26th International Congress of Mechanical Engineering
COBEM 2021
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-1208
COMPARATIVE ANALYSIS OF DESIGN POINT DIRECT NORMAL IRRADIANCE SPECIFICATION METHODS

João Humberto Serafim Martins [a]
Lauro Augusto Jerônimo de Oliveira [b]
Edson Bazzo [b]
Júlio César Passos [a]
[a] Laboratory of Energy Conversion Engineering and Energy Technology (LEPTEN), Department of Mechanical Engineering, Federal University of Santa Catarina (UFSC), Eng. Agronômico Andrei Cristian Ferreira, 88040-900, Florianópolis, SC, Brazil.
joao.martins@lepten.ufsc.br, julio.passos@lepten.ufsc.br

[b] Laboratory of Combustion and Thermal Systems Enginering (LabCET), Department of Mechanical Engineering, Federal University of Santa Catarina (UFSC), Eng. Agronômico Andrei Cristian Ferreira, 88040-900, Florianópolis, SC, Brazil.
lauro.ajo@labcet.ufsc.br, e.bazzo@ufsc.br

Abstract. *This study presents a comparison of the main approaches used for obtaining the design point direct normal irradiance (DNI), a fundamental input for the design and simulation of concentrated solar power (CSP) plants, aiming to assess its impacts on the facility's technical and economic performance. The software System Advisor Model (SAM) is used for parametric analysis and estimation of the levelized cost of energy (LCOE) and the capacity factor (CF) under different design point DNIs. The first method appraised defines the design DNI as the solar irradiance at noon of the summer solstice, the second at noon of the spring equinox, and the third at noon of the autumn equinox. In addition to these conventional methods, the average value of the daily maximum irradiances and a methodology based on the frequency distribution of the TMY were considered as selection methods. The analysis was carried out for plants with a rated electric output of 125 MW_e and 7 hours TES capacity at different locations with CSP projects in operation or under development worldwide. In general, it was found that the solstice and equinox-based methods result in considerable variability in the design DNI for both tropical and temperate zones, which led to a higher dispersion for the resultant LCOEs and CFs, and also made some simulations unfeasible. In contrast, the TMY-based methods resulted in a smaller spread. Despite that, the calculated LCOEs were not very sensitive to method change, with a slight advantage for the last methodology. At the same time, it brought a stronger influence to the CF, which was higher for the methodologies based on the whole TMY because of the higher optimized SMs for such locations. This study's importance lies in comparing these methods to fill a gap in the literature, which can guide their choice for future CSP simulations.*

Keywords: *Design point direct normal irradiance, Parabolic trough collector, Concentrated solar power, System Advisor Model*

1. INTRODUCTION

The need to generate electricity for the ever-growing energy consumption while shifting the energy matrix to a more diverse and sustainable generation is one of humanity's vital global challenges. Solar thermal power generation, also known as concentrated solar power (CSP), is a renewable energy technology that collects the heat of concentrated and absorbed solar radiation. It can generate electricity at a base-load through the association of a thermal energy storage (TES) and/or hybridization with biomass or natural gas. Also, through these associations, solar thermal power plants can have high generation flexibility decoupling generation from the solar resource availability. Solar thermal power plants may use one of the commercially available CSP concentration technologies such as parabolic trough concentrators (PTC), linear Fresnel concentrators (LFC), and solar power tower (SPT), also called central receiver. The PTC stands out as the most mature technology and is widely used on existing CSP plants worldwide (Fuqiang *et al.*, 2017).

The implementation of new CSP projects requires assessing the project's technical and economic viability. For such evaluation, it is necessary to simulate the plants as precisely as possible. Before this, a critical step is the design and sizing of the plant's solar field. Proper sizing of the solar field is essential because it represents the most significant cost involved in such a enterprises, accounting for 40% to 50% of the total investment (IEA, 2014). Consequently, it directly affects the plant's output and its electricity revenue.

Optimum solar field sizing requires choosing appropriate values for three relevant parameters: the design point direct normal irradiance (DNI), the solar multiple (SM), and the TES capacity. The SM is the ratio between the thermal power produced by the solar field at the design point DNI and the thermal energy required by the power block at nominal conditions. The TES capacity is the time of continuous nominal generation the storage can provide. Hence, the optimum solar field size is achieved when the plant operates at nominal conditions for the maximum time during the year, while producing electricity at the lowest price possible. Suppose the combination of the relevant parameters is not correctly chosen. In that case, when selecting a low design point DNI, the solar field may be oversized. As a result, it may absorb more thermal energy than it is possible to use or store, needing to dispose of useful energy. When selecting a high design point DNI, the solar field may be undersized, leading to fewer hours of nominal condition operation through the year (Sharma *et al.*, 2016).

