USER REQUIREMENTS AND RESEARCH NEEDS FOR RENEWABLE GENERATION FORECASTING TOOLS THAT WILL MEET THE NEEDS OF THE CAISO AND UTILITIES FOR 2020

A White Paper Report

Prepared by CIEE

Authors: Lloyd Cibulka, Merwin Brown, Larry Miller, Alexandra Von Meier
Date: September, 2012

A CIEE Report

ACKNOWLEDGEMENTS

The authors wish to acknowledge the technical contributions of all those we interviewed for this white paper, and the community of renewables forecasting researchers whose conference presentations and published technical papers cited herein provided invaluable information on the state of the forecasting art and on the needs of users of the technology.

Special thanks are due to the following persons for their input, guidance and support on numerous occasions: Jim Blatchford of the California Independent System Operator (CAISO); Dr. Case Van Dam of the University of California, Davis (UCD); Byron Washom, Dr. Jan Kleissl and Dr. Carlos Coimbra of the University of California, San Diego (UCSD); Kevin Cross of Pacific Gas & Electric Co. (PG&E); and Jack Peterson of Southern California Edison Co. (SCE).

The leadership and technical guidance of the Energy Commission, and in particular Jamie Patterson, Fernando Pina, Avtar Bining and Consuelo Sichon, is especially acknowledged and appreciated.

PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

User Requirements and Research Needs for Renewable Generation Forecasting Tools That Will Meet the Needs of the CAISO and Utilities for 2020 is the report for the Energy Commission project Staff Workshops Forums on Integrating Renewable Generation with the Electricity Grid (contract number 500-10-055, work authorization number WA002), Task 2: White Paper on User Requirements and Research Needs for Renewable Generation Forecasting Tools That Will Meet the Needs of the CAISO and Utilities for 2020, conducted by the California Institute for Energy and Environment. The information from this project contributes to PIER's Energy Systems Integration Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

The objectives of this white paper were to: assess the current state of the art in renewable generation (solar and wind) forecasting tools, including their various components, reliability, shortcomings, and the current research efforts to improve these tools; determine the specific requirements of the California end-users of the technology, including the CAISO and the California utilities, for effective management of renewable resources as California strives to achieve 33% renewable penetration by 2020 in accordance with the state's Renewable Portfolio Standard (RPS); and determine the renewable forecasting technology gaps that will exist by 2020, and identify the research efforts necessary to address those gaps. This white paper is intended to provide information that will help target future solicitations for research toward applications that will help California better reach its near-term renewable energy goals.

Keywords: California Energy Commission, renewable energy, forecasting, RPS, Renewable Portfolio Standard, solar generation, wind generation, renewable penetration.

Please use the following citation for this report:

Cibulka, Lloyd; Brown, Merwin; Miller, Larry; von Meier, Alexandra. (California Institute for Energy and Environment). 2012. ***User Requirements and Research Needs for Renewable Generation Forecasting Tools That Will Meet the Needs of the CAISO and Utilities for 2020.*** California Energy Commission. Publication number: CEC-XXX-2012-XXX.

TABLE OF CONTENTS

Acknowledgements i

PREFACE iii

ABSTRACT iv

TABLE OF CONTENTS v

Introduction 1

Purpose of the White Paper 1

Renewables Forecasting Technology – Overview 1

Renewables Forecasting in Electric System Operations – Overview 2

Findings of the Dec. 16, 2012 Renewables Forecasting Workshop 1

Purpose of the Workshop 1

Solar and Wind Forecasting: Achieving a 33% Solution (CAISO) 1

Wind and PV Forecasting (SDG&E) 2

Renewable Resource Forecasting (SCE) 3

Perspectives on Renewables Forecasting (PG&E) 4

Solar and Wind Forecasting: Achieving a 33% Solution (UWIG) 4

UCSD Microgrid (UC-San Diego) 4

Summary of DOE Renewable Resource Forecasting R&D (US DOE) 5

Wind Forecasting Research Efforts (UC-Davis) 6

Solar Forecasting Concepts and Summary of Research Projects at UCSD 6

SolAspect Forecast Engine (UC-San Diego) 7

PV Output Variability Modeling (Clean Power Research) 7

Multiple Look-ahead Time Scale Solar Generation Forecast System (AWS TruePower) 7

Renewables Forecasting & Integration (KEMA) 8

Wind & Solar Forecasting (Enernex) 9

Predicting Uncertainties for Real-Time and Day-Ahead Operations (PNNL) 10

Roundtable Discussion on User Needs 10

Information Supplemental to Workshop 12

Overview 12

Summary of Responses to Workshop 12

UVIG Variable Generation Forecasting Workshop, Tucson, AZ, February 8-9, 2012 15

CAISO Renewable Forecasting Tool Specification 19

Recommended Research Areas and User Needs **19**
Solar Forecasting .... **Error! Bookmark not defined.**
Wind Forecasting .... **Error! Bookmark not defined.**
User Needs 22
References **24**
Solar Forecasting References 24
Wind Forecasting References 25
Links .... **Error! Bookmark not defined.**

Introduction

Purpose of the White Paper

The purpose of this White Paper is to present the findings of the Dec. 12, 2011 Renewables Forecasting Workshop, and the subsequent and associated activities, to identify the user requirements and research needs for forecasting tools needed by the CAISO and the utilities. These determinations are intended to be used in research solicitations so that researchers can define and carry out research and development projects for forecasting tools that will meet one or more of the needs of electric customers, especially large customers such as a university, the CAISO and California utilities for use in 2020. This work will build on the foundations of Energy Commission-funded, and other known, renewables forecasting work completed and underway; will conduct literature searches and interactions with users and technical experts to identify additional developments needed as well as recent technical advances made; and will evaluate and assess information acquired before, during and following Energy Commission workshops and other industry meetings, including meetings with technical advisory committees, technology experts, and other stakeholders.

Renewables Forecasting Technology – Overview

The actual energy production of renewables plants is typically characterized by variability (changes due to time of day, season, etc.) and intermittency (smaller, short-term fluctuations in output on the order of seconds to minutes). The result is energy output that varies with the wind or solar input, and is difficult to predict or control, making integration with the existing mix of mostly controllable generating sources problematic, in that total generation must sum to the system load in real time, and system operators must deal with any imbalances lest adverse consequences to system reliability or adequacy result. Proposals for dealing with or mitigating the variable output of renewables include the application of storage systems, the use of which would make the output more dispatchable, but such solutions remain very expensive and not feasible in all locations. Another approach is to aggregate renewable plants over a wider geographic area; the principle being that the variations in plant outputs vary by area or region, and would tend to balance out in the aggregate, which would tend to improve overall forecasting accuracy. The approach addressed in this paper focuses on the application of various forecasting technologies and techniques, with the objective of estimating the output of renewable plants within certain accuracy bounds of magnitude and future time. These estimates are then provided in real time to system operators and utility personnel for the purposes of managing the operation of the electric system.

In general practice, meteorological data, in the form of solar insolation and wind speed at various monitoring locations, are fed into algorithms (computer-based models) that forecast the meteorological parameters at the desired times in the future, based on the real-time data, knowledge of past trends, and other factors. These estimates are then input into models of the renewable plants that produce forecasts of the plants' power output at various times in the future. The accuracy of the forecasts will depend on the number and locations of the monitoring locations, the accuracy of the meteorological forecasts, and the accuracy of the renewable plant models. Applications, or tools, are often developed and used to enhance the usefulness of the forecasts by translating the forecasts into actionable information, such as ramping resource requirements, for grid operators and planners (see Figure 1). Research and development is ongoing to provide continuing improvement at all stages of the forecasting process.

Renewables Forecasting in Electric System Operations – Overview

The primary purpose of forecasting of renewable generation in California, as elsewhere in the US and the world, is to determine as accurately as possible the output of wind and solar generation plants in the near term, typically for 15-minute, hour-ahead and day-ahead time periods. This information is provided in near-real time to electric system and utility operators and other end-users for the purpose of determining the required generation dispatch, reserve capacity requirements, and ancillary services requirements for the given time periods, in order to minimize the costs and impacts of renewable integration. If renewables forecasts turn out to be too high, under-scheduling of reserve capacity and ancillary services can result, with possible negative impacts to system reliability and resource adequacy, or at the minimum, excess costs for spot-market capacity. Forecasts that are too low can result in the scheduling of excess resources in the hour-ahead or day-ahead markets, which then must be compensated for cutting back their scheduled output to accommodate the renewables.

The closer the actual renewable plant output is to the forecast, the lower the difficulty to the system operator of scheduling the ramping capacity, generator reserves and other ancillary services required to compensate for the intermittency and variability of the renewable generation, and the lower the cost impact to ratepayers. Therefore, the ultimate goal of research in renewables forecasting is to improve the accuracy of the forecasts in order to reduce these impacts and their resultant costs.

Figure 1 illustrates both the number of research projects currently being conducted in California with DOE and PIER funding, but also how these advanced renewables forecasting technologies are being integrated into grid operations in a coordinated and comprehensive approach.

