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Direct normal irradiance forecasting and its application to concentrated solar thermal output forecasting – A review

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Abstract

Solar irradiance forecasting can reduce the uncertainty of solar power plant output caused by solar irradiance intermittency. Concentrated solar thermal (CST) plants generate electricity from the direct normal irradiance (DNI) component of solar irradiance. Different forecasting methods have been recommended for a range of forecast horizons relevant to electricity generation. High DNI forecast accuracy is important for achieving accurate forecasts of CST plant output which are shown to increase CST plant profitability. This paper reviews the DNI forecast accuracy of numerical weather prediction models, time series analysis methods, cloud motion vectors, and hybrid methods. The results of the reviewed papers are summarised to identify the best DNI forecast accuracy for particular forecast horizons. The application of DNI forecasts to operate CST plants is also briefly reviewed.

This paper found that additional research is required for time series analysis methods to corroborate current results and for satellite-based cloud motion vectors to establish DNI forecast accuracy. It was also concluded that future research should use the same error metrics to report results to facilitate fair comparison of DNI forecast accuracy from different studies. In addition, the creation of a common high quality DNI data set to evaluate all forecasting methods would also help to verify best forecast accuracy. The review of DNI forecasting for CST plants found that using accurate 2-day ahead DNI forecasts can increase revenue and decrease penalty costs. Future research should investigate benefits from using short-term DNI forecasts from the intra-hour forecast horizon up to the 6-h forecast horizon to determine CST plant operation. Another aspect to research is to determine whether the benefit of DNI forecasts for a CST plant is affected by different regulations in different electricity markets.

Keywords: DNI forecasting; Numerical weather prediction; Time series analysis; Cloud motion vector; Forecast accuracy; Concentrated solar thermal power

1. Introduction

Solar energy is a renewable resource that has established itself in both small-scale and large-scale electricity generation. Electricity can be generated from solar irradiance by either non-concentrated photovoltaic (PV) modules or by concentrated solar thermal (CST). PV output is calculated from global irradiance on the plane of the PV modules which can be derived from global horizontal irradiance (GHI) (Lorenz et al., 2009, 2011). GHI consists of diffuse irradiance and direct normal irradiance (DNI) components. In contrast to PV, CST output calculations only use the DNI component because diffuse irradiance cannot

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Nomenclature

AERONET	Aerosol Robotic Network
AFSOL	Aerosol-based Forecasts of Solar Irradiance for Energy Applications
AI	artificial intelligence
ANN	artificial neural network
AOD	aerosol optical depth
AR	autoregressive
ARIMA	autoregressive integrated moving average
ARMA	autoregressive moving average
ARPS	Advanced Multiscale Regional Prediction System
BOM	Australia Bureau of Meteorology
BRL	Boland–Ridley–Lauret model
CARDS	Coupled AutoRegressive and Dynamical System
CSM	clear sky model
CST	concentrated solar thermal
DNI	direct normal irradiance
ECMWF	European Centre for Medium-range Weather Forecasts
ESRA	European Solar Radiation Atlas
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GFS	Global Forecast System
GHI	global horizontal irradiance
HIRLAM	High-resolution Limited Area Model
JMA	Japan Meteorology Agency
libRadtran	library for radiative transfer
LS-SVM	least squares support vector machine
MA	moving average
MACC	Monitoring Atmospheric Composition and Climate
MAE	mean absolute error
MAPE	mean absolute percentage error
MASS	Mesoscale Atmospheric Simulation System
MBE	mean bias error
MLP	multi-layer perceptron
MM5	Fifth-generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model
MOS	Model Output Statistics
MRM	Meteorological Radiation Model
MSG	Meteosat Second Generation
MW h	Megawatt-hour
NAM	North American Model
NDFD	National Digital Forecast Database
NEM	National Electricity Market
NESDIS	NOAA's Satellite and Information Service
nMAE	normalised MAE
nMBE	normalised MBE
NOAA	National Oceanographic and Atmospheric Administration
nRMSE	normalised RMSE
NWP	numerical weather prediction
PV	photovoltaic
REST2	Reference Evaluation of Solar Transmittance – 2 Bands
RMSE	root mean square error
RTM	radiative transfer model
SUNY	State University of New York GOES satellite-based solar model
SVM	support vector machine
SVR	support vector regression
TDNN	time delay neural network
TES	thermal energy storage
THI	time horizon invariant
TSA	time series analysis
TW h	Terawatt-hour
WRF	Weather Research and Forecasting
WRF-CLDDA	high-resolution direct-cloud-assimilating WRF

be effectively concentrated. GHI and DNI are intermittent due to events like clouds temporarily covering the sun, thus causing uncertainty in the electricity supply from solar power plants. High uncertainty in supply increases the risk of an unexpected imbalance in supply and demand occurring, which can result in network voltage and frequency exceeding safe operation limits thereby reducing network reliability and security (NERC, 2009; AEMO, 2010). A network will have ancillary services or operating reserves allocated to correct these imbalances and high supply uncertainty makes it more difficult to ensure that the allocation is both sufficient and economic (Ela et al., 2011). Weather forecasting methods can be applied to forecast solar irradiance, which in turn can be used to forecast solar power plant electricity output and reduce supply uncertainty.

Forecasts can be obtained for various horizons and the relevant forecast horizons are determined by the local electricity market regulations. For example, the Australian National Electricity Market (NEM) requires power plants to submit dispatch offers up to 40 h ahead every day and allows power plants to update dispatch quantities up to 5 min before dispatch orders are made (Elliston and MacGill, 2010). Based on these regulations, it would be useful to have forecast methods that are accurate at the forecast horizons of 40-h and 5-min ahead, in addition to other forecast horizons that are relevant to NEM regulations.