conducted by comparing the 2016 light spring case to the FNET/GridEye measurements. The FNET/GridEye frequency measurement data are selected from six different locations. The fault locations and generation trip amounts estimated by FNET/GridEye are used to decide the simulation scenarios. One test case is given in this section as an example, as shown in Fig. 2.

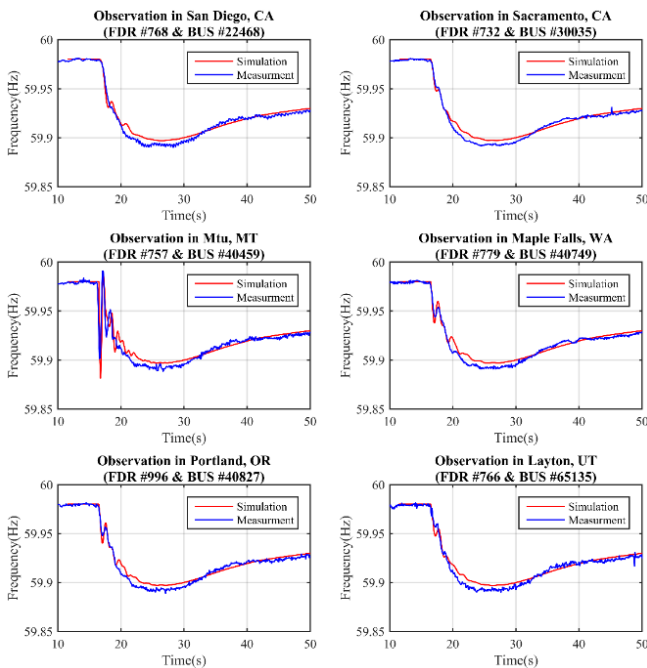


Figure 2. WECC model sanity check results

Fig. 2 shows that the simulated frequency response curves match well with the actual measured curves. Further, the frequency oscillation can be observed at FDR #757, which is located in Montana. In the simulation, those oscillations are replayed. In particular, the first- and second-swing frequencies are accurately captured by the simulation. This means that this WECC model can truly reflect the frequency response dynamics of the WECC system during the event. This proves that the validated model has high fidelity.

### B. Base Case Overview

The 2022 Light Spring case was developed to look at a high-renewables future from the WECC planning

perspective; this includes wind and solar build-out. The renewable penetrations in this case are intended to be consistent with state RPS requirements in 2022.

A detailed understanding of the type of generation in the simulations is critical to gain insight into the effects of increased variable renewable generation. The 2022 Light Spring case is modeled at a very detailed level with more than 19,000 buses and more than 4,000 generators. It contains 21 areas, 424 zones, and 492 owners. Each type of power plant has corresponding dynamic models, including generator, exciter, and turbine governor models; these can vary widely because of the diversity in power plant configurations. Fig. 3 and Fig. 4 show the types and numbers of the generator dynamic models and prime mover models in the 2022 Light Spring case.

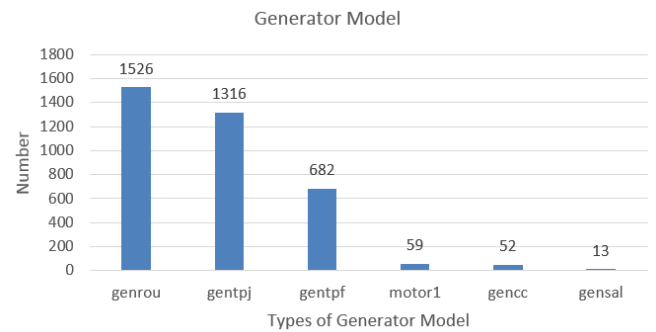


Figure 3. Number of generator models in the WECC 2022 Light Spring case.

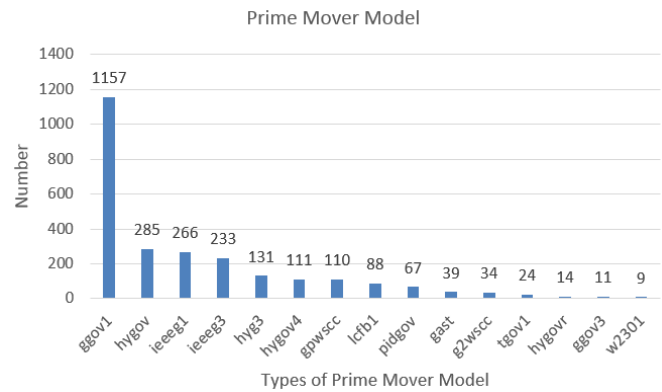


Figure 4. Number of prime mover models in the WECC 2022 Light Spring case.

