Universidade de Évora - Instituto de Investigação e Formação Avançada

Programa de Doutoramento em Ciências da Terra e do Espaço

Área de especialização | Física da Atmosfera e do Clima

Tese de Doutoramento

DNI measurement and long-term prediction of its availability in the South of Portugal

Afonso Manuel Dias Cavaco

Orientador(es) | Manuel Pedro Ivens Collares Pereira
Paulo Manuel Ferrão Canhoto

Évora 2020

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Évora 2020

O tese de doutoramento foi objeto de apreciação e discussão pública pelo seguinte júri nomeado pelo Diretor do Instituto de Investigação e Formação Avançada:

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ABSTRACT

The knowledge of Direct Normal Irradiance (DNI) availability is becoming essential nowadays for solar concentration applications, particularly for the development of Concentrated Solar Power (CSP) plants. Thus, DNI measurements and the application of reliable solar radiation data processing methodologies are required to provide the most accurate results as possible.

This thesis presents the work carried out to develop and maintain a solar radiation monitoring network and discusses the results obtained to assess the long-term DNI annual availability in the South of Portugal. The work comprised the installation, calibration and continuous operation of new measuring stations, with the objective of obtaining high quality data series. Procedures for solar radiation data gathering and processing are presented and new methods to estimate the long-term DNI annual availability based on global and diffuse horizontal irradiation are proposed and discussed. The measurements obtained and the application of the developed methods allowed to estimate and map the DNI resource in the region.

Keywords

Solar radiation, Solar energy, Direct normal irradiance, Solar resource assessment, Concentrated solar power.

RESUMO

Medição de DNI e previsão a longo prazo da sua disponibilidade no sul de Portugal

O conhecimento da disponibilidade média anual de Irradiância Directa Normal (DNI) está-se a tornar essencial para aplicações de concentração solar, particularmente para o desenvolvimento de centrais de concentração solar (CSP). Deste modo, é necessária a medição de radiação solar directa normal e aplicação de métodos de processamento de dados fiáveis de modo a providenciar os resultados mais precisos possíveis.

Esta tese apresenta o trabalho realizado para desenvolver e manter uma rede de medição de radiação solar e discute os resultados obtidos para avaliar a disponibilidade média anual de DNI a longo prazo no sul de Portugal. O trabalho desenvolvido incluiu a instalação, calibração e operação contínua de novas estações de medição, com o objectivo de se obterem séries de dados de elevada qualidade. Procedimentos para recolha e processamento de dados de radiação solar são apresentados e novos métodos para estimar a disponibilidade anual de DNI a longo prazo, com base em irradiação solar global e difusa, são propostos e discutidos. As medições realizadas e a aplicação dos métodos desenvolvidos permitiram estimar e mapear o DNI na região.

Palavras-chave

Radiação solar, Energia solar, Irradiância Directa Normal, Avaliação de recurso solar, Energia solar de concentração.

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LIST OF PUBLICATIONS

List of publications related to the research topic of the thesis:

1. Luis Guerreiro, Carlos M. Fernández-Peruchena, Afonso Cavaco, Martin Gastón and Manuel Collares Pereira, "Experimental Validation of a Novel Methodology for Fast an Accurate Analysis of Solar Energy Yields Based on Cluster Analysis", Conference Proceedings ISES EuroSun 2016
   DOI: 10.18086/eurosun.2016.09.03

2. A. Cavaco, P. Canhoto, M. J. Costa, M. Collares-Pereira, "DNI measurements in the South of Portugal: Long term results through direct comparison with global and diffuse radiation measurements and existing time series", SOLARPACES 2015, AIP Conference Proceedings 1734
   DOI: 10.1063/1.4949233

3. Afonso Cavaco, Hugo Silva, Paulo Canhoto, Samuel Neves, Jorge Neto and Manuel Collares Pereira, "Annual Average Value of Solar Radiation and its Variability in Portugal", WES 2016 - Workshop on Earth Sciences, Institute of Earth Sciences

4. Afonso Cavaco, Hugo Silva, Paulo Canhoto, Samuel Neves, Jorge Neto and Manuel Collares Pereira, "Radiação Solar Global em Portugal e a sua variabilidade", Renováveis Magazine vol.28

5. Francis M. Lopes, Hugo G. Silva, Rui Salgado, Afonso Cavaco, Paulo Canhoto, Manuel Collares-Pereira, "Short-term forecasts of GHI and DNI for solar energy systems operation: assessment of the ECMWF integrated forecasting system in southern Portugal", Solar Energy 170 (2018) 14–30
   DOI: 10.1016/j.solener.2018.05.039

6. Afonso Cavaco, Hugo Gonçalves Silva, Paulo Canhoto, Tiago Osório, Manuel Collares-Pereira, "Progresses in DNI Measurements in Southern Portugal", SOLARPACES 2017, AIP Conference Proceedings 2033, 190004 (2018)
   DOI: 10.1063/1.5067189

7. Afonso Cavaco, Paulo Canhoto, Manuel Collares-Pereira, "ESTIMATION OF PHOTOVOLTAIC ENERGY PRODUCTION IN PORTUGAL", 5th Workshop in Earth Sciences, Atmosphere and Space, Évora (2019)

8. Hugo Gonçalves Silva, Edgar F.M. Abreu, Francis M. Lopes, Afonso Cavaco, Paulo Canhoto, Jorge Neto, Manuel Collares-Pereira, "Solar Irradiation Data Processing using Estimator Matrices (SIMS) validated for Portugal (southern Europe)", Renewable Energy (2019)

   DOI: 10.1016/j.renene.2019.09.009

List of submitted papers related to the research topic of the thesis:

9. Cavaco A., Canhoto P., Collares-Pereira M., Horta P., "DNI Alentejo – Avaliação da disponibilidade média anual de Irradiação Directa Normal no Alentejo", submited to CIES 2020 - XVII Congresso Ibérico e XIII Congresso Ibero-americano de Energia Solar (November 2019)

10. Cavaco, A., Canhoto, P., Collares-Pereira, M., "Procedures for solar radiation data gathering and processing and their application to DNI assessment in Southern Portugal", submitted to Renewable Energy (January 2020)

11. Cavaco, A., Canhoto, P., Collares-Pereira, M., "Predicting DNI from GHI and DHI data bases", submitted to Renewable Energy (March 2020)

List of other published papers related to solar energy:

12. Ailton Tavares, Afonso Cavaco, Manuel Collares Pereira and Nuno Oliveira Martins, "The SUNTASTE, a new cork based solar box cooker", CONSOLFOOD 2018 – International Conference on Advances in Solar Thermal Food Processing, Faro (2018)

13. Manuel Collares-Pereira, Afonso Cavaco, Ailton Tavares, "Figures of merit and their relevance in the context of a standard testing and performance comparison methods for solar box – Cookers", Solar Energy 166:21-27

    10.1016/j.solener.2018.03.040

List of conference posters related to the research topic of the thesis:

14. Francis M. Lopes, Hugo G. Silva, Rui Salgado, Afonso Cavaco, Paulo Canhoto, Manuel Collares Pereira, "Day-ahead forecasts of GHI and DNI for solar energy systems operation in southern Portugal", Eurosun 2018

    DOI: 10.13140/RG.2.2.17485.90084

15. Afonso Cavaco, Hugo Gonçalves Silva, Paulo Canhoto, Tiago Osório, Manuel Collares-Pereira, "Progresses in DNI Measurements in Southern Portugal", SOLARPACES 2017

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List of other conference posters related to solar energy:

16. Ailton Tavares, Afonso Cavaco, Manuel Collares Pereira and Nuno Oliveira Martins, “The SUNTASTE, a new cork based solar box cooker”, CONSOLFOOD 2018 – International Conference on Advances in Solar Thermal Food Processing, Faro (2018)

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ACRONYMS

AREANATejo	Regional Energy and Environment Agency from North Alentejo
Btu	British Thermal Unit
CSP	Concentrated Solar Power
DHI	Diffuse Horizontal Irradiance
DLR	German Aerospace Center
DNI	Direct Normal Irradiance
EIA	Energy Information Administration (United States)
EMSP	Évora Molten Salt Platform
Enercoutim	Solar Energy Association from Alcoutim
FCT	Foundation for Science and Technology
GHI	Global Horizontal irradiance
GIS	Geographic Information System
ICT	Institute of Earth Sciences
IEFP	Institute of Employment and Professional Training
INEGI	Institute of Science and Innovation in Mechanical and Industrial Engineering
IPMA	Portuguese Institute for Sea and Atmosphere
kWh	Kilowatt-hour
LNEG	Portuguese National Laboratory of Energy and Geology
PECS	Solar Concentrators Testing Platform
PSA	Almeria Solar Platform
REC	Renewable Energies Chair
STE	Solar Thermal Electricity
UÉvora	University of Évora
UV	Ultraviolet radiation

CHAPTER 1. Introduction

Energy consumption has grown from year to year and it is expected to keep growing for many years to come, Figure 1. In the next three decades it is expected that the world consumption of primary energy sources is still going to be dominated by the use of fossil-fuel based energy sources, such as coal, natural gas, petroleum and other liquids (Figure 1), while it is expected that the share of renewable energy sources in the primary energy mix increases steeply. When analyzing the end-use energy consumption by type of fuel, electricity appears with a great share of consumption, evidencing that coal and natural gas are still being used in the next three decades as primary energy source to produce electricity for end-use consumption.

The exploration and transport of fossil fuels lead to serious environmental disasters with severe impacts on the ecosystems, such as oil spillages and ground/water contamination associated with fracking activities, among others [1, 2, 3]. On the other hand, the use of such forms of fossil-fuel energy sources have a cost associated, the emission of greenhouse gas emissions, as is the case of carbon dioxide (CO_2), and particulate matters (PM) with health impacts on human beings. Those emissions contribute to the greenhouse effect that, in turn, leads to global warming with vast impact on the Earth's ecosystems.

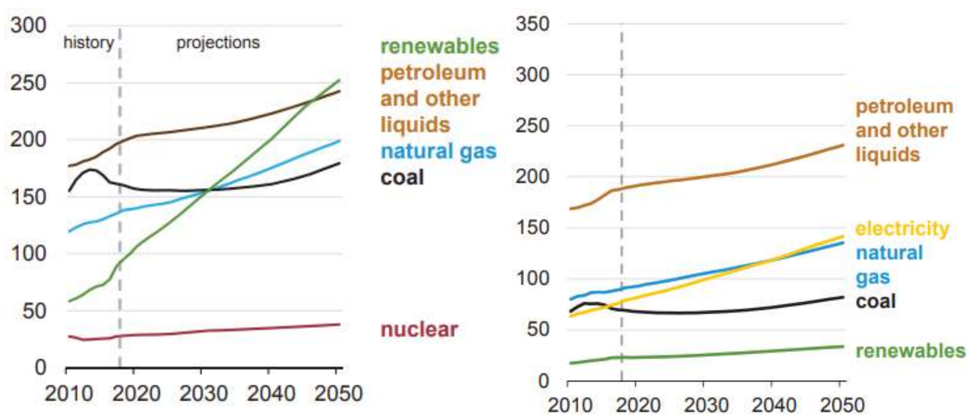

Figure 1 – Left: World primary energy consumption by energy source. Right: End-use energy consumption by fuel (quadrillion of BTU) [4].

The world consumption of fossil fuels has been growing and is expected to keep growing for the forthcoming years to fulfill energy demand and, with it, an increase of CO_2 emissions is also expected, as shown on Figure 2. When analyzing the increase of CO_2 concentration in the atmosphere it is evident its relation with the use of fossil fuels, being also evident the start of its sharp increase with the industrial revolution, as shown in Figure 3.

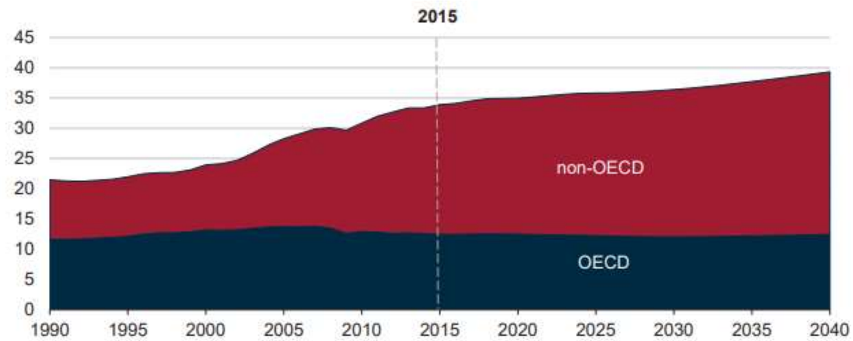

Figure 2 - World energy-related carbon dioxide emissions (billion metric tons) [5].

Figure 3 evidences the cause-effect relation of increasing CO_2 atmospheric concentration associated with the increase of Earth's surface average temperature, which is responsible for shifting world dynamics such as ocean currents with direct impact on global climate, causing an higher frequency of extreme events, drought seasons, defrosting, sea level rising, among others [6, 7, 8, 9]

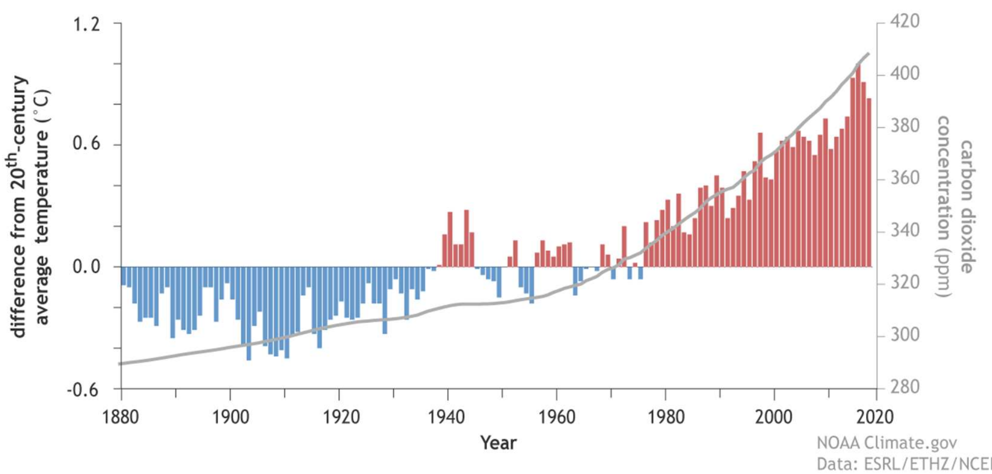

Figure 3 - Atmospheric carbon dioxide and Earth's surface temperature (1880-2018) [6].

Given this dramatic scenario, in the last decades the global warming driven by the consumption of fossil fuel energy sources has been raising concern from political decision makers, thus accelerating the implementation of the must needed use of alternative and clean energy sources.

In the last two decades, Portugal has been investing in the integration of renewable energy sources in the energy mix and becoming more energy efficient, following the commitments taken within the scope of the directive 28/2009/CE. Hydropower has already a significant share since a few decades while wind power has grown significantly in recent years. However, so far, the only solar energy investment for electricity production has been made on solar photovoltaics technology due to the technology cost reduction in the last decade. As Figure 4 shows, electricity from solar energy resource only starts to appear in the first years of the last decade. Before that, its contribution was considered neglectable when compared to the electricity produced from other sources.

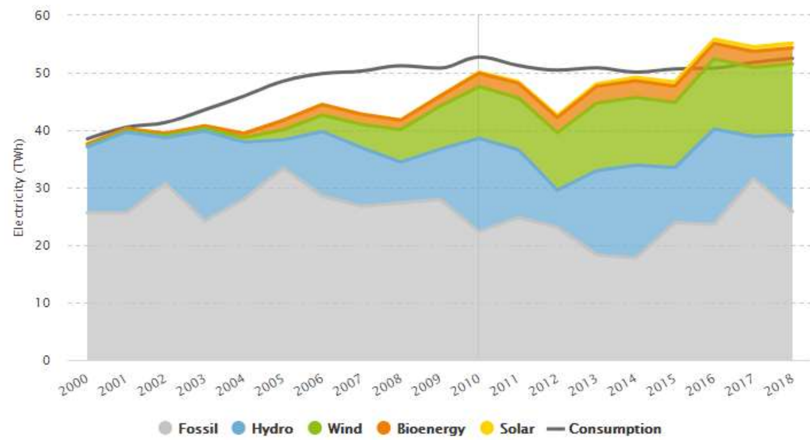

Figure 4 - Evolution of the Electricity Generation in Mainland Portugal [10].

However, even with the investments made in the last few years, solar photovoltaics contribution for the Portuguese electricity mix is only of 2.2% in 2019, corresponding to an electricity generation of 1.1 TWh, Figure 5 [11]. The mix of energy sources for electricity production in Portugal varies, as expected, from year to year, mainly due to precipitation variability. However, the great influence of hydropower in the yearly total electricity production, is quite noticeable. In years in which the hydropower production was smaller, it has to be compensated with a large coal-based production and electricity imports. Portugal, particularly in the south region, has been facing consequences from climate changes, with more frequent drought seasons that may even jeopardize the supply of potable water and, in turn, causing a reduced hydro electricity production [12].

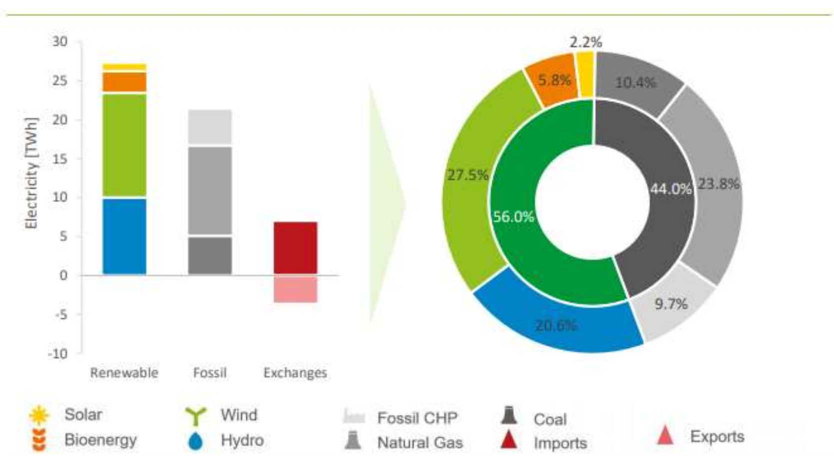

Figure 5 - Electricity generation by energy source in Mainland Portugal (Jan-Dec 2019) [11].

Considering the vast annual availability of solar energy, the amount that reaches the earth's surface surpasses the amount of energy consumed in the whole world. With the potential increase of drought seasons, which could lead Portugal into a more desertic climate, the need for a decarbonization of the economy and consequently of energy creates a tremendous opportunity for solar energy to thrive.

Conventional solar photovoltaics is now a cheaper solution for solar energy production. However, those systems do not have storage capacity since large battery systems still are expensive. On the other hand, Concentrated Power Plants (CSP) for Solar Thermal Electricity (STE) production offer the possibility of storing energy at a lower cost, allowing increased electricity dispatchability. Even though its Levelized Cost of Electricity (LCOE), without storage, is higher[1], it can provide dispatchable electricity which offers flexibility to the grid management [13]. When dispatchability is considered, the comparison is favorable to CSP with storage against PV with batteries.

Portugal has recently implemented two strategic plans for energy decarbonization, with different time horizons, the first is the National Plan for Energy and Climate 2030 (NPEC 2030) and the Roadmap for Carbon Neutrality 2050 (RNC 2050) that indicate the shutdown of coal power plants and an increased solar energy share in the electric mix (up to 27% by 2030 and up to 50% by 2050) [14, 15]. The foreseen shutdown of coal power plants in the next few years will require the implementation of systems capable of offering energy dispatchability to the grid so that energy demand can be supplied as needed.

The inevitability of the solar energy share growth in the growth of Renewable's penetration in Portugal's electrical mix, and the consequent need of knowing in more detail the solar energy resource, led to the strategic creation of a new solar radiation network with the capacity of measuring Direct Normal Irradiance (DNI), the solar radiation component that is intercepted by the high concentrating optics used in CSP systems, since there were no significant ground-based measurements of DNI available. Although, typically, DNI ground-based measurements are not performed with a good geographical coverage and long-term data series as in the case of Global Horizontal Irradiance (GHI) or even Diffuse Horizontal Irradiance (DHI) measurements. Given the recent and growing interest on commercial CSP plants, the technicalities that such measurements require will increase the need of detailed DNI resource assessment. In the absence of DNI ground-based measurements, one alternative is to resort to satellite data to assess the best locations for CSP applications and then follow with a period of local measurements for further assessment.

[1] Global weighted average for LCOE in 2018 of 0.085 $/kWh for PV and 0.185$/kWh for CSP [13]. The last auction for installed PV capacity in Portugal reached the value of 0.0145 €/kWh, a World record low [16]

The use of satellite databases to overcome the lack of DNI data is the present best solution in situations in which no ground-based measurements exist in the vicinity of the location under analysis. Satellite observations consist in the integration of an area described as a pixel, typically about 3.0 km to 4.5 km, which creates problems in complex regions where diverse natural conditions mix-up, such as fog [17]. Adding to that complexity, the scarcity of atmospheric parameters databases (e.g. aerosols and water vapor content) with sufficient spatial coverage and detail that are capable of describing local atmospheric conditions [17]. Overall, satellite based solar radiation data quality is limited by used input data and its underlying models, causing deviations in the output data in relation to observations which can be minimized with the use of site adaptation techniques [17].

There are several products that yield satellite-based solar irradiance data and comparisons have shown that GHI is retrieved with negligible bias and standard deviation (SD) ranging from 17% to 24%, DNI with a -10% to +12% bias with SD ranging from 34% to 49% and DHI with bias from 35% to 58% with SD ranging from -16% to 23% [18]. The comparisons evidenced Solargis as the solar irradiance data product with the best performance in terms of bias and standard deviation for GHI and DNI, making it the most accurate. Globally, all product models tend to underestimate DNI under clear sky conditions and overestimate it for intermediate conditions [18].

Satellite-based solar irradiation products, as Solargis, require data inputs from high quality ground-based measurements to make adjustments of their own models. In locations where no such inputs exist, the models tend to present higher deviations [18]. Solargis announces that the expected DNI bias on their models is within ±8% to ±12% outside of validation sites, as is the case of Portugal [19].

The lack of DNI ground-based measurements is a common issue, since typically the required instrumentation is only installed on few locations, without significant land area coverage [20, 21]. Although, there are some organized infrastructures around the World that have developed capacities to assess DNI over large geographical areas, making possible the thorough assessment and geographical mapping of solar energy availability [22, 23]. Both situations allow the development of models and methods to estimate DNI based on more readily available GHI and DHI measurements. Several models and methods to estimate DNI at different timescales have been proposed in literature, compared and analyzed [24]. Depending on the analyzed timescale and time of the year, prevalence of clearer skies or more severe conditions and even specific local conditions, the results accuracy also varies [24].

1.1. Motivation

The motivation of this work is to provide the tools and DNI datasets for the development of CSP plants in Portugal, promoting the decarbonization of the Portuguese energy mix with an increased solar energy share. With this in mind, this thesis proposes to merge individual efforts and implement a DNI measuring network in the South of Portugal, with special focus in the region of Alentejo, known for its high solar radiation availability [25]. In this region there were only a few individual initiatives of measuring DNI for self-purposes, such as research and CSP plant operation and management.

A new infrastructure was created with the objective of gathering individual efforts to perform a thorough assessment of direct normal irradiation in the region for CSP applications. This kind of assessment is necessary for thorough viability assessment of such kind of investments, supplying necessary information to overcome lack of measured data and high satellite data uncertainty. However, for a solar radiation dataset to be considered statistically significant it has to comprise, at least, ten years of measurements so that the effects of solar radiation interannual variability do not impact significantly the mean annual availability value [26, 27, 28].

This kind of infrastructure is also a driver for solar radiation research development in many of its topics. One of the topics that motivated the development of this thesis was the study and development of correlations to estimate long-term DNI based on GHI and DHI ground-based measurements. The idea is that If a reliable correlation to estimate DNI based on GHI and DHI can be achieved, then its correlation and accuracy should hold when used for the long-term, therefore, yielding statistically significant solar radiation data series to determinate long-term DNI mean annual availability at locations where DNI measurements are not available but at least long-term GHI data exist. Thus, a more significant direct normal irradiation availability map can be obtained. This is a way of estimating statistically significant DNI resource based on statistically significant GHI and DHI data.

1.2. Objectives

This thesis depended on the implementation of a solar radiation network with the objective of mapping the Direct Normal Irradiance (DNI) average annual availability in Alentejo, for the definition of the places of excellence for the construction of high concentration solar power plants. Several studies were also developed while the DNI data series was growing with time.

This Thesis had the following objectives:

- Implementation of a solar radiation monitoring network in the region of Alentejo with special focus on the DNI;
- Operation, maintenance, data quality assurance and expansion of the solar radiation network;
- Assessment of Global Horizontal Irradiance (GHI) availability and interannual variability in Portugal;
- Correlate the direct (DNI) with global (GHI) and diffuse (DHI) solar radiation components to develop correlations to estimate long-term DNI;
- Validation and application of the developed DNI correlations using data from other meteorological stations.

