A PUBLIC-PRIVATE-ACADEMIC PARTNERSHIP TO ADVANCE SOLAR FORECASTING

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ABSTRACT

The National Center for Atmospheric Research (NCAR) is leading a multi-disciplinary team to perform use-inspired research to advance solar power forecasting. The research focuses on a series of technologies that span the continuum of solar forecasting from 15 min to 36 hours. Solar radiation measurement and cloud observation and tracking techniques are being advanced along with methods to quantify and track aerosols that affect cloud formation and radiative transfer, including the prediction of haze and contrails. Other efforts focus on short-term prediction of cloud properties based primarily on observations, assimilation of cloud observations from various sources into numerical weather prediction (NWP) models, and integration of new cloud physical processes and parameterizations into NWP models. The team aims to transition the research toward operational use in the Weather Research and Forecasting (WRF) based High Resolution Rapid Refresh (HRRR) system. The project will incorporate a prototype solar forecasting system into operations and test it in collaboration with utilities and independent system operators in geographically diverse areas, such Long Island, Colorado, coastal California, Florida, and Hawaii.

1. INTRODUCTION

Because solar energy is a highly variable natural resource, it is critical to be able to forecast it in order to integrate it into the energy mix efficiently, reliably, and economically. The goals of the project reported here are to build a solar power forecasting system to advance the state-of-the-science through cutting edge research; test and evaluate the system with appropriate metrics in several geographically-diverse, high penetration solar utilities and ISOs; and disseminate the research results widely to raise the bar on solar power forecasting technology.

The National Center for Atmospheric Research (NCAR) was recently awarded a cooperative agreement from the US Department of Energy (DOE) to demonstrate a solar power forecasting system in several commercial solar farms. NCAR is partnering with the National Renewable Energy Laboratory (NREL), Brookhaven National Laboratory (BNL), the National Oceanographic and Atmospheric Administration (NOAA); universities – Penn State, Colorado State, Hawaii, and Washington; utilities – Long Island Power and Light, New York Power Authority, Public Service of Colorado, Sacramento Municipal Utility District (SMUD), Southern California Edison, and the Hawaiian Electric System (HECo); independent system operators (ISOs) – New York ISO, California ISO (CAISO), Xcel Energy, and Hawaiian Electric; and commercial forecast providers – Schneider/Telvent DTN, Atmospheric and Environmental Research (AER), Global Weather Corporation (GWC), and MDA Information Systems in this project. This team is in the process of developing a solar power forecasting system that advances the state-of-the-science through cutting edge research, plans to test it in several high penetration solar utilities and ISOs with geographic diversity, and then will disseminate the research results widely.

2. APPROACH TO SOLAR FORECASTING

Research has begun to develop an advanced solar power prediction system applicable across several U.S. climate regions. A major challenge for solar power forecasting is accurately forecasting cloud cover and aerosols. That is a topic of considerable interest for many users across multiple sectors (e.g., agriculture, aviation, surface transportation, water resource management, etc.) and it requires enhancements in the state-of-the-science at several temporal and spatial scales. Not only do clouds move around under the influence of the wind at their level, they also form, dissipate, and change shape. Improvements in the understanding of cloud physics and precipitation processes are required as well as the translation of this information into numerical weather prediction (NWP) models. When one considers the needs for day-ahead forecasting as well as very short-term forecasts, it is obvious that those are very different requirements from wind prediction and, like wind power forecasting, requires a systems approach. Significantly advancing solar irradiance forecasting requires performing research in several targeted core areas including:

- Solar radiation measurement and cloud observation techniques
- Methods to quantify and track aerosols that affect cloud formation and radiative transfer, including prediction of haze and aircraft contrails
- Methods to provide short-term prediction of cloud properties based primarily on observations
- Assimilation of cloud observations from various sources into weather prediction models
- Cloud physical process prediction integrated into numerical weather prediction models
- Radiative transfer through disparate types of clouds and aerosols
- Numerical weather prediction tuned for solar radiation at specific locales
- Rapid cycle modeling, for nowcasting of cloud development, movement, and dissipation
- Statistical learning methods for blending disparate forecast models
- Real-time learning techniques to optimize irradiance forecasts under dynamic conditions
- Irradiance to power conversion methods, to include data mining for temporal changes in power output.