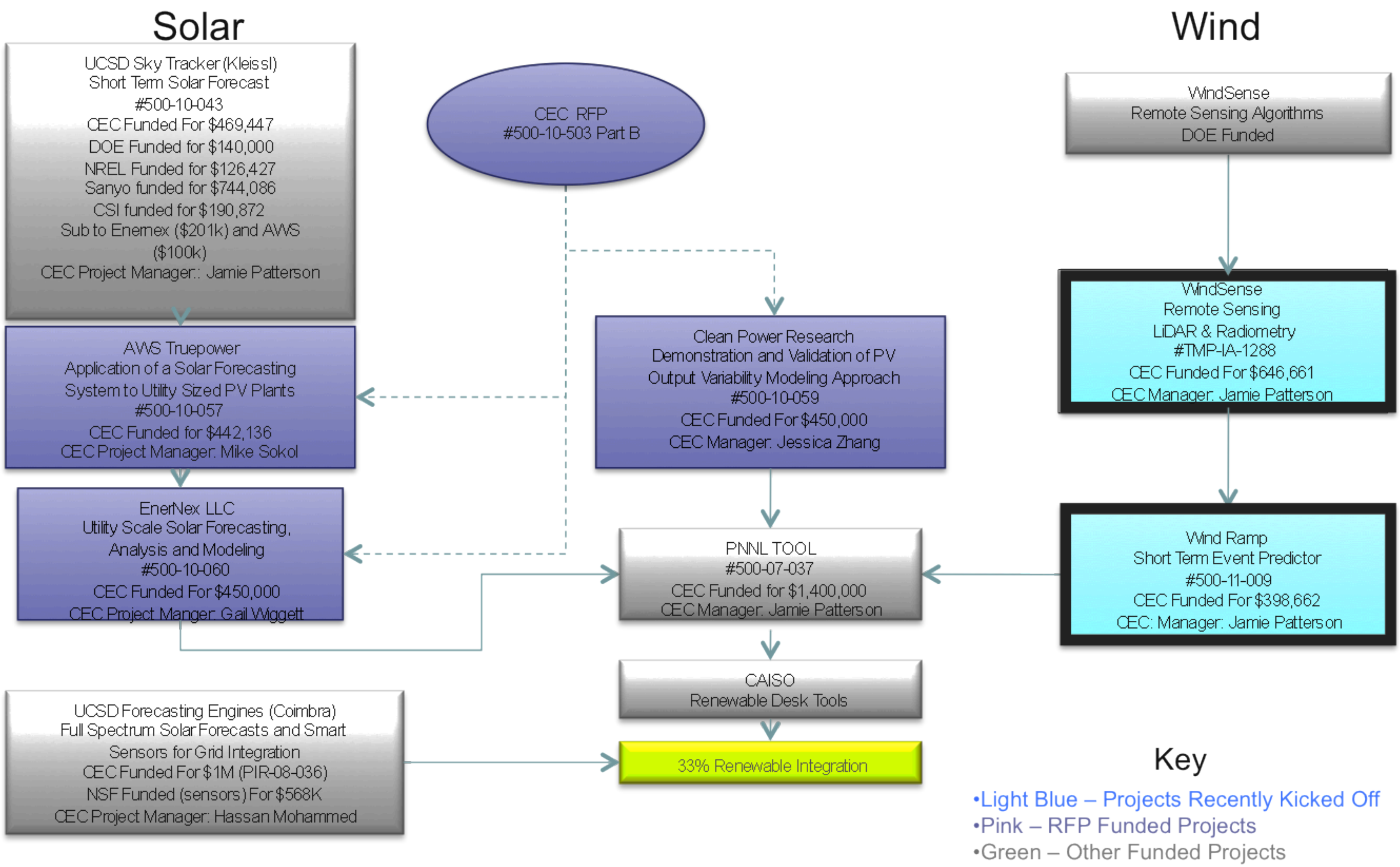

Figure 1. Renewable Forecasting Tools Research and Implementation in California

Findings of the Dec. 16, 2012 Renewables Forecasting Workshop

Purpose of the Workshop

The primary goals of the workshop were to discuss the current state of solar and wind forecasting tools, their various components, and their accuracy, reliability and shortcomings, and to develop the end-user specifications needed to accurately predict and utilize solar and wind energy resources, by means of a discussion among the California Independent System Operator (CAISO), utilities, and customers. The results of this workshop are intended to inform future solicitations for research toward applications that will help California better reach its near-term renewable goals.

Figure 1, presented during introductory remarks by the Energy Commission, summarizes how the Commission's past and current research efforts in renewable forecasting have contributed to these goals. The PIER Program has funded several projects in solar and wind forecasting, and leveraged their results with projects funded by DOE and others, to produce more accurate and timely forecasts of wind and solar energy production from the renewables plants in California. These energy forecasts are then fed into the Ramping Tool, which was developed by Pacific Northwest National Laboratory (PNNL) with PIER funding, and is installed at the CAISO Renewables desk in the Control Center in Folsom. The Ramping Tool combines the renewables forecasts with system load forecasts and with outage forecasts of the generation fleet to determine the short-term generation ramping and capacity reserves for the electric grid. System operators therefore have the best information possible with which to make generation dispatch decisions.

Following is a summary of the presentations and findings of the Workshop.

Solar and Wind Forecasting: Achieving a 33% Solution (CAISO)

Presenter: Jim Blatchford, California Independent System Operator (CAISO).

The CAISO faces major challenges in operating the grid while meeting the state's energy and policy goals, particularly the anticipated 33% renewables by 2020. System reliability must be maintained with fewer fossil units than are available today, the ramping requirements imposed by renewables must be understood and addressed, achieving accurate forecasting of renewable plant output, all while ensuring reasonable cost to the ratepayer. To meet these challenges, CAISO has installed the first-of-its-kind renewable desk for operators in its control center in Folsom, CA.

Wind generation in the CAISO control area will be 11.3 GW and solar generation will be 12.3 GW by 2020. CAISO estimates that 1700 MW of wind and 2000 MW of PV generation will be "invisible" to system operators, because it will be installed on the distribution system and net-metered; it will also be masking load.

Ramping is a key operational concern, especially for wind, which is inversely correlated with load; solar can ramp up/down quickly due to cloud layers. This poses a real challenge in terms of scheduling and operating other generators on the system to mitigate the impacts. CAISO is working with UCSD and UC-Davis on research (PIER-funded) to characterize ramps and improve system response to them.

To illustrate the economic benefits of better renewables forecasting: a reduction in wind forecasting error of 10% at 14% renewable penetration would mean about $28M/yr savings for WECC; a reduction in error of 10% at 24% penetration would equal about $100M/yr savings.

Forecasts can under-predict unit availability, so it's especially important to understand what's happening at the renewable plant sites. Getting data from specific wind sites, especially behind-the-meter data from renewable plant owner-operators or inverter vendors, can greatly improve forecasting. For example, Tehachapi shows great variability across plants; denser instrumentation is going in there.

Internal activities at CAISO include developing new algorithms, developing and training the Renewable Desk operators, and looking at other forecasting techniques as they become available. Externally, CAISO is looking at acquiring "behind-the-meter" data, working with UC-San Diego on solar forecasting and UC-Davis on wind ramping, and reaching out to inverter manufacturers to investigate methods for obtaining data from inverters directly.

During the discussion following SCE's presentation, the following issues were identified:

- The CAISO's Participating Intermittent Resources Program (PIRP) process is heavily weighted in favor of persistence. Also, it's market-oriented and not generation-oriented.
- Are wind forecasts based too heavily on persistence? Should we be looking at "smart" persistence methods?
- The "Thanksgiving Day ramp" of 2011 had high winds with a lot of customer outages at a time when the forecast was lower than what would have been expected on a typical workday. Should this be investigated for evidence of errors in the models?
- We should be looking to identify clusters of solar panels, and get better predictions of their output to include in renewables forecasts. Florida Power & Light (FPL) gets 15-minute data to improve their load forecast. They are looking to see where solar is and develop a proxy forecast/bid.
- Confidentiality issues come into play in the effort to get better data.
- There's a need for sharing of weather and load (including non-QF) data.
- High wind ramp events can be associated also with load loss (downing of lines). That is, characterization of down-ramps must take into account those events that are system-related, not wind-related.

Wind and PV Forecasting (SDG&E)

Presenters: Lena Fotland and Dallas Cormier, SDG&E.

Current renewables forecasting projects at SDG&E include micro-scale daily forecasting of wind and temperatures using a network of 130 weather station sites; modeling the past 50 years for wind, solar radiation and temperature; forecasting winds in support of wind generation projects (beginning next year); and PV generation forecasting and marine layer modeling.

SDG&E is seeing very sharp ramp rates in solar generation, and is looking into methods for better forecasting of cloud cover to address this issue. Most forecast errors occur early in the day, and at coastal stations due to the marine layer. Improved analysis is expected through integration of available live instrumentation data into the models.

Next steps include intensive modeling of the marine layer, and integration of results into forecasting; acquisition of real-time data for improved day-ahead forecasting; and investigation of mechanical issues with some sensors, which may require algorithmic corrections or different sensors.

Renewable Resource Forecasting (SCE)

Presenter: Jack Peterson, SCE.

SCE is conducting a number of activities related to renewables forecasting. These include forecast trials with multiple vendors, different instrumentation siting schemes, and new technologies; "blind" proof-of-concepts, both vendor-to-vendor and in-house-to-vendor; in house projects such as quality checks of vendor forecasts, improvements in in-house capabilities, and reorganization of the short-term forecasting group; and evaluation of the CAISO's PIRP/EIRP (Eligible Intermittent Resources Protocol) forecast.

In the modeling area, SCE has obtained a number of results. One finding is that analog modeling performed better on inversion days while the Modeling Output Statistics (MOS) approach performed better on non-inversion days for solar forecasting. Another finding is that performing multiple analog runs resulted in an ability to average for better accuracy. SCE was also able to determine the typical time lag for ramping events.

SCE concluded from its efforts to date that quality meteorological instrumentation is necessary, and maintenance and calibration of that equipment is critical, for best forecast accuracy; this is true for both wind and solar. For solar forecasting, cloud tracking in real time is imperative.

During the discussion following SCE's presentation, the following comments were made and issues identified:

- Silos are an issue: operators, transmission, markets, etc., need to share information
- Plant availability and real-time power data are needed; currently these lag ~15 minutes behind weather
- Getting accurate and timely forecasts for weather coming off the ocean is a problem
- High concentrations of PV on warehouses is a major headache
- Some forecast vendors are good at some things, but not others, e.g., ramp-up but not ramp-down
- SCE also has a renewables desk for markets in their control room
- Sharing of data among utilities and CAISO is important
- A topology vector in forecasting is important where there are mountains
- Avoid visual overload for operators, especially for solar
- Accuracy goal for 2-hr forecast should be <10% error; 15% to 20% being done now.
- Modeling is the weak link in forecasting
- Training models are needed
- DG needs a Smart Grid for 2-way power flow, and for visibility to system operators
- Blind forecasting tests show that different vendors are capturing different pieces of the problems. What are they doing and not doing well? How are they not meeting needs for markets and scheduling?

Perspectives on Renewables Forecasting (PG&E)

Presenter: Kevin Cross, PG&E.

PG&E's assessment is that it's difficult for private vendors to find a role in renewables forecasts in California, given the rules governing the CAISO's Participating Intermittent Resources Program (PIRP) process. Utilities are paying for the PIRP forecasts, so the incentive is to use those rather than consider going with a private forecast vendor. Perhaps there could be some change in the rules going forward to address this, because there is some indication that private vendors may be able to provide more accurate forecasts in some situations.