The work developed to pursue these objectives originated several research papers in which the results and answers obtained are presented. These papers should be considered as contributions for solar radiation assessment, with a particular focus on the DNI assessment in the south of Portugal.

1.3. Structure

This thesis starts by presenting the organization and implementation of a network of stations to measure solar radiation. This network is the foundation of the objectives proposed in this thesis and without it, it would not be possible to attain the proposed objectives.

Chapter 2 describes the network that was created, how it evolved since its beginning, the installed instrumentation, the maintenance and operation activities performed to guarantee the highest data quality possible. This chapter also presents some of the issues that occurred in the operation and management of this kind of systems with the objective of analyzing some of the most common and other uncommon issues while operating this kind of stations.

Since this thesis relied on solar radiation measurements and the network had just recently started at the time this work begun, it would take some time to obtain data series long enough to allow statistically significant studies. While such kind of studies were not yet feasible, a cooperation with the Portuguese Institute for Sea and Atmosphere (IPMA) was developed. **Chapter 3**, describes the work developed in the assessment of Global Horizontal Irradiation (GHI) availability and its interannual variability in Portugal, representing the obtained results as maps. This chapter has particular relevance for the solar energy sector, as no reference of recent studies of GHI assessment using ground-based measurements are known in Portugal, particularly including the study of interannual variability of GHI availability. This is also important because that data will be used to assess DNI availability through correlations between the different solar radiation components.

Chapter 4 describes the efforts made during the course of this work to answer the main questions the thesis meant to answer. It starts, in Section 4.1, with a published paper about the solar radiation network, first measurements and first proposal of a method to determine a correlation between DNI and the difference of GHI with DHI.

Once the solar radiation dataset grew in time, it allowed for a thorough assessment of solar radiation in the South of Portugal. Section 4.2 content consists on a recently submitted paper describing the process of evaluating solar radiation availability in the south of Portugal with emphasis in the development of a thorough methodology to process solar radiation data seeking the assurance of high data quality.

It follows with the presentation of several correlations to predict DNI with basis on GHI and DHI measurements, Section 4.3., it continues and deepens the study initially shown in Section 4.1. With the obtained correlations, a DNI mean yearly availability estimation is made in Section 4.4., with the application of one of the previously obtained correlations over IPMA's GHI national network data, yielding an estimated national DNI availability.

The conclusions are summarized in **Chapter 5**, where the main results and conclusions in published and submitted papers are highlighted.

The thesis ends with **Chapter 6**, with a brief discussion about the future of the solar radiation network, projects and research lines that can be developed to contribute for a solar powered future.

Where appropriate, the published or submitted works were directly incorporated into the structure of the thesis, keeping the submitted structure and format. The additional publication which were not included are present in the List of Publications.

References

1. Prince Emeka Ndimele, Abdulwakil O. Saba, Deborah O. Ojo, Chinatu C. Ndimele, Martins A. Anetekhai, Ebere S. Erondu, Chapter 24 - Remediation of Crude Oil Spillage, The Political Ecology of Oil and Gas Activities in the Nigerian Aquatic Ecosystem, Academic Press, 2018, Pages 369-384, ISBN 9780128093993, DOI: 10.1016/B978-0-12-809399-3.00024-0

2. Wayne K. Talley, Di Jin, Hauke Kite-Powell, Vessel accident oil-spillage: Post US OPA-90, Transportation Research Part D: Transport and Environment, Volume 6, Issue 6, 2001, Pages 405-415, ISSN 1361-9209, Doi: https://doi.org/10.1016/S1361-9209(01)00002-5

3. U.S. Energy Information Administration (EIA), International Energy Outlook 2019 with projections to 2050, September 2019. Accessed February 5, 2020 [https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf]

4. Qingmin Meng, The impacts of fracking on the environment: A total environmental study paradigm, Science of The Total Environment, Volume 580, 2017, Pages 953-957, ISSN 0048-9697, DOI: 10.1016/j.scitotenv.2016.12.045

5. Lindsey, Rebecca. (2019, Sep 9). If carbon dioxide hits a new high every year, why isn't every year hotter than the last? NOAA Climate.gov. Accessed February 5, 2020 [https://www.climate.gov/news-features/climate-qa/if-carbon-dioxide-hits-new-high-every-year-why-isn%E2%80%99t-every-year-hotter-last].

6. Rodell, M., Famiglietti, J.S., Wiese, D.N. et al. Emerging trends in global freshwater availability. Nature 557, 651–659 (2018). DOI: 10.1038/s41586-018-0123-1

7. R. S. Nerem, B. D. Beckley, J. T. Fasullo, B. D. Hamlington, D. Masters, G. T. Mitchum. Climate-change–driven accelerated sea-level rise. Proceedings of the National Academy of Sciences Feb 2018, 115 (9) 2022-2025; DOI: 10.1073/pnas.1717312115

8. Shepherd, A., Ivins, E., Rignot, E. et al. Mass balance of the Antarctic Ice Sheet from 1992 to 2017. Nature 558, 219–222 (2018). DOI: 10.1038/s41586-018-0179-y

9. Hughes, T.P., Kerry, J.T., Baird, A.H. et al. Global warming transforms coral reef assemblages. Nature 556, 492–496 (2018). DOI: 10.1038/s41586-018-0041-2

10. Portuguese Renewable Energy Association (APREN), Production. Accessed February 5, 2020 [https://www.apren.pt/en/renewable-energies/production/]

11. Portuguese Renewable Energy Association (APREN), Portuguese Renewable Electricity Report, December 2019. Acessed February 6, 2020 [https://www.apren.pt/contents/publicationsreportcarditems/portuguese-renewable-electricity-report-dec-19-vf.pdf]

12. Database of Contemporary Portugal (PORDATA), Total rainfall. Accessed February 6, 2020 [https://www.pordata.pt/en/Portugal/Total+rainfall-1070-10195]

13. IRENA/International Renewable Energy Agency. RENEWABLE POWER GENERATION COSTS IN 2018. 2018. Accessed November 18, 2019 [https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018]

14. PNEC 2030 – Plano Nacional de Energia e Clima. January 28, 2019. Accessed November 18, 2019 [https://www.portugal.gov.pt/download-ficheiros/ficheiro.aspx?v=0eada7c4-4f17-4d13-a879-6700f302b7e0]

15. RNC – 2050 Roteiro para a Neutralidade Carbónica. December 4, 2018. Accessed November 18, 2019 [https://descarbonizar2050.pt/uploads/RNC2050_Sessao_publica_4dez2018.pdf]

16. DGEG – Direccção Geral de Energia e Geologia, Leilão 7AGO2019 - Resultado final. Acessed Mars 10, 2020. [http://www.dgeg.gov.pt/]

17. Tomas Cebecauer and Marcel Suri, Site-adaptation of Satellite-based DNI and GHI Time Series: Overview and SolarGIS Approach, AIP Conference Proceedings 1734, 150002 (2016); DOI: 10.1063/1.4949234

18. Pierre Ineichen, Long Term Satellite Global, Beam and Diffuse Irradiance Validation, Energy Procedia, Volume 48, 2014, Pages 1586-1596, ISSN 1876-6102. DOI: 10.1016/j.egypro.2014.02.179.

19. SOLARGIS. December 3, 2018. Accessed February 12, 2020 [https://solargis.com/docs/accuracy-and-comparisons/overview]

20. S. Moreno-Tejera, M.A. Silva-Pérez, I. Lillo-Bravo, L. Ramírez-Santigosa, Solar resource assessment in Seville, Spain. Statistical characterisation of solar radiation at different time resolutions, Solar Energy, Volume 132, 2016, Pages 430-441, ISSN 0038-092X, DOI: 10.1016/j.solener.2016.03.032.

21. D. Perez-Astudillo, D. Bachour, DNI, GHI and DHI Ground Measurements in Doha, Qatar, Energy Procedia, Volume 49, 2014, Pages 2398-2404, ISSN 1876-6102, DOI: 10.1016/j.egypro.2014.03.254.

22. Erica Zell, Sami Gasim, Stephen Wilcox, Suzan Katamoura, Thomas Stoffel, Husain Shibli, Jill Engel-Cox, Madi Al Subie, Assessment of solar radiation resources in Saudi Arabia, Solar Energy, Volume 119, 2015, Pages 422-438, ISSN 0038-092X, DOI: 10.1016/j.solener.2015.06.031.

23. A. Kumar, S. Gomathinayagam, G. Giridhar, I. Mitra, R. Vashistha, R. Meyer, M. Schwandt, K. Chhatbar, Field Experiences with the Operation of Solar Radiation Resource Assessment Stations in India, Energy Procedia, Volume 49, 2014, Pages 2351-2361, ISSN 1876-6102, DOI: 10.1016/j.egypro.2014.03.249.

24. Simone Dugaria, Andrea Padovan, Vincenzo Sabatelli, Davide Del Col, Assessment of estimation methods of DNI resource in solar concentrating systems, Solar Energy, Volume 121, 2015, Pages 103-115, ISSN 0038-092X, DOI: 10.1016/j.solener.2015.07.043.

25. Afonso Cavaco, Paulo Canhoto, Manuel Collares Pereira, Procedures for solar radiation data gathering and processing and their application to DNI assessment in Southern Portugal, submitted to Renewable Energy (January 2020).

26. Stoffel, T., et al. “Concentrating Solar Power: Best Practices Handbook for the Collection and Use of Solar Resource Data (CSP)”, 2010.

27. Gueymard, C.A., Wilcox, S.M., “Assessment of spatial and temporal variability in the US solar resource from radiometric measurements and predictions from models using ground-based or satellite data”. Sol. Energy 85 (5), 2010, 1068–1084.

28. Vignola, F., et al., “Building a bankable solar radiation dataset”. Sol. Energy 86 (8), 2012, 2218–2229.

CHAPTER 2. Solar radiation network

This chapter provides a description of the solar radiation network developed in the south of Portugal under the research projects DNI and DNI-ALENTEJO, aiming at the measurement and assessment of Direct Normal Irradiance (DNI) in the Alentejo, Portugal, hereinafter referred to as DNI Network. It starts with a description of how the network was initially set, how it evolved regarding a larger geographical coverage and how it is expected to develop further in the future. A description of a typical solar radiation monitoring station in this network is provided, describing the used sun tracking systems and radiometers, followed by a description of the operation and maintenance procedures to guarantee high quality data. The chapter ends with a description of some of the most common and other uncommon issues found within the DNI Network, in Section 2.4, and how they were solved. This section does not cover every single intervention that had to be taken on the stations, neither describes the routine maintenance checks since most of this work and the time it took cannot be fully and even properly described here in detail.

2.1. Network description and development

The solar radiation network started in 2014 with the funding of a regional research project, named DNI - "Mapping of the normal direct solar radiation in Alentejo - Definition of excellence locations for the installation of solar concentration power plants" under the Grant Ref. ALENT-07-0827-FEDER-002316. This project marks the beginning of the network with the objective of mapping DNI to assess its average annual availability in Alentejo, seeking the definition of locations of excellence for the construction of high concentration solar power plants. The project was led by the University of Évora in a cooperation between the Renewable Energies Chair and the ICT – Institute of Earth Sciences and had ARENATejo - Regional Energy and Environment Agency from North Alentejo as co-promoter [1, 2].

The referred project also gathered several other entities, either public institutions or private companies, which had solar radiation monitoring stations with the capacity to measure DNI and, with those, a network was set up. These partners are AREANATejo with a station in Portalegre, Lógica E.M. with a station in Moura, Capwatt with a station in Martim Longo, LNEG – The Portuguese National Laboratory of Energy and Geology with a station in Lisbon and INEGI - Institute of Science and Innovation in Mechanical and Industrial Engineering with a station in Oporto. Once the project was approved, in mid of 2014, the University of Évora acquired two stations, one was installed near Évora, at PECS - Solar Concentrators Testing Platform in December of 2014, and the second one was installed at Sines, in April 2015. Meanwhile, the ICT – Institute of Earth Sciences of the University of Évora had previously acquired a complete solar radiation monitoring station which was used firstly in a campaign at the Alqueva dam, also in the Alentejo region, being then moved to ICT observatory at the Évora city (Colégio Luis António de Verney), in March 2015 [1, 2]. IPES – Portuguese Solar Energy Institute, was contracted by the project to manage and maintain the operation of the network stations in the region around Évora.

This first project had a duration of approximately a year and a half and was fundamental for the set up of the network and start of DNI measurements in the new stations. It defined the first phase of the DNI Network with the geographical distribution shown in Figure 6.

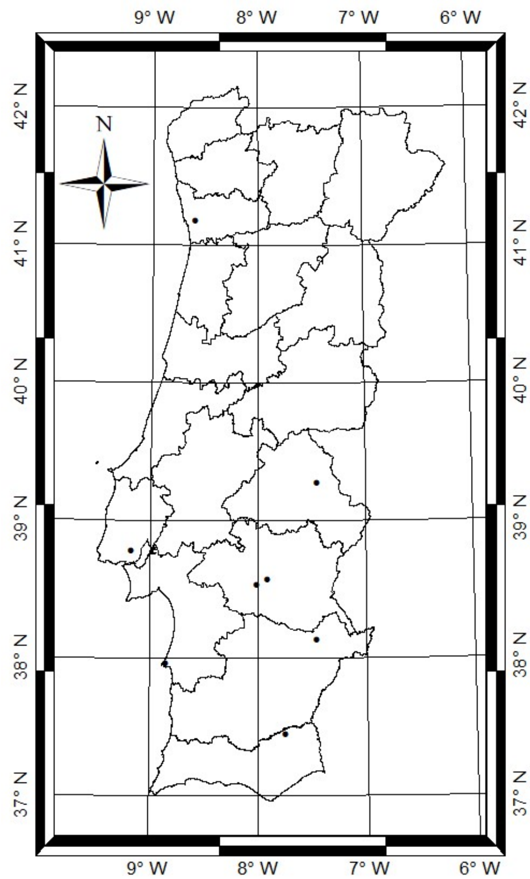

Figure 6 - Geographical distribution of solar radiation monitoring stations in the first phase of the DNI Network.

In December 2015 a new project was submitted to a regional funding call, which was approved in March 2016 and started in July 2016. This project, with an initial duration of 3 years, was set to expand and continue the operation of the network in order to improve the DNI availability assessment in the region, as a result of a broader geographical coverage and a longer period of measurements. At that time, only estimations were possible since data series were not yet statistically significant given its reduced temporal extension, as many more years, typically 10, will be necessary to achieve that classification [3, 4]. The approval of a new project was of high importance for the development of the solar radiation network.

The new project, named “DNI-ALENTEJO - Measurement and evaluation of the direct solar radiation in Alentejo: the interaction with local effects and respective implications in the mapping of this energy resource” was defined as a continuation of the previous project. For that purpose, two new stations were acquired, one was installed in Beja, in the center of lower Alentejo, and the other one was installed near Évora, at EMSP – Évora Molten Salt Platform, close to the PECS station, with the objective of serving as the reference of solar radiation measurement for the test and operation of the Parabolic Through solar field under the scope of the Renewable Energies Chair projects.

Meanwhile, during the development of this second project, three DNI stations were added to the DNI Network, one from IPMA – The Portuguese Institute for the Sea and the Atmosphere, located at Olhão in the Algarve; one from Enercoutim – Solar Energy Association from Alcoutim, located at Martim Longo; and one from EDP Innovation also near Évora, between EMSP and ICT (Verney-Évora) stations.

With the acquisition of two stations and acquaintance of tree other stations to the network, the solar radiation network reached its current phase, as shown in **Figure *7*** - Current geographical distribution of solar radiation monitoring stations of the DNI Network [2].Figure 7. At the moment the network counts with 13 solar radiation stations. In the figure it is not possible to see all the stations since some of them are close to each other and there is an overlap [2].

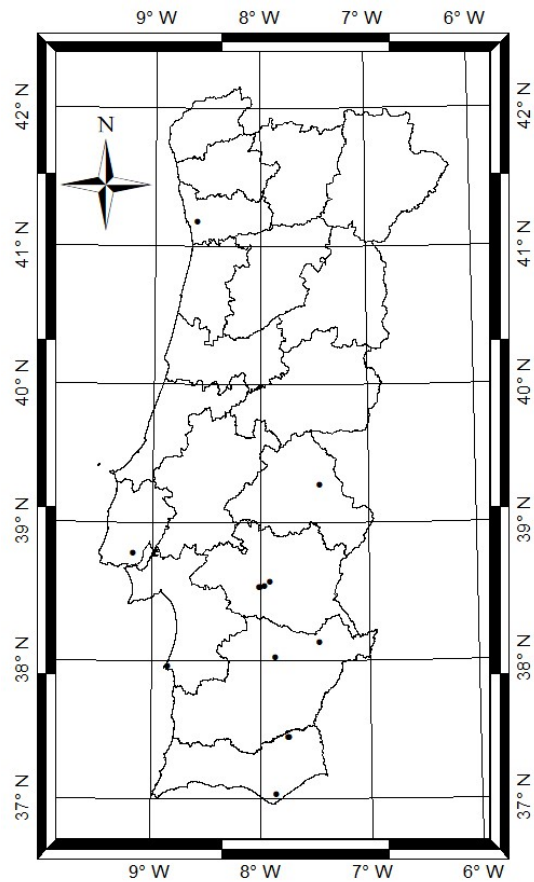

Figure 7 - Current geographical distribution of solar radiation monitoring stations of the DNI Network [2].

Table 1 shows the geographic coordinates of each of the 13 DNI Network stations and its elevation in meters above the mean sea level.

Table 1 - Geographic coordinates and elevation of the solar radiation network stations (in parenthesis the reference to the location where it is installed or to the company that owns the station) [2].

Station	Latitude (° N)	Longitude (° W)	Elevation (m)
Évora 1 (PECS)	38.5306	8.0112	222
Évora 2 (Verney)	38.5677	7.9117	276
Évora 3 (EMSP)	38.5289	8.0053	231
Évora 4 (EDPI)	38.5417	7.9632	228
Portalegre	39.2692	7.4428	342
Beja	38.0249	7.8672	252
Lisboa	38.7734	9.1779	111
Sines	37.9576	8.8473	99
Moura	38.1329	7.4536	207
Oporto	41.1793	8.5943	159
Martim Longo 1 (Capwatt-Brainpower)	37.4410	7.7491	282
Martim Longo 2 (Enercoutim)	37.4431	7.7409	283
Olhão	37.0329	7.8546	6

It is an objective of the promotors of the referred research projects to expand the network further in the Southwest region of Portugal, ideally in Algarve, in the region of Vila do Bispo. A contact had already been established with the local Town Hall for that same purpose. Another alternative would be to install a new station in the southwest of the lower Alentejo region. An extra station will provide a better geographical coverage of the Alentejo region for DNI assessment and will contribute to a better response from Geographic Information Systems (GIS), when using geographic interpolation methods for DNI assessment. The locations of the stations create a polygon and when GIS applications are working outside of this area, the extrapolation process may yield biased results.

2.2. Solar radiation monitoring stations

Most of the stations are equipped with Kipp&Zonnen sun tracking systems and solar radiation sensors (radiometers). Although there are small variations within the network, the common setup consists on a Solys 2 Sun Tracker, one CHP1 pyrheliometer measuring Direct Normal Irradiance (DNI), one CMP11 pyranometer measuring Global Horizontal Irradiance (GHI) and another CMP11 pyranometer shaded by a shadow ball assembly to block the direct beam and circumsolar components, measuring Diffuse Horizontal Irradiance (DHI). Figure 8 is a picture of the Évora 1 station of the DNI Network according to the referred setup [5].

Figure 8 – Picture of the Évora 1 (PECS) station.

The CHP1 pyrheliometers and CMP11 pyranometers are characterized according to the highest possible classification of ISO 9060:2018, Spectrally Flat Class A. This classification means that the sensors are provided with black absorbers, either with or without diffusor, and data post processing is not required to achieve reliable results under different sky conditions. CHP1 pyrheliometers are characterized by its excellent low temperature dependence, linearity and long-term stability, while CMP11 pyranometers are characterized by its excellent linearity, fast response time and low tilt error. For these reasons, this kind of sensors are the most appropriate for research purposes given their excellent reliability [5].

The Évora 1 station, Figure 8, also has a dedicated sensor (Sun Sensor) connected to the Solys 2 to improve sun tracking accuracy from <0.1° to <0.02°, by actively correcting the sun tracker position for direct beam irradiance ≥200 W/m^2 [5].

The sensors installed in each station of the solar radiation network are presented in Table 2.

Table 2 - Sensors installed in each station of the DNI Network.

<table>
<tr><th>Station</th><th>DNI Pyrheliometer</th><th>GHI Pyranometer</th><th>DHI Pyranometer</th><th>Averaging Period</th></tr>
<tr><td>Évora 1 (PECS)</td><td rowspan="13">CHP 1</td><td>CMP 11</td><td>CMP 11</td><td rowspan="6">1 min</td></tr>
<tr><td>Évora 2 (Verney)</td><td>CM 6B[2]</td><td>CM 6B[2]</td></tr>
<tr><td>Évora 3 (EMSP)</td><td rowspan="11">CMP 11</td><td rowspan="8">CMP 11</td></tr>
<tr><td>Évora 4 (EDPI)</td></tr>
<tr><td>Portalegre</td></tr>
<tr><td>Beja</td></tr>
<tr><td>Lisboa</td><td>2 min</td></tr>
<tr><td>Sines</td><td rowspan="3">1 min</td></tr>
<tr><td>Moura</td></tr>
<tr><td>Oporto</td></tr>
<tr><td>Martim Longo 1 (Capwatt-Brainpower)</td><td>NA</td><td>15 min</td></tr>
<tr><td>Martim Longo 2 (Enercoutim)</td><td rowspan="2">CMP 11</td><td>1 min</td></tr>
<tr><td>Olhão</td><td>10 min</td></tr>
</table>

[2] The CM6B pyranometers have a lower classification than CMP11 pyranometers according to the ISO 9060:2018. However, the CM6B output is subject to a correction due to the sensor temperature through a correlation with the temperature of a pyrgeometer also installed in the sun tracker system, right next to the pyranometers. Additionally, both the GHI and DHI pyranometers readings are corrected in real time (samples) for the zero offset through a correlation with the net thermal radiation exchange between instruments and the sky, which is also measured by the pyrgeometer. This allows improving the accuracy of CM6B data and make them equivalent to that obtained from a higher class pyranometer such as CMP11.

2.3. Network maintenance and operation for high quality data assurance

When setting up a solar radiation monitoring station with a configuration as described in Section 2.2, the first maintenance and operation procedure to implement is the regular cleaning and inspection of pyranometer domes and pyrheliometer windows [5]. This kind of care is mandatory as soiling and dirt accumulation will increase with time, reducing the amount of solar radiation that reaches the sensor element of the instruments. This reduction will strongly impact the sensors output, causing a reduction of measured solar irradiance in relation to the solar irradiance that would be measured in optimal conditions. This impact is higher on pyrheliometers, as these devices only measure the direct normal irradiance, and any scattering or absorption due to accumulation of particles in the pyrheliometer window will have a significant impact in the measurements. Pyranometers are also affected, however the impact is not as great as in the case of pyrheliometers since these sensors also measure scattered radiation.

The impact of soiling accumulation is minimized with the implementation of routine cleaning procedures. Ideally, the domes and windows should be cleaned and inspected on a daily basis [5]. However, in some locations that periodicity is hard to guarantee since some stations are installed in remote locations where there are no people on a daily basis. With this in mind, different cleaning frequencies were tested in order to assure quality data. Generally, at least, cleaning once a week was found sufficient to maintain data quality within recommended values [6].

The data quality is typically checked in real-time by checking measurements consistency through the comparison between measured GHI and the GHI (I_h) calculated from the DHI (I_d) and DNI ($I_{b,n}$) values according to the energy closure function, Equation (1) [6] :

$$I_h = I_d + I_{b,n} \times \cos\theta \tag{1}$$

where θ is the solar zenithal angle determined according NREL's Sun Position Algorithm, which is the angle between the sun axis and the normal to the sensing element of the pyranometer measuring global horizontal irradiance [7].

For clear sky or stable weather conditions, the difference between measured and calculated GHI should be within the limits of the BSRN – Baseline Surface Radiation Network recommendations. That difference should be lower than 2% or 15 W/m^2, whichever is less, for sun elevations ≥10º. If greater differences are found, it might result from the lack of sensors cleaning, slight misalignments or calibration constants drift of the instruments. In case of unstable weather conditions, characterized by fast changing conditions of solar irradiance, or for lower sun elevation, and since the response time of the pyrheliometer and pyranometers is different, higher differences between measured and calculated GHI may be observed. For such situation, the differences should not exceed 3.5% or 20 W/m^2, whichever is less. If greater differences appear, additional testing is required to unveil the source of the problem [6].

