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Bibliografía

- [AAASL18] G. Abal, D. Aicardi, R. Alonso Suárez, and A. Laguarda. Performance of empirical models for diffuse fraction in uruguay. *Solar Energy*, 141:166–181, 2018.
- [AD13] G. Abal and V. DuraÑona. Manual Técnico de Energía Solar Térmica, Vol I: Fundamentos. Technical report, Facultad de Ingeniería, UDELAR, 2013. Disponible en <http://les.edu.uy>.
- [ADCG10] G. Abal, M. D’Angelo, J. Cataldo, and A. Gutiérrez. Mapa Solar del Uruguay. In *Analys of the IVth Latin-American Conference on Solar Energy (IV ISES-CLA)*, Cusco, Perú, 1–5 November 2010.
- [Ang29] A. Angstrom. On the atmospheric transmission of sun radiation and on dust in the air. *Meteoreorological Magazine Beitrage zur Physik der AtmosphaereBeitr*, 11(2):156–166, 1929.
- [ASAMS14] R. Alonso-Suárez, G. Abal, P. Musé, and R. Siri. Satellite-derived solar irradiation map for Uruguay. In *Elsevier Energy Procedia*, volume 57, pages 1237–1246, 2014.
- [ASASM12] R. Alonso-Suárez, G. Abal, R. Siri, and P. Musé. Brightness-dependent tarpley model for global solar radiation estimation using GOES satellite images: application to Uruguay. *Solar Energy*, 86(11):3205–3215, Nov 2012.
- [ATUP⁺19] F. Antonanzas-Torres, R. Urraca, J. Polo, O. Perpiñán Lamigueiro, and R. Escobar. Clear sky solar irradiance models: A review of seventy models. *Solar Energy, Renewable and Sustainable Energy Reviews*:374–387, 2019.

- [BP19] BP. BP statistical review of world energy. Technical report, British Petroleum Co., BP, 1 St James's Square. London., June 2019.
- [CBdS04] Juan C. Ceballos, M.J. Bottino, and J.M. de Souza. A simplified physical model for assessing solar radiation over Brazil using GOES 8 visible imagery. *Journal of Geophysical Research: Atmospheres*, 109(D2), 2004.
- [Coo69] P.I. Cooper. The absorption of solar radiation in solar stills. *Solar Energy*, 12:3, 1969.
- [DB06] J.A. Duffie and W.A. Beckman. *Solar Engineering of Thermal Processes*. Wiley and Sons, Inc., Hoboken, New Jersey, third edition, 2006.
- [DMT⁺12] Reda Djebbar, Robert Morris, Didier Thevenard, Richard Perez, and James Schlemmer. Assessment of SUNY version 3 global horizontal and direct normal solar irradiance in Canada. In *Elsevier Energy Procedia*, volume 30, pages 1274–1283, 2012.
- [DTAC11] M. D'Angelo, P. Toscano, G. Abal, and J.C. Ceballos. Spatial distribution of daily mean global solar irradiation in Uruguay. In *Annals of the Solar World Congress (SWC 2011)*, Kassel, Germany, 28 August–4 November 2011.
- [EB83] C. Espoz and A. Brizuela. Application of remote sensing and agrometeorological methods for crop assessment in the Pampa Húmeda. Technical report, FAO, Division of the Assessment and Information Services Center., Columbia, Missouri, USA., November 1983.
- [ECG12] Yehia Eissa, Matteo Chiesa, and Hosni Ghedira. Assessment and recalibration of the Heliosat-2 method in global horizontal irradiance modeling over the desert environment of the UAE. *Solar Energy*, 86(6):1816–1825, 2012.
- [ECP⁺14] Rodrigo A. Escobar, Cristián Cortés, Alan Pino, Enio Bueno Pereira, Fernando Ramos Martins, and José Miguel Cardemil. Solar energy resource assessment in Chile: Satellite estimation and ground station measurements. *Renewable Energy*, 71:324–332, 2014.