In the literature, different approaches are taken to determine the best design point DNI. The most common and simple practice is to select the radiation at the solar noon on a specific date, like the solstices or equinoxes. However, this kind of method does not consider the yearly distribution of the radiation throughout or consider the economic impact this design choice can have. To fill the gap of design DNI selection criteria, Quaschning *et al.* (2002) performed solar field size optimizations for minimum levelized cost of energy (LCOE), and proposed the optimum design radiation for parabolic trough CSP plants should be located in the range of 55% to 60% of the cumulative frequency distribution of the hourly non-null radiation. More recently, Chen *et al.* (2018) analyzed the combined effects of the required solar field sizing parameters in the techno-economic performance of a SPT CSP plant with TES in different regions of China. They tried to determine the relationship between the optimum sizing parameters and the solar resource. As a result, they found the higher the design DNI, the higher the related optimum SM. They also found the optimum TES capacity is directly dependent on the design point DNI and SM employed (low design DNI or high SM results in the increase of the optimal TES capacity). The results obtained placed the optimum design DNI for solar tower solar field in the range of 25% to 28% of the cumulative frequency distribution of the hourly non-null radiation.

Taking into account the design point DNI is a crucial design parameter, since it should represent the yearly solar resource distribution and availability. The present work focuses on the preliminary analyses of different design point DNI specification methods to unravel which one leads, more consistently, to better techno-economical results. The presented research is done for a typical PTC power plant on different sites worldwide, to identify the relationship between the design point DNI, the yearly solar radiation distribution, and the plant's annual performance.

2. DESIGN POINT DNI SPECIFICATION

The design point is the state in which the thermal power generated in the solar field is enough to keep the power block working on full-load conditions and store a fixed surplus of thermal energy for later use. This state is defined by a representative day and hour, the available DNI in this instant, and other weather conditions such as the solar position, the ambient temperature and wind speed. The design point is the base for the specification of the solar field size, TES capacity, the power plant's annual power output, the plant equipment's efficiency etc, and also the relationship among these crucial factors (Wang, 2019).

Defining the design point condition is, therefore, a prerequisite to designing the CSP power plant. Several studies in the literature don't use a specific method to determine the design DNI. They opt without any clear methodology for a round value like 700 W m^{-2} or 950 W m^{-2}. On the other hand, it is also a common practice to take the solar noon of a typical day (such as the spring equinox, autumnal equinox, or summer solstice) and the DNI at this moment, the annual mean ambient air temperature, and the local annual mean wind speed as design point conditions (Wang, 2019). The selection of the design DNI by a typical day has different supporting reasons. For temperate locations (23.27° < |latitude| < 66.56°), the solar noon of the summer solstice is the date with minimum optical losses, given the declination angle is at its maximum. Similarly, at the solar noon of the spring or autumn equinox the optical losses are reduced for tropical locations (|latitude| < 23.27°), especially those closer to the Equator. However, despite being the most widely employed technique, defining the design DNI only by a date and time does not consider the location's weather conditions. Even with ideal the solar alignment, there is a considerable risk the solstice and equinoxes coincide with high cloudiness and precipitation periods. The DNI in such circumstances would be underrated, making it an inadequate yearly representation and leading to poor design results.

To avoid the previously mentioned downsides, other methods take in consideration the DNI distribution during the whole year to select the design irradiance. The first alternative methodology focuses on adopting the mean value of the daily maximum irradiance as design. The reasoning behind this method is that it carries the information of all days in the year and, therefore, using it as design parameter would result in a more reasonable solar field not too oversized or undersized. The second alternative is the use of the DNI on a given fraction of the cumulative frequency distribution as design irradiance. The determination of this percentage is coupled to the specific CSP technology and plant conceptual design. As consequence, this method yields better results when the specific percentage of the cumulative frequency distribution is obtained through the wide optimization of the solar field key design parameters of a given CSP technology. Quaschning *et al.* (2002) obtained such percentage after optimizing a parabolic trough solar field located in Spain, while Chen *et al.* (2018) came to find such percentage after optimizing a SPT heliostat solar field located in China. Other examples from the sited methodologies can be found in Tab. 1.

Table 1. Review of CSP simulation studies. The design point DNI adopted and the method for its specification are presented alongside their scope.