In the case of a total misalignment of the sun tracking system, the use of the energy closure function, Equation 1, will not directly detect the quality issues, since there will not be DNI readings and DHI readings will be equal or similar to GHI outputs. Thus, the summation of DHI with GHI will yield the same or a similar value as the GHI sensor readings. However, total misalignments may be detected when GHI and DHI are nearly equal and DNI is close to zero for a larger period of time during which it is known that unobstructed sun periods occurred. Such misalignments may result of power outages or from any sun tracking device malfunction, causing a severe misalignment. This kind of misalignments, within the DNI Network, can only be detected with visual inspection of graphical plots of measured DNI, GHI and DHI data, as explained above. If a partial misalignment occurs, situations in which the sun disk is not fully within the acceptance angle of the pyrheliometer and the shadow ball assembly is only partially blocking the direct beam irradiance incidence on the DHI pyranometer, the GHI readings will differ from the GHI value obtained with the closure function; thus, allowing the detection of those data quality issues.

Each solar radiation sensor is unique, with its own characteristics, the most important characteristic being the sensitivity, the constant that converts the voltage generated by the sensor to irradiance units. This constant, over time, starts drifting from its original value due to exposure to the sun, mainly ultraviolet radiation, and other meteorological factor such as temperature variation. Since the whole system has, at least, three unique sensors it is necessary to have a regular calibration procedure to adjust calibration constant of each sensor in order to maintain high quality readings.

Having in consideration the importance of sensors calibration in a network, such as the DNI Network, an extra CHP1 pyrheliometer and an extra CMP11 pyranometer were acquired to be used as references for calibration of the other network sensors. This set of instruments is taken to each location to verify if the field instruments are measuring with relative consistency, following the ISO Standards 9059:1990 and 9847:1992 calibration procedures [8, 9]. If significant changes are found, then upon data analysis the sensitivities found are applied [1, 2].

The set of reference sensors are also calibrated against reference sensors traceable to the World Radiometric Reference (WRR) at the World Radiation Centre in Davos. To this end, they have been calibrated by the DLR - German Aerospace Center solar energy department, at PSA – Almeria Solar Platform

(Spain) using an absolute cavity pyrheliometer, following the ISO Standard 9846: Calibration of Field Pyranometers using a reference Pyrheliometer and a reference pyranometer and the ISO Standard 9059: Calibration of field pyrheliometer using a reference pyrheliometer [8, 9].

The referred procedures are necessary to ensure that the entire station is functioning properly. This consistency is a way of fully using the fact that three high quality instruments are measuring the same solar irradiance source, with the pyrheliometer and shading assembly aligned with the sun axis, adding significant confidence and accuracy to the final result [1,2].

When processing measured data, several other quality check procedures are applied, as thoroughly described in Section 4.2 [2].

2.4. Technical issues in the operation of solar radiation stations

This section identifies operational issues found during the course of this thesis related to the operation of the solar radiation stations and an explanation of how such problems were solved is provided.

Since the start-up of the network several technical issues arose and were solved or are being analyzed for troubleshooting. This section describes the problems found in several Kipp&Zonen systems, troubleshooting process and solutions found. In some situations, several travels had to be made until the situation was totally solved. Given the distance from Évora to most of the stations and need of proper meteorological conditions, unfortunately, sometimes the troubleshooting and solution process took longer than expected. However, this kind of work is essential for the sustainability of such kind of infrastructure.

2.4.1. Sun tracking system misalignment

In the early stages of the solar radiation network, from time to time, the sun tracker of the Portalegre station had tracking inaccuracies, with total misalignments of the pyrheliometer and shading assembly with respect to the sun axis. At first, it was considered that this problem could be the result of some isolated tracking issue and the position of the instruments installed in the zenithal axis of the sun tracker were mechanically adjusted by unlocking the side disks, repositioned at the correct position and locked again. Whenever this process was performed, the system would operate normally for a few days and then started to slowly misalign. This procedure was repeated a few times until it was considered that the equipment was faulty. The product warranty had to be activated and the sun tracker was sent to Kipp&Zonen for further analysis. Unfortunately, the sun tracker axis was damaged during the transportation and had to be totally repaired, making it impossible to assess the real cause of the sun tracking system misalignment. Although, after the reparation, that issue did not recur and, therefore, it is assumed that the zenithal axis had an issue.

2.4.2. Fixation of pyrheliometer supports

A common issue found on the Solys 2 systems is the way as pyrheliometer metallic support plates are fixed. Those plates are made of aluminum and fixed with stainless steel screws which often get stuck and renders impossible the removal of the plates and attached pyrheliometers. This may be explained by the fact that aluminum and steel have different thermal expansion coefficients and, over time, by expanding and contracting differently, this issue arises [10]. If the screws get stuck while unscrewing and that process is forced, typically the screw's head breaks due to exaggerated mechanical torsion or the screw's head wears out. In such situations, a possibility is to drill the screw with a larger diameter drill and use a screw with a larger diameter for future fixation. However, the relatively small thickness of the aluminum plate does not allow to repeat this process more than once. Another possibility is to replace the referred metallic plates, which are expensive (over 200€ plus taxes).

Since this problem appeared in several stations, a better way of dealing with it had to be found. After some time looking for solutions, a cooperation was established with the local government Employment and Training Institute (IEFP). They have CNC – Computer Numeric Control machines which allow the creation of pieces with high precision. With this cooperation, a set of aluminum supports was made at a fraction of the market cost, around 10€, which greatly eases the management of this issues over time.

2.4.3. Internal fans of the sun tracking system

Over the course of this thesis, the heater fans of two Solys 2 sun trackers had to be replaced. The Solys 2 sun tracker is equipped with a 5V fan coupled to a 100W heater, responsible for spreading the heated air in the interior, so that the hardware is not damaged or affected during low temperature conditions. Since the beginning of the network, two Solys 2 sun tracker required the fan to be changed. That need is identified by the status led of the Solys 2, typically by a green blinking light which indicates temperature over -20ºC when the fan is faulty, input voltage OK and fan error. For temperatures lower than -20ºC, the blinking light changes from green to red [5].

To replace the fan, it was necessary to open the Solys 2 sun tracker, while unpowered, make the necessary interventions to remove the fan, disconnect it and connect the new one. To connect the new one, ideally, the new electrical connection has to be soldered and protected to avoid eventual electric contacts that could affect the fan behavior or even damage it. This type of fan can be found on the market at a very low cost (typically under 10€).

2.4.4. GPS sensor

Recently, the Solys 2 sun tracker installed in Sines became unable to track the sun position. The system started up and performed the startup routine, however it was unable to locate a GPS connection that is essential to determine the sun position as a function of location and time of the day. Given the distance of Sines from Évora, the sun tracker was temporarily moved to Évora for troubleshooting, after several failed attempts to resolve it locally. The GPS sensor was replaced with a new one, which required the sun tracker to be open for the replacement process. After the replacement of the GPS sensor, the sun tracker operated in normal conditions at Évora and was reinstalled in Sines. Once reinstalled, it was unable to acquire GPS signal and, therefore, it was unable to track the sun position. The sun tracker was again brought back to Évora, for further testing, and until now is working normally in Évora. The Solys 2 firmware was checked to verify the existence of flag errors, though no errors were found. The sun tracker is going to be reinstalled in Sines again, during April 2020 and, if it is unable to function normally again, then the firmware has to be checked for errors at the station location. If no errors are found, one possibility is to manually insert the geographical coordinates to verify if the sun tracker is able to track the sun position with that input, which require to communicate directly with the Solys 2 sun tracker system through a dedicated communication protocol.

References

1. Cavaco, P. Canhoto, M. J. Costa, M. Collares-Pereira, "DNI Measurements in the South of Portugal: Long Term Results through Direct Comparison with Global and Diffuse Radiation Measurements and Existing Time Series", AIP Conference Proceedings 1734, 150001 (2016); Doi: 10.1063/1.4949233.

2. Afonso Cavaco, Paulo Canhoto, Manuel Collares Pereira, Procedures for solar radiation data gathering and processing and their application to DNI assessment in Southern Portugal, submitted to Renewable Energy (January 2020).

3. Stoffel, T., et al. "Concentrating Solar Power: Best Practices Handbook for the Collection and Use of Solar Resource Data (CSP)", 2010.

4. Vignola, F., et al., "Building a bankable solar radiation dataset". Solar Energy 86 (8), 2012, 2218–2229.

5. Kipp & Zonnen. (n.d.). Retrieved November 18, 2019 from http://www.kippzonnen.com/

6. McArthur L.J.B., Baseline Surface Radiation Network (BSRN), Operations Manual, (2005)

7. Reda, I.; Andreas, A. (2003). Solar Position Algorithm for Solar Radiation Applications. 55 pp.; NREL Report No. TP-560-34302, Revised January 2008.

8. International Organization for Standardization (ISO). (1992). Solar energy — Calibration of field pyranometers by comparison to a reference pyranometer, (ISO 9847).

9. International Organization for Standardization (ISO). (1990). Solar energy — Calibration of field pyrheliometers by comparison to a reference pyrheliometer, (ISO 9059).

10. The Engineering Toolbox. (n.d.). Retrieved December 17, 2019 from https://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html

CHAPTER 3. Assessment of global horizontal irradiation in Portugal

This chapter results from a cooperation established with IPMA to analyze their GHI network data to assess the global horizontal irradiation (GHI) in Portugal. This work is thoroughly described in this chapter, focusing on the solar radiation data analysis and includes the study of interannual variability of GHI in Portugal. This is of particular interest since similar studies made in Portugal are not known. This work resulted in a scientific publication[3] submitted and presented at the WES 2016 – Workshop on Earth Sciences of the University of Évora and was latter published as technical report[4], distributed among the Portuguese solar energy sector.

The contents of Section 3.1 result from the incorporation of the publication submitted to WES 2016. However, Figures 4 and 5 of this section were replaced by the figures used in the technical report. These figures were generated with the same data but without the application of smoothing, thus better representative of GHI mean annual availability and its interannual variability in Portugal.

3.1. Annual Average Value of Solar Radiation and its Variability in Portugal

Afonso Cavaco, Hugo Silva, Paulo Canhoto, Samuel Neves, Jorge Neto and Manuel Collares Pereira

Abstract – Solar resource assessment is essential for the different phases of solar energy projects, such as preliminary design engineering, financing including due diligence and, later, insurance phases. An important aspect is the long-term resource estimation. This kind of estimation can only be obtained through the statistical analysis of long-term data series of solar radiation measurements, preferably ground measurements. This paper is a first step in this direction, with an initial statistical analysis performed over the radiation data from a national measurement network, consisting of eighty-nine meteorological stations. These preliminary results are presented in figures that represent the annual average values of Global Horizontal Irradiation (GHI) and its Variability in the Portuguese continental

[3] Afonso Cavaco, Hugo Silva, Paulo Canhoto, Samuel Neves, Jorge Neto and Manuel Collares Pereira, "Annual Average Value of Solar Radiation and its Variability in Portugal", WES 2016 - Workshop on Earth Sciences, Institute of Earth Sciences

[4] Afonso Cavaco, Hugo Silva, Paulo Canhoto, Samuel Neves, Jorge Neto and Manuel Collares Pereira, "Radiação Solar Global em Portugal e a sua variabilidade", Renováveis Magazine vol.28

territory. These results show that the South of Portugal is the most suitable area for the implementation of medium to large scale solar plants.

Keywords – Solar Energy, Assessment and Variability, GHI, Measurements, Solar Plants, Statistical Analysis.

INTRODUCTION

When seeking financing for medium to large solar energy applications, the characterization of the solar resource at a given site is essential for different phases of solar energy projects. In the early stages only a rough estimation of yearly values of solar radiation is needed, but the depth of solar radiation estimation availability increases as the projects advance. At a certain point a long-term estimation is needed and it can only be obtained through a statistical analysis of long-term solar radiation data series. For a reliable statistical characterization of solar resource, a minimum of ten years of data is required. Some Researchers propose different periods for analysis, from six to thirty years of data [1]. This kind of assessment is usually based on the supposition that the long-term average annual solar radiation from the past can provide an accurate estimation, without significant variability, for the availability of solar resources in the future [2] [3]. Discrepancies resulting from this assumption are often not considered or considered to be negligible in comparison to other uncertainties [4].

When simulating solar energy performance, a continuous series of solar radiation data is desirable. However, it is usual to find data gaps in the available recorded series, and, thus, there is a need to design and apply a sound gap filling procedure. A common procedure to estimate monthly and annual values data series with gaps is to fill the missing days with the average values of the available days of the same month. This procedure may result in inaccurate estimates, depending on the number of missing days [5]. Other authors suggest a simple linear interpolation when gaps are up to three hours and filling gap with neighbor data or data of the same day from other years for greater gaps [5]. There are other studies that suggest the use of correlations with the solar radiation data from nearby weather stations as the best option [6].

In Portugal there are ground measured solar radiation data series and average values reported from those, dating back to the fifties, sixties and seventies of the 20th century. These data were obtained with different instruments and calibration procedures not exactly as accurate as other more recent ones. Besides, the total radiation available at the ground level can change with solar activity and with climatic changes. For today’s usage it is important to use more recent data when assessing radiation availability at a given site, provided long enough recent series are available [7]. This work presents a thorough analysis performed to assess solar radiation in Portugal, providing also information about its annual variability. The results obtained are presented in terms of annual average values and are presented in a map format showing the Global Horizontal Irradiation (GHI) availability and its variability in the Portuguese continental territory.

EXPERIMENTAL DATA

The data analyzed in this study have been recorded by IPMA – Instituto Português do Mar e da Atmosfera (Portuguese Institute for Sea and Atmosphere) during the period 2001-2015, at eighty-nine stations in the Portuguese continental territory as shown in Figure 1. The global horizontal irradiance is measured in 30-s intervals with Kipp & Zonen CM11 and Hukseflux LP02 pyranometers, with the CM11 model being used in most of the stations. Both pyranometers are secondary standard instruments according to ISO standards.

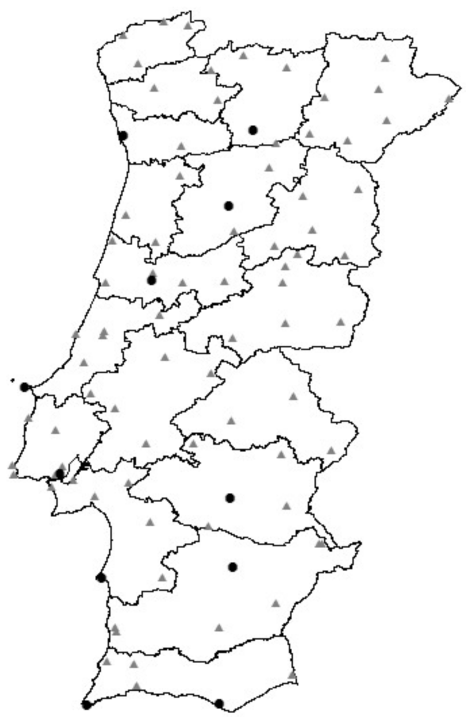

FIGURE 1 - IPMA's meteorological stations. (black dots - principal stations, grey triangles - secondary stations).

DATA QUALITY

The authors do not have accurate information about the proper operation of the instruments, thus the measurements could be affected by problems such as lack of calibration or malfunction and possible data acquisition failures. However, for the study of GHI annual variability it was considered that an eventual lower data quality of the analyzed series would not be much relevant since the consequences of calibration and data acquisition problems should not significantly affect the variability around an average value, regardless of whether it is reliable or not.

Due to the lack of information about the quality of the IPMA data series, a comparison between IPMA's and ICT - Instituto de Ciências da Terra (Institute of Earth Sciences, former CGE/UE - Geophysics Centre of Évora at the University of Évora) stations was performed for 2003-2015, Figure 2, since the distance between both stations is quite short, about 4.5 km. Data from the ICT (CGE/UE) station has been independently obtained with a good quality control and for a long period (13 years) [8]. The least square relation between the data series is high, R2=0.98, which shows a small difference between both stations. This is reinforced by a slope close to one, m=1.0067.

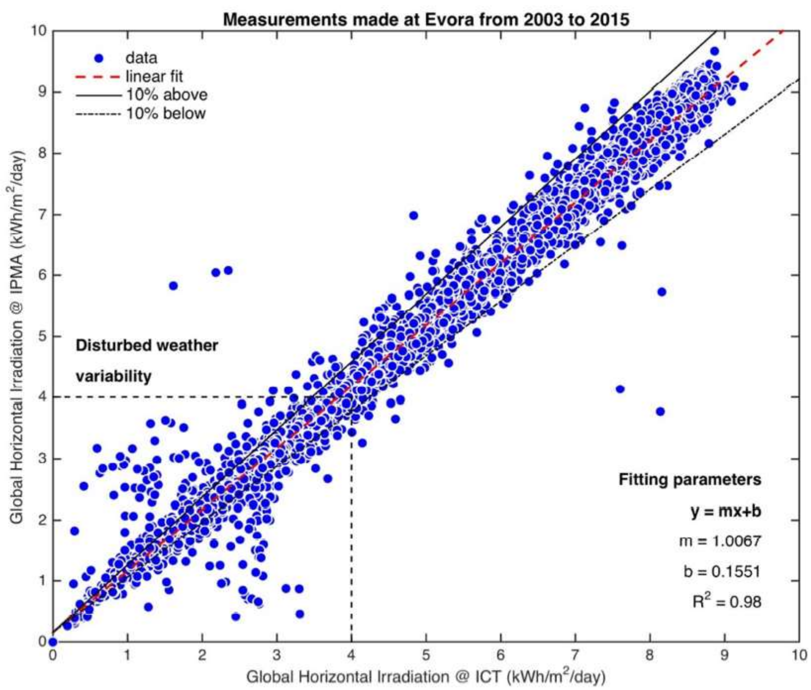

Figure 2 - Comparison of GHI data for IPMA's and ICT (CGE/UE) meteorological stations in Évora.

Since the ICT (CGE/UE) meteorological station is rigorously maintained (periodic clean up, maintenance and calibration of instruments), it can be assumed that the quality of data measured by IPMA's stations is acceptable.

Once the data series were analyzed another quality data comparison was performed. The annual average GHI for Faro, Évora, Lisboa, Coimbra, Porto and Bragança were compared with series measured in the seventies. The results show an overall increase of annual GHI availability of 3.5% to 6.0%, which can be explained, as already referred by the fact that present day instrumentation can be considered more accurate and perhaps better calibrated than before. Another explanation is the transition from a period of solar dimming to a one of brightening. Some studies have shown an inflection point in the eighties, which would be consistent with the fact that the higher values recorded are accordant with the possibility of a present period of brightening [7]. Yet another explanation is the modification of the atmospheric conditions due to climatic dynamics, compatible with the fact that Portugal could likely be moving towards a warmer and drier climate [9]. However, the quality and length of the available data series cannot be used to decide among these possibilities.

METHODOLOGY

In order to obtain reliable results it was necessary to perform quality data analysis and gap filling, after the pre-analysis, the annual values of GHI and its variability were determined. The applied criteria were:

1. Years that lack more that 5% of the total records are not considered for analysis;
2. For days that lack records for more than two hours, between sunrise and sunset are rejected and daily GHI availability for those days is estimated through the mean daily value of the same period for the other years of the data series;
3. For days that lack less than two hours, the corresponding gaps are interpolated from the values of the neighboring hours;
4. GHI average annual availability was determined by averaging the annual averages of GHI;
5. GHI annual variability was determined through the standard deviation of the annual averages of GHI;

RESULTS

With the results obtained through the application of the described methodology, the annual average values were processed in order to map the GHI availability in Portugal, Figure 3, and the relative variability of GHI, Figure 4. To produce Figure 4 and Figure 5 only meteorological stations with at least five years of valid data were used, resulting in the use of sixty-six out of the initial eighty-nine meteorological stations, as shown in Figure 3.

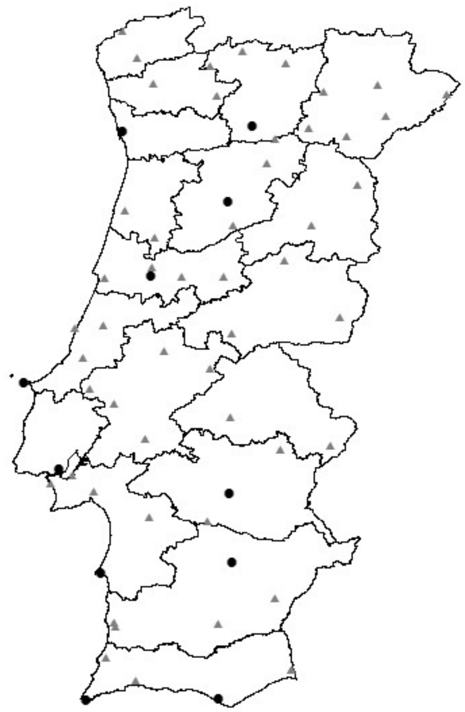

FIGURE 3 - IPMA's meteorological stations used for GHI mapping in Portugal (black dots - principal stations, grey triangles - secondary stations)

As shown in Figure 4, GHI availability is higher from North to South due to the latitude effect and the higher average cloudiness in the North region of Portugal. On the other hand, GHI availability also increases from West to East, especially in the North and Center regions most probably due to the frequent formation of fogs in seaside (because of earth-sea interactions). Both effects are also evident in Figure 5, where the GHI relative variability is higher in the zones where GHI availability is smaller [10].

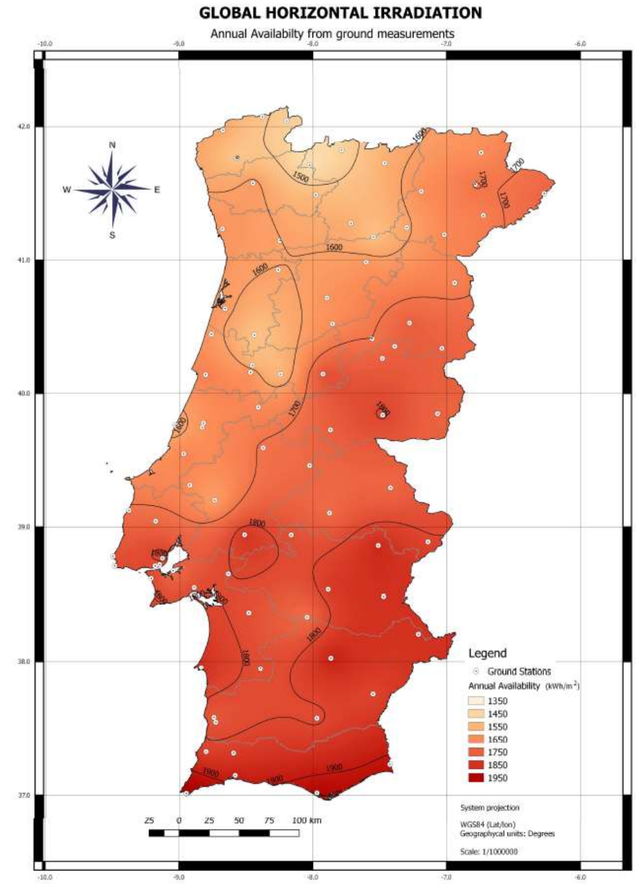

FIGURE 4 - GHI average annual availability in Portugal continental territory (kWh/m^2/year).

The average annual values of GHI availability and its variability are important for the definition of sites for the implementation of solar plants, i.e. medium to large scale solar Plants. The smaller the GHI annual variability the more reliable are the predictions of GHI estimations at a given place and, consequently, more reliable are the simulation outputs of solar applications performance.

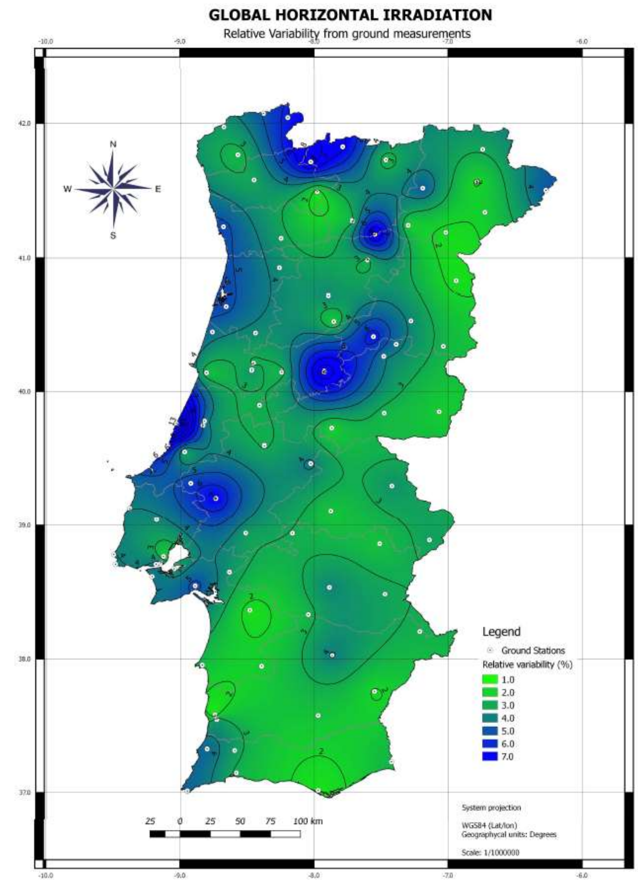

FIGURE 5 - Relative annual variability of GHI (%/year).