As is true for wind power forecasting, solar power forecasting largely depends on the type and quality of available measurements. Those observations should ideally include solar radiation and cloud measurements, satellite observations, observations from total sky imagers, and local meteorological observations.

Figure 1 depicts the types of forecast models to be included in an advanced Solar Power Forecasting System. As for wind power forecasting, the best approach for time frames beyond about 3 hrs will involve NWP [1]. NWP models typically predict a cloud fraction for each grid cell. Modern NWP includes assimilating cloud observations such as those from satellites, but there is often a lag in such assimilation due to slow update rates from satellite systems. At longer forecast lead times, model forecasts from national centers are blended. At the shorter terms, however, customized NWP serves to provide enhanced forecasts, both in terms of running at higher resolution over the domains of interest as well as enhancing the models to better forecast clouds and to assimilate specialized data. Plans to enhance the NWP customized forecasts include building WRF-Solar, which will include new shallow convection parameterization schemes, better cloud physics parameterizations that include incorporating best estimates of clear-sky aerosols, new satellite data assimilation algorithms, and enhanced radiative transfer schemes.

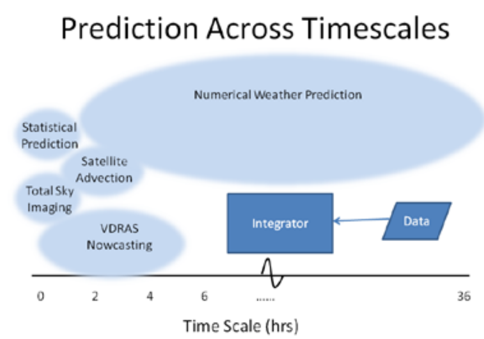

Figure 1. Elements of a Solar Power Prediction System.

Shorter term solar forecasting will rely on real-time cloud observations and nowcasting techniques as well as empirical statistical methods that build on historical datasets as well as current observations. For very short-term forecasts, information on radiation means and variability can be obtained by direct observation of conditions, using sky imagers, pyranometers, or satellites. A statistical prediction method will be devised to translate knowledge of the meteorological state and its expected short-term variability into a short-term empirical statistical prediction model.

Real-time observations of cloud at the site using sensing equipment such as total sky imagers (TSI) will provide information to make physical and dynamical short-term prediction of cloud motion. When three TSIs are located in close proximity, the images can also be used to triangulate cloud type and depth. Watching the changes in images in time provides information on cloud evolution and motion. This valuable information can then be used in several ways. The simplest way to use TSI data is simply to image process to determine cloud placement and motion, then project where the cloud will be in the very near future. A second use is to blend the data into a dynamical model, such as a rapid-refresh short-range version of WRF to dynamically advect the cloud according to the equations of motion. Finally, the TSI images can be assimilated into full NWP models such as WRF-Solar to provide initial conditions to predict cloud dynamics as well as their motion.

The advanced solar power forecasting system will also leverage satellite cloud observations and retrieval of cloud properties. The most refined short-term forecasting techniques account for such details as satellite parallax corrections and the solar geometry (shadow-casting), which can displace the influence of clouds by 10's of km (particularly for high/deep clouds and lower solar elevation angles), as well as the differential steering effects of a divergent wind field on cloud trajectories. The cloud data can either be used on its own and advected according to observed winds or assimilated into cloud scale or NWP models to initialize those with real-time cloud observations.

Short range high-resolution modeling will employ rapid-refresh modeling with satellite and TSI data assimilation to produce nowcasts and short-range forecasts. Such high resolution systems include the real model dynamics and blend in observations from local radar systems and specialized observations such as TSIs and satellite imagers.

As with wind power forecasting, the systems approach to blending data and technologies from all of these sources is expected to provide a better prediction of the resource than any particular single system. Statistical learning systems such as the Dynamic Integrated Forecast (DICast) System [2] can then customize the forecast to the location and the lead time. Once solar irradiance has been forecast, then it is necessary to convert to power. There exist some standard prediction models such as those derived by the US National Renewable Energy Laboratory and other organizations. It is not yet known whether empirical methods such as those employed in wind power forecasting will outperform these power conversion models. It is expected that the various centers throughout the world who are currently researching these methods for solar power forecasting will make great strides in accuracy and usefulness in the coming years that will help advance the adoption of solar power.