Method/Author(s)	Design point DNI [W m^{-2}]	Study scope
Summer solstice		
Leiva-Illanes *et al.* (2017)	1010	Exergetic cost analysis of solar thermal polygeneration plant
Binotti *et al.* (2017)	967	Analysis of supercritical CO_2 in SPTs
Hou *et al.* (2015)	910	Solar thermal assisted coal-fired plant performance analysis
Montes *et al.* (2009a)	900	Analysis of the performance of a DSG plant as a function of its solar manifold
Montes *et al.* (2009b)	850	Optimization of solar manifold
Marugán-Cruz *et al.* (2019)	850	Performance analysis of PTC plants with and without TES
Hou *et al.* (2011)	818	Performance analysis of biomass power plant with solar thermal assistance
Spring equinox		
Cardemil and Colle (2010)	775	Economic analysis for a PTC facility in Bom Jesus da Lapa, Brazil
Liu *et al.* (2016)	765	Performance analysis of two hybrid solar-biomass plants
Mohammadi *et al.* (2020)	765	Innovative SPT model associated with gas turbines using supercritical CO_2
Autumn equinox		
Palenzuela *et al.* (2011)	850	Evaluation of different configurations of PTC plants and desalination plants for arid regions
Bai *et al.* (2017)	682	Design of hybrid solar biomass plant
Average daily maximum		
Milani *et al.* (2020)	-*	Thecno-economic analisys for the main CSP technologies for Brazilian locations
Velasquez *et al.* (2020)	-*	Competitiviness analysis for PTC plants in Brazil
Optimization		
Desai and Bandyopadhyay (2015)	600	Optimization of PTC-based for a 1 MWe solar thermal power plant
Quaschning *et al.* (2002)	55-60%**	Optimization of PTC solar field input variables using Greenius
Chen *et al.* (2018)	25-28%**	Determination of key parameters for sizing the heliostat field and TES in SPT power plants
Desai *et al.* (2014)	-*	Optimization of design point DNI for PTC and LFR plants without hybridization and storage
Sharma *et al.* (2016)	-*	Analysis of the effect of design parameters on the performance of linear solar concentrators plants in India
Liu *et al.* (2018)	-*	Proposition of a critical design point DNI for PTC plants
El Hamdani *et al.* (2021)	-*	Use of artificial neural networks for optimizing a PTC solar field input variables
Cummulative DNI		
Cardemil and Colle (2010)	850	Economic analysis for a PTC facility in Bom Jesus da Lapa, Brazil
Burin (2015)	-	Design of hybrid solar-biomass plants for the sucroalcoholic sector
Almeida (2018)	-	Optimization of design point DNI for CSP power plants without storage
Non-specified		
Cabello *et al.* (2011)	1000	Optimization of PTC plant solar field with generic algorithms
Casella *et al.* (2014)	1000	Optimization of solar tower plant operation
Mihoub *et al.* (2017)	1000	Parameter optimization for CSP plant in Algeria
Moghimi *et al.* (2017)	1000	Optimization of central tower solar field
Boukelia *et al.* (2015)	950	Investigation of PTC plants with and without storage
Cocco *et al.* (2016)	900	Dispatch improvement of CSP-PV hybrid plant
Bellos *et al.* (2018)	900	Solar Biomass Hybrid polygeneration cycle analysis
Abbas *et al.* (2012)	850	Concentrator design LFR
Khalid *et al.* (2015)	850	Energy and exergetic analysis of hybrid solar biomass polygeneration plant
Pantaleo *et al.* (2020)	850	Techno-economic analysis of hybrid solar biomass plant combined with a Brayton and ORC cycle
Hou *et al.* (2016)	800	Solar thermal assisted coal-fired plant evaluation method
Milani *et al.* (2017)	750	Hybrid gasified biomass solar plant in Brazil
Morais *et al.* (2020)	700	Energy and exergetic analysis of hybrid solar biomass ORC plant
Malagueta *et al.* (2014)	689	Impacts of introducing CSP energy in the Brazilian electric grid
Oyekale *et al.* (2020)	501	Exergetic and exergoeconomic analysis of hybrid solar biomass ORC plant

* Multiple locations addressed.

** Percentage of the DNI frequency distribution.

Besides the use of specification methods, many studies focus on widely optimizing all key design variables at the same time, including the design DNI. Even though it may lead to better design outcomes, this methodology is more complex and highly site and technology dependent. It also requires more time and computational processing power not being practical for more simple analysis. An example of this method is the work of El Hamdani *et al.* (2021). They used an artificial neural network to find the optimum values for the design parameters.