A comparison of Fig. 3 to Fig. 4 shows that not all the synchronous generators are installed with governor models, which means that not all the synchronous generators can provide frequency response control. In reality, relatively few steam units provide governor response [25]. Nuclear power plants usually do not provide governor response because it is normally used to support the base load. Frequency response for the bulk system is mainly provided by hydropower, combined-cycle, and gas turbine generators.

Note that the dynamic model for each generator category, especially for the wind and solar units, needs close scrutiny. Because the dynamic behavior of wind and solar power plants is substantially different from that of thermal and hydro plants, it is important that the estimated models have the correct basic dynamic characteristics. In this case, wind power plants are modeled by Type 1, Type 2, Type 3, and Type 4 wind generation models and Type 3 and Type 4 GE wind turbine

models. Solar units are modeled by Type 4 or GE Type 4 wind generation models without the turbine models. All synchronous machines will provide inertial response. Wind and solar will not provide frequency response in this case.

Table IV summarizes the instantaneous output and penetration level of the total generation, load, wind and PV generation.

TABLE IV.  
SUMMARY OF GENERATION AND LOAD IN WECC 2022 LIGHT SPRING CASE

	Capacity	P <sub>gen</sub>
<b>WECC System Total (MW)</b>	312438	117238
<b>Load (MW)</b>	N/A	112990
<b>Wind Power</b>	26323	16464
<b>Wind Power Penetration</b>	8.4%	13.9%
<b>PV (MW)</b>	1838	1347
<b>PV Penetration (%)</b>	0.6%	1.1%

Table IV shows that the total generation in the 2022 Light Spring case is 117 GW; wind power is the largest renewable resource, at approximately 13.9% instantaneous penetration; and PV is a small portion of the renewables, at only 1.1% instantaneous penetration.

#### IV. SCENARIO DEVELOPMENT

The goal of this section is to collect realistic PV distribution information, including the current PV power plant location and penetration and future PV levels and locations in the WECC system. This information can be further used to develop a realistic baseline of the power system and different high-penetration scenarios based on the 2022 Light Spring case. In addition, to project PV distribution by states/areas, the collected PV resource data are used, including rooftop PV and utility-scale PV resource potential. After the generation composition is altered, the test cases are initialized to ensure that they are at steady state. This ensures that the load-generation balance has been achieved and that the test cases can be used for further analysis.

##### A. General Scenario

Based on the survey of 14 industrial participants from electric utilities, national labs, and research institutes from among all three U.S. interconnections, the to-be-developed scenarios are suggested in Table V.

TABLE V. SCENARIOS OF WIND AND PV CAPACITY AND INSTANTANEOUS PENETRATION IN WECC

Scenario	Wind Instantaneous Penetration	PV Instantaneous Penetration	PV Power Output (GW)
2022 LSP	14%	1%	1.3
20% RIP	15%	5%	5.9
40% RIP	15%	25%	29.4
60% RIP	15%	45%	52.8
80% RIP	15%	65%	76.3

RIP: renewable instantaneous penetration

In summary, the instantaneous penetration level of wind power is maintained at 15% in four PV penetration scenarios, and the instantaneous penetration level of PV is 5%, 25%, 45%, and 65%. The total renewable instantaneous penetration level in WECC reaches 20%, 40%, 60%, and 80%. A regional level of 100% PV is also suggested to be built because of strong interest from some electric utilities.

##### B. PV Distribution Projection for WECC

###### 1) Data Resource for PV Distribution

In April 2016, SEIA updated a list of major solar projects in the United States for informational purposes only [29]. The information in this list was gathered from public announcements of solar projects in the form of company press releases, news releases, and, in some cases, conversations with individual developers.

The NSRDB is a NREL-developed and publicly available database. It is a collection of meteorological and solar irradiance data sets for the United States and a growing list of international PV power plant locations. The NSRDB compiled some information from the SEIA database with some additions from independent NREL research and generated a location map of operational, utility-scale PV projects in the United States [30]. Some data resources used for PV projection in WECC are summarized in Table VI.