Figure 4 and Figure 5 evidence Alentejo and Algarve, South of Portugal, as the most suitable areas for the implementation of solar energy projects due to the combination of high GHI annual availability and its lower annual variability.

CONCLUSIONS

The knowledge of GHI availability is essential for viability analysis of solar projects. The existence of long-term statistical analysis is fundamental to estimate the real availability and variability of solar resource in Portugal. This study provides the best present insight over the Portuguese GHI annual variability and it constitutes fundamental knowledge when projecting medium to large scale solar plants.

Even though the overall data quality could not be determined with a high certainty level, variability analysis of GHI should not be too much affected since it is not dependent on the absolute accuracy of the annual GHI average value. However, a data quality comparison was performed, which allowed the assumption that the quality of the data measured by IPMA's stations is acceptable.

This study shows that GHI annual variability in Portugal is small, from 1.6% to 3.0%, for the locations with higher GHI availability (typically the region south of the river Tejo) and only 3.5% to 5.0% for the remaining locations. Another conclusion is that low GHI annual variability areas correspond to high GHI annual availability areas, making these areas quite interesting for the implementation of future solar plants.

In the future this kind of studies will be performed for Direct Normal Irradiance (DNI) measurements since the University of Évora and IPES – Portuguese Solar Energy Institute together with other institutions (LNEG, Logica, INEGI, AREANATejo, and Capwatt) are managing a DNI measurement Network with focus in the South of Portugal, a known area for having higher DNI availability [11]. IPMA will join this network with a recently acquired system that is able to measure DNI in order to join the effort to characterize the DNI annual availability and variability in the South of Portugal.

ACKNOWLEDGMENTS

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REFERENCES

1. Stoffel, T., et al. “Concentrating Solar Power: Best Practices Handbook for the Collection and Use of Solar Resource Data (CSP)”, 2010.

2. Gueymard, C.A., Wilcox, S.M., “Assessment of spatial and temporal variability in the US solar resource from radiometric measurements and predictions from models using ground-based or satellite data”. Sol. Energy 85 (5), 2010, 1068–1084.

3. Vignola, F., et al., “Building a bankable solar radiation dataset”. Sol. Energy 86 (8), 2012, 2218–2229.

4. Thevenard, D., Pelland, S., “Estimating the uncertainty in long-term photovoltaic yield predictions”. Sol. Energy 91, 2013, 432 – 445.

5. Moreno-Tejera, S., et al, “Solar resource assessment in Seville, Spain. Statistical characterisation of solar radiation at different time resolutions”, Solar Energy, Volume 132, July 2016, Pages 430-441.

6. Schwandt, M., et al." Development and test of gap filling procedures for solar radiation data of the Indian SRRA measurement network". Energy Procedia 57, 2014, 1100–1109.

7. Müller, B., et al. "Rethinking solar resource assessments in the context of global dimming and brightening", Solar Energy, Volume 99, 2014, Pages 272-282, ISSN 0038-092X.

8. Canhoto, P., "Preliminary Analysis of Irradiance Data for the Generation of a Typical Solar Radiation Year for Évora, Portugal", Technical Report, Institute of Earth Sciences, University of Évora, 2016. (http://hdl.handle.net/10174/18249)

9. Trigo, R. M., DaCAMARA, C.C.,Circulation weather types and their influence on the precipitation regime in Portugal, International Journal of Climatology,20,13,1559-1581,2000.

10. Vieira, R., Neto, J., Silva, A. "Radiação Solar Global Anual. Portugal Continental.", IPMA internal communication, 2008.

11. Cavaco, A. et al. "DNI measurements in the South of Portugal: Long term results through direct comparison with global and diffuse radiation measurements and existing time series", AIP Conference Proceedings, 1734, 150001, 2016.

CHAPTER 4. Direct normal irradiation assessment and long-term estimation

This chapter provides answers to the main objectives defined within the scope of this thesis. In the Section 4.1, the first scientific paper about the assessment of DNI in the South of Portugal being submitted, the DNI Network is presented, first measurements are analyzed and a first proposal for a method to correlate DNI with long-term GHI and DHI measurements is presented. At this stage, either the measurements analysis and proposed methodology were preliminary results and were meant to start the study of methodologies to estimate DNI.

The content of Section 4.2 consists on a manuscript submitted to Renewable Energy journal in January 2020. This manuscript focuses on the solar irradiance assessment in the South of Portugal with emphasis in the development of a data processing and analysis procedures. This work sets the starting point of Section 4.3., in which new methodologies to estimate DNI based on DHI and/or GHI measurements are proposed, with local application (Alentejo) and potential global application. This work was submitted to Renewable Energy Journal in February 2020.

Section 4.4. presents the application of one of the developed correlations over GHI data from IPMA's national Network to estimate DNI availability in Portugal.

The contents of Sections 4.1., 4.2. and 4.3. result from the incorporation of a published paper and two recently submitted papers.

4.1. DNI Measurements in the South of Portugal: Long Term Results through Direct Comparison with Global and Diffuse Radiation Measurements and Existing Time Series

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Abstract The present work describes the measurement effort for direct normal irradiance (DNI) evaluation in the sunny south of Portugal, with a network of eight radiation measurement stations in several locations (including Évora) providing a good coverage of the region. This new initiative for DNI measurement will still need many years (typically 10 or more) to produce a time series which can claim having long term statistical value. This problem can, however, be temporarily mitigated by measuring DNI at the same time as GHI and DHI, in a place where long term series dating back, already exist for those two. It so happens that a long-term series (20 years) of global and diffuse solar irradiation exists for the location Évora. So, the expectation is to establish correlations with the goal of attributing at least some long-term statistical significance to the short and recent DNI series. The paper describes the setup of the measuring stations and presents the preliminary measurements obtained. It further presents the first correlations of monthly averages between normal beam (DNI), global and diffuse radiation. It then uses these correlations, admittedly without acceptable statistical significance (short series of less than one year of measured data), to exemplify how to get a prediction of long term DNI for Évora. This preliminary obtained value is compared to that predicted by the commercial data from Meteonorm.

$\mathrm{I_{b,n}}$	Instantaneous beam irradiance at normal incidence
I_h	Instantaneous hemispherical irradiance
I_d	Instantaneous diffuse irradiance
$\bar{I}_{b,n}$	Hourly monthly average beam irradiance at normal incidence
$\bar{I}_h$	Hourly monthly average hemispherical irradiance
$\bar{I}_d$	Hourly monthly average diffuse irradiance
$\overline{H}_{b,n}$	Daily Monthly average beam irradiation
$\overline{H}_h$	Daily Monthly average hemispherical irradiation
$\overline{H}_d$	Daily Monthly average diffuse irradiation
Θ	Solar zenithal angle

INTRODUCTION

Solar Energy concentration can be used in different applications, including industrial process heat, desalination or solar electricity production among others. The use of solar concentrators requires the knowledge of direct normal irradiance (DNI) however this data is generally not available on a large scale. In particular, it is very important to know the long-term availability of DNI at any given location where the installation of a solar concentrating system is planned for. Global (GHI) and diffuse horizontal irradiance (DHI) measurements have been made all over the world in the last decades and a good geographical cover exists, even with long term series in many locations. These measurements are simple to make with fixed detectors, just requiring small tilt adjustments on the shadow band (every few days) in the case of DHI, plus very simple maintenance operations. That is not the case with DNI, requiring accurate continuous tracking of the sun's apparent motion. In the last few years applications like STE (Solar Thermal Energy) and CPV (Concentrating Photovoltaics) are strongly driving the need for setting up DNI measuring stations and the collection of reliable long term ground based data, enabling the proper sizing of solar systems and enough confidence on the results to facilitate financing and insuring the heavy investments associated with these systems.

This kind of investments is best done with reliance on accurate solar resource measurements, always preferable to modeled data and their associated uncertainties. But setting up DNI measurement stations to cover a significant area and time span is costly and takes time. Therefore, the need exists for the development of DNI models based on reliable ground measurements and with predictions as reliable as possible. In the past, several comparisons have been made between existing datasets and different models, showing significant disagreement in DNI predictions for different locations [1]. This in spite of a large variety of models to infer DNI from atmospheric data or from GHI data. In general, models have difficulty with giving good results for locations other than the one they were derived for [1] [2] [3].

However, a new initiative for DNI measurement will need many years (typically 10 or more) to produce a time series that can be claimed to have a long-term statistical value. So, there is hope that this problem can perhaps be partially resolved by measuring DNI at the same time as GHI and DHI, in a location where long-term series dating back a few years, already exist for those last two. Correlations [4] will then be established to help attribute a long-term statistical value to short and recent DNI series. It so happens that in this same location past long term series of atmospheric data also exists [5].

The present work describes the measurement effort just launched by the authors in the sunny south of Portugal, with a network of radiation measurement stations in several locations (including Évora), providing good coverage of the region and the use of long term series (20 years) of global and diffuse solar irradiation measured in Évora [5] [6]. An identical station is installed in Oporto, in a less sunny north of Portugal, to be used as a contrast point. This paper has the goal of establishing a series of measuring stations over a large area (the South of Portugal) to collect good quality data and make it available to all users. It also has the long-term goal of contributing to the quality assessment of DNI models.

Network of stations in the program: Installation, CaliBration and MAintenance

The participating sites are evenly distributed in the center and south of Portugal. There is a participating station in the north of Portugal (Oporto - INEGI), a location known for a lower average value of DNI and, as such, not so interesting for STE or CPV applications. This contrast should be apparent in the final results and should help the production of a clearer picture of the country's DNI potential. The locations chosen are: two on the western Atlantic coast (Lisbon – LNEG; and Sines – University of Évora), Évora, sort of in the center and all the others (Portalegre – AREANATejo; Moura – Lógica; and Martim Longo – Capwatt) closer to and along the portuguese-spanish border, should provide good conditions for the coverage of different and relevant average conditions and a reliable geographical extrapolation for any location in the whole region. Figure 1 (a), below, shows the locations chosen for the network of DNI, global and diffuse measuring stations and a view of one of the stations (Mitra).

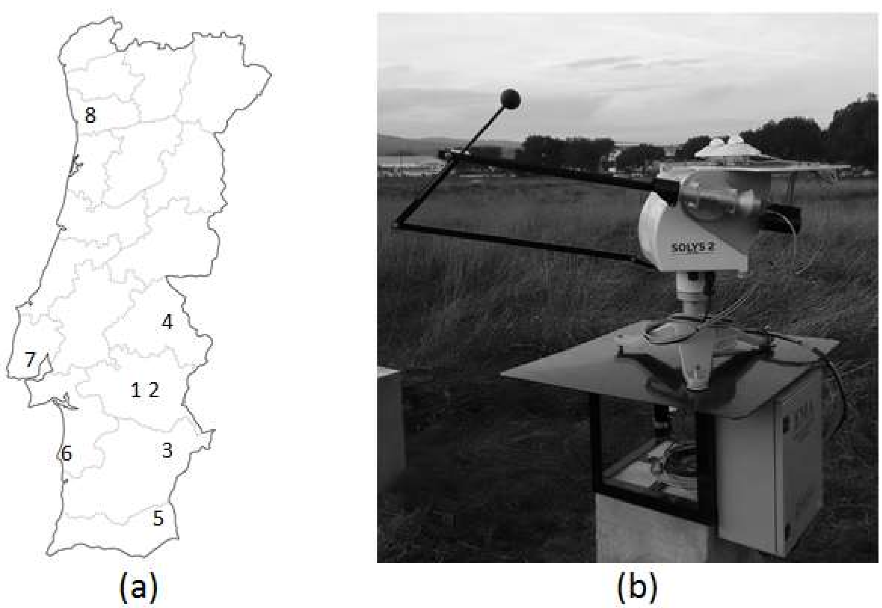

Figure 1 - (a) DNI, GHI and DHI measuring stations network, and (b) view of one of the stations (Mitra).

All stations have been installed and some have already been providing data since the end of 2014, the last one started measuring only in April 2015. As an example, the Mitra station (in the vicinity of Évora city) shown in Figure 1 (b) consists of a sun tracker, model Solys2 [7] with a shading ball assembly [7] for diffuse radiation measurement, one pyrheliometer model CHP 1 [7], two pyranometers model CMP 11 [7] and a data logger (DT80) [8] for data acquisition, data storage (buffer) and communication. The same instruments are used in all other stations. A process of relative calibration is under way. The procedure is to take the same reference pyrheliometer and pyranometer around, to every station, and compare readings, making sure that all instruments are measuring with relative consistency, following the ISO Standards 9059:1990 and 9847:1992. Besides, another permanent degree of measurement consistency is obtained through the comparison of the measurements obtained for GHI (I_h), DHI (I_d) and DNI ($I_{b,n}$) with Equation (1) [9]:

$$\mathrm{I_h = I_{b,n} \times \cos(\theta) + I_d (W/m^2)} \tag{1}$$

where Θ is the instantaneous solar zenithal angle, which is the same angle as between beam radiation and the sensing element for the pyranometer measuring hemispherical irradiance.

This consistency is a way of fully using the fact that three high quality instruments are measuring the same solar input, with the pyrheliometer and its tracking system aligned with the apparent solar position, adding significant confidence and accuracy to the final result. All the radiometers were also checked for their zero offset. This correction was carried out by finding the average of two other mean values: the signal output during the 60-minute interval before the morning astronomical twilight (Θ>108°) for the same day and the equivalent period after the sunset. This mean zero offset is then subtracted to the measured data. This method of zero offset correction is a standard procedure and assumes that the instruments net exchange of infrared radiation with the environment remains constant throughout the solar day [10].

A cleaning protocol for the instruments was defined and implemented. The instrument domes and desiccant check were done once a week. In the near future there will conditions to increase this periodicity in every network station.

MEASUREMENTS AND FIRST RESULTS

The DNI, GHI and DHI measurements are made on a 5-second time step and recorded for each minute. In this work hourly and monthly values are used. Tables 1, 2 and 3 show the first measurements of $\overline{\mathrm{H}}_{\mathrm{b,n}}$, $\overline{\mathrm{H}}_{\mathrm{h}}$and $\overline{\mathrm{H}}_{\mathrm{d}}$ (corresponding to the average daily monthly beam, hemispherical and diffuse irradiation in $kWh/m^2/day$) for each station, based on 1-min average values. The data shown for each location does not cover exactly the same period of time, since the project started recently with various installations in different locations, which also resulted in different startup dates. There are also some data gaps due to different reasons, such as technical issues, maintenance and calibration activities. The station in Martim Longo is not measuring diffuse radiation. However, another and fully equipped station is expected to be installed very soon near the existing one and also integrated into the network.

Table 1 - $\overline{H}_{b,n}$ (kWh/m²/day) measured for each station since the beginning of the project.

	1-Évora	2-Mitra (Évora)	3-Moura	4-Portalegre	5-Martim Longo	6-Sines	7-Lisboa	8-Porto
June 14	Not installed	Not installed	7,4	7,0	5,1	Not installed	7,1	(a)
July 14			(a)	8,2	8,7		8,1	
Aug. 14				(a)	8,5		(a)	
Sept. 14			4,5		4,6		4,1	
Oct. 14			4,2		4,0		2,9	
Nov. 14			2,4		2,2		1,6	
Dec. 14			3,6		4,1		4,1	
Jan. 15		4,2	4,3		4,5		3,9	
Feb. 15		4,4	4,5		4,3		3,6	
Mar. 15	6,2	6,0	6,2		5,6		5,8	4,7
April 15	4,2	3,7	4,4	4,2	4,2		4,2	4,2
May 15	8,1	7,4	(a)	7,6	7,7	7,8	7,9	7,0
June 15	7,9	6,9	7,8	6,8	7,7	6,7	7,6	6,8

(a) Unavailable data

Table 2 - $\overline{H}_{h}$ (kWh/m²/day) measured for each station since the beginning of the project.

	1-Évora	2-Mitra (Évora)	3-Moura	4-Portalegre	5-Martim Longo	6-Sines	7-Lisboa	8-Porto
June 14	7,4	Not installed	7,6	7,1	5,3	Not installed	7,1	(a)
July 14	7,6		(a)	7,5	7,8		7,5	
Aug. 14	7,5			(a)	7,3		(a)	
Sept. 14	4,7		4,8		4,9		4,4	
Oct. 14	3,6		3,7		3,7		3,2	
Nov. 14	2,1		2,4		2,3		1,8	
Dec. 14	2,4		2,2		2,4		2,2	
Jan. 15	2,6	2,5	2,6		2,7		2,3	
Feb. 15	3,1	3,3	3,4	3,2	3,6		3,0	
Mar. 15	5,1	4,8	4,9	4,1	4,9		4,8	5,1
April 15	4,7	5,2	5,2	5,0	5,3		4,8	4,9
May 15	7,4	7,2	(a)	7,2	7,4	7,5	7,3	6,8
June 15	7,4	7,1	7,7	7,1	7,5	7,0	7,3	7,2

(a) Unavailable data

Table 3 - $\overline{H}_d$ (kWh/m²/day) measured for each station since the beginning of the project.

<table>
<tr><th></th><th>1-Évora</th><th>2-Mitra (Évora)</th><th>3-Moura</th><th>4-Portalegre</th><th>5-Martim Longo</th><th>6-Sines</th><th>7-Lisboa</th><th>8-Porto</th></tr>
<tr><td>June 14</td><td>2,5</td><td rowspan="7">Not installed</td><td>2,3</td><td>2,1</td><td rowspan="13">No DHI measurements</td><td rowspan="11">Not installed</td><td>1,5</td><td rowspan="9">(a)</td></tr>
<tr><td>July 14</td><td>1,8</td><td rowspan="2">(a)</td><td>1,6</td><td>1,4</td></tr>
<tr><td>Aug. 14</td><td>1,7</td><td rowspan="6">(a)</td><td>(a)</td></tr>
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<tr><td>Nov. 14</td><td>1,2</td><td>1,3</td><td>1,0</td></tr>
<tr><td>Dec. 14</td><td>0,8</td><td>0,8</td><td>0,6</td></tr>
<tr><td>Jan. 15</td><td>0,8</td><td>0,8</td><td>0,9</td><td>0,7</td></tr>
<tr><td>Feb. 15</td><td>1,1</td><td>1,2</td><td>1,2</td><td>1,2</td><td>1,1</td></tr>
<tr><td>Mar. 15</td><td>1,4</td><td>1,4</td><td>1,4</td><td>1,3</td><td>1,2</td><td>2,0</td></tr>
<tr><td>April 15</td><td>2,2</td><td>2,6</td><td>2,2</td><td>2,2</td><td>1,8</td><td>2,1</td></tr>
<tr><td>May 15</td><td>2,3</td><td>1,9</td><td>(a)</td><td>1,6</td><td>1,8</td><td>1,5</td><td>2,0</td></tr>
<tr><td>June 15</td><td>2,3</td><td>2,2</td><td>2,0</td><td>1,8</td><td>2,0</td><td>1,5</td><td>2,2</td></tr>
</table>

(a) Unavailable data

As a validation procedure, Equation (1) can be rewritten to yield Equation (2):

$$\cos(\theta) = \frac{(I_h - I_d)}{I_{b,n}} \tag{2}$$

Therefore, Figure 2 can be obtained by plotting the cosine of zenith resulting from the ratio shown in Equation (2), but now calculated as a function of the average hourly values, against the cosine of the average hourly angle.

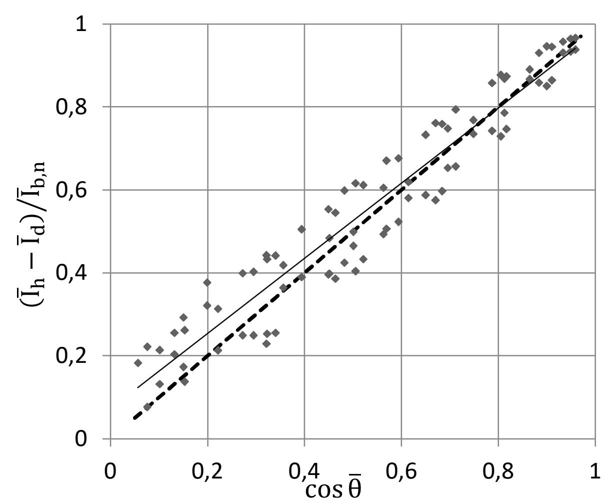

Figure 2 - Comparison of the cosine of zenith calculated through the measurements, Equation (2), with the cosine of the average zenith angle for each hour for Mitra station.

A least square fit of plotted values can be made (solid line), with an R2= 0.93, yielding the follow Equation:

$$\frac{(\bar{I}_h - \bar{I}_d)}{\bar{I}_{b,n}} = 0.91 \times \cos(\bar{\theta}) + 0.07 \qquad (3)$$

As shown in Figure 2, this fit deviates slightly from the broken line, of slope 1; this deviation can be attributed mainly to a larger cosine effect error in radiometers for high zenithal angles (>80º) and to a random dispersion around unit slope, in general because during an hour, significant variations can be observed, especially from the change between clear and cloudy moments.

In future work these data will be analyzed and compared, once the amount of data gathered exceeds at least one full year. In the meantime, and as an example of the investigations that can be done, the data gathered at the Mitra station (and that one only) is used below.

CORRELATION FOR MONTHLY AVERAGE VALUES OF DNI IN RELATION TO GHI AND DHI MEASUREMENTS

Weather variability affects the amount of incident solar radiation in any given place. Long-term average behavior is quite important for solar energy applications, their performance estimate and guarantee.

As stated above, many stations do not measure DNI and it is interesting to be able to retrieve the DNI value from GHI and/or DHI measurements. But, quite beyond that, once just a few years of DNI data are gathered in this project, it is legitimate to ask how representative of long-term behavior the measured short-term series thus obtained is. This paper makes the assumption that if correlations between measured DNI, GHI and DHI are made with the measured data, these should also hold for the same location in respect to long-term series of GHI and DHI data obtained in the past, thus allowing for a more reliable "long-term" estimate of DNI. For this purpose, the paper will use 10 years (later even 20 years) of data already available and processed for the city of Évora, including GHI and corrected DHI data (with shadow band correction) [12].

Firstly, the measured monthly data from the new station in Mitra (10 km from Évora) was compared to the corresponding 10-year monthly averages (see table 4) and for the first seven months of 2015. This comparison shows that the measured values are close to the 10-year average ones.

Table 4 - Comparison between $\overline{H}_h$ and $\overline{H}_d$ measured values and 10-year series average.

		Jan.	Feb.	Mar.	Apr.	May	June	July
$\overline{H}_h$ (kWh/m²/day)	Mitra measurements*	2,5	3,3	4,8	5,2	7,2	7,1	7,9
	10 year series average	2,4	3,3	4,5	5,6	6,8	7,7	8,0
$\overline{H}_d$ (kWh/m²/day)	Mitra measurements*	0,8	1,2	1,4	2,6	1,9	2,2	1,5
	10 year series average	0,9	1,3	1,8	2,6	2,6	2,3	1,8

*The same values in Tables 2 and 3.

With the measured data presented above, Table 1-Monthly daily averages of DNI and the corresponding GHI and DHI of Table 4, the graphic in Figure 3 can be produced.

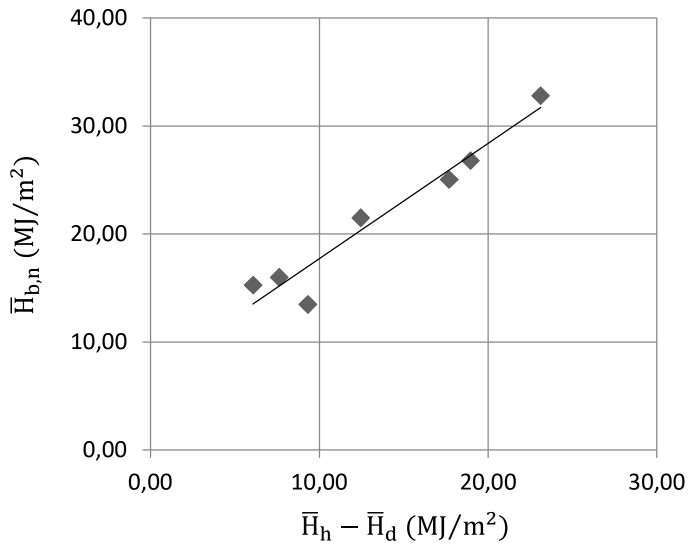

Figure 3 - Measured $\overline{H}_{b,n}$ (MJ/m²) as function of $\overline{H}_h$-$\overline{H}_d$ (MJ/m²), Mitra station.

A preliminary linear least square fit (R^2=0.94) can be made, Equation (4):

$$\overline{H}_{b,n} = 1.07 \times \left(\overline{H}_h - \overline{H}_d\right) + 7.04\ (\mathrm{MJ/m^2}) \tag{4}$$

With more data the significance and the correlation factor will certainly be better, allowing an improved estimation of monthly average DNI values.

