

Woodhead Publishing Series in Energy

# Renewable Energy Forecasting

From Models to Applications

*Edited By*

***George Kariniotakis***



**WP**

WOODHEAD  
PUBLISHING

An Imprint of Elsevier

# Contents

List of contributors	xi
<b>Part One Introduction to meteorology and measurement technologies</b>	<b>1</b>
<b>1 Principles of meteorology and numerical weather prediction</b>	<b>3</b>
<i>Sue Ellen Haupt, Pedro A. Jiménez, Jared A. Lee, Branko Kosović</i>	
1.1 Introduction to meteorology for renewable energy forecasting	3
1.2 Observational data and assimilation into numerical weather prediction models	8
1.3 Configuring numerical weather prediction to the needs of the problem	12
1.4 Postprocessing	18
1.5 Probabilistic forecasting	19
1.6 Planning for validation	20
1.7 Weather forecasting as a Big Data problem	22
Acknowledgments	23
References	23
Further reading	28
<b>2 Measurement methodologies for wind energy based on ground-level remote sensing</b>	<b>29</b>
<i>Sven-Erik Gryning, Torben Mikkelsen, Christophe Baehr, Alain Dabas, Paula Gómez, Ewan O'Connor, Lucie Rottner, Mikael Sjöholm, Irene Suomi, Nikola Vasiljević</i>	
2.1 Introduction	29
References	52
<b>Part Two Methods for renewable energy forecasting</b>	<b>57</b>
<b>3 Wind power forecasting—a review of the state of the art</b>	<b>59</b>
<i>Gregor Giebel, George Kariniotakis</i>	
3.1 Introduction	59
3.2 Time series models	64
3.3 Meteorological modeling for wind power predictions	68
3.4 Short-term prediction models with NWP	75

---

3.5	Upscaling models	80
3.6	Spatio-temporal forecasting	81
3.7	Ramp forecasting	83
3.8	Variability forecasting	85
3.9	Uncertainty of wind power predictions	85
3.10	The ANEMOS projects and other major R&D activities	92
3.11	Conclusions	93
	Glossary	95
	Acknowledgments	96
	References	96
<b>4</b>	<b>Mathematical methods for optimized solar forecasting</b>	<b>111</b>
	<i>Hugo T.C. Pedro, Rich H. Inman, Carlos F.M. Coimbra</i>	
4.1	Introduction	111
4.2	Regression methods	112
4.3	Artificial intelligence techniques	122
4.4	Hybrid systems	132
4.5	State of the art in solar forecasting	135
4.6	Conclusions	146
	References	147
<b>5</b>	<b>Short-term forecasting based on all-sky cameras</b>	<b>153</b>
	<i>Andreas Kazantzidis, Panagiotis Tzoumanikas, Philippe Blanc, Pierre Massip, Stefan Wilbert, Lourdes Ramirez-Santigosa</i>	
5.1	Introduction	153
5.2	Sky camera systems	153
5.3	Image processing techniques	156
5.4	Geometrical calibration of all-sky cameras	167
5.5	Case study: solar resource and forecasting methodology in the frame of DNICast project	170
5.6	Conclusions and future trends	176
	References	177
<b>6</b>	<b>Short-term solar power forecasting based on satellite images</b>	<b>179</b>
	<i>Philippe Blanc, Jan Remund, Loïc Vallance</i>	
6.1	Introduction	179
6.2	Surface solar irradiance retrieval from meteorological geostationary satellite	181
6.3	Different approaches for satellite-based forecasting	186
6.4	Conclusion and perspectives	192
	Acronyms	194
	References	194

<b>7</b>	<b>Wave energy forecasting</b>	<b>199</b>
	<i>Gordon Reikard</i>	
7.1	Introduction	199
7.2	Characteristics of the data	199
7.3	The physics models	202
7.4	Statistical and time series models	206
7.5	Physics versus statistics	207
7.6	Wave energy converters	208
7.7	Simulating wave farms	213
7.8	Conclusions	213
	References	214
<b>8</b>	<b>Forecasting intrahourly variability of wind generation</b>	<b>219</b>
	<i>Claire L. Vincent, Pierre-Julien Trombe</i>	
8.1	Introduction	219
8.2	Meteorological causes of hour-scale wind variability	222
8.3	Observing hour-scale wind variability	224
8.4	Forecasting wind power variability	225
8.5	Correlation between wind fluctuations at spatially distributed sites	228
8.6	Using wind variability information to improve wind farm operations and scheduling	229
8.7	Conclusions and future developments	230
	Acknowledgments	231
	References	231
<b>9</b>	<b>Characterization of forecast errors and benchmarking of renewable energy forecasts</b>	<b>235</b>
	<i>Stefano Alessandrini, Simone Sperati</i>	
9.1	Introduction	235
9.2	ANEMOS benchmark	236
9.3	WIRE benchmark	242
9.4	Discussion and conclusions	253
	References	255
<b>Part Three Applications of forecasting to power system management and markets</b>		<b>257</b>
<b>10</b>	<b>Wind power in electricity markets and the value of forecasting</b>	<b>259</b>
	<i>Nicoló Mazzi, Pierre Pinson</i>	
10.1	Introduction	259
10.2	Electricity market context	260
10.3	From market revenue to forecast value	263
10.4	Formulation of offering strategies	265

10.5	Test case exemplification	273
10.6	Overall conclusions and perspectives	277
	References	278
<b>11</b>	<b>Forecasting and setting power system operating reserves</b>	<b>279</b>
	<i>Manuel Matos, Ricardo Bessa, Audun Botterud, Zhi Zhou</i>	
11.1	Introduction	279
11.2	Integration of uncertainty forecasts in operating reserve estimation	282
11.3	Conceptual frameworks	283
11.4	Illustrative results	293
11.5	A look into the future	303
	Acknowledgments	304
	References	305
<b>12</b>	<b>Forecasting for storage management</b>	<b>309</b>
	<i>Edgardo D. Castronuovo</i>	
12.1	Introduction	309
12.2	Mathematical formulations	310
12.3	Coordinating renewable producers and hydro-pumped storage for optimal participation in the market	313
12.4	The cooperation of renewable producers and storage facilities in isolated systems	318
12.5	Storage sizing	319
12.6	Reliability studies of the combined operation of wind power plants and storage facilities	320
12.7	Conclusion	320
	Acknowledgment	321
	References	321
<b>13</b>	<b>Dynamic line rating forecasting</b>	<b>325</b>
	<i>Romain Dupin, Andrea Michiorri</i>	
13.1	Introduction	325
13.2	Dynamic line rating calculations	326
13.3	Dynamic line rating devices	328
13.4	Dynamic line rating forecasts	329
13.5	Benefits of dynamic line rating forecasting	334
13.6	Conclusions	336
	References	337

---

<b>14</b>	<b>The role of predictability in the investment phase of wind farms</b>	<b>341</b>
	<i>Javier Sanz Rodrigo, Laura Frías Paredes, Robin Girard, George Kariniotakis, Kevin Laquaine, Nicole Stoffels, Lueder von Bremen</i>	
14.1	Introduction	341
14.2	A model chain for wind resource and predictability assessment	342
14.3	The value of predictability in spatial planning	343
14.4	Conclusions	354
	References	355
<b>Index</b>		<b>359</b>