Solar and Wind Forecasting: Achieving a 33% Solution (UWIG)

Presenter: Charlie Smith, Utility Wind Integration Group (UWIG)

[Note: UWIG is changing its name to Utility Variable Generation Integration Group (UVIG), encompassing both wind and solar generation.]

At UWIG we say, "It's all about dealing with variability and uncertainty." How do wind and solar generation affect existing variability and uncertainty? What are the costs associated with the changes?

We've learned that different kinds of forecasts (and different metrics) are needed for different time periods, and forecast errors can be reduced with increased region size.

Forecasting is important to system economics, reliability, and market operations.

The NERC Task Force made the following recommendations:

1. Real-time data is critical for wind and solar plant forecasts.
2. Wind plant output forecasts should be adopted as standard system and market operation tools.
3. What really matters is how forecasts are used.
4. Adjusting operating rules and practices can achieve substantial benefits.
5. Ongoing innovation is needed.

The electric industry needs to learn how to do better forecasts quickly. Significant value can be achieved using the results available from current generation of technology. But we still have a long way to go.

Discussion:

- Adjusting operator rules and practices is important for making maximum use of forecasts (e.g., look at the MISO Dispatchable Intermittent Resource (DIR) policy with a 15-min schedule adjustment).
- Synchrophasor data can be used for validation of plant models.

UCSD Microgrid (UC-San Diego)

Presenter: Jan Kleissl, UCSD.

The UCSD Microgrid currently consists of 42 MW peak load, 30 MW natural gas combined cooling, heating and power (CCHP) plant, 1.2 MW of PV, 40,000 ton-hr thermal energy storage (TES), 69 kV substation, 96 12kV U/G feeders, 4 12kV substations, and 50,000 energy data points metered. Planned infrastructure includes: Power Analytics/Viridity Scheduler/Optimizer, 2.8 MW fuel cell using methane gas, 1.8 MW/11.2 MWh storage, 1.9 MW additional PV, 2 MW/8 MWh PV-integrated storage, $250M/yr building expansion, and a $72M energy efficiency program.

Solar forecasts are used to help optimize the power systems; USCD uses numerical weather prediction (NWP) global horizontal irradiance (GHI) forecasts to predict power output. Daily GHI and power forecasts are produced for each campus, along with Sky Imager forecasts at a 10-min. horizon. Increased efficiency at UCSD is being studied using forecasts input to UCSD's Smart Grid Power Optimizer.

Discussion:

- Better inversion forecasting is needed. Some data exists for high level winds (geotropic) which are good predictors of inversions.

Summary of DOE Renewable Resource Forecasting R&D

Presenter: Merwin Brown, CIEE.

DOE's goal is to develop better wind and solar forecasting tools for better operator decisions in the day-ahead market, operation, and unit commitment. For real-time operations the targets are 1-6 hours ahead for wind, 1-3 hours ahead for solar, for frequency regulation and load following functions.

Particular emphasis is placed on short-term ramp forecasting. There are potentially significant economic benefits in terms of reducing short-term power management costs.

DOE is conducting research in Wind Ramp Forecasting:

- DOE/NOAA/Private Sector Wind Forecasting Improvement Project, with ERCOT/AWS Truepower and MISO/WindLogics
- WindNet Project, with DOE/NREL, Hawaiian Utilities, and WindSense Industry Group

These projects address advanced wind monitoring instrumentation: "forward-looking" radar, Sodar, Lidar, etc.) for hourly updates of NOAA numerical weather prediction (NWP) models used in many industry forecasting services.

DOE is conducting research in Solar Ramp Forecasting:

- Solar Resource Variability and Forecasting Project with Hawaii Solar Forecasting, and the DeSoto NREL/FPL/Sandia Project
- UCSD Solar Variability and Forecasting Project, with DOE/NREL, CEC, CPUC, SDG&E/Sempra
- Advanced Sky Cloud Tracker monitoring and ramp forecasting technology

DOE targets the following major tech transfer paths:

- UVIG Workshop, February 2012, Tucson, AZ – UVIG (formerly UWIG) now addresses solar generation as well as wind
- Industry wind and solar forecasting services

- Major ISO wind forecasting service users
- Wind and solar energy industry developers

Wind Forecasting Research Efforts (UC-Davis)

Presenter: Case Van Dam, UC-Davis.

UC-Davis just began a PIER-funded research project to quantify wind ramps in a state-of-the-art wind plant in California: the Solano plant in the SMUD service area. The results of this project will feed into the CAISO Ramp Tool.

Present research is concerned with quantifying the beneficial impacts of wind forecasts on system operation. The goal is to isolate the effects of wind forecasts on power system operations and evaluate the benefits forecasts provide. Wind forecasts and the major power system processes are modeled, and simulations performed. The forecasts are evaluated in terms of absolute error, mean average error (MAE) or root mean square (RMS) error.

Next Steps:

- Wind Ramp Event Prediction Tool:
  - Identify wind ramp events in CAISO production data and corresponding atmospheric conditions for all four California wind resource areas
  - Develop and calibrate event the Wind Ramp Event Prediction Tool for CAISO
  - Evaluate the Tool's effectiveness in real time
- Improve short-term forecasts via upstream instrumentation:
  - Identify optimal locations and sensor types needed upwind of Tehachapi for short term forecasts
  - Run forecast models with and without upwind data to quantify forecast improvements
  - Conduct cost/benefit analysis

Solar Forecasting Concepts and Summary of Research Projects at UCSD

Presenters: Jan Kleissl & Byron Washom, UC-San Diego.

UCSD has six major projects underway involving solar forecasting research.

A. UCSD's Microgrid: Numerical weather prediction (NWP) global horizontal irradiance (GHI) forecasts are used to predict solar power output and optimize the microgrid.

B. Solar Forecasting in San Diego County and UCSD: Simulation of "geographic smoothing": distributed PV shows largest reduction in variability at 1 to 5 minute ramps over an averaging area of 1 mile. This project performs intra-hour solar forecasting with a Total Sky Imager, cloud motion vectors, and irradiance measurements. Forecast results at the UCSD testbed include:

- Error increases with forecast horizon, but still 25% better than persistence after 5 minutes
- Sky Imager provides situational awareness to CAISO over 10-25 min. horizon
- Demonstration studies with Sempra Energy at 48 MW PV and SCE for rooftop PV

"If we can achieve the forecasting breakthroughs, 7 sky trackers would provide intra-hour forecasts for the majority of the LA/Orange County market."

C. Advanced Sky Imagers Hardware Development [Sanyo]: Improvements in dynamic range, smaller shadowband, controllable image capture over previous Sky Imager. Evaluate the ability to more accurately capture the cloud field, resulting in better irradiance forecast performance. Also evaluate improved red/blue ratio (RBR) calculations for enhanced cloud decision imaging.

D. Solar Forecasting for Utility-scale DG in SCE (PI: Enernex): Objective is to forecast fleet (39 sites) power output ramps with Sky Imager networks. Focus is on the Los Angeles warehouse roof market under contingency scenarios (e.g., marine layer burn-off).

E. Renewable Resource Management at UCSD: Evaluate solar forecasting via ground data, and optimal forecasting using ground/satellite/NWP data.

F. Solar Forecasting for Utility-Scale Centralized PV at Sempra Utilities (PI: AWS Truepower): (See AWS TruePower presentation, below.) Project is focused on the Copper Mountain 48 MW thin-film PV plant (the largest in the US). Objectives are to integrate Sky Imager, satellite (Clean Power Research), and NWP (AWS Truepower) forecasts, and to evaluate and improve the forecast products.

SolAspect Forecast Engine (UC-San Diego)

Presenter: Carlos Coimbra, UC-San Diego.

SolAspect is a full-spectrum, multiple-input solar forecasting engine. It uses the Merced Testbed which covers 8.5 acres and has 1 MW of thermophotovoltaic (TPV) systems. It produces 1-hr ahead PV power forecasts with no telemetry and no image processing. It employs the Evolutionary Non-Integer Order (ENIO™) algorithm for 2-hr ahead forecasts, which is much better than the 1-hour ahead forecast with traditional methods.

The ENIO algorithm has unprecedented robustness and forecasting skills using the most diverse sets of inputs, and it has been productized by SolAspect for solar, wind and load forecasting.

PV Output Variability Modeling (Clean Power Research)

Presenters: Richard Perez & Tom Hoff, Clean Power Research.

The Power Clerk used by NYSERDA forecasts PV output up to 6 days ahead, with 20-second data granularity. It can be interrogated by the user to produce a number of useful real-time reports, including: system maps, total PV fleet energy production, program summaries, installation status, cumulative production and capacity, prices and price deviations by county, and solar capacity distribution. Power Clerk employs advanced cloud motion tracking technology. A recent study measured and simulated 10-second data from locations in a 4 km x 4 km grid in Napa, CA.

Multiple Look-ahead Time Scale Solar Generation Forecast System (AWS TruePower)

Presenter: Glenn Van Knowe, AWS TruePower.

AWS TruePower is conducting a PIER-funded project (see Figure 1) whose objectives are to refine, integrate, test and validate a set of existing solar forecasting tools that can provide the highest possible performance for frequently updated predictions of solar power production in California over a broad range of look-ahead time periods from minutes to many days ahead. The Sempra solar generation facility in Henderson, NV was chosen as the test venue and evaluation site.

The project approach is to refine the most promising existing tools for specific look-ahead time scales, develop an algorithm that optimally blends methods for each look-ahead period, and iteratively evaluate and refine the individual and integrated methods.

The challenge is to produce the best forecasts for various time scales: minutes-ahead tools employing persistence, skycams, and local irradiance trends; hours-ahead tools using satellite-based cloud motion and numerical weather prediction (NWP); and days-ahead tools using NWP with statistical adjustments.

Intra-hour forecasts are based on pattern recognition techniques applied to cloud images, which estimate the motion vector of cloud elements from sequential images, and project future cloud patterns from the motion vector. Greatest value is obtained for 0 to 30 minute ahead forecasts.

Standard metrics used are the mean average error (MAE), root-mean-square error (RMSE), bias, etc.

Renewables Forecasting & Integration (KEMA)

Presenter: Nellie Tong, KEMA.