It is worth to note that if this correlation is assumed to have a relevant statistical value and adequately represent the whole year, it is possible, by using the average $\overline{H}_h$ and $\overline{H}_d$ of the 10 year series, to estimate the $\overline{H}_{b,n}$ value for each month and thus the total expected average DNI for this specific location. This exercise was attempted, and Table 5 is the result, yielding a result for the average expected DNI of 1985 kWh/m²/yr.

Table 5 - $\overline{H}_h$ and $\overline{H}_d$ average values for the ten-year data series and estimated $\overline{H}_{b,n}$.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
$\overline{H}_h$ (kWh/m2/day)	2,4	3,3	4,5	5,6	6,8	7,7	8,0	7,0	5,5	3,7	2,5	2,1
$\overline{H}_d$ (kWh/m2/day)	0,9	1,3	1,8	2,6	2,6	2,3	1,8	1,8	1,8	1,4	1,0	0,8
$\overline{H}_{b,n}$ (kWh/m2/day)*	3,6	4,1	4,8	5,2	6,5	7,7	8,7	7,5	5,9	4,4	3,6	3,3

* Results from Equation (4).

This value can be compared with the long-term estimates which are easily obtained from data sets produced by data generating algorithms. A possible choice is Meteonorm which yields a value of 2118 kWh/m^2/yr for the Évora location (with an uncertainty of 85 kWh/m^2/yr) [12]. The preliminary value obtained (1985kWh/m^2/yr) is lower and slightly outside the uncertainty range indicated. No big significance is attributed to this fact at this stage, given the very short amount of data (not even a complete year) used in this calculation.

CONCLUSIONS

A very preliminary report was made on a new initiative concerning the DNI measurement in the South of Portugal, where a total of seven measuring stations for beam, global and diffuse radiation were set up. An extra station in the North of the country (OPorto) was also included in the study to clearly establish the known north-south expected differences.

These stations will be operated for a few years and several types of analysis are planned to be made with the data gathered. Among them is the idea of adding long term, statistical significance to the beam radiation measured, by establishing correlations with Global and Diffuse radiation at one of the locations (Évora) with long term series of Global and Diffuse solar radiation data available for that location.

The paper reported on the first few months of data and, as an example of the method proposed, attempted a calculation of the average beam radiation to be expected on a yearly basis. The value obtained of 1985 kWh/m^2/yr is slightly below the value of 2118 kWh/m^2/yr (± 85 kWh/m^2/yr) estimated for the location by Meteonorm [12].

However, it is clear that no firm conclusions should be made yet from the amount of data gathered up to now.

Acknowledgements

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References

1. Gueymard, C.A.: Progress in direct irradiance modeling and validation. Proc. Solar Conf., Phoenix, AZ, American Solar Energy Society (2010)

2. R. Perez, et al.: Climatic evaluation of models that predict hourly direct irradiance: prospects for performance improvements. Solar Energy, 44 (2), 99–108 (1990)

3. F.J. Batlles, M.A. Rubio, J. Tovar, F.J. Olmo, L. Alados-Arboledas.: Empirical modeling of hourly direct irradiance by means of hourly global irradiance. Energy 25, 675–688 (2000)

4. Collares-Pereira, M., Rabl, A.: The average distribution of solar radiation correlations between Diffuse and hemispherical and between daily and hourly insolation values. Solar Energy 22(2), 155-164 (1979)

5. Mateos, D., A. Sanchez-Lorenzo, M. Antón, V. E. Cachorro, J. Calbó, M. J. Costa, B. Torres, and M. Wild (2014), Quantifying the respective roles of aerosols and clouds in the strong brightening since the early 2000s over the Iberian Peninsula, J. Geophys. Res. Atmos., 119, doi:10.1002/2014JD022076.

6. Salgueiro, V., Maria João Costa, Ana Maria Silva, and Daniele Bortoli, 2014: Variability of the Daily-Mean Shortwave Cloud Radiative Forcing at the Surface at a Midlatitude Site in Southwestern Europe. J. Climate, 27, 7769–7780. doi: http://dx.doi.org/10.1175/JCLI-D-13-00696.1

7. Kipp & Zonen, retrieved from http://www.kippzonen.com/

8. DataTaker, retrieved from http://www.datataker.com/DT80.php

9. Rabl, A., Active Solar Collectors and Their Applications, (Oxford University Press, New York 1985)

10. McArthur L.J.B., Baseline Surface Radiation Network (BSRN), Operations Manual, (2005)

11. Iqbal, Muhammad, An Introduction to Solar Radiation, (Academic Press, New York, 1983), Chap. 12, 362-365

12. Meteonorm yearly irradiation data

4.2. Procedures for solar radiation data gathering and processing and their application to DNI assessment in Southern Portugal

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Abstract

This work proposes a data gathering and processing methodology of solar irradiance measurements for producing filtered and continuous data series that can be used for solar energy availability assessment. The method is applied to data from 13 measuring stations established in Portugal, with special focus in the southern region, for the assessment of Direct Normal Irradiance (DNI). With the current amount of measuring locations and as the measurement period continuously increases, it allows a better regional characterization of DNI availability and creates conditions for in depth studies. This infrastructure has high relevance for the region, known for its high annual availability of Global Horizontal Irradiance (GHI) and its reduced inter-annual variability, thus a high annual DNI availability is expected.

The proposed data processing methodology is discussed, analyzed and its application is demonstrated over several stations. With the application of the proposed methodology, the assessment of mean yearly DNI availability is performed. It is expected that this effort will significantly help to realize the region high potential for the development and implementation of Concentrated Solar Power (CSP) Plants, with annual mean DNI availabilities ranging from 1945 to 2116 kWh/m^2/year.

Keywords

Solar Energy; CSP; DNI; Data Quality; Assessment

1. Introduction

Concern over environmental pollution and climate change associated with fossil fuel-based energy consumption is fast increasing and, thus, accelerating the need for alternative and clean energy sources. Abundant Scientific and Technological efforts are being made on the development and optimization of advanced solar energy technologies, both in photovoltaics (PV) and Concentrated Solar Power (CSP), to produce clean electricity.

Portuguese regulators have set specific targets to start a steep decarbonization of economy, by defining a National Energy Climate Plan 2030 (PNEC 2030) aiming to ensure coherent policies between the areas of energy and climate to achieve 2030 horizon set targets, in articulation with the 2050 Roadmap for Carbon Neutrality. PNEC 2030 sets the country roadmap for the horizon 2021-2030, with a strong focus and investment on the solar energy sector, it is expected that solar energy in Portugal will increase from 0.5 GW installed power in 2015 to 8,1 - 9,9 GW in 2030, corresponding to a 22% - 27% share of the annual electric energy generation in Portugal. It is also foreseen that this share can grow up to 50% in 2050 [1, 2].

The International Renewable Energy Agency (IRENA) reports that in 2018 Levelized Cost of Energy (LCOE) decreased 17% for PV and 26% for CSP, taking the values from 2017 as reference. Analyzing the period from 2010 to 2018, International Renewable Energy Agency (IRENA) reports a LCOE reduction of 77% in PV plants and 46% in CSP plants, with a global weighted average for LCOE in 2018 of 0.085 $/kWh and 0.185$/kWh respectively [3].

Foreseeing the referred context, a Direct Normal Irradiance (DNI) measurement initiative was started in 2014, in Portugal, since the planning and construction of CSP plants require accurate assessment of DNI availability. On the other hand, the information on DNI availability is also of high importance for policy makers when defining new policies or plans.

However and in general, DNI ground-based measurements have not been performed on a scale comparable to that of solar global horizontal (GHI) and even to that of diffuse horizontal (DHI) irradiances, due to the technical challenges that DNI measurements entail and also to the fact that widespread interest on the commercial applications of solar energy concentration is still recent. Thus, only GHI and DHI measurements are available all over the World, with good geographical coverage and long-term data series in many locations. Those measurements are simpler to perform than DNI measurements since the sensors are fixed, requiring simple maintenance operations and in case of DHI measurements, typically only a few small tilt adjustments of a shadow band over the year are needed. In contrast, DNI measurements require expensive equipment to continuously track the apparent motion of the Sun and more extensive calibration and maintenance procedures to ensure data quality. Solar Concentration Technologies, mainly CSP, are driving the need for setting up DNI measuring stations, providing reliable data for the proper design of such systems, with enough confidence on the energy output predictions to facilitate financing and performance insurance of the large investments made in this power plants.

The lack of DNI data has been overcome by using databases based on satellite data. However, such kind of data is not as reliable as ground-based measurements, as its accuracy is affected by the impact of clouds and several other atmospheric parameters. These models show different responses depending on the locations analyzed, evidencing different bias due to local geographical conditions. Also, in a case where there is no data validation for nearby locations, the satellite data models predict DNI on the assumption that the response is consistent with that of the closest validated points. The existing satellite data results from dedicated models that need to be calibrated with good quality ground-based measurements in order to reduce bias of the provided outputs. In Europe, for example SOLARGIS® estimates an average bias of ±8% to ±12% for DNI annual average values [4, 5].

For those reasons, a DNI network in Portugal was initiated in 2014 in order to provide reliable ground-based measurements to assess the best locations to build CSP power plants [6]. This network has grown and provides today a dense distribution of measuring stations in Southern Portugal, with a good regional coverage. It is expected that the amount of stations will increase, especially in the southwest region of the country to consolidate full geographical coverage. It can be said that the type and scale of the effort reported in this paper has pioneer characteristics and will hopefully be replicated in other areas of the World.

When analyzing solar radiation data sets, data must be filtered and tested for quality issues. Thus, a consistent data processing methodology is necessary to detect and overcome common data sets issues, such as gaps, data quality issues, measuring system operation and statistical analysis.

This paper is organized as follows: **Section 2** presents the DNI measurement network in terms of geographical distribution, measuring period and operational maintenance; **Section 3** describes the procedure to assure data quality used for assessment; **Section 4** presents the assessment of the data quality procedure for long term DNI data; **Section 5** reports the application of the proposed procedure to assess DNI availability and inter-annual variability in Southern Portugal; **Section 6** presents the main conclusions.

2. DNI Network

The DNI network consists of 13 location scattered mainly in the Southern Portugal, wherein 8 measuring stations were installed at the start (Figure 1 and Table 1). Two other stations are located in the west coast of Portugal, one in Lisbon within the city and with several horizon constraints due to the surroundings buildings, and another one in Sines, near the ocean shoreline. On the east side of Portugal, near the Spanish border, there is one station in Portalegre, Moura and two in Martim Longo, in the Algarve. In Algarve, there is one station in Olhão at the center of Algarve by the seashore. In the central area of Alentejo there are 5 stations, 4 in or near Évora and one in Beja.

The current distribution of meteorological stations provides a good coverage of different and relevant environmental and climatic conditions, thus allowing for a reliable and meaningful geographical DNI interpolation over the region. It is expected that, in a near future, a new measuring station will be installed in the Southwest region to provide further coverage and better bound the area of interest, thus improving interpolation processes accuracy. The geographical coordinates and elevation of the stations are described in Table 1 and mapped in Figure 1.

Table 1 - Geographical location of the DNI Network Stations and data period analyzed.

Station	Latitude (°N)	Longitude (°W)	Elevation (m)	Data Period
Évora 1 (PECS)	38.5306	8.0112	222	01/2015 to 06/2019
Évora 2 (Verney)	38.5677	7.9117	276	04/2015 to 06/2019
Évora 3 (EMSP)	38.5289	8.0053	231	**n/a**
Évora 4 (EDPI)	38.5417	7.9632	228	**n/a**
Portalegre	39.2692	7.4428	342	04/2015 to 06/2019
Beja	38.0249	7.8672	252	09/2017 to 06/2019
Lisboa	38.7734	9.1779	111	01/2015 to 06/2019
Sines	37.9576	8.8473	99	05/2015 to 06/2019
Moura	38.1329	7.4536	207	01/2015 to 06/2019
Oporto	41.1793	8.5943	159	**n/a**
Martim Longo 1 (Sonae)	37.4410	7.7491	282	01/2015 to 06/2019
Martim Longo 2 (Enercoutim)	37.4431	7.7409	283	**n/a**
Olhão	37.0329	7.8546	6	**n/a**

Stations whose data period are identified as "n/a" were not analyzed in the frame of this work due to lack of data, for being redundant with another station nearby, the lower data quality or reduced amount of data in comparison with a nearby station. Each station was installed and started measuring at different times, therefore the measuring period for each location varies from location to location.

The measuring stations consist, typically, of a Kipp&Zonen Solys2 sun tracker equipped with a CHP1 pyrheliometer to measure DNI, two CMP 11 pyranometers to measure GHI and DHI and a shading assembly to block beam radiation from the sun in the case of the DHI pyranometer [7]. The data acquisition system and sampling frequency are different among the stations, as some of them are meant for other research purposes or for solar plants operation and control.

The stations have an ongoing cleaning protocol for the sensors which consists in cleaning the domes and desiccant checking at least once a week.

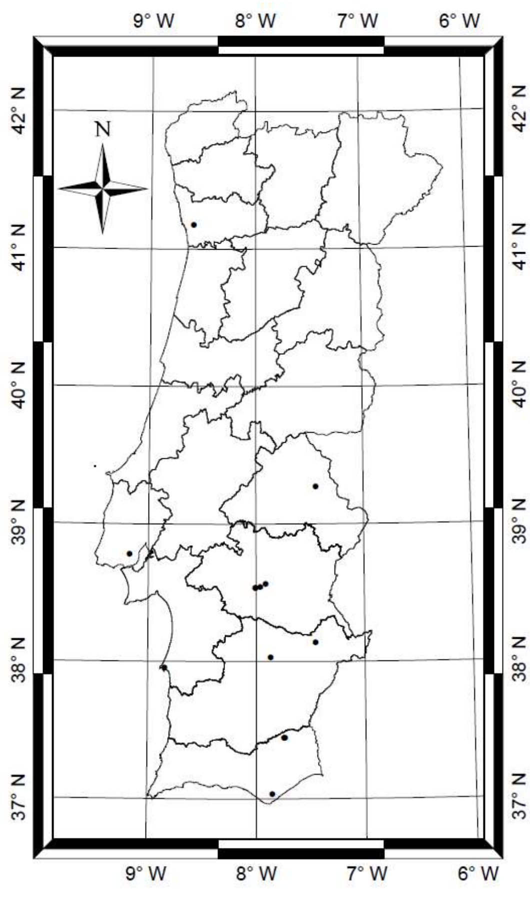

Figure 1 - Geographical distribution of the DNI network measuring stations

3. Data Quality Assurance

As a way of obtaining a consistent comparison, stations are regularly calibrated against the same two reference sensors, a CMP11 to calibrate pyranometers and a CHP1 to calibrate pyrheliometers. The calibration procedure consists in periodically, every two years, install the reference sensors in parallel with the local system of each station and compare readings to make sure that all sensors are measuring with relative consistency, according to ISO Standards 9059:1990 and 9847:1992. Another method to continuously check measurements consistency is obtained through the comparison of GHI (I_h), DHI (I_d) and DNI ($I_{b,n}$) values according to the energy closure function, equation (1) [8]

$$I_h = I_d + I_{b,n} \times \cos\theta \tag{1}$$

where θ is the solar zenithal angle determined according NREL's Sun Position Algorithm, which is the angle between beam radiation and the sensing element of the pyranometer measuring global horizontal irradiance [9].

This consistency check is a way of fully using the fact that three high quality calibrated instruments are correctly measuring solar radiation data, with the tracking system and pyrheliometer aligned with the sun, thus adding significant confidence to the measurements [10].

All radiometers are also checked for their zero offset. This correction is carried out by finding the average of two mean values for a given day: the average of the records for the hour before morning astronomical twilight ($\theta > 108°$) and the average of the records for the equivalent period after sunset. The daily mean zero offset is then subtracted to the measured data on that day. This method of correcting zero offset is a standard procedure and assumes that the net exchange of infrared radiation between the sensors and the environment is constant throughout the day [10].

The network did not start at the same date in every location, the sampling rate and data formats are different among locations. Those differences require a data processing methodology to allow the analysis and comparison of the different locations. The developed methodology follows the following criteria:

1. **To identify problems with DHI, GHI and DNI measurements due to possible sensors malfunction, following the BSRN recommendations for physical possible (phy) and extremely rare (ext) limits of DHI, GHI and DNI [11]**

$$\mathrm{DHI_{phy}} \leq 0.95 \times \mathrm{I_0} \times \varepsilon \times \cos\theta^{1.2} + 50\ [\mathrm{W/m^2}] \tag{2}$$

$$\mathrm{DHI_{ext}} \leq 0.75 \times \mathrm{I_0} \times \varepsilon \times \cos\theta^{1.2} + 30\ [\mathrm{W/m^2}] \tag{3}$$

$$\mathrm{GHI_{phy}} \leq 1.5 \times \mathrm{I_0} \times \varepsilon \times \cos\theta^{1.2} + 100\ [\mathrm{W/m^2}] \tag{4}$$

$$\mathrm{GHI_{ext}} \leq 1.2 \times \mathrm{I_0} \times \varepsilon \times \cos\theta^{1.2} + 50\ [\mathrm{W/m^2}] \tag{5}$$

$$\mathrm{DNI_{phy}} \leq \mathrm{I_0} \times \varepsilon\ [\mathrm{W/m^2}] \tag{6}$$

$$\mathrm{DNI_{ext}} \leq 0.95 \times \mathrm{I_0} \times \varepsilon \times \cos\theta^{0.2} + 10\ [\mathrm{W/m^2}] \tag{7}$$

where, I_0 = 1366 W/m^2 is the solar constant and ε accounts for the variation of Earth-Sun distance during the year[5].

The readings are tested to check whether the measured values exceed physical possible and extremely rare limits. If such limits are exceeded that is an indication that there were issues with the sensor or sun tracker, then those records are discarded and considered as gaps. These filters set the solar radiation limits, per component, that can occur under certain atmospheric circumstances, such as cloud reflections [11].

2. **Data gaps up to 2 hours per day were linearly interpolated regardless of the records averaging rate (1 – 60 min.) and for solar zenith angles lower than 90º**

Such gaps result, usually, from power supply failure or dataloggers misbehaving, causing them to skip records. Or else they are related to data storage and communication issues. Linearly interpolating solar radiation data, under the referred conditions, is a way of reducing the amount of data gaps without significantly affect the data series since it takes into account records before and after the gap.

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[5] Different references indicate different solar constant values. For this purpose, the used solar constant value was proposed by: ISO, 2013. Space environment (natural and artificial) — Earth upper atmosphere. ISO 14222 standard, International Organization for Standardization.
Earth-Sun distance reference: Michalsky, J. 1988. ERRATA: The astronomical almanac's algorithm for approximate solar position (1950-2050). Solar Energy 41 (1), 113.

If daily gaps are larger than 2 hours, then no records are interpolated and remain as data gaps. The gaps were checked between sunrise and sunset and are summed in Table 2.

Table 2 - Gap Quantification before and after interpolation up to 2 hours per day.

Station	Gaps before interpolation (hours)	Gaps before interpolation (%)	Gaps after interpolation (hours)	Gaps after interpolation (%)
Évora 1 (PECS)	704.92	3.520	676.63	3.380
Évora 2 (Verney)	10.97	0.055	2.15	0.011
Portalegre	484.03	2.420	480.10	2.400
Beja	7.93	0.099	6.80	0.085
Lisboa	2068.30	10.340	1544.70	7.720
Sines	2520.82	13.530	2519.73	13.530
Moura	10214.50	51.080	10093.30	50.480
Martim Longo 1	550.00	1.400	39.00	0.090

3. **Daily Zero Offsets were determined and 1-minute records were corrected.**

The daily Zero Offset is found by averaging the mean values, for the same day, during the hour before morning astronomical twilight (θ>108°) and the equivalent period after sunset [10][6]. The correction of the zero offset is a standard procedure and assumes that the thermal radiation net exchange between instruments and the environment (sky) remains constant throughout the solar day. This process is a local quality procedure, which improves data quality, up to some level of uncertainty, within the station location. This correction is essential for the development of solar radiation correlations, for other studies that require quality data and for quality resource assessment [10].

4. **Records for negative solar altitudes were discarded**

Once the daily zero offsets were determined, records corresponding to negative solar altitudes were filtered and discarded. For assessment purposes only readings between sunrise and sunset hours were considered, during the solar day.

[6] As an example, the mean zero offset values obtained for Évora 1 station were -0.36 W/m^2 for DNI; -1.21 W/m^2 for DHI and -1.19 W/m^2 for GHI.

5. **Daily total availabilities of measured GHI and calculated GHI (Equation 1) were compared to check data quality**

Determining GHI from the measured DNI and DHI is a way of checking if the entire system, solar radiation sensors and sun tracking system, is running under desired operational conditions. If poor agreement between measured and calculated GHI is found, it does not necessarily mean there are issues with the system itself, it can be related to external interferences in the measurements. Those interferences are, usually, related to solar radiation being blocked by horizon obstacles. This is a common issue in the periods after sunrise and before sunset, in which the solar zenithal angle is higher, and beam solar radiation can be obstructed by mountains in the horizon line, trees or other obstacles, thus affecting GHI due to the impact on DNI. The measurement uncertainty in those periods is higher for pyranometers due to higher incidence angles, increasing measurement uncertainty. Such differences occur mainly in 1-minute data in days or periods in which the atmospheric conditions are not stable and fast changes in the atmosphere occur, not allowing the sensors output to stabilize and due to the different response times of sensors.

A linear fit between measured and calculated GHI values was determined as an indication of measurements quality. If good agreement is found, high R-squared value, it is an indication of proper maintenance and operation of the station.

Calculated GHI was determined on 1-minute basis, reducing the error of using an average value of zenithal angle, and then hourly and daily totals were determined for comparison purposes.

6. **The Standard Deviation of the difference between measured and calculated GHI is determined**

The difference between measured and calculated GHI was determined, according to Equation 1. If significant differences are found, those may result from soiling deposition on the sensors or partial and long misalignments of the pyrheliometer or of the DHI shading assembly.

To ensure overall data quality, measured GHI values were filtered within ±5 STD or 0.5 kWh/m^2/day, whichever is smaller, in relation linear equation fit (Step 5) to remove outliers resulting from the causes referred above. Typically, for a well-maintained station the STD value is near to 0.1 kWh/m^2/day, filtering days which differ up to 0.5 kWh/m^2/day in relation to the linear fit between measured and calculated GHI values allows small differences that may result from different sensors response times which can have impact in days with fast changing atmospheric conditions

Step 1 of this procedure does not guarantee, by itself, overall data quality. It defines the maximum values each solar radiation component can reach. Solar radiation statistical distribution is usually represented, on a clear sky day or on a near clear sky day, as a normal distribution. Having that in mind, the Standard Deviation of the sample can be used to identify outliers in the sample data. Those outliers are related to operational issues, soiling deposition in the sensors, poor calibration, DNI or DHI sensor misalignment and calibration activities.

Using five standard deviation (STD) or 0.5 $kWh/m^2/day$ as a cut-off for identifying outliers ensures that measured GHI data is within the specified range of calculated GHI values (± 5 STD or ±0.5 $kWh/m^2/day$). This outlier cut-off ensures that the whole system is operating in adequate conditions. Considering that a high degree of quality is desired and very low standard deviations values were found, typically lower than 0.1 $kWh/m^2/day$, with only 2 stations exceeding the referred limit, it was considered that five standard deviation or 0.5 $kWh/m^2/day$ would be an adequate final choice, as it cuts-off more disperse data and ensures high confidence in data quality while still being widely representative of the sample data.

The outliers, on a daily basis, may occur due to pyranometer uncertainty together with the horizon interference (DNI blockage), maintenance operations, unshaded DHI pyranometer due to calibration activities (in such situation, DHI can be determined by rearranging Equation 1), days with fast changing atmosphere may result in higher differences between measured and calculated GHI values since pyrheliometers respond faster to changes of radiation intensity than pyranometers due to their lower response time.

For assessment purposes it is proposed that an outlier cut-off is performed on daily basis values, since only a few days are cut-off and can later be restored by daily linear interpolation, step 7.

7. Daily gaps were identified

Days whose gaps are greater than two hours per day, resulting from limit checking or data quality filtering were considered as daily gaps.

8. Daily gaps were linearly interpolated, up to 5 days per month

Daily gaps, as described in step 7, were linearly interpolated up to 5 days per month. This is a measure to restore the monthly statistics with reduced impact on the assessment of average annual solar radiation availability.

Table 3 - Gap Quantification before and after interpolation up to 5 days per month.

Station	Gaps before interpolation (days)	Gaps before interpolation (%)	Gaps after interpolation (days)	Gaps after interpolation (%)	Days in the Series (days)
Évora 1 (PECS)	70	4.27	59	3.60	1641
Évora 2 (Verney)	4	0.26	0	0.00	1551
Portalegre	64	4.13	39	2.51	1551
Beja	6	0.90	0	0.00	668
Lisboa	182	11.01	119	7.25	1641
Sines	197	12.95	113	7.43	1521
Moura	865	52.71	825	50.27	1641
Martim Longo 1	51	3.11	2	0.12	1641

9. Monthly mean values of solar energy availabilities were determined based on the average daily availabilities

The monthly mean values of solar energy availability can be obtained either by (a.) the integration for the whole month of the daily mean availabilities for that month, for all years within the data series (e.g. January 1st results from the average of the daily availability of that same day for all years in the data series and the same for other calendar day of the year) or by (b.) calculating directly the monthly mean values of solar energy availability by averaging the correspondent monthly availabilities, for each year of the series.

