Solar Energy Forecasting and Resource Assessment, 1st Edition

Preface, Jan Kleissl

Chapter 1: Tom Stoffel - Terms and Definitions, In Solar Energy Forecasting and Resource

Abstract
What is solar-resource assessment? What are the key scientific and engineering elements associated with solar-forecasting? These are important questions to be addressed by solar-project developers, financiers, scientists, engineers, and electricity-grid operators as they prepare for higher penetrations of centralized and distributed solar-power generation into the nation's electrical-power grid. The purpose of this chapter is to address these questions by providing the reader with foundational information and an appreciation for the terminology used in this uniquely comprehensive volume on solar-energy resources.

Complex interactions of solar radiation with the Earth-atmosphere-ocean form the basis for understanding the weather-driven nature of this abundant source of renewable energy. Specifically, the effects of clouds, aerosols, and other atmospheric constituents on photons leaving the Sun and reaching the Earth's surface continue to be the subject of active research, as highlighted in this book.

Chapter 2: Richard Perez, Tomáš Cebecauer and Marcel Šúri - Semi-Empirical Satellite Models

Abstract
This chapter discusses the basic principles of solar-irradiance modeling based on the use of input data from geostationary satellites and atmospheric models. Two operational approaches (SUNY/SolarAnywhere and SolarGIS), which are based on the use of semi-empirical models, are presented in the context of recent developments.

Chapter 3: Steven D. Miller, Andrew K. Heidinger and Manajit Sengupta - Physically Based Satellite Methods

Abstract
Ephemeral clouds and atmospheric aerosols pose the greatest challenges in exploiting sunlight as a viable (both stable and reliable) source of energy. The passage of cloud shadows across a solar array results in significant fluctuations, or ramps, in available energy, while scattering aerosols redistribute direct and diffuse components of solar irradiance in a subtle but pervasive and more sustained way. The timescales of these fluctuations are highly diverse, varying from seconds, in the case of fair-weather cumulus clouds, to hours, in the case of a prefrontal cirrus shield, and to days or more in association with aerosol loading within a synoptic-scale air mass. The spectrum of spatial scale for aerosol and cloud parameters is broad, and monitoring from terrestrially based systems is an inherently ill-posed problem from the standpoints of cost and coverage. Here, satellite-based observations, particularly those from geostationary platforms capable of monitoring the temporal evolution of clouds, provide unique and indispensable

capabilities with regard to solar-energy forecasting and resource assessment. In this chapter, we provide a high-level cross-section of environmental satellite observing systems and considerations for their application to quantitative, physically based estimates of solar irradiance at the surface for use in solar forecasting.

Chapter 4: Andrew C. McMahan, Catherine N. Grover and Frank E. Vignola - Evaluation of Resource Risk in Solar-Project Financing

Abstract
The solar resource is one of the most critical elements in a technical due-diligence report in support of solar-power project financing. The financing of a solar project includes a variety of stakeholders with different appetites for risk and abilities to manage fluctuating income (the result of a fluctuating fuel supply—that is, the solar resource). Solar-resource uncertainty and inherent seasonal variability represent a performance and revenue risk for a project that is tied primarily to the quality of the data available and the commercial risks dictated by the contractual arrangements governing the sale of energy from the project. In this chapter, methods for allocating performance and revenue risk related to the solar resource are described.

Chapter 5: Frank E. Vignola, Andrew C. McMahan and Catherine N. Grover - Bankable Solar-Radiation Datasets

Abstract
The characteristics of solar-irradiance datasets used to forecast the performance of solar electrical systems and to estimate the ability of the electricity generated to meet scheduled loan repayments are discussed in this chapter. Examples are given of datasets currently available, and their strengths and weaknesses are illustrated. Measured datasets, ground-based measurement models, and satellite-derived models are evaluated. Steps needed to create a sound, bankable solar-radiation database are described. A discussion of the use of such datasets to generate P50, P90, and P99 probabilities of exceedance is presented along with a description of the bootstrap method used to generate a larger dataset for a more robust analysis of these probabilities.