Four projects are currently underway in Renewables Forecasting at KEMA:

1. Concentrating Solar Power – Thermal Energy Storage (CSP-TES) Modeling (PIER Project)
The objective of this project is to define the benefits, costs, and impacts of increasing penetration of coupled CSP-TES, along with the system configurations and control strategies needed to optimize economic and engineering performance. CSP developers and operators have experience in plant-level system decisions, but lack grid-wide perspective; grid operators have the grid perspective, but lack experience in integrating CSP-TES. This project will bridge the gap through the use of end-to-end system modeling spanning from the plant to grid.

2. European Union DG Study (CEC/PIER and CAISO Project)
The objective of this project is to perform a comparison between the electric distribution systems in Europe and California to determine the differences that affect California's ability to successfully integrate more intermittent DG in California's grid. Governor Brown's Clean Energy Jobs Plan sets a goal to develop 12,000 MW of localized electricity generation by 2020. A comparative analysis of how Germany and Spain integrate large quantities of intermittent DG into their electric distribution systems, while still maintaining system control and reliability, will be beneficial to California's efforts to integrate its 12,000 new MW of local generation.

3. DER Visibility & Control Study (CAISO)
The objective of this project is to evaluate the market impacts and operational benefits of, and to quantify the costs associated with, the integration of DER, including PV, CHP, wind, EV, storage and demand response. The requirements for intermittent resources on the distribution network are not well-defined. The aggregate impact could significantly impact balancing,

capacity planning and regulation. This project will address these issues by means of market simulations with different scenarios of DER penetration.

4. Predictive AGC (CAISO)

The objective of this project is to identify the operational benefits and costs of applying modern control theory to automatic generation control (AGC) with regard to integrating 33% renewables by 2020. Traditional AGC algorithms are inefficient at providing regulation with high penetrations of variable renewable power because they do not use all relevant system information. The goal of this project is to use KEMA's KERMIT model to test new AGC algorithms that predict generator, renewables, and system performance.

Wind & Solar Forecasting (Enernex)

Presenter: Kay Stefferud, Enernex.

There are major challenges with integrating renewables:

- The RPS goal of 33% renewables by 2020 is aggressive.
- Wind and solar variability are sometimes correlated, sometimes independent of each other.
- Renewable forecasting effects range from economics to transmission and distribution electrical system design to long range planning to social engineering.
- California climate zones are highly variable.
- The best solar and wind sites are far from living areas, which drives bulk generation and transmission impacts.
- Multiple forecasting time frames required: these can be seconds, minutes, hours, or days ahead of time.
- Currently, standards limit the ability of solar inverters to contribute to power quality.

Solar forecasting has levels of complexity: the selection of the best set of measurable variables, the methodology, and the forecasting algorithms are all critical elements of producing accurate forecasts.

Possibilities for future renewable energy research include:

- Investigate the economically optimal location and size of storage; the optimal locations of distributed vs. centralized renewable resources; possible changes in electricity market design and grid infrastructure to facilitate renewables integration.
- Determine the T&D upgrades required to maintain/increase reliability in order to serve 100% renewable generation.
- Determine the dynamics and grid effects of asynchronous generation with some synchronous generation, versus the current state of mostly synchronous generation.
- Solar Forecasting:
  - Combine Kalman filter and cloud vector solar forecasting methods
  - Add cloud density estimates to motion vector estimates
  - Evaluate the effects of changes in the IEEE 1547 inverter standard on the economic value of DER and grid reliability
  - Determine the best statistically optimal variables
- Wind Forecasting: Incorporate offshore wind generation

Predicting Uncertainties for Real-Time and Day-Ahead Operations (PNNL)

Presenter: Jeff Dagle (for Yuri Makarov), PNNL.

PNNL developed the Ramp & Uncertainty Prediction Tool for the CAISO, with CEC/PIER support. This tool (see Figure 1) has the following key features:

- Integrates renewable forecasting and energy production tools into the grid resource planning and operation tools in the CAISO control room.
- Forecasts generation capacity and ramp ranges needed from grid resources to balance the system.
- Incorporates all sources of uncertainty and variability: wind and solar generation and demand (load).
- Incorporates a Probabilistic Tool Design approach: data acquisition, uncertainty assessment through statistical analysis, prediction of future grid balancing requirements for specified time horizons and confidence levels, and multi-dimensional uncertainty analysis.
- The Tool has been developed and deployed in the CAISO control room to help real-time dispatchers anticipate and address ramping needs due to renewable generation.
- Its forecasts enable real-time displays of load-following requirements, capacity and reserve requirements, and ramping requirements.
- It has received positive feedback from the CAISO specialists, and deployment to other ISOs is planned.

Suggestions for future improvements:

- Develop and test new uncertainty prediction approaches based on modern statistical methods.
- Feed in uncertainty and ramp information for wind and solar generation weather-based forecasts.
- Investigate the impacts of the Balancing Area ACE Limit (BAAL) standard, interchange control and inadvertent interchange accumulations on the uncertainty analysis and propose solutions.
- Implement active and pro-active integration approaches to incorporate uncertainty information back into the unit commitment and dispatch processes.
- Quantify the cost of uncertainty and develop mechanisms for allocating the cost to specific sources and their aggregates.

Roundtable Discussion on User Needs

Facilitator: Jim Blatchford, CAISO.

The purpose of this panel session was to provide an open forum for discussion of user needs in renewables forecasting and for identification of technology and research gaps. The following is a synopsis of ideas, issues and comments developed during this session.

California's Participating Intermittent Resources Program (PIRP) focuses upon understanding the cost drivers for wind generation resources and reducing their cost impacts by improving the forecast accuracy of the resources. It also includes development of a tariff, administered through the CAISO, to address the appropriate charges associated with the export of energy from PIRP resources. An issue that has been identified is that PIRP doesn't provide incentives for utilities to use commercially available renewables forecasts. Utilities pay for PIRP forecasts, so the incentive is to use them, even if they're sometimes inaccurate and cost the utilities money. Utilities would like to pursue other alternatives to see if they're more cost-effective, but economically there's a negative incentive to do so.

Standards for forecast data, forecasting metrics, and forecast accuracy are needed. It is recognized that considerable research is being done both nationally and internationally on these topics.

Wind forecasting needs more sensors, and better correlation of weather sensor data to wind plants' actual energy production.

Solar forecasting might benefit from improvements in satellite monitoring; mining of these types of data could be valuable.

SMUD has 71 solar sensors on a 5-km grid, suitable for distribution feeders, inverter usage, or PV dispatch.

Cleaning and maintenance of sensors tend to be expensive, and the labor involved is also an issue.

Ways to use data from PV systems themselves for short term forecasting should be investigated.

Forecasting errors need to be reduced; new technologies will be more beneficial than tweaks to existing methods; and better models are needed.

DOE, EPRI, NREL, NOAA are all doing research and development in this area; they should be good sources for identification of new R&D needs.

CAISO is just now starting to know what it needs for forecasting.

Need better <u>resource</u> forecasting. How do we translate weather into MW? How do we use/implement data that we have? What is actionable? Can we translate regional forecasts to more site-specific forecasts?

How well are models "self-tuning" for local conditions?

Information on variability (standard deviation) is desired from multiple forecasts. But how does one interpret that information? This can help to determine what the risks are. Probabilistic ("ensemble") forecasting would be helpful.

Data from synchrophasors (phasor measurement units) would probably be overkill for renewables forecasting, but could be helpful in validation of models (especially at wind plants).

Backplane temperatures can be used to estimate the efficiency of solar systems.

Key Needs (Takeaways):

1. Better short-term forecasting of ramps is imperative.
2. Understanding the data, and the forecasts derived from the data, is necessary to translate the information into <u>actionable</u> information.
3. Better site-specific information (both load and resource) is a critical need.

4. Underlying all of this would be access to confidential data, such as inverter data or wind plant data used by aggregators. Getting access to such data might be a more accurate and cost-effective approach than installing more sensors and developing more models.

Information Supplemental to Workshop

Overview

Subsequent to the Energy Commission's IEPR Workshop on December 16, 2011, "Solar and Wind Forecasting: Achieving a 33 Percent Solution," the authors followed up with Workshop participants, to acquire additional information regarding the subject of renewables forecasting. The goal was to obtain a fuller picture of the research underway, what was needed in terms of further research, and how the tools being developed will address users' needs. In some cases, presenters were able to supply additional insights regarding their and others' presentations on the subjects covered. Also, since some additional time had passed between the Workshop and the follow-up conversations, researchers were able to discuss further progress that had been made since Dec. 16, 2011.

Also, one of the authors was able to attend the UVIG Variable Generation Forecasting Workshop held in Tucson, AZ on February 8-9, 2012. At this event, many of the same presenters from the Dec. 16 workshop also gave presentations and/or participated in panel sessions. Thus, their work was presented and discussed in a broader context of national and international research and technology developments. Information from this workshop, comprising presentation material and follow-up discussions with Workshop participants, was used to augment the information gleaned from the post-Dec. 16 IEPR Workshop interviews and conversations.

The CAISO has developed specifications for a next-generation Ramping Tool, incorporating their anticipated future needs, which is included here as a specific potential new area of research. Many of the desired specs may require focused research to advance the state of the forecasting art beyond what is currently being done.

Finally, a literature search on the subjects of wind and solar forecasting was performed, and relevant published material has been included in the List of References at the end of this paper.

Summary of Responses to Workshop

The achievement of the 33% RPS goal by 2020 is a primary objective in California, and the Energy Commission's leadership and support in renewables forecasting research will be critical in achieving the state's (and the nation's) renewable energy goals. The interchange of ideas and viewpoints among all stakeholders in the renewables forecasting arena is a critical activity that will foster the quickest progress of research and its ultimate transfer into commercial usage. The Dec. 16, 2011 Renewables Forecasting Workshop was an important step forward in this process, as was evident from the follow-up responses obtained from the participants. A summary of these responses is presented here.

The past and current PIER-funded projects in renewables forecasting are seen as being leading-edge work, of value not just to California but nationally and even internationally. Researchers performing PIER work routinely attend industry conferences and interact with other researchers doing related work, thereby learning and benefiting from others' research and contributing to technical progress on many levels. This was especially evident at the Dec. 16, 2011 IEPR Workshop on Renewables Forecasting, and also at the Feb. 8-9, 2012 UVIG Variable

Generation Workshop, which was attended by a large and diverse group of researchers, utilities and consultants from all over the world. The PIER work was part of a comprehensive global, cooperative effort to find solutions to the questions of renewables forecasting.