The first method (a.) was chosen instead of the second method (b), since it results in less data being removed from the series.

A more detailed discussion of this option is as follows:

in the case of a month, of a given year, with more than 5 days of missing data, that month would be eliminated with method b., which would result in having one month less for determining the monthly average. This removal would cause the corresponding months of the series, of other years, to have an increased statistical weight in the determination of the monthly average and, in consequence, in the determination of the annual availabilities.

In contrast, for the same situation, method a. would consider all existing days in that month, independently of the number of missing days.

In order to help clarifying any potential concerns on the methodological option explained above, a comparison was performed for 3 stations of the network, with different levels of missing data.

Table 4 - Comparison of methods to determine monthly mean values solar energy availability and respective impact on the annual values (kWh/m^2/year).

	Évora 1 (PECS)		Évora 2 (Verney)		Sines	
	Method a.	Method b.	Method a.	Method b.	Method a.	Method b.
DNI (kWh/m^2/year)	2040	2027	2116	2116	2080	2064
DHI (kWh/m^2/year)	541	542	540	540	565	568
GHI (kWh/m^2/year)	1761	1754	1793	1793	1824	1815

Évora 2 has no gaps after daily interpolations (step 8) and, therefore, both methods yield the same result. While for Évora 1, few missing data days, and Sines station, a more significative amount of missing days, the results are within less than 1% in terms of relative differences. Given the above considerations and the results obtained, shown in Table 4, method a. was adopted as the one yielding more meaningful results in the calculation of monthly and yearly average availabilities.

10. Correction of eventual daily gaps in monthly solar energy availabilities

If after step 9 days with missing data still exist, which would only occur in the unlikely situation of the same calendar day, or days, show data issues in all the years of the series, there are two ways of correcting such gaps:

a) Interpolate, on a daily basis, up to 5 days per month, as before.
b) Normalize the monthly mean solar energy availability in relation to the fraction of days for the month in analysis.

This correction its unlikely to be used, since it would require the same day to have issues causing missing data, for all years of the data series.

11. Determination of the mean annual solar energy availability

Once the average monthly solar energy availabilities of the data series were obtained, the average annual solar energy availability results from the integration of monthly solar energy availabilities.

12. Exceptions

Situations in which there is a total misalignment of the sun tracking system cannot be identified by the proposed procedure, neither can be identified by the BSRN recommendations since in those cases the DNI value tends to zero, DHI pyranometer is unshaded and therefore it is also measuring GHI. When comparing measured and calculated GHI both will tend to be equal and will not stand out in the quality analysis, remaining in the processed time-series.

For meteorological stations with DNI, DHI and GHI measurements, except Martim Longo 1 station, if steps 5 and 6 show large differences between measured and calculated GHI, then those periods were manually checked. Typically, such large differences are due to, at least, 1 missing solar radiation component measurement.

In situations in which one solar radiation component is missing, it was determined with basis on Equation 1 as a way to restore solar radiation statistics. If two solar radiation components are missing, then all three components are considered as Gaps.

For Martim Longo 1 station steps 5 and 6 were not applied since the station does not have DHI measurements.

4. Data Quality Analysis

Having in mind the quality validation of measured data, a comparison between measured GHI and calculated GHI, Equation 1, was performed according to the steps 5 and 6 of the data treatment chapter. Such comparison highlights the quality of the measurements, and it is expected that well measured data will shows a low dispersion in this comparison. If the difference is bigger than 5 Standard Deviations, as considered by the authors, then those records are considered invalid due to lack of quality. This procedure is a way of assuring that all the instruments are measuring in adequate conditions: properly calibrated and maintenance, with no soiling accumulation, the sun tracker is well aligned with an accuracy ranging from 0.02º to 0.1º, and not totally misaligned, and there are no obstructions due to horizon interference. Such method can be applied to daily total irradiation values since small errors are not significant over such periods of time, presenting a residual impact on the final outcome.

Figure 2 shows the application of steps 5 and 6 of the proposed data quality control for the Évora 1 station. As can be seen, when comparing measured and calculated GHI, there are a few days outside of ±5 STD or ±0.5 kWh/m^2/day, whichever is less. The proposed cut-off limit guarantees that only quality data is used. The removed data points refer to days in which data was affected during significant periods of time to cause a deviation in measured values in relation to calculated GHI values. If small deviations occur, a few minutes, the impact in the day is neglectable and will not be enough to stand out in quality control.

Figure 2 and Table 5 show that overall the data quality is good within the network since there are few data points outside cut-off limits and standard deviation is low. Regarding the linear fit equations in Table 5, typically the slopes are 1 or close to 1, and offsets close to zero. Such offsets and slopes different of 1 can result from the different response times, with CHP1 pyrheliometers typically, responding faster than pyranometers to changes in irradiance variation [7]. Other causes are the higher effect of soiling in pyrheliometers when compared to pyranometers, as the readings are more affected, and the approximation made when correcting the sensors daily offsets.

In resume, the proposed procedure can be used as a way of assuring data quality at different time scales. The authors consider that for long term assessment purposes the procedure is appropriate since it only filters data points in which the measurements differ significantly from daily expected values.

Table 5 - Linear fit equation, R-Squared and Standard Deviation between measured and calculated daily global horizontal irradiation.

	Linear Fit (y=mx+b)	**R-Squared**	**Standard Deviation (kWh/m^2/day)**
Évora 1 (PECS)	1x-0.0090	1	0.058
Évora 2 (Verney)	1x-0.019	1	0.064
Portalegre	0.97x+0.074	1	0.092
Beja	0.98x+0.046	1	0.055
Lisboa	0.98x+0.0044	1	0.130
Sines	0.98x+0.032	1	0.081
Moura	0.95x+0.053	0.99	0.190
Martim Longo 1 (Sonae)	NA	NA	NA

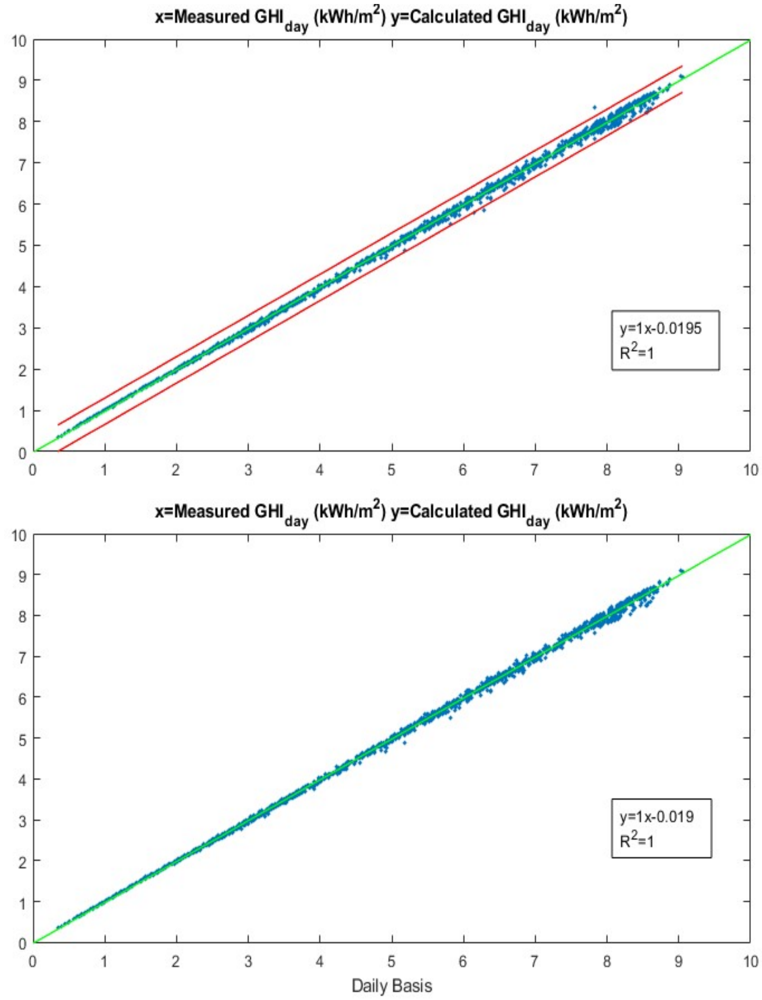

Figure 2 - Application of outlier filtering for Évora 2 station: green line – linear fitting, red lines – confidence band based on standard deviation.

5. DNI Assessment

After the application of the method described in Chapter 3, the mean yearly solar energy availability was determined for each component. Results show that DNI mean availability ranges from 1876 to 2116 kWh/m2/year in the South of Portugal. Unfortunately, the station of Moura has had many issues, as shown in Tables 2 and 3. The values obtained, for all the analyzed locations, are presented in Table 6.

Using the mean annual solar energy availability (kWh/m^2/year) for each location (Table 6), a map was generated through geographical interpolation for the mean annual DNI availability to characterize the region, Figure 3. This map is merely indicative and its purpose is only to serve as a geographical distribution estimation of the annual DNI in the region of Alentejo.

This stations network will still need more years, typically up to a total of at least 10 consecutive years, to yield statistical significative solar radiation assessment. Meanwhile, the network is crucial as it allows several research lines along the measured data while increasing data series.

Table 6 - Mean annual solar energy availability in each station of the network and for each solar radiation component.

Station	DNI (kWh/m^2/year)	DHI (kWh/m^2/year)	GHI (kWh/m^2/year)
Évora 1 (PECS)	2040	541	1761
Évora 2 (Verney)	2116	540	1793
Portalegre	2056	526	1770
Beja	2077	543	1791
Lisboa	1945	516	1723
Sines	2080	565	1824
Moura	1876	655	1808
Martim Longo 1 (Sonae)	2105	NA	1846

Values from Moura station are lower than expected due to several data issues identified upon manual analysis of the data series. The system had problems related to power supply that caused the tracking system to turn off and often made the sun tracker restart afterwards and misalign for a few minutes. Those issues were manually identified, filtered and defined as gaps. The authors compared the period of data from Moura, after solving the technical problems, with nearby stations and the energy availabilities were similar. Given the poor quality of data from Moura, this station was not considered for the map of Figure 3.

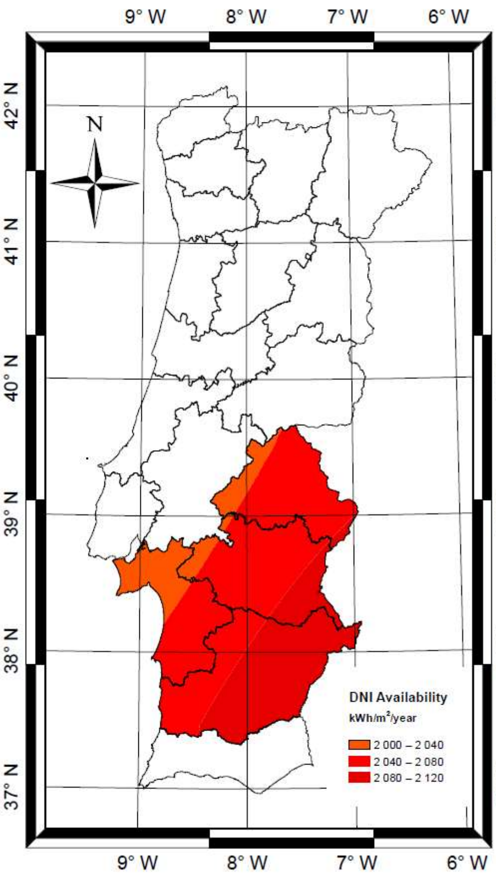

Figure 3 - Geographical distribution of the mean annual DNI availability in the Alentejo region (kWh/m^2/year)

The obtained DNI distribution pattern, Figure 3, is in line with what was expected, given the obtained GHI distribution patterns shown in previous studies [13, 14, 15].

6. Conclusions

This work describes a procedure for solar radiation data gathering and processing, with emphasis in data quality assurance, and their application to DNI assessment in Southern Portugal. Data from a network of thirteen DNI, DHI and GHI measuring stations in the Southern Portugal were used, from which eight stations were selected to develop and test a procedure for producing filtered and continuous data series. The proposed procedure is robust and takes into account operational parameters, such as physical and extremely rare sensor output limit checking, while providing a methodology to minimize the effect of missing data on the solar energy availability assessment. However, there are situations in which the data quality control procedures cannot identify operational issues, as is the case of total misalignment of the sun tracking system. Such issues can only be identified by visual data inspection, as happened for the Moura station.

The implementation of limits based on a confidence band of 5 STD or 0.5 kWh/m^2/day difference between measured GHI and calculated GHI from DNI and DHI for outlier filtering showed that most stations are providing quality data, with this filtering procedure functioning as an additional measure of quality assurance.

The monthly mean solar energy availabilities were determined based on the average of the daily mean availability for each calendar day, instead of averaging the monthly solar energy availabilities for each year (Table 5). The statistical significance added to calendar days, on months with few days absent is low. In the limit, according to the amount of missing days, the additional statistical weight for calendar days by following this option will be the same as if a whole month was removed.

The DNI Network will still need many years of operation to yield truly statistical significative results, typically 10 years of data. Nevertheless, measured values can already be used for regional DNI availability estimations. On the other hand, many research lines are developing based on these measurements. In a near future it is expected that the network increases in size, and further geographical coverage, with a new station in the southwest of Portugal, in the lower Alentejo or even in Algarve.

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References

1. PNEC 2030 – Plano Nacional de Energia e Clima. January 28, 2019. Retrieved November 18, 2019, from https://www.portugal.gov.pt/download-ficheiros/ficheiro.aspx?v=0eada7c4-4f17-4d13-a879-6700f302b7e0

2. RNC – 2050 Roteiro para a Neutralidade Carbónica. December 4, 2018. Retrieved November 18, from https://descarbonizar2050.pt/uploads/RNC2050_Sessao_publica_4dez2018.pdf

3. IRENA/International Renewable Energy Agency. RENEWABLE POWER GENERATION COSTS IN 2018. 2018. Retrieved November 18, 2019 from https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018

4. SOLARGIS. (n.d.). Retrieved November 18, 2019 from http://solargis.com/support/accuracy-and-comparisons/overview/

5. T. Cebecauer, M. Suri, "Site-adaptation of satellite-based DNI and GHI time series: Overview and SolarGISapproach", AIP Conference Proceedings 1734, 150002 (2016); Doi: 10.1063/1.4949234.

6. A. Cavaco, P. Canhoto, M. J. Costa, M. Collares-Pereira, "DNI Measurements in the South of Portugal: Long Term Results through Direct Comparison with Global and Diffuse Radiation Measurements and Existing Time Series", AIP Conference Proceedings 1734, 150001 (2016); Doi: 10.1063/1.4949233.

7. Kipp & Zonnen. (n.d.). Retrieved November 18, 2019 from http://www.kippzonnen.com/

8. Rabl, A. (1985). Active Solar Collectors and Their Applications. New York, NY. Oxford University Press

9. Reda, I.; Andreas, A. (2003). Solar Position Algorithm for Solar Radiation Applications. 55 pp.; NREL Report No. TP-560-34302, Revised January 2008.

10. McArthur L.J.B., Baseline Surface Radiation Network (BSRN), Operations Manual, (2005)

11. Long, C. N. and Dutton, E. G. (2010): BSRN Global Network recommended QC tests, V2.x, Bremerhaven, PANGAEA

12. Iqbal, M. (1983). An Introduction to Solar Radiation (Chap. 12, pp. 362-365). New York, NY. Academic Press

13. Silva HugoGonç, Abreu EFM, Lopes FM, Cavaco A, Canhoto P, Neto J, Collares-Pereira M, Solar Irradiation Data Processing using estimator MatriceS (SIMS)validated for Portugal (southern Europe), Renewable Energy (2019), doi: https://doi.org/10.1016/j.renene.2019.09.009

14. A. Cavaco, H. G. Silva, P. Canhoto, S. Neves, J. Neto and M. Collares-Pereira, Annual Average Value of Solar Radiation and its Variability in Portugal, Workshop On Earth Sciences 2016

15. A. Cavaco, H. G. Silva, P. Canhoto, S. Neves, J. Neto and M. Collares-Pereira, Technical Report: Radiação Solar Global em Portugal e a sua variabilidade, mensal e anual, 2016

4.3. Predicting DNI from GHI and DHI data bases

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Abstract

The present work uses high quality experimental data to establish correlations to predict DNI when only monthly mean values of GHI and DHI are available, and even when only GHI data series exist. This approach uses the measurements performed in a DNI measuring network in Southern Portugal, with focus in the Alentejo region. Firstly, the relation between monthly mean values of daily DNI, GHI and DHI is analyzed and the impacts of location (latitude) and partition between direct and diffuse components are assessed when using such integrated values of solar irradiance. These relations are used to estimate the DNI based on both GHI and DHI measurements and on GHI only. Then, a monthly mean cosine of the solar zenith angle is used to account for the latitude effect and a relation between GHI and DHI is also tested to estimate the diffuse component. It is further proposed that these correlations, refined with the removal of the latitude effect, can be applied to other locations with data from existing long-term series measurements of GHI and DHI or only GHI. It is argued that depending on the quality of these data, it can provide a statistically meaningful long-term prediction of DNI availability.

1. Introduction

Solar concentration technologies have a wide range of applications, including industrial process heat, desalination, water purification, electricity production, among others. The use of such technologies requires the knowledge of DNI availability; however, such kind of data are not available on a large scale or for long measurement periods.

In the past, only GHI and DHI or even only GHI measurements have been commonly made across the globe, providing good data coverage, with long-term series that go back several decades. Given the simplicity of these measurements, since only a levelled pyranometer is necessary to measure GHI, and a shadow band requiring only a few tilt adjustments over the year to set its position according to the solar declination, in the case of DHI. The maintenance operations that those sensors entail are reduced, rendering them easy to install and operate. On the other hand, DNI measurements require a continuous tracking of the apparent position of the sun in the sky, thus implying the use of tracking devices requiring more frequent checking and maintenance operations to guarantee data quality. Given the complexity of these systems, the associated cost is considerably higher, making DNI measurements significantly more expensive than GHI or DHI measurements and, therefore, also less available around the globe.

Given the lack of long-term ground-based measurements of DNI, CSP promoters often have to resort to satellite data to identify and assess adequate locations for such kind of applications and then follow up with local measurements during an adequate period to determine the bias of the satellite data estimations, which are known to have considerable uncertainties and tend to overestimate DNI [2, 3].

Setting up a DNI measurement network to cover a significant area is costly and a long period of time is required for the measured data to be considered statistically significant, desirably at least 10 years of measurements [4, 5]. In this sense, the development of methods to estimate DNI based on the available historical measurements is crucial to respond to the actual need for such data. With this in mind, a DNI network was initiated in 2014 in Portugal to provide reliable ground-based DNI data for the assessment and identification of locations with good DNI availability to build CSP power plants. This network has grown and today provides a dense distribution of DNI measuring stations in Southern

Portugal, with a good regional coverage. It is expected that the amount of stations will further increase, especially in the southwest of the country to obtain a good geographical coverage [6, 7].

As it was being collected, the data gathered did not yet possess the statistical significance of that corresponding to a long-term series. Possible approaches to address this issue were previously proposed [6]. Today, the data series already covers a larger period, and an update on the study on the correlations used to estimate DNI at locations in which DHI and GHI or only GHI measurements are available, was performed. Such correlations can be applied to extend data series thus improving the statistical significance to be assigned to long-term DNI estimations [6].

This paper starts, **Section 2**, by summarizing the ongoing effort to measure DNI, GHI and DHI in the South of Portugal, with a network of solar radiation measurement stations in several locations scattered in this region, thus providing good geographical coverage [1, 6, 7].

Section 3 presents the development of correlations to estimate monthly mean values of daily DNI based on DHI and GHI or GHI measurements. The usage of well-known global DHI-GHI correlations instead of DHI measurements was assessed and resulting DNI estimations were compared with measurements. The application of these correlations adapted to include the removal of the latitude effect was also addressed in order to obtain DNI values from long term GHI data series. **Section 4** presents the main conclusions.

2. Measuring network and solar radiation data

The current geographical distribution of radiometric stations with DNI measurements in the South of Portugal provides a good coverage of this region, including also other relevant meteorological variables, thus allowing a reliable and meaningful geographical interpolation. The geographical coordinates and elevation of each station are described in Table 1 and mapped in Figure 1 [1].

Table 1 - Location of the radiometric stations and data period analyzed [1].

Station	Lat. (° N)	Long. (° W)	Elev. (m)	Data Period
Évora 1 (PECS)	38.530550	8.011210	222	01/2015 to 06/2019
Évora 2 (Verney)	38.567686	7.911720	276	04/2015 to 06/2019
Évora 3 (EMSP)	38.528890	8.005292	231	NA
Évora 4 (EDPI)	38.541738	7.963164	228	NA
Portalegre	39.269220	7.442770	342	04/2015 to 06/2019
Beja	38.024885	7.867249	252	09/2017 to 06/2019
Lisboa	38.773435	9.177901	111	01/2015 to 06/2019
Sines	37.957556	8.847338	99	05/2015 to 06/2019
Moura	38.132870	7.453640	207	NA
Oporto	41.179348	8.594278	159	NA
Martim Longo 1 (Capwatt)	37.441017	7.749052	282	01/2015 to 06/2019
Martim Longo 2 (Enercoutim)	37.443141	7.740906	283	NA
Olhão	37,032911	7,854635	6	NA

In Table 1, stations whose data period is identified as "NA" were not analyzed due to lack of a minimum acceptable period of measurements or for being redundant with another station close by, having a lower data quality or shorter period of data in comparison with that nearby station [1].

The measuring stations consist, typically, of a Kipp&Zonen Solys2 sun tracker equipped with a CHP1 pyrheliometer measuring direct normal irradiance and two CMP 11 pyranometers measuring global horizontal and diffuse horizontal irradiance, and with a shading assembly to block the direct beam from the sun and circumsolar irradiance in the case of the diffuse pyranometer [8]. The data acquisition system and the recording rate of average values are different in some stations, ranging from 1 to 15 minutes as some stations are meant for research purposes and others for solar plants operation and control. Each station was also installed and started measuring on different dates, therefore the measuring period for each location varies from one to the other.

A cleaning protocol of the sensors is followed, which consists in the alignment checking, cleaning the domes and desiccant checking at least once a week. This procedure is essential for data quality, which is assessed by comparing measured global horizontal irradiance with the that determined from the direct normal and diffuse horizontal irradiance measurements, following the reference data quality criteria to verify the cleaning status and operation or calibration issues [1, 6, 7, 9].

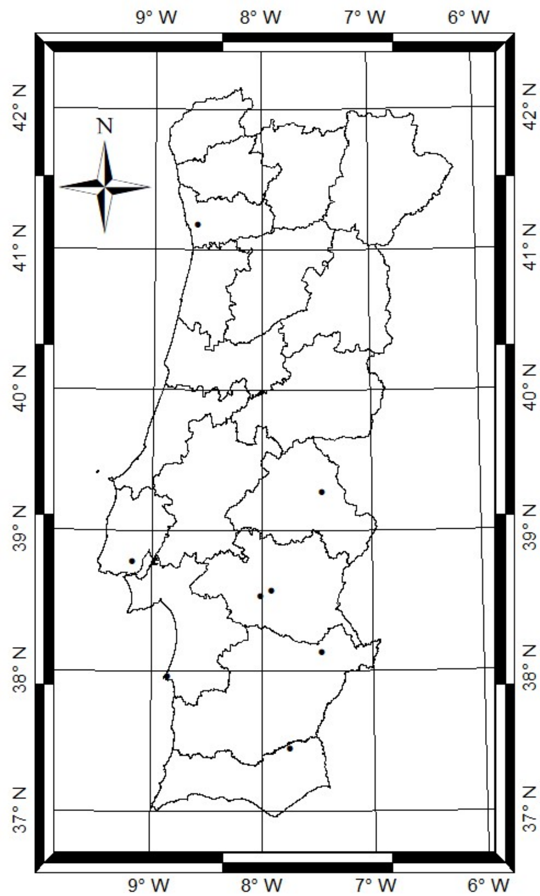

Figure 1 - Geographical distribution of the DNI network measuring stations [1].

3. Estimation of long-term DNI availability based on monthly mean values of daily GHI and DHI

In the following section, the monthly mean values of daily solar irradiation are determined based on data from the network stations (Section 2) for the DNI, DHI and GHI components, correlations are then developed in order to estimate the DNI in other locations in the same region where only the long-term GHI is known.

With the objective of providing DNI values for locations for which only monthly mean GHI or GHI and DHI are available, experimental data were used to establish correlations between DNI and GHI together with DHI and with GHI only. Then, it is further proposed that if a good correlation exists between these data, that it should also hold in respect to long-term data series of GHI and/or DHI obtained in the past, thus allowing for an immediate and statistically significant long-term DNI estimation.