TABLE VI.  
SUMMARY OF DATA RESOURCE FOR WECC PV DISTRIBUTION PROJECTION

Data Resource	Description	Usage
NSRDB Data	Estimated PV power data based on average annual direct normal irradiance	<ul style="list-style-type: none"> <li>To build out utility-scale PV at the state level</li> <li>As a reference for PV location and distribution in different states.</li> </ul>
WECC 2022 LSP Base Case	Load and generation for different areas and renewables location and penetration	<ul style="list-style-type: none"> <li>Provides current PV penetration and distribution of the 2022 LSP base case</li> <li>As a reference for the maximum penetration in each area and future dynamic simulations.</li> </ul>
SEIA's Data	Current capacities and locations for utility-scale PV project in different states	<ul style="list-style-type: none"> <li>Real data as a reference for the minimum installed capacity and penetration.</li> </ul>
RPS 2022 Data Sheet	RPS 2022 goals by state and type, capacity, location, and project process of renewable projects.	<ul style="list-style-type: none"> <li>As a reference for future PV distribution in different states</li> <li>To improve the dynamic model in future studies.</li> </ul>

SEIA stated that in 2014 new installed solar PV capacity in the United States was 6,200 MW, with 3,900 MW of utility-scale PV, 1,000 MW of commercial PV, and 1,200 MW of residential PV [31]. This is approximately 63% utility-scale and 37% commercial/residential PV. The bulk of the PV (79%) has been in the West, with 17% in the East. So it is fair to build out a PV scenario that is 60% utility-scale and 40% rooftop PV.

###### 2) Renewable Siting Method

This study proposes using the PV resource data as indicators to distribute solar build-out by states/areas. Rooftop PV and utility-scale PV are distinguished because of the significant difference in technique and installing conditions and the methods to estimate their technical potentials. We use NSRDB data to decide the future utility-scale PV distribution, and results' from NREL's previous work are adopted to distribute the future rooftop PV [32]. Several assumptions were made for the study:

1. This study was not a transmission planning study. To reduce the impact of transmission-related issues, the renewable penetration level was increased without modifying the interchange power flow among the WECC areas.
2. According to the analysis in Section IV-B-1 of historical data, all PV scenarios comprise 60% utility-scale PV and 40% rooftop PV.
3. The 2022 Light Spring base case has 21 areas in the model of the positive sequence load flow analysis software. To maintain consistency, the statewide solar technical potential data will be manually and roughly distributed to the areas according to the geographic locations.
4. The minimum PV capacity was aligned with SEIA's data, and the maximum PV capacity was aligned with the rooftop PV technical potential and utility-scale technical potential, respectively.

Because the purpose of this study is to investigate the frequency response of WECC, and frequency is a system-wide indicator, our effort is mainly to make high PV scenarios more realistic in terms of resource distribution in different areas. The initial renewable penetration condition in the 2022 Light Spring base case was used as a starting point. The rooftop PV was distributed to each area proportional to the rooftop PV technical potential. In the same manner, the utility-scale PV was proportionally projected according to utility-scale PV technical potential, which was estimated by using NSRDB data. Some realistic resource constraints and operational constraints were considered, such as the maximum and minimum installed PV capacity in each area and the exchange of power flow among the areas. If a certain penetration level could not be fulfilled with all constraints, partial constraints were relaxed until that penetration level was reached. The flowchart of this process is shown in Fig. 5.

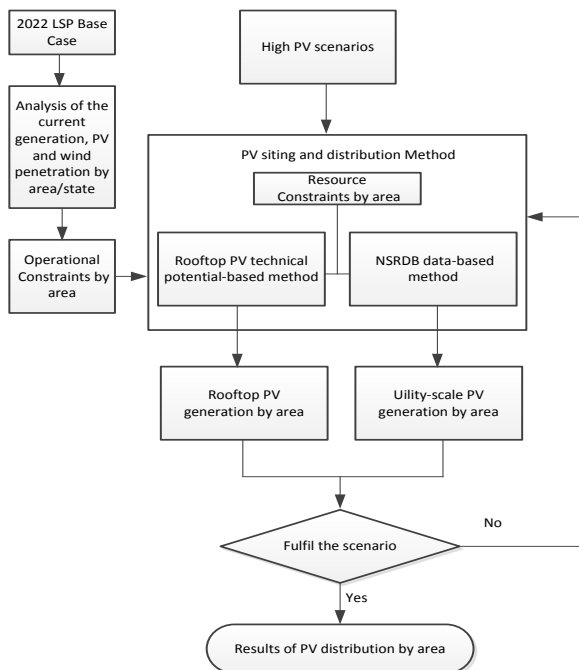


Figure 5. Flowchart of PV distribution projection in WECC.