3. CSP PLANTS SIMULATION

Following the explanation of the previous sections, this study aimed on comparing the performance of a typical PTC CSP plant with solar field sized using the following design point DNI definition methods: *a)* DNI at solar noon of the summer solstice; b) DNI at solar noon of the spring equinox; c) DNI at solar noon of the autumn equinox; d) average daily maximum DNI; e) 90% of the cumulative DNI frequency distribution.

The considered CSP plant, presented in Fig. 1, is composed of a PTC solar field, using synthetic oil as heat transfer fluid (HTF), a TES with molten salt as heat storage media and a typical Rankine cycle power block. No auxiliary boiler was considered. According to (NREL, 2021), this is the most mature and widely used configuration with energy storage commercially available. The plant capacity and TES autonomy were specified to represent the most current PTC plants. According to the SolarPACES database (NREL, 2021), there are 21 PTC plants under construction or development stages, with a average net electric output around 125 MW_e and 7 full-load hours of storage capacity. The main plant parameters can be found in Tab. 2.

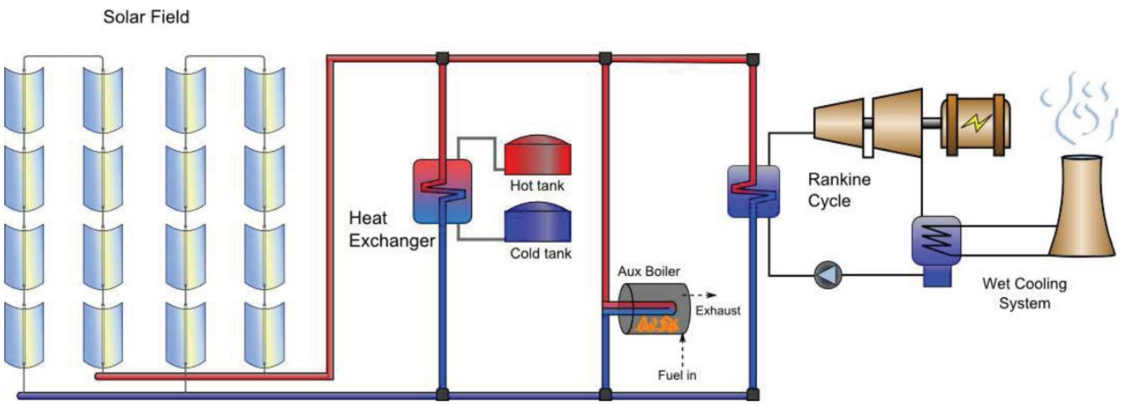

Figure 1. CSP power plant subsystems: solar field, piping, two-tank indirect TES, auxiliary heater, and the power block. Retrieved from Wagner and Gilman (2011).

Table 2. Plant design conditions.

Parameter	Value	Unit
Solar field		
Collector	SkyFuel SkyTrough	-
Receiver tubes	Schott PTR80	-
Heat transfer fluid	Therminol VP-1	-
Loop inlet temperature	295	°C
Loop outlet temperature	395	°C
Thermal energy storage		
Heat storage media	HITEC Solar Salt	-
Configuration	Two-tank indirect	-
Storage capacity	7	h
Power block		
Turbine gross output	138.89	MW_e
Turbine net output	125.00	MW_e
Turbine inlet pressure	100	bar
Cycle thermal efficiency	35.6	%

The modeled plant was simulated for nine strategic locations with solar power generation projects in operation, under development or in the planning stage. The list of the considered locations, their coordinates and the respective solar power generation projects can be found in Tab.3. Furthermore, each location considered can be visualized in the DNI distribution world map of Fig.2.

The simulations were performed using the System Advisor Model (SAM) software, designed by the United States National Renewable Energy Laboratory (NREL, 2020). The models chosen were the "Physical Trough" for performance, and "Power Purchase Agreement - Single Owner" for financing. The typical meteorological year (TMY) of each location was acquired at the free-access and NREL recommended weather data repositories EnergyPlus, Austela, and Climate.OneBuilding. The main meteorological data of each location considered can be found in Tab. 4. All costs and financial parameters followed SAM's default values, as described by Turchi *et al.* (2019).

Table 3. CSP projects at the locations addressed. Based on NREL (2021).