3.1. Experimental data processing

The DNI, DHI and GHI measurements were analyzed for quality issues [1], and a final reliable solar radiation assessment was proposed for the period shown in Table 1. Resulting annual mean values are shown in Table 2, while Table 3 presents the monthly mean values of daily irradiation [1].

Table 2 - Mean yearly solar energy availability (kWh/m^2/year), per solar radiation component [1].

Station	DNI (kWh/m^2/year)	DHI (kWh/m^2/year)	GHI (kWh/m^2/year)
Évora 1	2040	541	1761
Évora 2	2116	540	1793
Portalegre	2056	526	1770
Beja	2077	543	1791
Lisboa	1945	516	1723
Sines	2080	565	1824
Martin Longo 1	2105	NA	1846

Table 3 – Monthly mean values of daily irradiation (kWh/m^2/day)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
						DNI (kWh/m^2/day)						
Évora 1	3.89	4.25	5.10	4.79	6.24	7.40	8.83	7.93	6.90	4.44	3.93	3.25
Évora 2	3.88	4.33	5.42	5.23	6.61	7.78	8.83	7.98	7.01	4.65	4.19	3.54
Portalegre	3.94	4.24	5.04	5.00	6.18	7.43	8.55	7.68	6.82	4.80	4.20	3.60
Beja	4.10	5.23	5.28	4.92	6.43	6.67	8.15	7.28	7.16	5.33	3.83	3.97
Lisboa	3.44	3.76	5.13	4.90	6.68	6.66	7.70	7.62	6.97	4.33	3.79	2.84
Sines	3.94	4.28	5.37	5.59	6.55	7.36	8.47	7.38	6.87	4.57	4.39	3.54
Martim Longo 1	4.19	4.15	5.12	4.93	6.76	7.84	9.09	7.49	6.77	4.46	4.49	3.77
						DHI (kWh/m^2/day)						
Évora 1	0.84	1.25	1.57	2.28	2.11	2.14	1.54	1.60	1.44	1.28	0.89	0.84
Évora 2	0.89	1.30	1.57	2.21	2.11	2.06	1.55	1.60	1.40	1.30	0.91	0.86
Portalegre	0.76	1.21	1.53	2.12	2.27	2.02	1.52	1.62	1.41	1.21	0.86	0.77
Beja	0.86	1.18	1.54	2.17	1.99	2.30	1.68	1.78	1.35	1.20	1.02	0.84
Lisboa	0.85	1.23	1.46	2.15	1.84	2.09	1.66	1.36	1.31	1.27	0.89	0.85
Sines	0.94	1.32	1.57	2.15	2.33	2.11	1.69	1.78	1.44	1.38	0.93	0.94
Martim Longo 1						Not Measured						
						GHI (kWh/m^2/day)						
Évora 1	2.38	3.28	4.49	5.45	6.40	7.30	7.72	6.91	5.59	3.61	2.57	2.08
Évora 2	2.42	3.37	4.66	5.60	6.63	7.43	7.71	6.88	5.61	3.70	2.67	2.17
Portalegre	2.25	3.18	4.36	5.41	6.60	7.46	7.79	7.01	5.67	3.70	2.58	2.08
Beja	2.46	3.65	4.61	5.46	6.53	7.05	7.52	6.95	5.79	3.96	2.62	2.31
Lisboa	2.25	3.11	4.49	5.47	6.64	6.94	7.31	6.72	5.58	3.57	2.51	1.94
Sines	2.50	3.37	4.72	5.89	7.00	7.47	7.71	6.78	5.66	3.76	2.76	2.25
Martim Longo 1	2.62	3.43	4.72	5.59	6.84	7.70	8.02	6.95	5.71	3.79	2.87	2.35

a. Correlation between measured monthly mean values of daily irradiation

The starting point of this analysis is the closure relation between direct normal ($\mathrm{I_{b,n}}$), diffuse horizontal ($\mathrm{I_d}$) and global horizontal ($\mathrm{I_h}$) irradiance, given by Eq. 1.

$$\mathrm{I_h} = \mathrm{I_{b,n}} \cos\theta + \mathrm{I_d} \qquad (1)$$

were θ is the solar zenith angle. This relation holds for instantaneous values of irradiance provided that the aperture angle of the pyrheliometer measuring direct normal irradiance and the respective penumbra function are similar to that of the diffusometer (shading sphere or disk) that prevents the direct beam and circumsolar components from reaching the sensing element of the pyranometer measuring the diffuse horizontal component. Some limits for the deviation from this relation are reported in the guidelines of the Baseline Solar Radiation Network for data quality check [1, 9]. The partition of the global horizontal irradiance between direct and diffuse components depends on the atmospheric conditions, namely the total water column, aerosol concentration and type and cloud coverage. However, when trying to establish this partition for global horizontal irradiation (integrated values), as for example monthly mean values of daily irradiation, two main issues arise: i) which mean value of $\cos\theta$ should be used; ii) how the integrated values of DNI correlate with the GHI and DHI and with GHI only (important in locations in which only GHI measurements are available). In the following, the goodness of these correlations is addressed as well as the impact of using or not a mean $\cos\theta$ based on the monthly mean values of daily solar irradiation. The objective is to obtain a simple correlation between irradiation values without the need for a more elaborated calculation of the one based on the instantaneous values of irradiance and solar zenith angle.

i. Simple correlations between irradiation values based only on raw data measurements

Firstly, two correlations based on monthly mean values of measured daily solar irradiation were tested. One correlation is between DNI ($\overline{\mathrm{H}}_{\mathrm{b,n}}$), GHI ($\overline{\mathrm{H}}_{\mathrm{h}}$) and DHI ($\overline{\mathrm{H}}_{\mathrm{d}}$) [5], and a linear relation in the form of Eq. (2) was fitted to the data. Table 4 presents the fitting parameters and the determination coefficient between $\overline{\mathrm{H}}_{\mathrm{b,n}}$ and $\overline{\mathrm{H}}_{\mathrm{h}} - \overline{\mathrm{H}}_{\mathrm{d}}$ for all the stations analyzed.

$$\overline{\mathrm{H}}_{\mathrm{b,n}} = (\overline{\mathrm{H}}_{\mathrm{h}} - \overline{\mathrm{H}}_{\mathrm{d}}) \times \mathrm{m} + \mathrm{b} \qquad (2)$$

The other relation tested is between $\overline{\mathrm{H}}_{\mathrm{b,n}}$ and only $\overline{\mathrm{H}}_{\mathrm{h}}$ and a correlation in the form of Eq. (3) was also fitted to the data, with the respective fitting parameters and determination coefficients being presented in Table 4 for all stations.

$$\overline{\mathrm{H}}_{\mathrm{b,n}} = \overline{\mathrm{H}}_{\mathrm{h}} \times \mathrm{m} + \mathrm{b} \qquad (3)$$

Table 4 – Fitting parameters and determination coefficients for each station according to the relation of Eq. (2) and Eq. (3) between monthly mean values of daily solar irradiation.

Station	Eq. (2)	R^2	Eq. (3)	R^2
Évora 1	1.090x+1.96	0.98	0.852x+1.48	0.89
Évora 2	1.070x+2.13	0.98	0.849x+1.62	0.91
Portalegre	0.956x+2.37	0.98	0.748x+2.00	0.90
Beja	0.922x+2.55	0.95	0.691x+2.31	0.85
Lisboa	1.040x+1.90	0.97	0.831x+1.40	0.91
Sines	0.978x+2.33	0.98	0.757x+1.91	0.91
Martim Longo 1	NA	NA	0.817x+1.63	0.89
All	1.010x+2.19	0.97	0.795x+1.75	0.89

Overall, there is a fairly good correlation for all locations in the case of Equation 2, with R-Squared values equal or higher than 0.95. Given the very similar fitting parameters shown in Table 4, it is proposed to use only one fit to represent the whole region. For that purpose, the measured data from all stations were used altogether to fit the relation of Eq. (2) as shown in Fig. 2, with the fitting parameters and determination coefficient being given also in Table 4. The same procedure was done for the case of the second correlation between DNI and GHI as shown in Fig. 3 and Table 4. However, and as expected, slightly worse correlations were obtained in the second case, with a determination coefficient of only 0.89 when all stations were used to fit the relation of Eq. (3). The higher degree of dispersion of points in this graph shows that, even when using monthly mean values of daily global horizontal irradiation, the effect of partition between direct normal and diffuse components of the global irradiation still is important and impacts on the correlation quality. Other factor that decreases the goodness of these correlations, which is common to both the correlations tested, is the fact that solar zenith angle was not accounted for on this fitting.

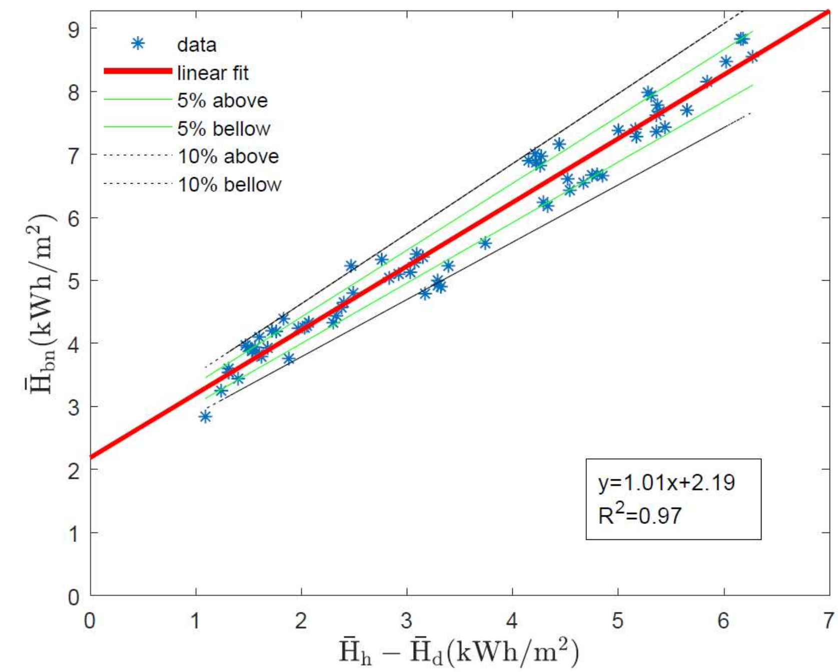

Figure 2 - Correlation between monthly mean values of daily irradiation of DNI and the difference between GHI and DHI for all stations.

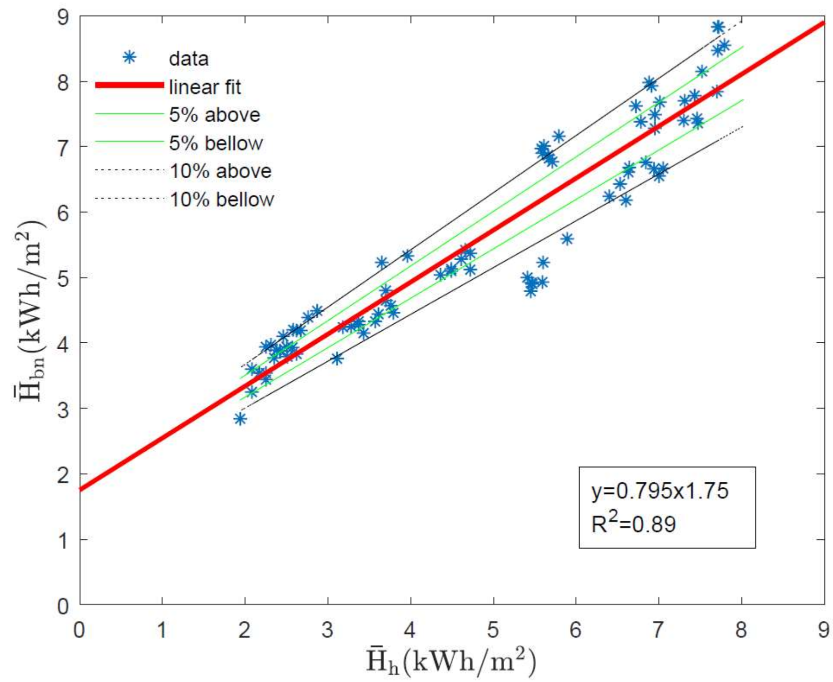

Figure 3 - Correlation between monthly mean values of daily irradiation of DNI and the GHI for all stations.

Nevertheless, Eq. (2) already expresses the DNI availability in the region with a high degree of confidence. This result shows that the DNI varies almost proportionally with the horizontal DNI projection, in spite of the obtained offset which is due to the normal incidence of the solar beam radiation in relation to the obtained projected values. Table 5 compares the results obtained with the correlation shown in Figs. 2 and 3 with the values from Table 2.

Table 5 - Comparison between estimated DNI based on Eq. (2) and (3) and measured DNI annual availability (kWh/m²/year).

	Évora 1	Évora 2	Portalegre	Beja	Lisboa	Sines	Martim Longo 1
DNI measurement	2040	2116	2056	2077	1945	2080	2105
DNI estimation, Eq. (2)	2031	2065	2056	2061	2018	2071	NA
Relative Difference (%)	0.43	2.42	0.02	0.75	3.77	0.45	NA
DNI estimation, Eq. (3)	2038	2064	2046	2065	2008	2089	2106
Relative Difference (%)	0.08	2.45	0.49	0.57	3.25	0.43	0.07

As can be seen, the relative differences between measured and estimated values through the correlation of Eq. (2) are, overall, rather small. The Lisboa station has a higher relative difference and that should be associated with the fact that this station is located within a city and its DNI availability will, most likely, be higher if there were no horizon obstructions. The correlation shown in Fig. 2 is highly reliable to estimate mean annual DNI availabilities in the region of Alentejo. On the other hand, the DNI annual availability estimated through Eq. (3) also presents higher differences in comparison with the experimental values, which can be explained by the lack of information on the diffuse component, but also due to the lack of information of the mean cosine of the solar zenith angle as in the previous case.

ii. Effect of latitude on the correlations of monthly mean values of daily irradiation

The correlations shown in Figs. 2 and 3 are affected by the different location of the stations (local latitude) since the solar zenith angle was not included in the comparison. If this correlation is to be generalized and applied to other locations, that dependence must be removed. To address this aspect, a mean cosine of the solar zenith angle is proposed and another correlation is tested, now for the horizontal DNI projection given by the product of monthly mean values of daily DNI multiplied by a monthly mean cosine of the solar zenith angle ($\overline{\cos}\,\theta$). Eq. (4) describes that relation:

$$\overline{\mathrm{H}}_{\mathrm{b,n}} \times \overline{\cos}\,\theta = (\overline{\mathrm{H}}_{\mathrm{h}} - \overline{\mathrm{H}}_{\mathrm{d}}) \times \mathrm{m} + \mathrm{b} \tag{4}$$

Here, $\overline{\cos}\,\theta$ is the monthly mean cosine of the solar zenith angle, which is determined by averaging $\cos\theta_{i,j} \leq 90$ for the days $j = 1, \ldots, N_i$ of the month i with N_i days. This averaging period corresponds to the integration period of the monthly mean values of daily irradiation used in Eq. (4). The solar zenith angle was determined through the Solar Position Algorithm of the NREL and the monthly mean values for selected latitudes and the mean sea level altitude are presented in tabular form in Appendix A [9]. The effect of using different altitudes (e.g. between 0 to 2000 m above the m.s.l.) is negligible in this case. This table allows to easily determine the monthly mean cosine of solar zenith angle as a function of latitude through interpolation, thus without the need for completing (or repeating) a large set of detailed calculations with the SPA algorithm. This procedure was used to generate the values of $\overline{\cos}\,\theta$ for the stations analyzed in this study, as shown in Table 6.

The data for all the stations and the linear fit of Eq. (4) are plotted in Fig. 4, in which the intercept is now closer to zero, as expected, since the DNI is projected in the horizontal plane through the used monthly mean cosine of the solar zenith angle. Still, the small offset in the intercept is due to the different response times of the pyrheliometer and pyranometers and, mainly, due to the integrated effect of the reflections in the cloud that affect both the GHI and DHI but not the DNI readings.

The resulting slope slightly differs from 1 because a mean cosine of the solar zenith angle is used, while the effect of $\cos\theta$ is present in every single reading of GHI for unobstructed sun conditions. Nevertheless, it was decided to proceed with this analysis based on the monthly mean values aiming to found a simple relation for long-term DNI prediction and to explore its potential application to other locations with historical measured data.

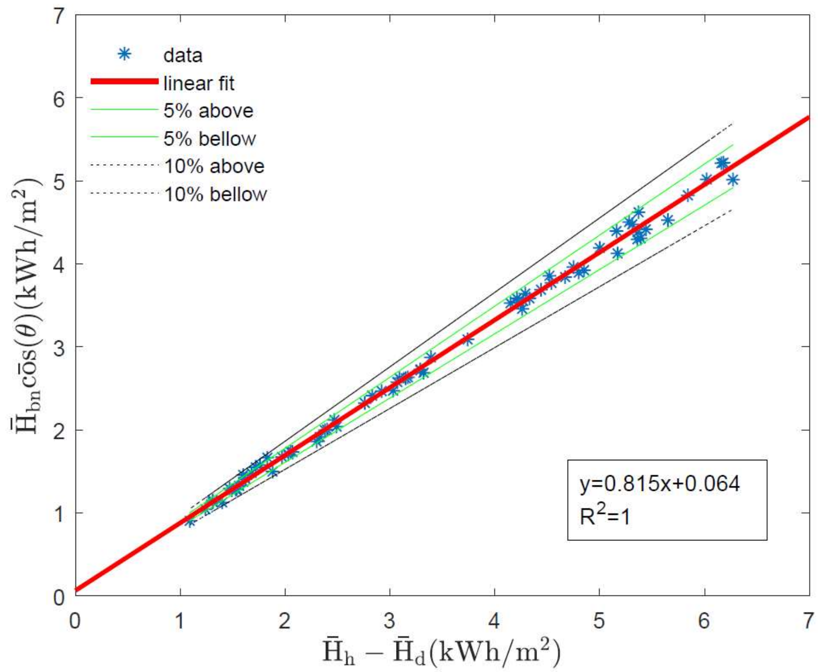

Figure 4 - Correlation between the product of monthly mean values of daily DNI and monthly mean cosine of solar zenith angle and the difference between monthly mean values of daily GHI and DHI.

Table 6 – Monthly mean cosine of the solar zenith angle for the stations analyzed in this work.

	ÉVORA 1	**ÉVORA 2**	**PORTALEGRE**	**BEJA**	**LISBOA**	**SINES**	**MARTIM LONGO 1**
JAN	0,331	0,330	0,323	0,335	0,327	0,336	0,341
FEB	0,401	0,401	0,395	0,405	0,398	0,406	0,410
MAR	0,484	0,484	0,478	0,488	0,482	0,488	0,491
APR	0,550	0,549	0,545	0,552	0,548	0,553	0,555
MAY	0,583	0,583	0,580	0,586	0,583	0,586	0,589
JUN	0,594	0,594	0,594	0,594	0,589	0,595	0,594
JUL	0,591	0,590	0,586	0,592	0,588	0,592	0,594
AUG	0,564	0,564	0,561	0,567	0,564	0,568	0,569
SEP	0,511	0,511	0,507	0,515	0,509	0,514	0,518
OCT	0,431	0,431	0,425	0,436	0,429	0,436	0,440
NOV	0,377	0,376	0,368	0,380	0,371	0,379	0,386
DEC	0,321	0,321	0,314	0,326	0,318	0,326	0,331

The DNI annual availabilities obtained with Eq. (4) were again compared with the values from Table 2, as shown in Table 7.

Similarly, the relation between measured DNI and GHI is also analyzed using a relation in form of Eq. (5), in which the monthly mean cosine of the solar zenith angle is included to account for the location effect, with the $\overline{\cos}\,\theta$ values obtained from Table 5.

$$\overline{\mathrm{H}}_{\mathrm{b,n}} \times \overline{\cos}\,\theta = \overline{\mathrm{H}}_{\mathrm{h}} \times \mathrm{m} + \mathrm{b} \tag{5}$$

The data from all stations and the linear fit of Eq. (5) are shown in Fig. 5.

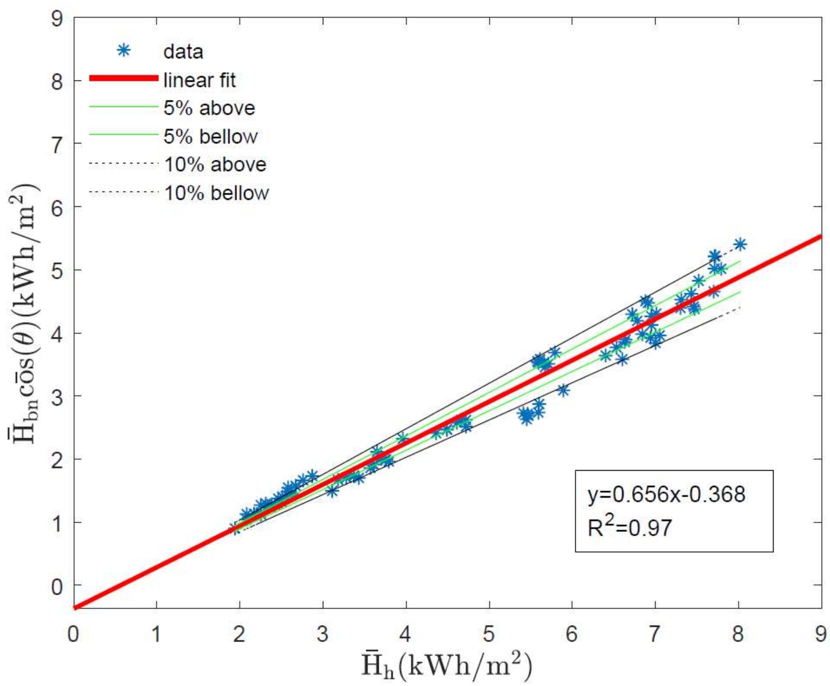

Figure 5 - Correlation between the product of the monthly mean values of daily DNI with the monthly mean cosine of the solar zenith angle and the monthly mean values of daily GHI.

This comparison shows that Eq. (5) expresses with a sufficient degree of confidence the DNI availability in the region as a function of GHI measurements. This correlation estimations were also compared with the measured annual DNI availabilities from Table 2, as shown in Table 7.

Table 7 - Comparison between estimated DNI based on Eq. (4) and measured DNI annual availability (kWh/m^2/year).

	Évora 1	Évora 2	Portalegre	Beja	Lisboa	Sines	Martim Longo 1
DNI measurements	2040	2116	2056	2077	1945	2080	2105
DNI estimation, Eq. (4)	2020	2075	2078	2074	2000	2071	NA
Relative Difference (%)	0.98	1.92	1.08	0.15	2.85	0.44	NA
DNI estimation, Eq. (5)	2018	2065	2045	2063	1973	2092	2111
Relative Difference (%)	1.11	2.43	0.55	0.66	1.46	0.55	0.28

The relative difference between measured and estimated values (Eq. (4)) are rather small, as expected. The differences obtained in Table 7 vary from the ones found in Table 5 since the estimated values are affected with the use of the monthly mean cosine of the solar zenith angle.

When comparing the data points and linear fits of Figs. 4 and 5, a higher dispersion is observed in the second case, as expected. The correlation shown in Fig. 4 minimizes the impact of DHI uncertainty by subtracting it from the GHI measurements, while the second correlation shown in Fig. 5 only uses GHI.

There are periods of the year in which this effect is more evident and coincide with higher presence of scattered clouds in the sky that increases the diffuse component of solar radiation, as shown in Fig. 5. Typically, in this region, April and May are associated to a higher cloud fraction, during which higher DHI availabilities are measured which impact on DNI estimations. In Fig. 6, the difference between measured and estimated monthly mean values of daily DNI from Eq. (5) is compared with the monthly mean values of daily DHI, showing that when DHI increases the DNI estimation error also increases. This shows that its advantageous using a way of estimating the monthly mean values of DHI when only GHI measurements are available.