### Rooftop PV Technical Potential-Based Method

The rooftop PV technical potential data are from a recent NREL report [32]; the report provides a detailed data-driven analysis of U.S. (at the national, state, and ZIP code level) rooftop PV availability and technical electricity generation potential. This study provides a realistic estimation of future rooftop PV installation. According to the report, the total estimated technical potentials for rooftop PV by state are shown in Table VII.

TABLE VII. TOTAL ESTIMATED TECHNICAL POTENTIAL (ALL BUILDINGS) FOR ROOFTOP PV AND UTILITY-SCALE PV BY STATE

State		CA	AZ	UT	CO	NM	WA
R	Installed Capacity Potential (GW)	129	16	7	16	6	22
	Population (in Millions)	39	6.8	3.0	5.5	2.1	7.2
	Percentage (%)	56	7	3	7	2.7	9.9
U	Total Energy (1,000 GWh)	164	122	91	105	128	61
	Percentage (%)	13.6	10.1	7.5	8.7	10.6	5.1
State		NV	WY	ID	MT	OR	
R	Installed Capacity Potential (GW)	8.70	1.70	4.70	3.20	14.10	
	Population (in Millions)	2.9	0.6	1.7	1.0	4.0	
	Percentage (%)	3.8	0.7	2.0	1.4	6.1	
U	Total Energy (1,000 GWh)	121	99	82	139	94	
	Percentage (%)	10.0	8.2	6.8	11.5	7.8	

R: Rooftop PV; U: Utility-scale PV

### NSRDB Data-Based Method

The NSRDB data set provides the estimated PV average power that is converted from the irradiance data by considering geographic factors (e.g., site latitude, longitude, elevation), weather factors (e.g., ambient temperature and wind speed), and PV cells technology. The reliable data resource can represent a state's typical solar generation for the whole year (for example, see Arizona, California, Colorado, and Idaho in Fig. 6), which can be used for utility-scale PV development.

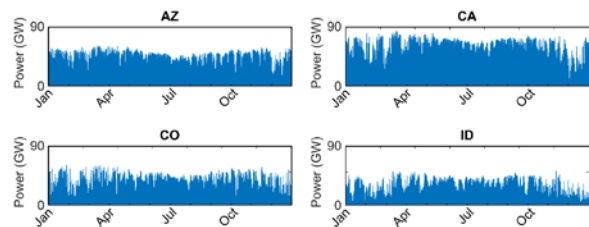


Figure 6. PV potential estimation in the form of power (2014).

In this study, we use one-year PV power data by states to roughly estimate the technical potential of the utility-scale PV shown in Table VII. Note that this estimation is from the perspective of the solar resource, and some other factors can be considered to improve the accuracy of the technical potential estimation of the utility-scale PV, such as potential land use and transmission build-out.

## V. RESULTS AND DISCUSSIONS

The projection results of instantaneous penetration level and power output of rooftop PV, utility-scale PV, and wind by area in WECC are shown in Fig. 7.