3. TECHNOLOGY ADVANCES

To achieve a substantial advance in solar power forecasting requires performing basic and use-inspired research in several targeted core areas [3, 4, 5, 6]. First, metrics will be developed with significant involvement of stakeholders to measure improvements in solar forecasts and the benefits generated. These metrics will include traditional metrics like root mean squared error (RMSE) but will go well beyond that to include spatial and temporal verification to verify and validate individual model components. In addition to verifying model weather variables, it is important to verify power output. It is the power prediction that is of critical importance to the utilities and ISOs. Finally, value of the forecasts will be assessed. To develop the appropriate value metrics, economic expert elicitation will be accomplished with the commercial partners. Additionally, conjoint experiments will be used to determine the stakeholder's assignment of value to various options.

Use of solar radiation measurement and cloud observation and tracking techniques will also be advanced. Methods to quantify and track aerosols that affect cloud formation and radiative transfer, including the prediction of haze and contrails, will be investigated.

A major advance will be in designing a specialized version of the Weather Research and Forecasting (WRF) model that is specifically tuned to the needs of solar power forecasting: WRF-Solar. WRF has been primarily developed and maintained at NCAR and is an accepted forefront NWP model [7] with over 10,000 users across the world.

WRF-Solar will have advances in several specific ways. A new shallow convective parameterization scheme will better model cloud formation [8, 9]. The integration of new cloud physical processes and parameterizations together with better estimates of aerosol transport and formation of aerosols that become the cloud condensation nuclei will also aid in better estimates of cloud formation and dissipation [10]. Radiative transfer through distinct types of clouds and aerosols and capabilities tuned for solar radiation at specific locales will advance the model's ability to estimate solar insolation [11, 12]. Finally, assimilating cloud observations directly obtained from satellite data and TSIs will provide better initial conditions for both advecting clouds through the models and for initializing cloud properties [13].

Additionally, statistical learning methods for blending disparate forecast models, real-time learning techniques to optimize irradiance forecasts under dynamic conditions are essential. NCAR is leveraging 15 years of research on building the DICast system [2], which blends disparate forecasts to produce best estimates of various meteorological variables. DICast accomplishes this in a two-step process: first, each input model data is calibrated using a model output statistics (MOS) approach, which calibrates the model and removes biases. Second, the models are weighted according to weights derived by a learning algorithm that minimizes the error in historical forecasts. The learning algorithm is updated frequently to implicitly include seasonal effects. These algorithms are applied locally to produce the best forecast for a particular solar farm. Then irradiance-to-power conversion methods are applied, including data mining for when the system fails to meet potential power output, will be explored. These methods are necessary to turn the best weather predictions into best forecasts of solar irradiance and power generation. The forecast provider partners will apply and test their own algorithms to provide forecasts to partners as well as their own clients.

A key aspect of the project will be providing forecasts across a range of temporal and spatial scales. This process requires a large amount of carefully planned systems engineering to deal with data formats, data transfer, system integration, and reliable transmittal to the end users. The system technologies will leverage solar radiation and cloud measurements, including images from total sky imagers; satellite observations; local meteorological observations; publically available NWP modeling results, including the HRRR; a customized version of the WRF model (WRF-Solar) tuned for cloud prediction and assimilating specialized data; radiative transfer modeling; statistical blending of forecast technologies tuned to prediction times ranging from 15 min to 36 hrs; irradiance to power conversion models; displays tuned to the needs of the end user; and built-in assessment metrics.

4. DEMONSTRATION

The advanced technologies will be incorporated into a prototype solar forecasting system that will be tested in collaboration with utilities and ISOs in geographically diverse areas, such Long Island, Colorado, New Mexico, Florida, coastal California, and Hawaii. After the research has been accomplished to design, test, and validate the various components described above, the system will be integrated and run quasi-operationally. The first six months will be a testing phase, in which the individual components and the integrated system is constantly evaluated, verified, and improved in an iterative process. Then for a full year, the system will be run quasi-operationally in order to fully test its capabilities under a variety of seasons and weather conditions. The geographic diversity of the test locations will enable advancing capabilities in a wide range of climate zones and weather patterns.