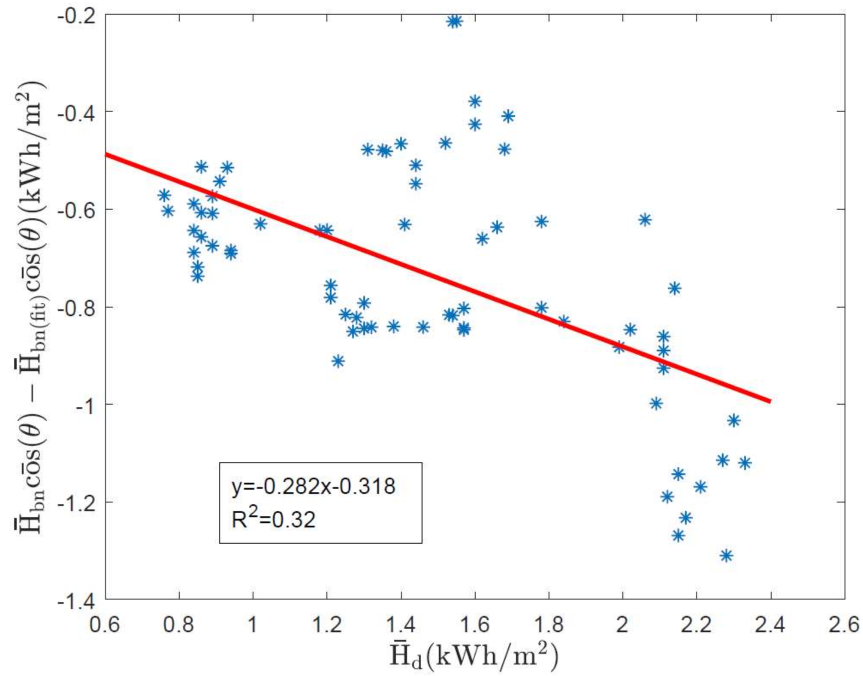

Figure 6 - Correlation between the error of DNI estimation and the monthly mean values of daily DHI.

iii. Prediction of long-term DNI based on GHI measurements and DHI estimations

Other possibility to estimate DNI in locations wherein only GHI is measured is to estimate DHI from well-established correlations between GHI and DHI. For this purpose, DHI was estimated here using the Collares-Pereira & Rabl method, globally applicable [10]. However, if specific methods developed to estimate DHI for the location in study exist, these should yield a better result and, thus should be preferred. The Collares-Pereira & Rabl method used to obtain estimated DHI has the following form:

Daily extraterrestrial irradiation, H0, is determined [10]:

$$H_0 = \frac{T}{\pi} I_{o,n} \left[1 + 0.033 \cos\left(\frac{2\pi n}{365.25}\right)\right] \cos\lambda \cos\delta \left(\sin\omega_s - \omega_s \cos\omega_s\right) \quad (6)$$

with T= length of day in seconds; $I_{o,n}$=1366W/m2 = solar constant; n= Julian day; λ=geographic latitude; ω_s=$\arccos[-\tan\lambda\tan\delta]$ = sunset hour angle and $\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right]$ [10].

1. Daily clearness Index is given by [10]:

$$K_h = \frac{H_h}{H_0} \tag{7}$$

2. Daily DHI estimation is given by (H_d) [10]:

$$H_d = \begin{cases} 0.99 \text{ for } K_h \leq 0.17 \\ H_h\left[1.188 - 2.272K_h + 9.473{K_h}^2 - 21.856{K_h}^3 + 14.648{K_h}^4\right] \text{ for } 0.17 < K_h < 0.8 \end{cases} \tag{8}$$

The estimated monthly mean values of DHI are shown in Table 8 for the stations analyzed in this study.

Table 8 – Monthly mean values of daily DHI estimated by Collares-Pereira & Rabl correlation, $\overline{H}_{d\ estimated}$ (kWh/m²/day).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Évora 1	1.26	1.55	1.99	2.60	2.77	2.61	2.19	2.00	1.73	1.68	1.26	1.17
Évora 2	1.21	1.49	1.92	2.51	2.69	2.53	2.19	2.01	1.72	1.63	1.21	1.12
Portalegre	1.20	1.52	1.98	2.58	2.69	2.52	2.16	1.94	1.65	1.61	1.20	1.07
Beja	1.19	1.36	1.95	2.52	2.64	2.75	2.31	2.01	1.64	1.48	1.29	1.06
Lisboa	1.27	1.56	1.97	2.57	2.67	2.85	2.43	2.12	1.73	1.67	1.28	1.18
Sines	1.23	1.54	1.90	2.33	2.49	2.52	2.21	2.09	1.74	1.65	1.26	1.12
Martim Longo 1	1.24	1.58	1.96	2.55	2.58	2.36	2.05	2.01	1.73	1.63	1.26	1.14

With these estimated values of daily DHI, the relation of DNI with the difference between GHI and estimated DHI was tested, according to Eq. (9), where again the latitude effect was removed as explained in Section 3.2.2:

$$\overline{H}_{b,n} \times \overline{\cos}\,\theta = (\overline{H}_h - \overline{H}_{d\ estimated}) \times m + b \tag{9}$$

The data from all stations was compared according to Eq. (9) to verify how well measurements correlate along the studied region, as shown in Fig. 7.

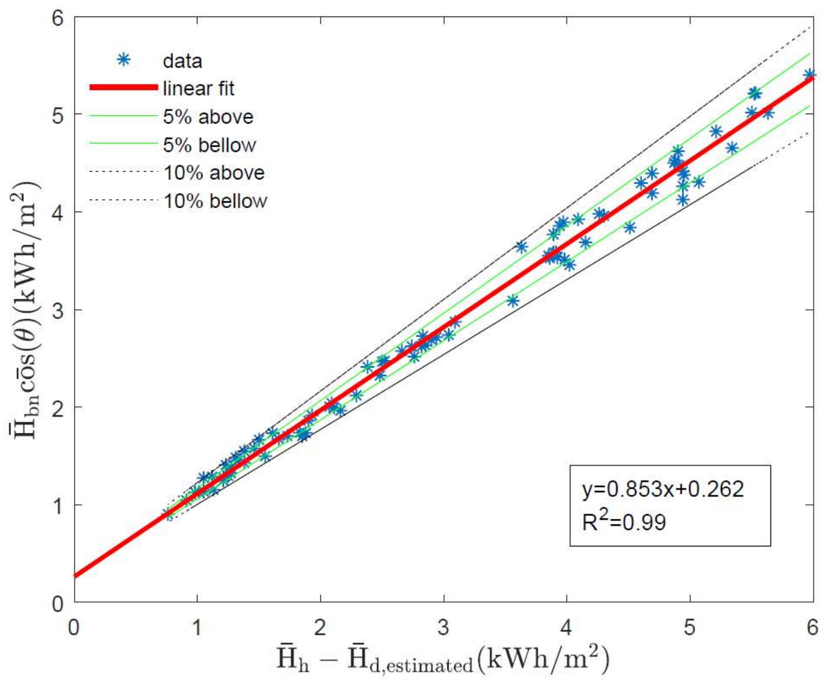

Figure 7 - Correlation between the product of the monthly mean values of daily DNI with the monthly mean cosine of the solar zenith angle and the difference between monthly mean values of measured daily GHI and estimated DHI.

A very high correlation was obtained, with an R-Squared value of 0.99. The annual DNI availability estimated with this correlation were compared with the values from Table 2 as shown in Table 9. For higher x-axis differences there is some dispersion around the fit line, which is associated with the use of DHI estimated values, as those are estimated with basis on daily totals of GHI.

Table 9 - Comparison between estimated DNI based on Eq. (9) and measured DNI annual availability (kWh/m^2/year)

	Évora 1	Évora 2	Portalegre	Beja	Lisboa	Sines	Martim Longo 1
DNI measurements	2040	2116	2056	2077	1945	2080	2105
DNI estimation, Eq. (9)	1992	2086	2061	2095	1908	2129	2156
Relative Difference (%)	2.38	1.43	0.26	-0.87	1.89	2.37	2.40

4 Conclusions

This work addresses the efforts made in the study of correlations to estimate long-term DNI with basis in GHI and DHI and only GHI measurements. It uses data from a solar radiation network with DNI measurements in the south of Portugal, with focus on the Alentejo region.

When studying correlations to predict DNI with basis on raw data measurements, coefficients of determination higher or equal to 0.95 were obtained when estimating DNI with basis on GHI and DHI and higher or equal to 0.85 only with GHI data.

If only raw data is used, the obtained correlations to estimate DNI are affected by a local latitude dependence as the solar zenithal angle is not included. However, that dependence can be addressed if such correlations are developed to estimate horizontal projected DNI, the product of DNI with the cosine of the zenithal angle, instead of DNI. The obtained correlations rendered a coefficient of determination of 1.00 when comparing horizontal projected DNI with the difference of GHI with DHI and a coefficient of determination of 0.97 if only compared with GHI. When comparing only against GHI there are data dispersion due to associated DHI uncertainty, as expected, leading to a lower coefficient of determination.

Another proposal is made with the use of a known methodology to estimate DHI with basis only on GHI measurements, being the correlation to estimate horizontal projected DNI with basis on the difference of GHI with estimated DHI, rendering a coefficient of determination of 0.99.

Such kind of correlations can be applied over long-term GHI and DHI or only GHI measurements to estimate statically significant long-term DNI for locations where DNI measurements do not exist. It is assumed that those correlations should hold in respect to long-term data series of GHI and DHI obtained in the past, thus allowing a more reliable long-term DNI estimation around the globe.

Appendix 1 presents a table of monthly mean daily average values of the cosine of the zenithal angle, in latitude intervals of 10°. The purpose of this appendix is to provide the tools to estimate DNI at different locations around the globe, seeking use and further study of the proposed correlations.

Acknowledgments

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References

1. Afonso Cavaco, Paulo Canhoto, Manuel Collares Pereira, Procedures for solar radiation data gathering and processing and their application to DNI assessment in Southern Portugal, submitted to Renewable Energy.

2. Pierre Ineichen, Long Term Satellite Global, Beam and Diffuse Irradiance Validation, Energy Procedia, Volume 48, 2014, Pages 1586-1596, ISSN 1876-6102. DOI: 10.1016/j.egypro.2014.02.179

3. SOLARGIS. (n.d.). Retrieved November 18, 2019 from http://solargis.com/support/accuracy-and-comparisons/overview/

4. Stoffel, T., et al. "Concentrating Solar Power: Best Practices Handbook for the Collection and Use of Solar Resource Data (CSP)", 2010.

5. Vignola, F., et al., "Building a bankable solar radiation dataset". Solar Energy 86 (8), 2012, 2218–2229.

6. A. Cavaco, P. Canhoto, M. J. Costa, M. Collares-Pereira, "DNI Measurements in the South of Portugal: Long Term Results through Direct Comparison with Global and Diffuse Radiation

Measurements and Existing Time Series", AIP Conference Proceedings 1734, 150001 (2016); doi: 10.1063/1.4949233.

7. A. Cavaco, H. G. Silva, P. Canhoto, T. Osório, M. Collares-Pereira, "Progresses in DNI Measurements in Southern Portugal", AIP Conference Proceedings 2033, 190004 (2018); doi: 10.1063/1.5067189.

8. Kipp & Zonnen. (n.d.). Retrieved November 18, 2019 from http://www.kippzonnen.com/

9. McArthur L.J.B., Baseline Surface Radiation Network (BSRN), Operations Manual, (2005)

10. Collares Pereira, M. & Rabl, A. (1979), The average distribution of solar radiation correlations between diffuse and hemispherical and between daily and hourly insolation values, Solar Energy Vol. 22, pp. 155-164

Appendix A

Table 10 - Monthly mean daily average values of the cosine of the zenithal angle, per latitude.

$\overline{\cos}\,\theta$ – MONTHLY MEAN DAILY VALUES

	-60°	-50°	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°
JAN	0.455	0.529	0.581	0.612	0.630	0.623	0.594	0.547	0.483	0.404	0.316	0.215	0.108
FEB	0.414	0.493	0.554	0.599	0.624	0.635	0.609	0.586	0.536	0.470	0.388	0.296	0.194
MAR	0.331	0.419	0.495	0.556	0.601	0.627	0.636	0.621	0.589	0.539	0.473	0.394	0.303
APR	0.222	0.322	0.411	0.487	0.550	0.598	0.618	0.633	0.619	0.589	0.541	0.476	0.396
MAY	0.127	0.233	0.332	0.422	0.496	0.556	0.602	0.622	0.626	0.613	0.577	0.523	0.449
JUN	0.080	0.188	0.294	0.384	0.471	0.533	0.577	0.609	0.627	0.617	0.590	0.538	0.463
JUL	0.103	0.210	0.311	0.402	0.482	0.547	0.595	0.622	0.629	0.614	0.583	0.531	0.457
AUG	0.185	0.287	0.381	0.463	0.528	0.584	0.616	0.630	0.621	0.601	0.557	0.497	0.419
SEP	0.292	0.384	0.466	0.533	0.585	0.621	0.632	0.628	0.607	0.560	0.502	0.427	0.340
OCT	0.388	0.470	0.536	0.585	0.618	0.633	0.619	0.602	0.555	0.494	0.419	0.331	0.233
NOV	0.431	0.509	0.567	0.610	0.633	0.631	0.601	0.570	0.519	0.449	0.362	0.264	0.160
DEZ	0.459	0.534	0.584	0.614	0.625	0.615	0.586	0.540	0.476	0.398	0.306	0.205	0.098

4.4. Long-term estimation of Direct normal irradiation in Portugal

A correlation to estimate DNI based on GHI measurements and DHI estimated values is presented in Section 4.3, with the linear fit equation being given by:

$$\overline{\mathrm{H}}_{\mathrm{b,n}} \times \overline{\cos}\,\theta = (\overline{\mathrm{H}}_{\mathrm{h}} - \overline{\mathrm{H}}_{\mathrm{d\ estimated}}) \times 0.853 + 0.262 \qquad (1)$$

The obtained linear equation fit has a very good R-Squared value, 0.99, and therefore it rises the interesting possibility to estimate DNI on locations where only GHI measurements are available, since DHI can be estimated using well known estimation methods, such as the Collares Pereira & Rabl [1].

Given the existence of a large amount of GHI data from the IPMA network in Portugal, it becomes possible to estimate DNI availability using GHI data only. With that in mind, hourly GHI measurements between 2001 to 2018 from IPMA network were processed according the following steps [2]:

1. Check data against the physically possible limits, as defined in BSRN Global Network recommended Quality Control tests [14];
2. Fill data gaps gaps up to 2 hours per day through linear interpolation;
3. Determination of daily GHI availability;
4. Fill daily gaps through linear interpolation, up to 5 days per month;
5. Determination of GHI availability for each calendar day and determination of clearness index, K_h, to estimate daily DHI, as described Section 4.3.;
6. Determination of monthly-mean values of daily GHI ($\overline{\mathrm{H}}_{\mathrm{h}}$), estimated DHI ($\overline{\mathrm{H}}_{\mathrm{d,estimated}}$) estimation of DNI ($\overline{\mathrm{H}}_{\mathrm{b,n}}$), as described in Section 4.3.

Table 3 - Comparison of DNI Network measured DNI with IPMA network estimated DNI.

		Sines	Beja	Évora	Lisboa	Portalegre
DNI Network	GHI (kWh/m^2/year)	1824	1791	1793	1723	1770
	DNI (kWh/m^2/year)	2080	2077	2116	1945	2056
IPMA Network	GHI (kWh/m^2/year)	1864	1903	1837	1774	1736
	$DNI_{estimated}$ (kWh/m^2/year)	2214	2321	2157	2042	1929

Table 1 presents the measured DNI in the solar radiation network and the estimated DNI obtained through the application of the global correlation given by Equation 1, based on the GHI measurements from IPMA's network. There are significant differences, as expected given the different time periods of each data series. The DNI network has rigorous maintenance and data control quality, while for the IPMA's network the same degree of confidence cannot be assured. The larger difference found was in Beja, with a relative difference of 10.5%.

Figure 9 presents a map that represents the application of the referred procedure to estimate DNI, given by Equation 1. The map results from the use of geographical interpolation over the obtained estimated DNI values for each location of IPMA's network.

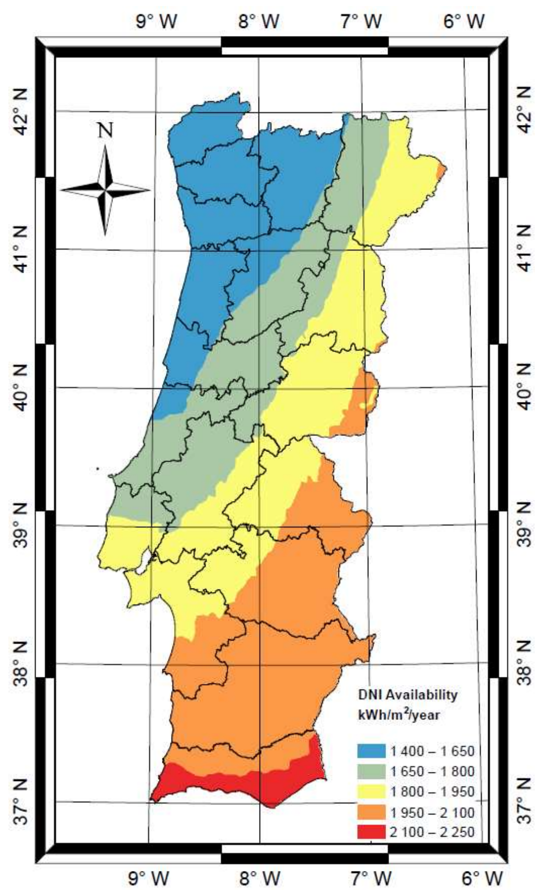

Figure 9 - Estimated DNI obtained from the GHI values of IPMA network.

Even though some doubts exist about GHI data quality, the approximations made when correlating DNI with GHI, and the significative relative differences when comparing DNI values (Table 3), this particular application can be used as indicative of DNI availability for the identification of proper locations for the implementation of CSP power plants, being followed by a period of ground-based measurements for further preliminary assessment.

On the other hand, when using GIS methodologies over the estimated data the value for each location is determined recurring to neighboring locations. The result of this process, shown on Figure 9, indicates that the DNI availability in the region of Alentejo does no differ much from the ones obtained with the measurements of the solar radiation network, ranging from 2000 to 2120 kWh/m^2/year as shown in Figure 3 of Section 4.2..

References

1. Collares Pereira, M. & Rabl, A. (1979), The average distribution of solar radiation correlations between diffuse and hemispherical and between daily and hourly insolation values, Solar Energy Vol. 22, pp. 155-164
2. Cavaco, A., Canhoto, P., Collares-Pereira, M., “Determination of methodologies to predict DNI with basis on DHI and/or GHI measurements with application to Southern Portugal”, submitted to Renewable Energy (February 2020)

CHAPTER 5. Conclusions

The operationalization of the solar radiation network is in fact the foundation of this thesis and is of high importance for several other thesis and research lines developed in the University of Évora, either in the Renewable Energies Chair and the ICT – Institute of Earth Sciences.

To keep a solar radiation network of this kind running is by itself a real challenge, as many hours are required for periodic checks, maintenance operations, calibration activities and troubleshooting to keep it running under the best possible conditions. This kind of work would not be possible without a network of partners and colleagues committed to this purpose.

This chapter summarizes the main results and conclusions obtained in the course of this thesis, more extensive conclusions are presented in the chapters in which published or submitted publications were incorporated.

This thesis proposed to start the DNI assessment in the south of Portugal, a strategic decision at many levels, particularly in the region of Alentejo. It was thought that such kind of infrastructure and the knowledge obtained would be highly relevant for approved CSP and CPV licenses and other future solar concentration technologies. However, the development of new solar concentration power plants was slowed down to a level of nearly no new projects were being developed in Europe. Nevertheless, any kind of solar radiation assessment needs many years of continuous measurements in order to reach statistical significance, typically at least 10 years of measurements are necessary. A solar radiation data series with a shorter timespan will serve as indicative, since it is highly susceptible to years with more or less solar radiation availability.

Meanwhile, an analysis of GHI availability in Portugal was performed over a dense network of GHI measuring locations. It allowed to assess GHI mean annual availability and included an important new factor, the interannual relative variability, providing an indication of how the solar resource varies, on average, around its mean value. This metric is highly important as it indicates how stable the solar resource is in a given location.

Chapter 4 summarizes the answers to the main objectives that this thesis had proposed to address. Section 4.1. addresses a first approach to correlate DNI with the difference of GHI with DHI and obtained a correlation, converted from MJ/m^2 to kWh/m^2, of $y=1.07x+1.96$, with only seven months of data in PECS/Mitra - Évora 1 station. On the other hand, in Section 4.3., the correlation shown in Table 4 for that same location shows the correlation for Évora 1 station is y=1.09x+1.96, using 4.5 years of data. This similarity of slope and offset indicates a trend in the behavior of the DNI with the difference of GHI with DHI, giving indication that this relation should hold in the future. On the other hand, Section 4.3. addresses the possibility of two methods to correlate DNI with GHI and DHI and with only GHI to be globally applicable. Those correlations are independent of local latitude, being the one that uses only GHI the most important since it is the solar resource component most commonly measured across the world. Correlate DNI with only GHI introduces some degree of uncertainty given by the presence of DHI in the GHI values. If one removes it either by subtracting DHI from GHI or estimated DHI with basis on GHI and then subtracts it from GHI, the uncertainty caused by the variation of DHI is reduced in this comparison. There are globally applicable methods to estimate DHI, as the one used, as there are methods developed for certain locations which can also be used with this correlation.

This thesis had as one its most important objectives the assessment of DNI availability in the Alentejo, and for that purpose a thorough methodology to process and validate solar radiation data is proposed on the manuscript included in the Section 4.2. This section addresses several issues typically found when dealing with such kind of data, presents and discusses ways of solving them in order to assess solar radiation. A further step was given in Section 4.4, with the application of a correlation to estimate DNI based on GHI measurements and estimated DHI values over the IPMA's network, thus allowing to obtain a map with the estimative of the mean annual DNI availability in the entire Portuguese mainland. The values shown in this map for the region of Alentejo do not differ significantly from the map resulting from the measurements, ranging from 2000 to 2120 kWh/m^2/year. This kind of application is a way of estimating DNI mean annual values using statistically significant data series and, in this way, allowing a more significant estimation of DNI.

The author expects that the work developed under the scope of this thesis will contribute for the development of the solar concentration industry in Portugal, specially CSP. For now, the solar market is greatly dominated by PV as it is cheap, simple to install, operate and maintain. However, the phase out of the coal power plants in Portugal opens the opportunity for CSP due its capacity to store energy during the day and dispatch it during the night, offering flexibility to the grid management, when PV is not able to dispatch energy, due to expensive or unfeasible energy storage systems, and there is high electricity demand. Dispatchable energy is going to be necessary and that is a role that can be partially fulfilled by CSP plants.

CHAPTER 6. Future work

During the course of this thesis many ideas came up as interesting lines to further investigate and work, which had to be left on hold either for lack of time or lack of resources. At the beginning this thesis set a line of work and proposed its main objectives to address, which are now discussed in this document. However, this work is only a progress and not a final and conclusive outcome.

The solar radiation network will still need many years for its data to be considered statistically significant, since there are stations with only 2 years of data. On the other hand, there is a clear intention of expanding the network further to the southwest area of the country, to provide a better geographical coverage. As it is now, the southwest of Alentejo lacks coverage and that causes the geographic models to extrapolate data once the location under analysis is outside the area of the polygon formed by the stations. Thus, one of the main priorities for the near future is to get funding for expanding and continuing the operation of network and, with it, increase the period of data series.

For that purpose, at the date of submission of this thesis, a new project is being drawn to be submitted to an open funding call from FCT. This new project proposal seeks to materialize and develop some of the ideas that occurred during the development of this thesis. Some of the ideas that are being proposed are:

- Acquisition of a new sun tracker to be installed in the southwest of Portugal, ideally in the region o Vila do Bispo, given the contacts already made and the established pre-agreement for that same purpose;
- Acquisition of Sun Sensors to be installed in some of the stations of the University of Évora. Évora 1 and Évora 3 stations already have Sun Sensors, so the objective is to install it in Beja, Sines, Évora 2 and the new station to be installed in the southwest. These sensors improve the sun tracking accuracy, thus contributing for high quality data;
- Continue the solar radiation assessment in Alentejo, with focus on DNI for CSP applications. With this activity, the study and improvement of correlations to estimate DNI based on GHI and DHI is to be continued;
- Acquire a UV sensor to be installed at Évora 1 station aiming to measure and model ultraviolet radiation (UV) based on GHI and other relevant variables [1]. This acquisition will also provide important measurements for the progress of research lines from the Renewable Energies Chair,

contributing for the increase of knowledge and capacity in the development of solar photocatalysis for water treatment by degrading contaminants present in the water with UV;

- Start the research and development of competences on nowcasting models recurring to all sky images to track cloud motion, crossing this information with other variables as the wind speed to predict cloud motion. This kind of knowledge and competence is important for the operation of CSP solar fields, it provides the necessary information for the power plant operators to know if a cloud is going to partially or totally shade the solar field and is necessary to turn on auxiliary heat tracing systems or drain the circuit so that the HTF – Heat Transfer Fluid does not cool down and solidifies in the case of molten salt mixtures are being directly used, damaging many components. As the commissioning of the EMSP project is coming to an end, this kind of competence is of high relevance for the Renewable Energies Chair;

Other objective is to establish cooperation with Spanish institutions that have stations measuring DNI near the Portuguese-Spanish border, to expand the area of measurements beyond Portugal. This would allow to expand the DNI assessment, possibility to test the correlations developed to predict DNI based on GHI and DHI measurements and create an important synergy with Spanish researchers to further investigate this topic and others that may come up.

References

1. Habte, M. Sengupta, C. A. Gueymard, R. Narasappa, O. Rosseler and D. M. Burns, "Estimating Ultraviolet Radiation from Global Horizontal Irradiance," in IEEE Journal of Photovoltaics, vol. 9, no. 1, pp. 139-146, Jan. 2019. doi: 10.1109/JPHOTOV.2018.2871780