- [Eis01] R.M. Eisberg. *Fundamentos de física moderna*. Limusa Wiley, 2001.
- [Eis02] R. Eisberg. *Física cuantica / Quantum Physics*. Editorial Limusa S.A. De C.V., 2002.
- [EKD82] D.G. Erbs, S.A. Klein, and J.A. Duffie. Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy*, 28:293, 1982.
- [EM15] N.A. Engerer and F.P. Mills. Validating nine clear sky radiation models in Australia. *Solar Energy*, 120:9–24, 2015.
- [ERD⁺09] Bella Espinar, Lourdes Ramírez, Anja Drews, Hans Georg Beyer, Luis F. Zarzalejo, Jesús Polo, and Luis Martín. Analysis of different comparison parameters applied to solar radiation data from satellite and german radiometric stations. *Solar Energy*, 83(1):118–125, 2009.
- [FGG⁺88] L.A. Frulla, D.A. Gagliardini, H.Grossi Gallegos, R. Lopardo, and J.D. Tarpley. Incident solar radiation on Argentina from the geostationary satellite GOES: Comparison with ground measurements. *Solar Energy*, 41(1):61–69, 1988.
- [FGGA90] L.A. Frulla, H.Grossi Gallegos, D.A. Gagliardini, and G. Atienza. Analysis of satellite-measured insolation in Brazil. *Solar and Wind Technology*, 7(5):501–509, 1990.
- [Fro12] C. Frolich. Total solar irradiance observations. *Surveys in Geophysics*, 33:453–473, 2012.
- [GME02] C.A. Gueymard, D. Myers, and K. Emery. Proposed reference irradiance spectra for solar energy systems testing. *Solar Energy*, 73(6):443–467, 2002.
- [GMS⁺17] R. Gelaro, W. McCarty, M.J. Suárez, R. Todling, A. Molod, L. Takacs, C.A. Randles, A. Darmenov, M.G. Bosilovich, R. Reichle, and K. Wargan. The modern-era retrospective analysis for research and applications, version 2 (merra-2). *Journal of Climate*, 30:5419–5454, 2017.
- [GRA16] Christian A. Gueymard and Jose A. Ruiz-Arias. Extensive worldwide validation and climate sensitivity analysis of direct irradiance predictions from 1-min global irradiance. *So-*

- lar Energy*, 128:1–30, 2016. Special issue: Progress in Solar Energy.
- [Gue95] C.A. Gueymard. Simple model of the atmospheric radiative transfer of sunshine, version 2 (SMARTS2): algorithms description and performance assessment. Technical Report FSEC-PF-270-95, Florida Solar Energy Center, 1995.
- [Gue08] Christian A. Gueymard. Rest2: High-performance solar radiation model for cloudless-sky irradiance, illuminance, and photosynthetically active radiation – validation with a benchmark dataset. *Solar Energy*, 82(3):272–285, 2008.
- [Gue12] Christian A. Gueymard. Clear-sky irradiance predictions for solar resource mapping and large-scale applications: Improved validation methodology and detailed performance analysis of 18 broadband radiative models. *Solar Energy*, 86(8):2145–2169, 2012. Progress in Solar Energy 3.
- [Gue18] C. Gueymard. Smarts code, version 2.9.8 user’s manual. Technical report, Solar Consulting Services, 2018.
- [Ham00] Annette Hammer. *Anwendungsspezifische Solarstrahlungsinformationen Aus Meteosat-daten*. PhD thesis, Carl von Ossietzky University of Oldenburg, 2000. PhD Thesis.
- [HD80] J.E. Hay and J.A. Davies. Calculation of the solar radiation incident on an inclined surface. In J.E. Hay and T.K. Won, editors, *Proceedings of the first Canadian Solar Radiation Data Workshop*, page 59. Ministry of Supply and Services, 1980.
- [IDBL06] Frank P. Incropera, David P. DeWitt, Theodore L. Bergman, and Adrienne S. Lavine. *Fundamentals of Heat and Mass Transfer*. Wiley and Sons, Inc., Hoboken, New Jersey, sixth edition, 2006.
- [Ine08] P. Ineichen. A broadband simplified version of the Solis clear sky mode. *Solar Energy*, 82:758–762, 2008.
- [Ine14] Pierre Ineichen. Long term satellite global, beam and diffuse irradiance validation. In *Elsevier Energy Procedia*, volume 48, pages 1586–1596, 2014. Proceedings of the 2nd