Each component of the system will be verified and validated using evaluation techniques and metrics developed specifically for the project through in-depth interactions with stakeholders. The economic value of providing the forecasts will be assessed. The system will be deployed within operational environments of plant operators, utilities, and ISO partners with engagement of commercial forecast providers who will tailor the methods to the needs of the deployment. This will be an iterative process with user feedback leading to a forecast capability designed to add value to the partners. The results will be widely disseminated.

5. SUMMARY

The solar power forecasting project reported here will integrate observing systems, new and existing dynamical and physical models at a variety of scales, statistical learning systems, systems engineering, and other technologies to advance solar power forecasting. The new and enhanced models that are being developed will have broad applicability and will be made public. The end goal of the research and operational application of this effort is to make seminal advances in the state of cloud forecasting, and thus, solar irradiance forecasting, as well as integrating it into the grid and assessing the resulting value. Thus, the work reported herein strives to advance the ability to integrate solar energy and advance higher penetration of renewable energy.

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7. REFERENCES

(1) Mahoney, W.P., K. Parks, G. Wiener, Y. Liu, B. Myers, J. Sun, L. Delle Monache, D. Johnson, and S.E. Haupt, 2012: A Wind Power Forecasting System to Optimize Grid Integration, special issue of *IEEE Transactions on Sustainable* Energy on Wind Energy

(2) Myers, W., G. Wiener, S. Linden, and S.E. Haupt, 2011: A Consensus Forecasting Approach for Improved Turbine Hub Height Wind Speed Predictions," Proceedings of WindPower 2011

(3) Brown, B.G., E. Gilleland, and E. Ebert, 2012: Forecasts of spatial fields. In *Forecast verification: A practitioner's guide in atmospheric sciences*, I.T. Jolliffe and D.B. Stephenson, Editors. Wiley

(4) Casati B., L. J. Wilson, D. B. Stephenson, P. Nurmi, A. Ghelli, M. Pocernich, U. Damrath, E. E. Ebert, B. G. Brown, and S. Mason, 2008: Forecast verification: current status and future directions. *Meteorological Applications*, **15**, 3-18

(5) Davis, C.A., B.G. Brown, R.G. Bullock and J. Halley Gotway, 2009: The Method for Object-based Diagnostic Evaluation (MODE) Applied to Numerical Forecasts from the 2005 NSSL/SPC Spring Program. *Weather and Forecasting*, **24**, 1252-1267

(6) Gilleland, E., D.A. Ahijevych, B.G. Brown and E.E. Ebert, 2010: Verifying Forecasts Spatially. *Bull. Amer. Meteor. Soc*., **91**, 1365-1373

(7) Skamarock, W.C., and J.B. Klemp, "A time-split nonhydrostatic atmospheric model for research and NWP applications," J. Comp. Phys., special issue on environmental modeling, pp.3465-3485, 2007

(8) Deng, A., N. L. Seaman and J. S. Kain, 2003a: A shallow-convection parameterization for mesoscale models Part I: Sub-model description and preliminary applications. *J. Atmos. Sci*., **60**, 34-56

(9) Deng, A., N. L. Seaman and J. S. Kain, 2003b: A shallow-convection parameterization for mesoscale models Part II: Verification and sensitivity studies. *J. Atmos. Sci*., **60**, 57-78

(10) Thompson, G., P.R. Field, R.M. Rasmussen, and W.D. Hall, 2008: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. *Mon. Wea. Rev*., **136**, 5095–5115

(11) Ruiz-Arias, J.A., Gueymard, C.A., Dudhia, J., and Pozo-Vazquez, D., 2012a. Improvement on the WRF model for solar resource assessments and forecasts under clear skies. Proc. WREF Conf., Denver, CO, Am Solar En Soc

(12) Sengupta, M. 2011: Measurement and modeling of solar and PV output variability, NREL/CP-5500-51105, Proc. Solar 2011 Conf., Raleigh, NC, American Solar Energy Soc

(13) Lin, B., P. W. Stackhouse, P. Minnis, B. A. Wielicki, Y. Hu, W. Sun, T.-F. Fan, and L. M. Hinkelman, 2008: Assessment of global annual atmospheric energy balance from satellite observations, *J. Geophys. Res*., doi:10.1029/2008JD009869