Location		**Coordinates [°]**		**Project**	**Capacity [MW]**	**Status**
AU:	P. Augusta	-32.51	137.71	Aurora Solar Thermal Power	125 (SPT)	Development
BR:	B.J. da Lapa*	-13.27	-43.42	-**	-	-
CH:	Calama*	-22.47	-68.93	Cerro Dominador	110 (SPT) + 100 (PV)	Operational
CN:	Delingha	37.37	97.37	Delingha Thermal Oil Parabolic Trough	125 (SPT)	Operational
EG:	Hurghada	27.18	33.80	Hurghada Solar Power Plant	20 (PV)	Operational
IN:	Anantapur	14.65	77.55	Megha Solar Plant	50 (PTC)	Operational
PT:	Évora	38.54	-7.89	Évora Molten Salt Platform	3.4 (PTC)***	Demostration
SA:	Kathu	-27.67	23.00	Kathu Solar Park	100 (PTC)	Operational
US:	Blythe	33.61	-114.58	Genesis Solar Energy Project	250 (SPT)	Operational

* Bom Jesus da Lapa, Brazil, and Calama, Chile, are the only locations at the tropical zone.

** There are no CSP projects in Bom Jesus da Lapa. However, among the Brazilian sites with high-quality meteorological data, it presents the highest annual direct normal irradiation, available in Tab. 4.

*** The pilot plant in Évora, Portugal, has a capacity of 3.4 MW_{th}.

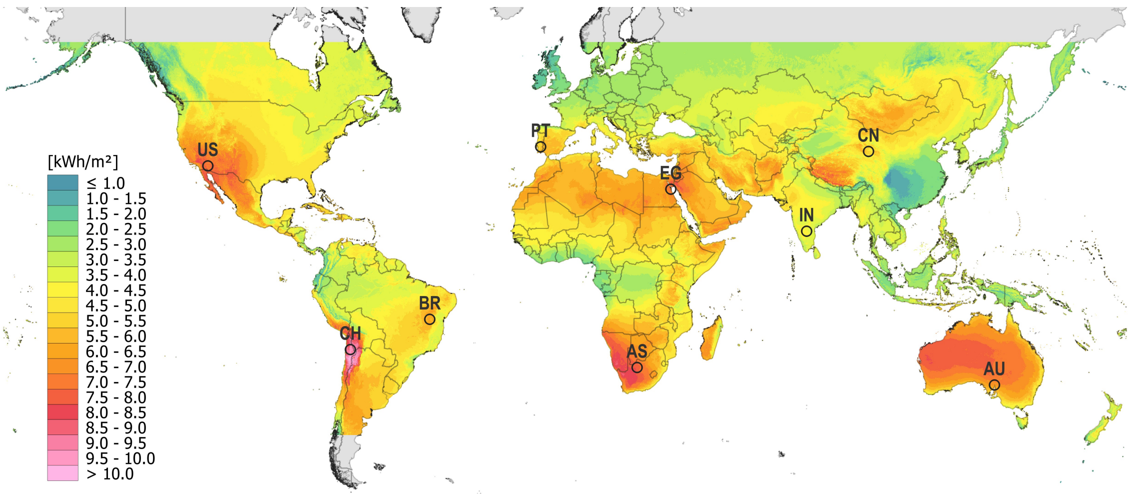

Figure 2. Distribution of the daily direct normal irradiation around the world, with emphasis on the locations addressed. Adapted from ESMAP (2019).

Table 4. Relevant meteorological condition of the locations addressed.

Parameter	**AU**	**BR***	**CH***	**CN**	**EG**	**IN**	**PT**	**SA**	**US**	**Unit**
Ann. dir. norm. irradiation	2456	2198	2496	1907	2509	1832	1811	2401	2893	$kWh\ m^{-2}$
Ann. dif. horiz. irradiation	-*	672	699	693	582	835	611	650	453	$kWh\ m^{-2}$
Average ambient temperature	19.6	26.1	13.6	4.8	25.3	26.5	16.2	11.1	24.1	°C
Average wind speed	5.3	1.6	7.3	2.1	6.1	2.8	3.5	3.1	2.3	$m\ s^{-1}$

* Not available at the TMY.