Arguably, the highest-priority issue for users such as utilities and the CAISO is forecasting of energy production "ramps": rapid increases and decreases in the output of wind and solar plants. Operators must have enough other generation on the system that can rapidly respond to counter these changes. In general, "ramp up" events are relatively easy to handle at present, because an increase in renewable generation can be countered with a reduction in output from controllable generation that is on the system. Conversely, "ramp down" events are more problematic, because a reduction in renewable generation must be addressed by rapidly increasing controllable generation, and operators need to be sure that there is enough reserve margin to supply the needed power. To the extent that these ramping events can be forecast from 5 minutes to 60 minutes ahead, operators have more ability to coordinate the available generation resources, including bringing off-line generation on-line, ensuring resource adequacy and minimizing the associated operational costs. Even a few percentage points of improvement in the accuracy of short-term forecasts can result in significant savings, especially in larger systems such as the CAISO control area and the Western Electricity Coordinating Council (WECC) system. The PIER-funded forecasting projects, combined with research results from other funders such as DOE, have been combined with the PIER-funded Ramping Tool that was developed by PNNL (it was also PIER-funded) and installed in the CAISO Control Room, to provide unprecedented operator information and flexibility to handle renewable ramping events. Continued refinement of this tool is strongly supported by the CAISO.

Regarding the economic benefits of better forecasts, the CAISO is conducting an internal study to better quantify how better forecasts can translate to economic savings. On a related topic, the 2005 Renewable Integration Study is in need of updating, using revised scenarios based on what is known today about the expected renewable generation in California. There would be benefits to looking beyond the 33% by 2020 goal, possibly even a 50% scenario.

From the point of view of the researcher community, virtually everyone acknowledges that current forecasting tools have some "blind spots." That is, some tools are good at forecasting in the very near term, others in the medium term, and others in the longer term (all with their respective error bounds), but there are gaps in the time scales covered by these tools that are not addressed adequately. Forecasting tools that address these gaps either individually or by combining methods for different time scales into one tool ("forecasting engine") will be needed for the purposes of system operations and minimization of costs.

Another common theme from the research community is that greater consensus is needed regarding accuracy and error estimation metrics. Virtually everyone agrees that forecast accuracy needs to be improved and is working diligently toward that goal, either directly or indirectly (in the latter case, by providing data for analysis, advising other researchers in analyzing forecast accuracy, etc.). But there is apparently insufficient agreement over exactly how to calculate and interpret such metrics as mean average error (MAE), root-mean-square error (RMSE), and others, for many applications and situations, especially for solar forecasting as opposed to wind forecasting, where the meteorological mechanisms and dynamics are very different. For utility operators, of course, the bottom line is the resultant energy production forecast, because that is what they need to operate by, and inaccurate forecasts result in higher costs and possibly reduced system resource adequacy and reliability. Several workshop participants noted that DOE has announced an upcoming solicitation on Solar Forecasting that will address this issue, and were hopeful that under DOE leadership significant progress will be made on the metrics question.

There is general consensus that the best meteorological forecasts should be available to and used by everyone; thereby fostering the most accurate forecasts of wind and solar generation on the part of all users of that data. Users of the data (e.g., utilities or the CAISO) generally do not want to be in the position of evaluating the accuracy of meteorological forecasts; national or standards organizations were seen as the appropriate authority for ensuring accuracy of such data. Weather data developed and provided by the National Weather Service (NWS) or the National Oceanic and Atmospheric Administration (NOAA) would likely be the most cost-effective, easily available, and reliable. Most of the researchers at the Dec. 16 Workshop are either actively engaged in these types of efforts, or are advocating them and watching or advising such developments closely.

Another approach to reducing forecast errors is "geographic smoothing," in which forecasts over a wider area are used to improve overall forecasting accuracy. A key issue with this approach is how to enable, on a regulatory and operational basis, the coordination and management of generation resources across balancing areas (BAs) in order to achieve the reduced reserve requirements and ancillary services that are theoretically possible using this methodology.

There is an ongoing debate in the forecasting community as to whether more sensors need to be installed in the field (i.e., producing greater raw granularity or resolution in the meteorological data), or whether fewer sensors more strategically placed (e.g., near wind plants or large solar plants) would achieve equal or better results, possibly in a more cost-effective way. Utilities and other users are sensitive to the costs involved with sensor deployment: not just the capital costs for acquiring and installing them, and replacing them over time, but also the ongoing maintenance costs for periodic cleaning and calibration, without which the accuracy degrades. At least one current PIER-funded project (at UCSD) uses a "dense network of ground stations" and may provide some data to address this question. Another possibility for acquiring the needed data at reduced cost is that owner-operators of renewable plants, or possibly system aggregators (those who organize diverse renewable plants into blocs for the purpose of bidding their energy into the market collectively), could be approached to provide access to the data that they may collect behind the point of interconnection (POI).

Electric energy storage systems are frequently cited as potential solutions to renewable plant intermittency, inasmuch as they could theoretically make renewables more dispatchable to better match system load, with the side benefit of reducing the criticality of weather or energy production forecasts. However, the high costs of storage systems, along with other technological and regulatory barriers, are effectively limiting the use of storage in the near term. Better forecasting would, arguably, yield more near-term benefits in terms of integrating renewables, while hopefully reducing the ultimate amount of storage that might be needed to mitigate the intermittency and variability of renewables.

As researchers gain more experience from their projects, some are seeing an opportunity for further research into stochastic learning methodologies. That is, they are seeing trends in their data that they characterize as "learnable bias," which they distinguish from the "normal" type of systematic bias that is present in, and accounted for, in most forecasting systems. As more is learned and more data acquired from monitoring in a given locality or region, for a specific purpose, the more there is potential for training the forecasting system to anticipate stochastic trends, account for them in the forecasting algorithms, and thereby increase forecast accuracy.

The Southern California utilities (SCE and SDG&E) agree that one of their most pressing issues is the problem of forecasting the burn-off of the morning marine layer near the coast. Current research (much of it PIER-funded and ongoing) using satellites, SkyTracker™ technology, and other methods are being closely monitored for solutions to this problem. The results of these studies, due within the next year or so, combined with research developments elsewhere, should be evaluated as soon as they are available and follow-on work pursued, if indicated.

For solar forecasting in general, prediction of cloud movement is a critical area. Again, there is a good amount of research underway at the present time, including PIER-funded, national and international efforts. There is particular interest in the comparative evaluation of methods using satellite data versus those that use SkyTracker™ technology, and researchers are optimistic that the next couple of years will produce significant improvements on this front. These results, too, should be assessed at the earliest practical time, as follow-on work pursued, if indicated.

UVIG Variable Generation Forecasting Workshop, Tucson, AZ, February 8-9, 2012

The Utility Variable Generation Integration Group (UVIG, formerly UWIG) sponsored the UVIG Variable Generation Forecasting Workshop, held in Tucson, AZ on February 8-9, 2012. At this event, many of the same presenters from the Dec. 16, 2011 CEC Renewables Forecasting Workshop also gave presentations and/or participated in panel sessions, along with many other persons representing national and international research organizations, government agencies, utilities and interest groups. The following is a brief synopsis of the events of the Workshop, including key takeaways for renewables forecasting.

Panel #1: Variable Generation Forecast Performance, Value, and Accuracy
The ultimate measure of the value of a variable generation forecast is whether it helps reduce system operating cost, improve market operation and maintain system reliability in the presence of variable generation. Significant attention is being devoted to understanding the uncertainty in any given forecast so as to best optimize commitment and dispatch decisions including allocation of reserves. Value comes in different forms and amounts to different classes of stakeholders (ISOs, market participants, non-market participants) and the value is contained in different forecast products (e.g. look-ahead times, applications etc.). This panel will discuss the latest thinking on the value and performance issues. Importantly, where is the bang for the buck?

Panelists:
Bri-Mathias Hodge, NREL: Wind Power Forecast Error Distributions
Sue Haupt, NCAR: Estimating Uncertainty in Forecasts
Bob Zavadil, EnerNex: Forecast Accuracy – Reserves, Economics, and Reliability
Audun Botterud, ANL: Probabalistic Forecasting Applications
Pablo Ruiz, CRA: Forecast Uncertainty and Trading Decision-making
Ron Lehr, AWEA: Forecasting and the VG NOPR
Steve Beuning, Xcel: Forecasting and the EIM

Summary and Key Points:
Very detailed and technical presentations on research and development of the various aspects of improving forecast accuracy, including error distributions, probabilistic versus ontic (inherent) forecasting, impacts of forecast uncertainty on trading decisions and markets, barriers to balancing resources across Balancing Authorities, and the use of "ensembles" to improve forecasts. Key comment: Theory is all well and good, but how are these tools being implemented in the control room?

Panel #2: Interesting High-Penetration Hours: What Have We Learned?
Concern is often expressed over instantaneous non-synchronous generation penetration in synchronous grids. Increasing global experience is becoming available on this question. What does it mean? Are any operating boundaries being approached? Are there any concerns for system stability at these instantaneous penetration levels? And is the system still operating?

Panelists:
Rui Pestana, REN: Portugal at 93%

David Bell, EirGrid: Ireland at 52%
Ana Rodriguez Aparicio, REE: Spain at 54%
Drake Bartlett, Xcel Energy: PSCo at 55%

Summary and Key Points:
Operating experience is highlighting a host of issues, some predicted, some not. Studies suggest that frequency issues will arise at penetration levels above 80%. Most utilities will experience the "minimum load problem" at some point, where renewable generation exceeds load for some periods. Wind ramp up is easier to deal with than ramp down; up-ramps replace generation already on the system, down-ramps may require bringing resources on-line quickly. Some systems will have to curtail the renewables. Voltage control can be impacted; low-voltage ride-through is a problem for many. Lower system inertia also contributes to frequency issues. PSCo reported that their wind plants successfully provided AGC service to the grid during a generator contingency.

Panel #3: Large System Forecasting Status and Progress
Several years of operating experience with wind plant output forecasting over broad geographical regions is now available from several different sources. This session will provide insights on what progress has been made on this front in the last few years. Where do we see the greatest progress? Have there been any surprises? Where do we see the future challenges?