- International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013).
- [Ine16] Pierre Ineichen. Validation of models that estimate the clear sky global and beam solar irradiance. *Solar Energy*, 132:332–344, 2016.
- [IP02] P. Ineichen and R. Perez. A new air mass independent formulation for the Linke turbidity coefficient. *Solar Energy*, 73(3):151–157, 2002.
- [Iqb83] M. Iqbal. *An Introduction to Solar Radiation*. Academic Press, Toronto, 1983.
- [ISO99] ISO. Energía solar: Vocabulario. Technical report, International Standardization Organization (ISO), 1999.
- [JPT86] C.G. Justus, M.V. Paris, and J.D. Tarpley. Satellite-measured insolation in the United States, Mexico, and South America. *Remote Sensing of Environment*, 20(1):57–83, 1986.
- [Kas84] F. Kasten. Parametrisierung der globalstrahlung durch bedekungsgrad und trubungsfaktor. *Ann. der Meteorol*, 20:49–50, 1984.
- [Kas96] F. Kasten. The Linke Turbidity Factor based on improved values of the integral Rayleigh optical thickness. *Solar Energy*, 56(3):239–244, 1996.
- [KL11] G. Kopp and J. Lean. A new, lower value of total solar irradiance: Evidence and climate significance. *GEOPHYSICAL RESEARCH LETTERS*, 38:L01706, 2011.
- [Kle77] S.A. Klein. Calculation of monthly average insolation on tilted surfaces. *Solar Energy*, 19:325, 1977.
- [Klu79] T.M. Klucher. Evaluating models to predict insolation on tilted surfaces. *Solar Energy*, 23:111, 1979.
- [Kon69] K. Ya. Kondratyev. *Radiation in the atmosphere*. Academic Press, New York, EEUU, first edition, 1969.
- [KY89] F. Kasten and A. Young. Revised optical air mass tables and approximation formula. *Applied Optics*, 28:4735, 1989.

- [LA16] A. Laguarda and G. Abal. Índice de turbidez de Linke a partir de irradiación solar global en Uruguay. *Avances en Energías Renovables y Medio Ambiente*, 20(ISSN 2314-1433):11.35–11.46, 2016.
- [LA17] A. Laguarda and G. Abal. Clear-Sky broadband irradiance: first model assessment in Uruguay. In *ISES Conference Proceedings, Solar World Congress 2017*, Solar Radiation Availability and Variability, pages 1–12, 2017.
- [Lio02a] K.N. Liou. *An Introduction to Atmospheric Radiation*. International geophysics series (book 84). Academic Press, 2002.
- [Lio02b] K.N. Liou. *An Introduction to Atmospheric Radiation*. International geophysics series (book 84). Academic Press, San Diego, CA, 2002.
- [LJ60] B.Y.H. Liu and R.C. Jordan. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy*, 4:1, 1960.
- [LJ63] B.Y.H. Liu and R.C. Jordan. The long-term average performance of flat-plate energy collectors. *Solar Energy*, 7:53, 1963.
- [LOB⁺13] Meirelle Lefèvre, Armel Oumbe, Philippe Blanc, Bella Espinar, Zhipeng Qu, Lucien Wald, Marion Schroedter Homscheidt, and Antti Arola. McClear: a new model estimating downwelling solar radiation at ground level in clear-sky conditions. *Atmospheric Measurement Techniques, European Geosciences Union*, 6:2403–2418, 2013.
- [MALL01] Blanco M., D.C. Alarcon, T. Lopez, and M.I. Lara. Computing the solar vector. *Solar Energy*, 70:431–441, 2001.
- [MEK12] J. Meydbray, K. Emery, and S. Kurtz. Pyranometers and reference cells, what’s the difference? Technical Report NREL/JA-5200-54498, National Renewable Energy Laboratory, March 2012.
- [MK05] B. Mayer and A. Kylling. Technical note: The libRadtran software package for radiative transfer calculations – description and examples of use. *Atmospheric Chemistry and Physics*, 5:1855–1877, 2005.