Such models were employed in CSP plants annual simulations, according to the following steps. First, the design point DNIs were obtained for each pair of location and specification method, totaling 45 runs. Then, parametric analysis were performed to identify the SM which results in the lowest LCOE for each combination of location and desing point DNI. The SM is defined as the ratio between the solar field area and the area required to power the power block under nominal conditions. It can also be interpreted as the ratio of the actual thermal power supplied by the solar field ($\dot{Q}_{SF}$) and the power required to operate the power block at nominal load ($\dot{Q}_{PB,ref}$). In Eq. (1), $\dot{E}gross$ is the facility net electric

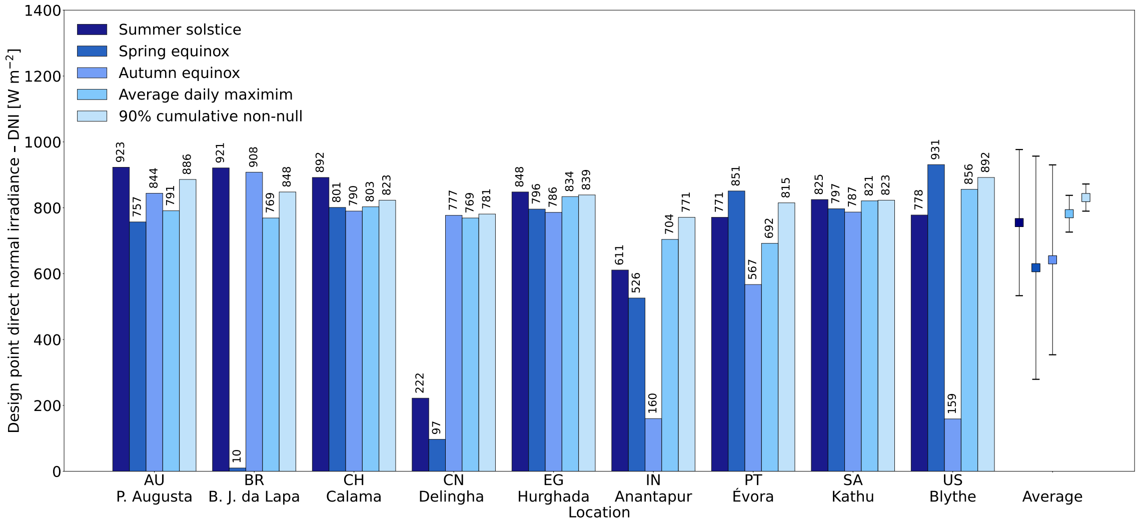

Figure 3. Design point DNI from the different specification methods.

power, η_{th} is the power block thermal efficiency and η_{mec} is the mechanical-to-electric efficiency.

$$SM = \frac{\dot{Q}SF}{\dot{Q}PB,ref} = \frac{\dot{Q}SF}{\left(\frac{\dot{W}gross}{\eta_{th}\eta_{gen}}\right)} \tag{1}$$

This kind of simulation can be performed in the "Parametrics" section of the software and works as multiple simulations for a array of input variable. The parametric simulation was performed with the SM as input and the LCOE and annual electric generation as output. Obtaining the electric generation is a necessary step to determine the plants capacity factor (CF). It represents the ratio between the actual annual eclectic generation ($E_{ann;net}$) and the maximum total electric output for the plant's given capacity (P_{PB}). It is described by Eq. (2).

$$CF = \frac{E_{ann,net}}{8760 P_{PB}} \tag{2}$$

A similar procedure can be found in Marugán-Cruz *et al.* (2019) study, which performed a parametric analysis varying the SM and the TES capacity for an LFR plant with a 50 MW_e DSG and a TES system using two concrete storage modules and a phase change material (PCM) unit located in Seville, Spain. In addition, such methodology is also used by Agyekum and Velkin (2020), who evaluate 100 MW_e SPT and PTC plants in Ghana.

The LCOE, in turn, represents the cost of the electricity revenue required to build and operate a facility over a specified investment recovery period (N). At this point, the net present value (NPV) is zero. It depends on the plant's annual net costs (C_i), the real discount rate (d_r), the nominal discount rate (d_n), and the yearly net electric output (E_i).

$$LCOE = \frac{\sum_{i=0}^{N} \frac{C_i}{(1+d_n)^i}}{\sum_{i=1}^{i} \frac{E_i}{(1+d_r)^i}} \tag{3}$$

4. RESULTS AND DISCUSSION

The following are the main results obtained using the methodology presented in section 3.

From the results presented in Figs. 4 to 6, it is possible to notice the absence of some values for the solstice and the equinox-based methodologies: the summer solstice for Delingha, the spring equinox for Bom Jesus da Lapa and Delinhga, and the autumn equinox for Anantapur and Blythe. This happens due to the low irradiance recorded at these locations during these periods, insufficient to allow SAM simulations or obtain coherent results, which reinforces the alternatives based on the entire time series, and not only on a specific time and date of the year.