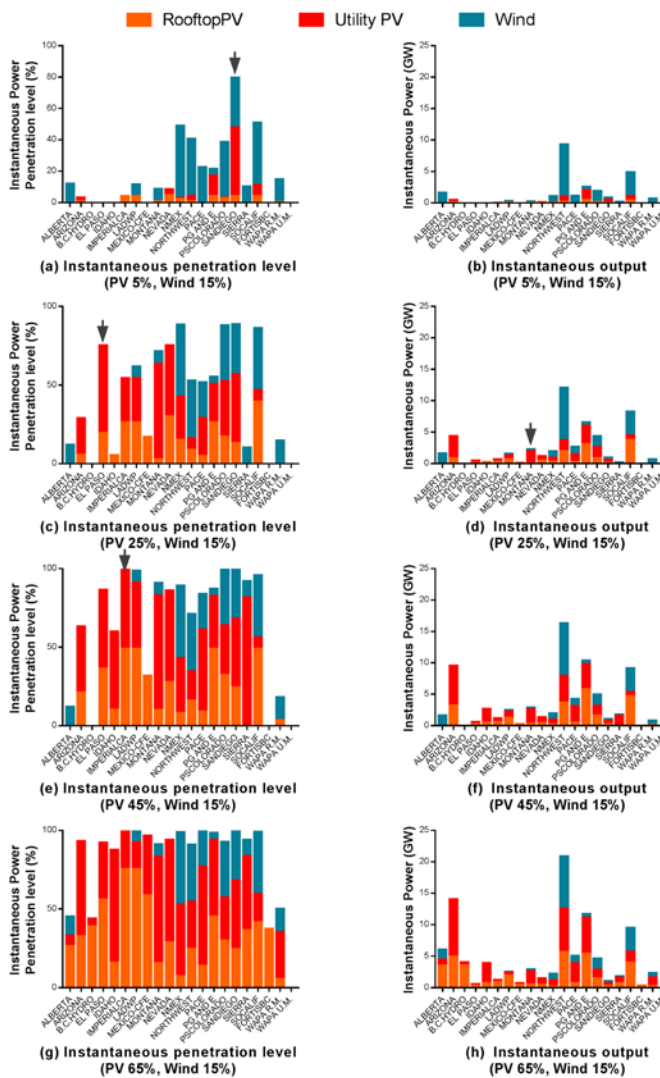


Figure 7. PV and wind penetration level and instantaneous power output for each area in WECC.

The bar plot shows the wind (blue), rooftop PV (orange) and utility-scale PV (red), respectively. A summary of the PV distribution in WECC is also given below:

### 20% Renewables Scenario (5% PV)

- In this case, the SANDIEGO area (located in California) has the highest regional instantaneous PV penetration level and renewable penetration level, which are 47.84% and 79.54%, respectively (see the arrow in Fig.7 (a)). One of the main reasons for this is because the original PV and renewable penetration level in this area is already as high as 43.73% and 75.43% in the 2022 Light Spring base case.
- The difference between the pattern of penetration level and power output can be observed. For example, SANDIEGO is a relative small area with a low amount of generation, even though it has a high penetration level of renewables.
- To fulfil the 15% wind penetration level, we increase the NORTHWEST area's instantaneous wind power output to 8350.76 MW according to [20].

### 40% Renewables Scenario (25% PV)

- Rooftop PV and utility-scale PV increased significantly compared to the 20% renewables scenario.
- SOCALIF (California), PG&E (California), and ARIZONA are the main contributors to this.
- EL PASO's (Texas) regional PV penetration level reaches as high as 75% in this case (see the arrow in Fig.7 (c)).
- The main PV contributors in MONTANA are utility-scale PV (see the arrow in Fig.7 (d)).

### 60% Renewables Scenario (45% PV)

- As the PV penetration level increases further, some areas will hit the upper boundary of the maximum for the area's generation when we distribute PV proportionally according to the resource-based method. Some modifications were applied in this case to keep the interchange among areas unchanged.
- The regional renewable penetration level in six areas reaches 90%: SANDIEGO (California), IMPERIALCA (California), PSCOLORADO (Colorado), LADWP (California), SOCALIF (California), and SIERRA (Nevada).
- IMPERIALCA (California) reaches a 100% PV penetration level (see the arrow in Fig.7 (e)).
- California and Arizona are the main contributors to increased PV generation.

### 80% Renewables Scenario (65% PV)

- In this case of extremely high PV penetration, we need to artificially increase the PV in the northern states to fulfill the total PV penetration goal. For example, northern states such as B.C.HYDRO and ALBERTA need more installed PV, which breaks the constraints of the ratio of PV in different states.
- The penetration levels of renewables in 15 states are more than 90%.
- California, Arizona, and the Pacific Northwest are the main contributors to the increased PV generation.

## VI. CONCLUSION

This paper has summarized useful metrics for frequency response, validated the WECC model with the measured frequency data, and developed a systematic method to project the PV in WECC by area.

Among the proposed scenarios, the highest wind and solar instantaneous penetrations in the Western Interconnection can reach 80%, composed of 65% PV and 15% wind. A 100% regional PV penetration case is created in IMPERIALCA in California. The total ratio of the utility-scale PV and the rooftop PV in WECC is 6:4. A practical method to distribute newly added PV by area is proposed based on realistic PV projects from various publicly accessible data resources. Rooftop PV and utility-scale PV are distinguished and projected based on their technical

potential by states/areas. All the constraints of the distribution method can be calculated and achieved based on NREL-published NSRDB data and reports.

The result shows that California and Arizona are the main contributors to increased PV generation. To fulfil the scenario of extremely high PV penetration (80% in WECC), the northern areas, such as B.C.HYDRO and ALBERTA, need to provide additional PV generation. Future power systems with low rotational inertia will make frequency control and power system operation more challenging. The work presented in this paper will be used for a follow-on study funding by the U.S. Department of Energy on the “Frequency Response Assessment and Improvement of Western Interconnection because of High Penetrations of Photovoltaic Generation.”

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