- [MMAK09] Isaac Moradi, Richard Mueller, Bohloul Alijani, and Gholam Ali Kamali. Evaluation of the Heliosat-II method using daily irradiation data for four stations in Iran. *Solar Energy*, 83(2):150–156, 2009.
- [NK10] Anders Nottrott and Jan Kleissl. Validation of the NSRDB–SUNY global horizontal irradiance in California. *Solar Energy*, 84(10):1816–1827, 2010.
- [NRF93a] M. Noia, C.F. Ratto, and R. Festa. Solar irradiance estimation from geostationary satellite data: I. statistical models. *Solar Energy*, 51(6):449–456, 1993.
- [NRF93b] M. Noia, C.F. Ratto, and R. Festa. Solar irradiance estimation from geostationary satellite data: II. physical models. *Solar Energy*, 51(6):457–465, 1993.
- [ORPE06] Lidia Otero, Holben Brent Ristori Pablo, and Quel Eduardo. Espesor óptico de aerosoles durante el año 2002 para diez estaciones pertenecientes a la red AERONET-NASA. *Óptica pura y aplicada*, 39(4):355–364, 2006.
- [PA18] I. Piccioli and G. Abal. Transporte de irradiación global horizontal a una superficie inclinada: Efecto de la separación directa-difusa. In *Anales del XVI Congreso Ibérico y XII Congreso Iberoamericano de Energía Solar - CIES18*, pages 785–792, 2018.
- [PH13] Richard Perez and Tom E. Hoff. Chapter 10 - SolarAnywhere forecasting. In Jan Kleissl, editor, *Solar Energy Forecasting and Resource Assessment*, pages 233–265. Academic Press, Boston, 2013.
- [PIM⁺02] R. Perez, P. Ineichen, K. Moore, M. Kmiecik, C. Chain, R. George, and F. Vignola. A new operational model for satellite-derived irradiances: description and validation. *Solar Energy*, 73(5):307–317, 2002.
- [PISZ90] R. Perez, P. Ineichen, R. Seals, and A. Zelenka. Making full use of the clearness index for parameterizing hourly insolation conditions. *Solar Energy*, 45(2):111–114, 1990.
- [PMdAR06] Enio Bueno Pereira, Fernando Ramos Martins, Samuel Luna de Abreu, and Ricardo Rüther. Atlas brasileiro de energia