Panelists:
Justin Sharp, Iberdrola: Iberdrola Renewables Experience
Corinna Moehrlen, WEPROG: European Experience
Ulrich Focken, energy & meteo systems: US ISO/RTO Experience
John Zack, AWS Truepower: US ISO/RTO Experience
Craig Collier, GL Garrad Hassan: ISO-NE Plans

Summary and Key Points:
Curtailment schemes can severely skew the data, frustrating efforts to train the models. Multiple independent weather forecasts can reduce forecast errors. Data obtained from wind facilities has improved greatly over time. Metrics are a key issue: standard definitions and specs should be agreed upon. Benchmarks are also problematic: sometimes difficult to know how accurate your forecasts are, as baseline data not always available. Some skepticism expressed about R&D being the answer to accuracy; more control-room experience and evaluation may yield better progress.

Panel #4: Advances in Applications of Short-term Variable Generation Forecasting
A number of projects whose objectives are to improve short-term (0-6 hr) power production time series and/or ramp forecasting have recently been completed or are still in progress. This session will provide a status update and a summary of the key results. Where do we see the greatest progress? Have there been any surprises? Where do we see the future challenges?

Panelists:
Ulrich Focken, energy and meteo systems: European Activities
Drake Bartlett, Xcel Energy: Early Performance Experience
Marty Wilde, WINDataNOW & Patrick Shaw, GL Garrad Hassan: Short-term Forecasting for Glacier Wind Plant
Patrick Mathiesen, UCSD: Cloud Forecasting for Solar
Bill Henson, ISO-NE: How Much Data is Enough?

Summary and Key Points:

Several methods were described for calculating generating reserves as a function of wind generation. Cloud cover forecasts are still the biggest source of error in solar forecasting. Regarding data adequacy: nobody really knows how much is enough in a deterministic sense, but there is some anecdotal data out there, for what it's worth. The New England Wind Integration Study might provide some answers for this, and other issues.

Panels #5 & #6: Integrating Forecasting into Market Operations, the EMS and Control Center
Most of the major ISOs/utilities with significant wind penetration on their systems have implemented centralized wind forecast systems. The type of forecast you need depends on what you are going to use it for. Is it more for system economics or system reliability? Is it for unit commitment or economic dispatch applications? System security assessment or congestion management? What specific applications are being developed around the available forecasts? What forecasting product will the new MISO Dispatchable Intermittent Resource tariff require? Many new users and system planners continue to be unsure of what type of performance to expect from the different types of forecasts, how to measure the performance, and the potential for improvement over the next few years. Updates from some of those who have implemented centralized forecasting systems will be provided.

Panelists, Session 1:
Darren Finkbeiner, IESO: What a Difference a Year Makes
Marc Keyser, MISO: MISO Experience with DIR
David Edelson, NYISO: What's New in NY
Claudine D'Annunzio, ERCOT: Market Operation One Year Later
Gerardo Ugalde, SPP: Progress at SPP

Panelists, Session 2:
Jacques Duchesne, AESO: Alberta, Canada
Ana Rodriguez Aparicio, REE: Spain
David Bell, EirGrid: Ireland
Rui Pestana, REN: Portugal
Corinna Moehrlen, WEPROG: CORESO (Coordination of Electrical System Operators)

Summary and Key Points:
Presentations from utilities followed the typical pattern of first giving an overview of their system, what their particular generation mix and renewables situation was, the processes and lessons learned from integrating renewables forecasts into their control centers, and how they were using forecasts (mostly short-term) to cope with the variability and intermittency of the renewables on their system. There was considerable discussion of the comparing-notes variety, but hard conclusions were few; most utilities are still on the learning curve with renewable generation in general, and understanding how forecasting could help them manage the impacts of the renewable generation, both in system operations and in electricity markets. A notable exception to this pattern was the presentation by Corinna Moehrlen of WEPROG, who spoke of using wind ensemble forecasts to forecast wind power production over a large swath of Western Europe, where the wind patterns are relatively homogeneous, a concept called "Supergrid" forecasting. This approach may have some application in California and parts of the US.

Panel #7: Wind Forecasting R&D Activities
DOE and other government entities are sponsoring major wind and solar forecasting research activities. The wind integration community has identified some keys areas for wind forecasting R&D that could lead to improvements in wind and solar power forecasting of significant value in system operation. The purpose of this session is to provide an update on the R&D activities underway, the topics they address, and the results to date.

Panelists:
Stan Calvert and Kevin Lynn, DOE; Melinda Marquis, NOAA: NOAA Cooperation Overview
Jim Wilczak, NOAA: WFIP Status and Preliminary Results
Stan Benjamin, NOAA: WFIP Data Assimilation and HRRR Modeling
Jeff Freedman, AWS Truepower: DOE/NOAA ERCOT-AWST Project
Cathy Finley, Windlogics: DOE/NOAA MISO-WindLogics Project
Lloyd Cibulka, CIEE: CEC Activities

Summary and Key Points:
DOE and NOAA collaborate in many areas of meteorological forecasting. NOAA has prime responsibility for much of the raw data provided to utilities and other users who need to turn the data into renewable energy forecasts. Much of their R&D efforts are focused on improving instrumentation, optimum location and number of monitoring sites for various applications, effects of climate change, collaboration with other agencies, integration of systems and methods, etc. The vendors on the panel spoke of the roles their monitoring technologies are playing in the various DOE/NOAA field projects: evaluation of monitoring accuracy as well as integration into the forecasting methodologies. CIEE presented an overview of the PIER-funded wind forecasting research projects currently underway, in the context of the overall renewables forecasting research program and integration of forecasts in CAISO’s system operations.

Panel #8: Solar Forecasting Early Applications
Many utilities and ISOs are beginning to wrestle with solar variability and uncertainty issues along with those of wind. This session will look directly at some of the solar forecasting issues, tools, projects, and some interesting early applications. What is "state-of-the-art" performance now? What can be expected over the next 5-10 years? What new requirements are on the horizon?

Panelists:
Ulrich Focken, energy and meteo systems: Germany
Carlos Rodriguez Huidobro, REE: Spain
Jim Blatchford, CAISO: California
Manajit Sengupta, NREL: NREL
Dora Nakafuji, HECO: Hawaii
Obadiah Bartholomy, SMUD: Solar Variability and Forecasting Research
Tom Hoff, Clean Power Research: Cloud Impact on Forecast

Summary and Key Points:
This session was a good roundup of some of the cutting-edge solar forecasting research going on worldwide. The companies represented here were all deeply involved in trying to use the latest research to improve their solar forecasts to reduce system impacts and improve the role of renewables in the energy markets. (Jim Blatchford spoke only on the solar forecasting projects at CAISO; Lloyd Cibulka had spoken to the wind forecasting in the previous panel.) Tom Hoff’s presentation was a much more technical and detailed exposition than his Dec. 16 workshop presentation on the subject of cloud tracking in solar forecasting. SMUD will soon begin a CPUC-funded project investigating high penetration of PV on a distribution feeder.

Panel #9: Closing Panel Discussion
We have discussed a broad range of topics on the status and applications of wind and solar forecasting. In the closing panel, we will hear a distillation of key messages from a cross-section of the participants, with a focus on the needs of the future, followed by a broader discussion with the participants.

Panelists:

Mark Ahlstrom, WindLogics
Bob Zavadil, EnerNex
Jeff Lerner, 3TIER
Drake Bartlett, Xcel Energy
Abraham Ellis, Sandia
John Zack, AWS Truepower
Ulrich Focken, energy and meteo systems
Corinna Moehrlen, WEPROG

Key Takeaways:

- Forecasts must be meshed with market design.
- System operators need more operating flexibility and situational awareness.
- Need to determine what data is actually required vs. what just seems nice to have.
- UVIG could take on the role of data clearinghouse.
- Probabilistic forecasting shows a lot of promise, especially for determining reserve capacity, but a lot of what's currently available isn't being used, and new tools are needed.
- Probabilistic forecasting is currently viewed skeptically by many operators; familiarity and education are needed.
- The tools that are being developed need to be tried and evaluated by the end-users.
- MAE and RMSE are the likely best metrics to use; standardization of definitions and uses will be key to best uses.
- Grid impacts of renewable integration still need a lot of study.
- There is a particular urgency for better solar forecasting; several utilities expressed it, and high-pen PV is coming.
- There are significant differences between the European and US approaches to wind forecasting, but there are some areas of commonality to leverage results.
- Better data is need for initialization and validation of models.

Recommended Research Areas and User Needs

CAISO Renewable Forecasting Tool Specification

Background

Pacific Northwest National Laboratory (PNNL) developed a prototype "Ramping Tool" for CAISO (see presentation by Jeff Dagle, above) with funding from CEC/PIER. This tool is currently in use at the CAISO Control Center in Folsom, CA, and CAISO and PNNL have worked together to update the Tool to reflect the increased frequency of data now received by the CAISO. The following specifications reflect the CAISO's desired performance characteristics for this tool.

CAISO's ultimate goal is to have a production grade (commercial) version of this tool available from a reputable vendor, with full customer support services, much like other commercial software systems installed in the control center. While this last step in commercial product development is not eligible for CEC funding, the development and testing of the enhanced capabilities CAISO would like to see integrated into the tool certainly qualify, and are necessary before a production grade tool can be produced to the CAISO's specs.

Tool Overview

The Renewable Forecasting Tool is not a tool which actually generates forecasts for wind and solar. Rather, it takes wind and solar forecasts and confidence levels for those forecasts from a service provider, combines those forecasts with load and capacity forecasts and generates graphical and numerical outputs aimed at the next 5 hours and the next 24 hours. It is a stand-alone system intended to provide grid operators with forecast requirements for up-ramp, down-ramp, and regulation requirements in real time or near-real time for the Hour Ahead and Day Ahead markets.

Input Specifications

- Wind and solar forecasts in 15-minute increments for 5 hours, and 1-hour increments for 24 hours, including confidence bars
- Load forecasts in 5-minute increments for 5 hours, 30-minute increments for 24 hours
- Non-wind and -solar capacity forecast (i.e., balance of existing generating fleet)
- Historical database

Output Specifications

- Up and down ramp forecasts in 5-minute intervals for 5 hours
- Up and down ramp forecasts in 15-minute intervals for 24 hours
- Up and down regulation forecasts in 5-minute intervals for 5 hours
- Up and down regulation forecasts in 15-minute intervals for 24 hours
- Forecast uncertainty bars

Accuracy Requirements

- Target accuracy has been suggested to be 5%, similar to that achieved in Spain and Germany.
- Priority should be on improving solar forecasts, as wind forecasting is actually pretty good, compared to solar.
- There is a need for improvements in load forecast accuracy. This has not received a lot of attention, but any improvement here is as significant as the same percentage improvement in renewable forecasts.