Chapter 6: Richard Perez and Thomas E. Hoff - Solar Resource Variability

Abstract
In this chapter, we describe a methodology to quantify variability of the solar resource. We describe how the considered temporal scales, from seconds to hours, and geographical scales, from a single point to a subcontinent, are interrelated and lead to a quantifiable smoothing effect. We discuss implications of the temporal/spatial nature of solar-resource variability for the solutions needed to absorb a growing proportion of solar-generated energy on power grids.

Variability is a general term that applies to many aspects of solar radiation. For example, it is used to refer to change in the solar resource from one year or one season to the next, as well as change from one site to another (Gueymard and Wilcox 2011, Vignola 2001).

Chapter 7: Matthew Lave, Jan Kleissl and Joshua Stein - Quantifying and Simulating Solar-Plant Variability Using Irradiance Data

Abstract

This chapter presents metrics for characterizing and simulating the variability of solar-power plant output. Especially important is the variability reduction, VR, which describes the geographic diversity and is defined as the ratio of variability at a point to the variability of an entire power plant. VR is a function of the size of the plant, the timescale of interest (ramp duration), and meteorological conditions. The wavelet variability model (WVM) was developed to simulate the variability of a solar-power plant using irradiance measurements at a point sensor as input and estimating the VR at each timescale. The WVM is described and validated at the Sempra U.S. Gas & Power Copper Mountain 48 MW photovoltaic plant. As an example application, the WVM is used to simulate the numbers of ramps larger than 10% of capacity per minute at various sizes of PV plants in Puerto Rico. These results are compared to WVM-simulated PV plants in San Diego, California, and Oahu, Hawaii, to show the effect of local climate on ramp rates. The WVM is an ideal tool to create virtual time series of power-plant output in the planning stage that can be used in the design phase to simulate the sizes and operation of ramp-rate mitigation tools such as solar forecasting and energy storage.

Chapter 8: Carlos F.M. Coimbra, Jan Kleissl and Ricardo Marquez - Overview of Solar-Forecasting Methods and a Metric for Accuracy Evaluation

Abstract

This chapter provides an introduction to and overview of the subsequent chapters, which discuss specific solar-forecasting technologies and time horizons. Solar-forecasting methods are classified by technique, time horizon, and application. Advantages and disadvantages of deterministic and stochastic forecasting approaches are laid out and discussed in the context of solar forecasting based on numerical weather prediction, satellite data, and ground measurements. Metrics to evaluate solar-forecasting techniques are then presented and a time horizon–invariant metric is introduced that allows comparing forecast errors across time horizons, geographical regions, and time steps. Finally, the metric is demonstrated with hour-ahead forecasts based on stochastic-learning and satellite cloud-motion vector techniques.

Chapter 9: Bryan Urquhart, Mohamed Ghonima, Dung (Andu) Nguyen, Ben Kurtz, Chi Wai Chow and Jan Kleissl - Sky-Imaging Systems for Short-Term Forecasting

Abstract

This chapter discusses the use of ground-based visible wavelength imagery for short-term forecasting of solar-power output. It begins with selected applications of short-term forecasting to both transmission- and distribution-scale generation. The hardware used in sky-imaging

systems is next presented, providing technical and historical information on system optics and sensory equipment (e.g., charge-coupled devices). A high-quality sky-imaging system designed by the authors (the USI) is then briefly examined. The core of the chapter consists of describing sky-imagery analysis techniques, followed by their application to a large solar-power plant. The techniques used to detect clouds, determine their height, and estimate their motion are explained. Application of these methods to generate a power forecast is presented in a case study of a 48 MW solar-power plant, for which a week of data was analyzed. The results are discussed and ideas for improvement are presented. Finally, recommendations for advancing ground-based visible-wavelength imagery and forecast performance are presented.