There are two sites located in the tropical zone and nine in the temperate zone. The smaller number of locations in the first zone reflects the smaller amount of land situated between the tropics of Cancer and Capricorn. Analyzing the sites according to this classification, also presented in Tab. 4, it becomes apparent the equinox-based methods are not effective in all cases, even though they provide the plant sizing under lower optical losses, resulting in inconsistent data for Bom Jesus da Lapa during the spring equinox. Similarly, for sites in the temperate zone, the summer solstice-based method does not allow simulations for Delingha.

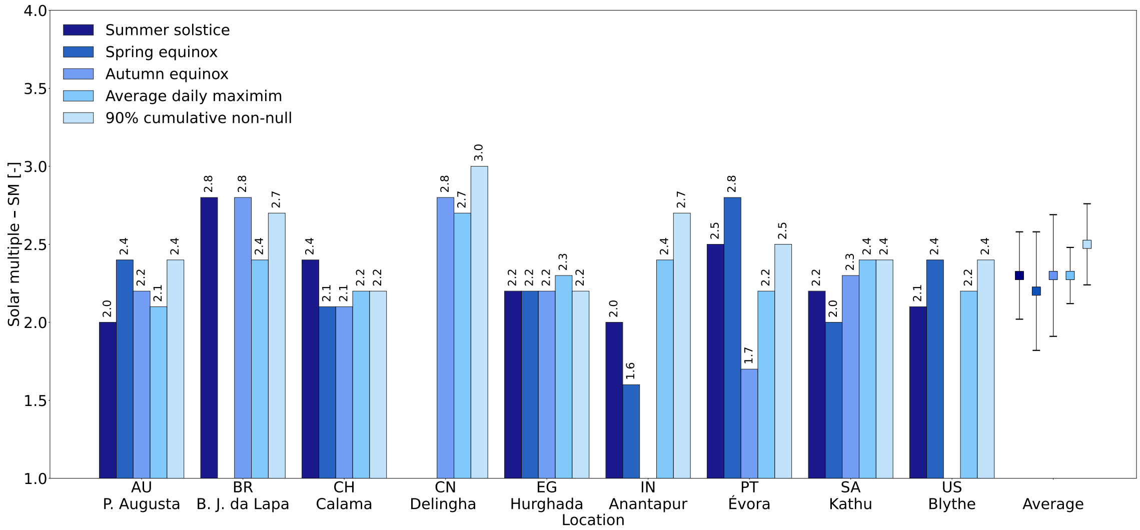

Figure 4. SM results. The rightmost values represent the mean SMs obtained for each method, as well as their standard deviation.

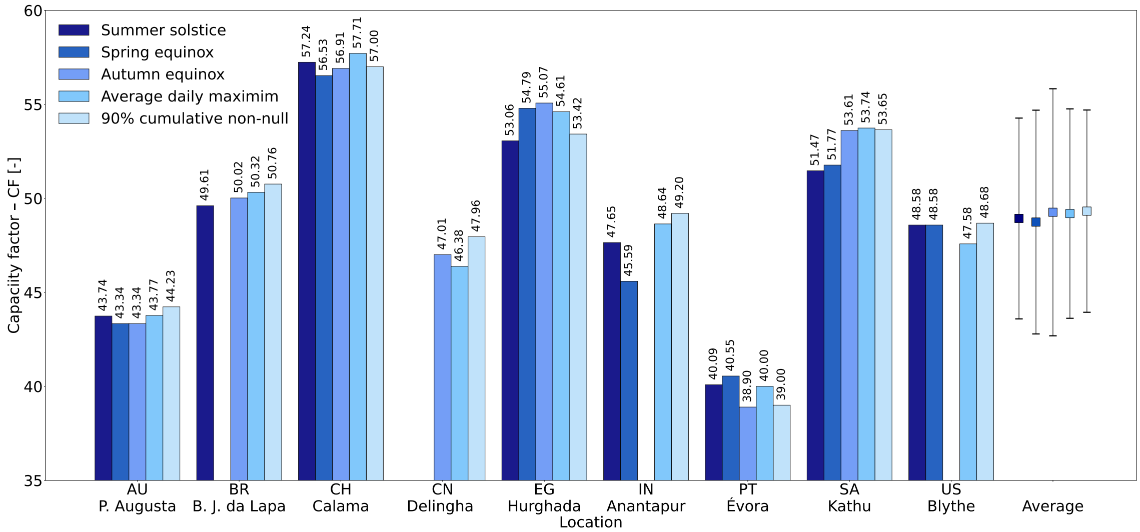

Figure 5. CF results. The rightmost values represent the mean CFs obtained for each method, as well as their standard deviation.