DOE FOA-0000649: Improving the Accuracy of Solar Forecasting

In January 2012, DOE issued a Request for Information (RFI) to solicit stakeholder comments on the issues relating to implementation of solar forecasting for the purpose of integrating renewable generation into utility operations, and received detailed comments and suggestions from over 40 respondents. To further discuss these issues, DOE also convened a Solar Forecasting Workshop in Tucson, AZ on February 10, 2012, which saw vigorous participation by over 70 attendees from various stakeholder categories including academia, power system operators, and the solar forecasting industry. The RFI respondents and workshop participants (which included all the major California stakeholders such as the CAISO and the IOUs) provided comments that were grouped into two main topics: (1) Achieving Consensus on Forecasting Metrics, and (2) Innovative Methods and Instrumentation Needs for Accurate Solar Forecasting. Specific inputs from the RFI and Workshop included the following research and user needs:

<u>Standardized Metrics</u>

- Standard *definitions* for metrics, especially for ramp rate and variability forecasts.

- Forecast accuracy evaluation is currently not consistent due to lack of standard metrics.

Metrics Categorization

- Based on their application – improving accuracy, better modeling, input data assimilation, use in power system planning/operations, etc.
- Temporal/Spatial Aggregation; Transmission vs. Distribution applications; Probabilistic vs. Deterministic, forecasts for PV vs. CSP, etc.

Target Values Formulation

- Measure accuracy with reference to a standard forecast such as persistence; also, further capture the *value* of a forecast.
- Some amount of initial analysis is required in determining the metrics; develop an iterative process in acquiring stakeholder feedback and performing more analyses.

Research

- Improved modeling and forecasting of cloud formation, cloud movement, aerosols etc.
- Developmental test bed center: bring in new research, translate into operations.
- Distinguish between long-term (weather, NOAA effort) and short-term (private industry effort).
- Model initialization and data assimilation are key challenges.

Instrumentation

- More on-the-ground instrumentation (such as sky imagers) for validating forecasts.
- More depth-specific information in atmosphere; also, measurements with spectral resolution and on fast time-scales.
- Satellite measurements are low-resolution; higher resolution and frequency of measurements needed; also, higher resolution in Numerical Weather Prediction (NWP) models.

Forecasting

- Different types of forecasts – solar irradiation on the ground (W/m^2) vs. actual power production from solar plants.
- Consider a range of time periods for forecasts, e.g., day-ahead and hour-/multi-hour-ahead are important for power markets.
- Translate probabilistic information into actionable decision-making (probabilistic forecasting) for operators.

DOE subsequently issued, as part of its "SunShot Initiative," FOA-0000649 with $9 million of available funding to solicit applications for improving the accuracy of solar forecasting in the short-term (0-6 hours) and day-ahead timeframes. Awards under this FOA are expected to be announced in the Fall of 2012, with projects having a period of performance up to three years.

Cofunding of California Stakeholder Research Activities Under DOE's FOA-0000649

The aforementioned DOE FOA is expected to produce a number of proposals that will improve the accuracy of solar forecasts with research results that can be used by California stakeholders. Many of the foremost researchers, such as UC-Davis and UCSD, may either be involved in these research efforts (beyond what they are already doing with CEC funding), or willing and able to carry them forward with additional research efforts if indicated. Therefore, the best course of action at this time is to monitor the rollout of DOE projects under this FOA, and to consider providing supplemental funding as needed to ensure maximum benefit to California stakeholders from these DOE projects.

Specific Forecasting Research Needs for California Stakeholders

Solar Forecasting Research Needs:

- **Cloud forecasting and tracking.** This is the single most important area of research for improving solar forecasts. California has specific needs related to the marine layers on its coast, and to inversion layers inland. Again, current research may provide results, but additional research may be needed.
- **Ramping of solar generation.** This is especially important in areas of the distribution system with high concentration of PV, where visibility of PV by system operators is poor or non-existent.
- **Development and evaluation of advanced forecasting engines.** Examples include the SolAspect engine being developed at UCSD, or the Multiple Look-Ahead system developed by AWS TruePower. These engines can produce full-spectrum forecasts, rather than aggregating results from multiple forecasting engines, or other types of systems with time gaps in their forecast zones.
- **Improved monitoring instrumentation and optimal location of monitors.** This by itself can provide real-time measurement of plant output, giving system operators better situational awareness rather than relying on possibly outdated or inaccurate forecasts; the data also can be used to improve short-term (15-min and hour ahead) solar forecasts.
- **Improved day-ahead forecasting through numerical weather models, with a focus on marine layer clouds.** Advanced algorithms to ingest satellite and ground measurements into their models, and advanced modeling parameterizations for clouds and the boundary layer should be applied. Of specific interest are ensemble forecasts integrated with machine learning tools to optimize dynamic selection of forecast models based on meteorological conditions.

Wind Forecasting Research Needs:

- **Ensemble forecasts.** These have been used with some success in Europe and elsewhere, and should be investigated for applicability in California.
- **Improved instrumentation, and optimal location of monitors.** As with solar, the benefits are better situational awareness for operators, and improved short-term forecasts, especially for ramp prediction.
- Offshore wind forecasting methodologies. for forecasting offshore wind and incorporating into current tools.

General Forecasting Research Needs:

- **Forecasting metrics** (both wind and solar) need to be better defined, and evaluated for applications to specific uses. MAE (mean average error) and RMSE (root mean square error) are the leading candidates, but others may be needed.
- **Geographic diversity and aggregation techniques,** especially across balancing areas, to achieve higher forecast accuracy.
- **Probabilistic/stochastic forecasting:** new methods and tools, operator training and evaluation.
- **Synchrophasors** for data acquisition (e.g., renewable plant output, input to ramping tools, improved forecast accuracy, etc.) and model validation.

- **Applications of storage systems** to smooth renewable plant output, augment forecasting methods and reduce errors.

User Forecasting Needs:

- **Short-term ramps** are important for operators; tools to deal with these are critical, and may be different for wind than for solar.
- **Forecast integration into CAISO operations.** Software development for identification of past analogs to current forecasts, metrics for selection of analogs, and operator training.
- **Better site-specific information** (both load and resource) is a critical need; improved metering, and access to inverter data or plant operator data, should be investigated.
- **Load forecasting.** Identify forecasting techniques to determine aggregated net (load minus solar generation) on distribution feeders and in balancing areas, and integration of these parameters into machine learning models to forecast net load hours to days ahead.
- The CAISO needs to have an **improved Ramping Tool** to meet its requirements by 2020. (See "CAISO Renewable Forecasting Tool Specification," above.)
- **Operator training and evaluation** is key to acceptance and realization of the benefits of new tools that are developed. Situational awareness should be enhanced, e.g., through improved monitoring and visualization tools, but information overload avoided.
- **Integration of forecasting tools with markets, and market designs per se.** The California PIRP process could be studied for improvements that could facilitate innovation.
- **DER penetration data sharing and location mapping:** a centralized database to collect distributed energy resource (DER) penetration level data in California.

References

Solar Forecasting References

Bacher, P., Madsen, H., Nielsen, H. A.: *Online Short-term Solar Power Forecasting,* Solar Energy 83:1772–1783, 2009.

Bofinger, S., Heilscher, G.: *Solar Radiation Forecasts Based on ECMWF and Model Output Statistics,* Technical Report, European Space Agency (ESA) ENVISOLAR Consortium, AO/1-4364/03/I-IW, EOEP-EOMD.

Breitkreuz, H., Schroedter-Homscheidt, M., Holzer-Popp, T., Dech, S.: *Short-Range Direct and Diffuse Irradiance Forecasts for Solar Energy Applications Based on Aerosol Chemical Transport and Numerical Weather Modeling,* Journal of Applied Meteorology and Climatology (JAMC), American Meteorological Society, September 2009.

Hamill, T. M., Nehrkorn, T.: *A Short-Term Cloud Forecast Scheme Using Cross Correlations,* Weather and Forecasting, American Meteorological Society, Vol. 8, Issue 4, pp. 401-411, December 1993.

Hammer, D., Heinemann, E., Lorenz, B., Luckehe, B.: *Short-term Forecasting of Solar Radiation: a Statistical Approach Using Satellite Data,* Solar Energy (67):1–3, pp. 139–150, 1999.

Heinemann, E., Lorenz, B., Girodo, M.: *Forecasting of Solar Radiation,* Solar Energy Resource Management for Electricity Generation from Local Level to Global Scale, E. Dunlop, L. Wald, and M. Suri, Eds., Commack, NY: Nova, pp. 83–94, 2006.

Jensenius, J. S., Cotton, G. F.: *The Development and Testing of Automated Solar Energy Forecasts Based on the Model Output Statistics (MOS) Technique,* Proceedings of the 1st Workshop on Terrestrial Solar Resource Forecasting and on the Use of Satellites for Terrestrial Solar Resource Assessment, American Solar Energy Society, 1981.

Kleissl, J.: *Current State of the Art in Solar Forecasting,* white paper submitted to the California Energy Commission, December 2010.

Lorenz, E., Hurka, J., Heinemann, D., Beyer, H.-G.: *Irradiance Forecasting for the Power Prediction of Grid-Connected Photovoltaic Systems,* IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, (2):1, 2009.

Modica, G. D., d'Entremont, R., Mlawer, E., Gustafson, G.: *Short-range Solar Radiation Forecasts in Support of Smart-grid Technology,* American Meteorological Society Conference, 2010.

Perez, R., Moore, K., Wilcox, S., Renne, D., Zelenka, A.: *Forecasting Solar Radiation – Preliminary Evaluation of an Approach Based upon the National Forecast Database,* Solar Energy 81:809–812, 2007.

Perez, R., Kivalov, S., Zelenka, A., Schlemmer, J., Hemker Jr., K.: *Improving the Performance of Satellite-to-Irradiance Models Using the Satellite's Infrared Sensors,* Proceedings of the American Solar Energy Society (ASES) Annual Conference, Phoenix, Arizona, 2010.

Perez, R., Kivalov, S., Schlemmer, J., Hemker Jr., K., Renne, D., Hoff, T.: *Validation of Short and Medium Term Operational Solar Radiation Forecasts in the US,* Solar Energy, 2010.