- solar. Technical report, Instituto Nacional de Pesquisas Espaciais, INPE, Sao José dos Campos, Brazil, 2006.
- [PP15] Richard Perez and Marc Perez. A fundamental look at supply-side energy reserves for the planet. *IEA-SHCP-Newsletter*, 62, November 2015.
- [PWRA⁺16] J. Polo, S. Wilbert, J.A. Ruiz-Arias, R. Meyer, C. Gueymard, M. Sári, L. Martín, T. Mieslinger, P. Blanc, I. Grant, J. Boland, P. Ineichen, J. Remund, R. Escobar, A. Troccoli, M. Sengupta, K.P. Nielsen, D. Renne, N. Geuder, and T. Cebecauer. Preliminary survey on site-adaptation techniques for satellite-derived and reanalysis solar radiation datasets. *Solar Energy*, 132:25–37, 2016.
- [RA08] I. Reda and A. Andreas. Solar position algorithm for solar radiation applications. Technical report, National Renewable Energy Laboratory, January 2008.
- [RAATPPV10] J.A. Ruiz-Arias, H. Alsamamra, J. Tovar-Pescador, and D. Pozo-Vázquez. Proposal of a regressive model for the hourly diffuse solar radiation under all sky conditions. *Energy Conversion and Management*, 51:881–893, 2010.
- [RB08] R. Righini and D. Barrera. Empleo del modelo de Tarpley para la estimación de la radiación solar global mediante imágenes satelitales GOES en Argentina. *Avances en Energías Renovables y Medio Ambiente*, 12:9–15, 2008.
- [RBD90] D.T. Reindl, W.A. Beckman, and J.A. Duffie. Evaluation of hourly tilted surface radiation models. *Solar Energy*, 45:9, 1990.
- [RBL10] B. Ridley, J. Boland, and P. Lauret. Modelling diffuse solar fraction with multiple predictors. *Renewable Energy*, 35:478–483, 2010.
- [RBW00] Christelle Rigollier, Olivier Bauer, and Lucien Wald. On the clear sky model of the ESRA — European Solar Radiation Atlas — with respect to the Heliosat method. *Solar Energy*, 68(1):33–48, 2000.

- [RLW04] C. Rigollier, M. Lefevre, and L. Wald. The method Heliosat-2 for deriving shortwave solar radiation from satellite images. *Solar Energy*, 77(2):159–169, 2004.
- [RW98] Christelle Rigollier and Lucien Wald. Towards operational mapping of solar radiation from Meteosat images. In *Proceedings of the EARSeL Symposium 1998 “operational remote sensing for sustainable development”*, pages 385–391, Enschede, Netherlands, 1998.
- [RWL⁺03] Jan Remund, Lucien Wald, Mireille Lefevre, Thierry Ranchin, and John Page. Worldwide Linke turbidity information. *Proceedings of ISES Solar World Congress*, 2003.
- [Spe71] J.W. Spencer. Fourier series representation of the position of the sun. *Search*, 2:172, 1971, <http://mail-archive.com/sundial@uni-koeln.de/msg01050.html>.
- [SRM⁺10] T. Stoffel, D. Renné, D. Myers, S. Wilcox, M. Sengupta, R. George, and C. Turchi. Best practices handbook for the collection and use of solar resource data. Technical Report NREL/TP-550-47465, National Renewable Energy Laboratory (NREL), September 2010.
- [TO15] Marios Theristis and Tadhg O’Donovan. Electrical-thermal analysis of iii–v triple-junction solar cells under variable spectra and ambient temperatures. *Solar Energy*, 118:533–546, 08 2015.
- [VGLM12] F. Vignola, C. Grover, N. Lemon, and A. McMahan. Building a bankable solar radiation dataset. *Solar Energy*, 86(8):2218–2229, 2012. Progress in Solar Energy 3.
- [VMS12] F. Vignola, J. Michalsky, and T. Stoffel. *Solar and Infrared Radiation Measurements*. CRC Press, 2012.
- [Weh85] C. Wehrli. Extraterrestrial solar spectrum. Technical Report no. 615, Physikalisch-Meteorologisches Observatorium and World Radiation Center, July 1985.
- [Wei92] S. Weider. *An introduction to Solar Energy for Scientists and Engineers*. Krieger, Malabar, Florida, reprint edition edition, 1992.

Bibliografía

- [WM08] S. Wilcox and W. Marion. Users manual for TMY data sets. Technical Report NREL/TP-581-43156, National Renewable Energy Laboratory (NREL), 2008.
- [WMO08] WMO. *Guide to meteorological instruments and methods of observation*. World Meteorological Organization, Geneva, Switzerland, seventh edition, 2008.
- [Yan16] D. Yang. Solar radiation on inclined surfaces: Corrections and benchmarks. *Solar Energy*, 136:288–302, 2016.
- [You94] A.T. Young. Air mass and refraction. *Applied Optics*, 33(6):1108–1110, 1994.