Chapter 10: Richard Perez and Tom E. Hoff, - SolarAnywhere Forecasting

Abstract
This chapter describes, and presents an evaluation of, the forecast models embedded in the SolarAnywhere platform. The models include satellite-derived cloud-motion–based forecasts for short to medium horizons (1–5 h) and forecasts derived from NOAA's numerical weather prediction models for long horizons up to several days ahead. In addition, the chapter describes a new high-frequency (1 min) application of the cloud-motion model for time horizons below 1 hour.

Chapter 11: Jan Kühnert, Elke Lorenz and Detlev Heinemann - Satellite-Based Irradiance and Power Forecasting for the German Energy Market

Abstract
Irradiance forecasts are fundamental to the prediction of power production from photovoltaic (PV) plants. Prediction is necessary to perform effective balancing of electricity demand and the variable and weather-dependent supply. Images from Meteosat Second Generation (MSG) satellites provide valuable information for forecasting clouds and solar irradiance several hours ahead using cloud-motion vectors (CMV). In this chapter we present our approach to deriving irradiance information from MSG images and to predicting the cloud situation by applying CMV. An evaluation of the irradiance forecast for single sites and regional averages on the basis of a 1 y dataset is presented. The CMV forecast shows superior performance in comparison to other methods such as numerical weather prediction (NWP) up to 5 h ahead. Additionally, an introduction to PV-power-prediction techniques is presented.

Chapter 12: Vincent E. Larson, - Forecasting Solar Irradiance with Numerical Weather Prediction Models

Abstract
Forecasts of solar irradiance with lead times greater than a few hours rely on numerical weather prediction (NWP) models. NWP is indispensable, but also complex and prone to error. This chapter aims to provide users of solar-irradiance forecasts with an appreciation of the character and magnitude of some errors in state-of-the-art NWP models. The chapter summarizes model structure, with emphasis on irradiance aspects. It then outlines the

configuration of several commonly used operational NWP models. Finally, the chapter discusses irradiance-related model errors and speculates on their cause.

Chapter 13: Andrew S. Jones and Steven J. Fletcher, - Data Assimilation in Numerical Weather Prediction and Sample Applications

Abstract
Accurate solar numerical weather prediction (NWP) requires proper data initialization to enable good cloud and solar insolation forecasts. This is achieved using mathematical data-assimilation (DA) techniques that substantially improve NWP model performance. Many such techniques are available, and all use various assumptions and approximations to adapt to operational requirements at the major global and regional DA centers. We review the major operational DA systems and explain how DA works, including its mathematical foundation, and we note important new research directions, identify trends, and discuss the future of all-weather NWP DA.

Chapter 14: Patrick Mathiesen, Jan Kleissl and Craig Collier - Case Studies of Solar Forecasting with the Weather Research and Forecasting Model at GL-Garrad Hassan

Abstract
A comprehensive solar forecast has three primary components: mean expected energy, a measure of uncertainty, and a quantification of variability. Since industry stakeholders must make quick, informed decisions, solar-forecast providers must take care to ensure that forecasts are informative and intuitive. In this chapter, the needs of two industry stakeholders (independent system operators, or ISOs, and energy traders), as they relate to the provision of accurate and useful solar forecasts, are described. Examples of day-ahead and intraday solar forecasts using Weather Research and Forecasting (WRF) numerical weather prediction are presented to describe how solar-generation variability, ramps, and price predictions influence the strategies of ISO and energy traders.

Chapter 15: Carlos F.M. Coimbra and Hugo T.C. Pedro - Stochastic-Learning Methods

Abstract
In this chapter, we discuss nonlinear regression and stochastic-learning methods for solar forecasting. A detailed comparison of non-stationary regression methods and different stochastic-learning methods based on kNN, ANN, and GA is presented. A hybrid GA/ANN method emerges as the most robust stochastic candidate to be used as the basis for development of high-fidelity forecast engines. We illustrate different applications of stochastic-learning by considering univariate and multivariate inputs, and we highlight some of the robust qualities of stochastic-learning for a wide range of time horizons.

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