Porter, K. and Rogers, J.: *Survey of Variable Generation Forecasting in the West,* report to the National Renewable Energy Laboratory (NREL), April 2012. [http://www.nrel.gov/docs/fy12osti/54457.pdf]

Remund, J., Perez, R., Lorenz, E.: *Comparison of Solar Radiation Forecasts for the USA,* 2008 European PV Conference, Valencia, Spain, 2008.

Schnitzer, M., Thuman, C., Johnson, P.: *Reducing Uncertainty in Solar Energy Estimates: Mitigating Energy Risk through On-Site Monitoring,* AWS TruePower white paper, July 2012. [http://www.awstruepower.com/wp-content/uploads/2012/07/Reducing-Uncertainty-in-Solar-Energy-Estimates-2012.pdf]

Schroedter-Homscheidt, M., Hoyer-Klick, C., Rikos, E., Tselepsis, S., Pulvermüller, B.: *Nowcasting and Forecasting of Solar Irradiance for Energy Electricity Generation*, International Energy Agency (IEA) Solar Power and Chemical Energy Systems (SolarPACES), 2009.

Stoffel, T.: *Solar Resources & Forecasting Workshop Highlights,* Solar Resources and Forecasting Workshop, June 2011. [http://ases.conference-services.net/resources/252/2859/pres/SOLAR2012_0828_presentation.pdf]

Wittmann, M., Breitkreuz, H., Schroedter-Homscheidt, M., Eck, M.: *Case Studies on the Use of Solar Irradiance Forecast for Optimized Operation Strategies of Solar Thermal Power Plants,* IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, (1):1, 2008.

Zack, J.: *Current Status and Challenges of Solar Power Production Forecasting,* Electric Reliability Council of Texas (ERCOT) Emerging Technologies Working group (ETWG) Solar Workshop, Austin, TX, April 25, 2011. [http://www.ercot.com/content/gridinfo/etts/solar/presentations/04_-_AWS_John_Zack_ERCOT_workshop_25apr11.pdf]

Wind Forecasting References

Ahlstrom, M., et al.: *Atmospheric Pressure - Weather, Wind Forecasting, and Energy Market Operations,* IEEE Power & Energy, Nov/Dec 2011. [http://www.uwig.org/ahlstrom.pdf]

Aitken, M., Rhodes, M., Lundquist, J.: *Wind LIDAR Performance in the Region of Turbine Rotor Disks*, 91st American Meteorological Society (AMS) Annual Meeting, January 2011. [http://ams.confex.com/ams/91Annual/webprogram/Handout/Paper177773/ATOC%20Poster.pdf]

Alliss, R.: *Introducing the Renewable Energy Network Optimization Tool (ReNOT): Part I*, 91st American Meteorological Society (AMS) Annual Meeting,January 2011. [http://ams.confex.com/ams/91Annual/webprogram/Manuscript/Paper178275/RenotPt1.pdf]

American Wind Energy Association: *U.S. Wind Industry First Quarter 2012 Market Report,* April 2012. [http://awea.org/learnabout/publications/reports/upload/AWEA_First_Quarter_2012_Market_Report_Public.pdf]

Botterud, A., et al.: *Use of Wind Power Forecasting in Operational Decisions,* Argonne National Laboratory, ANL/DIS-11-8, September 2011. [http://www.dis.anl.gov/pubs/71389.pdf]

Deppe, A., Takle, E., Gallus, W.: *Creation of a WRF Ensemble for Improved Wind Forecasts at Turbine Height,* 91st American Meteorological Society Annual Meeting, January 2011. [http://ams.confex.com/ams/91Annual/webprogram/Manuscript/Paper179923/wind_forecasting_expanded_abstract.pdf]

Dragoon, K. , Kirby, B., Milligan, M.: *Do Wind Forecasts Make Good Generation Schedules?,* WindPower 2008, NREL/CP-500-43507, June 2008.
[http://www.nrel.gov/wind/systemsintegration/pdfs/2008/milligan_wind_forecasting.pdf]

Ela, E., Milligan, M., Kirby, B.: *Operating Reserves and Variable Generation,* NREL/TP-5500-51978, August 2011.
[http://www.nrel.gov/wind/systemsintegration/pdfs/2011/milligan_operating_reserves.pdf]

Ferreira, C., et al.: *A Survey on Wind Power Ramp Forecasting,* Argonne National Laboratory, ANL/DIS-10-13, December 2010.
[http://www.dis.anl.gov/pubs/69166.pdf]

Giebel, G., et al.: *The State-of-the-Art in Short-Term Prediction of Wind Power,* January 2011.
[http://orbit.dtu.dk/fedora/objects/orbit:83397/datastreams/file_5277161/content]

Greaves, B., et al.: *Temporal Forecast Uncertainty for Ramp Events,* Garrard-Hassan & Partners, Ltd., August 2011.
[http://www.gl-garradhassan.com/assets/technical/Temporal_forecast_uncertainty_for_ramp_events.pdf]

Hodge, B. Milligan, M.: *Wind Power Forecasting Error Distributions over Multiple Timescales,* March 2011.
[http://www.nrel.gov/wind/systemsintegration/pdfs/2011/hodge_forecasting_error_distributions.pdf]

Jørgensen, J. Möhrlen, C.: *Increasing the Competition on Reserve for Balancing Wind Power with the Help of Ensemble Forecasts,* Weather and Wind Energy Prognosis (WEPROG), October 2011.
http://download.weprog.com/public_paper_WIW11_032_joergensen_et_al.pdf

Lew, D.: *Western Wind and Solar Integration Study,* WAPA/UVIG Wind and Solar Workshop, February 2012.
[http://www.uwig.org/Golden2012/WWSIS-WAPA-Lew.pdf]

Lew, D., et al.: *The Value of Wind Power Forecasting,* January 2011.
[http://www.nrel.gov/wind/systemsintegration/pdfs/2011/lew_value_wind_forecasting.pdf]

Makarov, Y., et al.: *Online Analysis of Wind and Solar*, Final Project Report, January 2012.
[http://uc-ciee.org/images/downloadable_content/electric_grid/OT_Final_Ramping_Tool_Report.pdf]

Makarov, Y., et al.: *Incorporating Wind Generation and Load Forecast Uncertainties into Power Grid Operations,* Pacific Northwest National Laboratory, January 2010.
[http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19189.pdf]

Malloy, N.: *Wind Speed Risk – Who Should Pay*, 3Tier, September 2011.
[http://www.3tier.com/static/ttcms/us/documents/publications/3TIER-Wind-Speed-Energy-Risk.pdf]

Marquis, M, et al.: *Forecasting the Wind to Reach Significant Penetration Levels of Wind Energy,* Bulletin of the American Meteorological Society (BAMS), September 2011.
[http://www.uwig.org/BAMS-Wind_Forecasting.pdf]

Mendes, J., et al.: *Development and Testing of Improved Statistical Wind Power Forecasting Methods,* Argonne National Laboratory, ANL/DIS-11-7, September 2011.
[http://www.dis.anl.gov/pubs/71390.pdf]

Monteiro, C., et al.: *Wind Power Forecasting: State of the Art – 2009,* Argonne National Laboratory, ANL/DIS-10-1, November 2009.
[http://www.dis.anl.gov/pubs/65613.pdf]

Myers, W., Cowie, J., Linden, S.: *DICast®: A Dynamic Integrated ForeCast System,* National Center for Atmospheric Research, Research Applications Laboratory (NCAR/NAL), March 2011.
[http://www.ral.ucar.edu/projects/dicast/presentations/Myers_Dicast_March2011.pdf]

Myers, W., Linden, S.: *A Turbine Hub Height Wind Energy Prediction System Developed for Xcel Energy*, 91st American Meteorological Society Annual Meeting, March 2011.
[http://ams.confex.com/ams/91Annual/webprogram/Paper187355.html]

NERC: *IVGTF Task 2.1 Report Variable Generation Power Forecasting for Operations*, May 2010.
[http://www.uwig.org/Variable_Generation_Power_Forecasting_for_Operations.pdf]

Porter, K.: *Variable Generation Forecasting Project,* Meeting of the Committee on Regional Electric Power Cooperation (CREPC), October 2011.
[http://www.westgov.org/wieb/meetings/crepcfall2011/briefing/present/k_porter1.pdf]

Porter, K., Rogers, J.: *Status of Centralized Wind Power Forecasting in North America: May 2009 - May 2010,* NREL, April 2010.
[http://www.nrel.gov/wind/systemsintegration/pdfs/2010/porter_centralized_forecasting.pdf]

Pyle, R.: *Wind Ramp Prediction – Improved Predictability for Wind Energy Production,* Vaisala, September 2010.
[http://www.vaisala.com/Vaisala%20Documents/Vaisala%20News%20Articles/VN182/vn182_10_wind_ramp_prediction.pdf]

Rogers, J., Porter, K.: *Central Wind Forecasting Programs in North America by Regional Transmission Organizations and Electric Utilities: Revised Edition,* NREL, March 2011.
[http://www.nrel.gov/wind/systemsintegration/pdfs/2011/rogers_wind_forecasting_programs.pdf]

Vidal, J. et al.: *Validation of a Wind Power Forecast System,* 2010 European Wind Energy Conference and Exhibition (EWEC2010), April 2010.
[http://www.ewec2010proceedings.info/posters/PO.154_EWEC2010presentation.pdf]

WEPROG: *Large-scale Forecasting with Ensemble Forecasts*, February 2012.
[http://download.weprog.com/uwig_s3_largesystemFC_weprog.pdf]

Wilczak, J.: *Enhancing Short Term Wind Energy Forecasting for Improved Utility Operations: Technical Description of a Joint DOE/NOAA/Private Industry Collaborative Field Program,* National Oceanic and Atmospheric Administration (NOAA), January 2011.
[http://www.esrl.noaa.gov/search/publications/5795/

Zack, J., et al.: *Observing System Simulation Experiments (OSSEs) for the Mid-Columbia Basin,* Lawrence Livermore National Laboratory (LLNL), September 2011.
[http://ckamath.org/yahoo_site_admin/assets/docs/LLNL-TR-499162.298232906.pdf]

Zack, J., et al.: *Development and Testing of an Innovative Short Term Large Wind Ramp Forecasting System,* 2010 European Wind Energy Conference and Exhibition (EWEC2010), April 2010.
[http://ewec2010proceedings.info/allfiles2/568_EWEC2010presentation.pdf]