On the other hand, when estimating the design DNI with the TMY-based methods, it is possible to obtain coherent values for all locations, regardless it geographical position, with less dispersion and dependence on the weather conditions of a specific day, as presented in Fig. 3.When comparing these two methods, it can be seen the DNI cumulative distribution tends to underestimate the irradiance, which results, however, in similar averages of LCOE and CF.

In Fig. 5 are presented the CF obtained for the nine sites, and also the average value and its dispersion achieved by each method. This average cannot be used to directly compare the methods based on one date and those based on the entire TMY, since with the former it was not possible to simulate all locations.

Similarly, Figure 6 contains the LCOE for each site. In contrast to what was observed for the CF, the LCOE was not greatly affected by the change of the design point DNI specification method. Furthermore, it is also possible to verify an inverse relationship between the SM and the LCOE, since the highest SMs result in the lowest LCOES, and vice versa.

5. CONCLUSIONS

In this study, different methodologies for the specification of the design DNI were analysed via parametric simulations of a PTC CSP plant with rated net capacity of 125 MW_e and two-tank indirect TES with 7-hour of capacity. The specification methodologies considered are grouped on those based on a specific date and time and those based on the entire TMY. The proposed analysis was done by comparing the impact of using the different methods on two very important plant indicators: the CF, which indicates the fraction of the plant's annual generation achieved, and LCOE, which indicates the minimum revenue cost of this energy in order to have a return on invested capital.

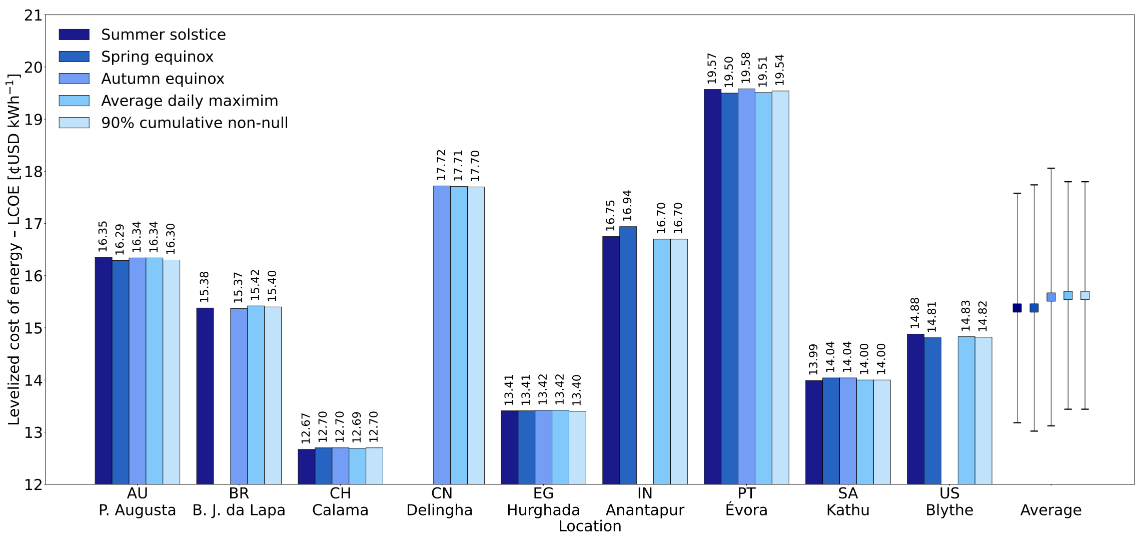

Figure 6. LCOE results. The rightmost values represent the mean LCOEs obtained for each method, as well as their standard deviation.

The findings show the methods based on the equinoxes and solstice can, in fact, result in poor design point DNI, what made simulations unfeasible. As expected, this outcome indicate the impossibility of universal use of the typical day methodologies, requiring caution when applied. On the other hand, those methodologies based on the entire TMY showed consistent results for all investigated sites, with, in general, a lower dispersion of the resulting LCOEs and CFs.

Furthermore, for the methodology that uses the cumulative frequency distribution, the irradiance of 90% was taken as a reference value, based on the literature. Despite the good results, this metric can still be optimized in order to provide the highest power generation and profit, or even to result in lower LCOEs.

6. ACKNOWLEDGMENTS

The authors acknowledge the support of the Coordination for the Improvement of Higher Education Personnel (CAPES), and CNPq, which through UFSC have supported LEPTEN and LabCET research on CSP.

7. REFERENCES

Abbas, R., Montes, M., Piera, M. and Martínez-Val, J., 2012. "Solar radiation concentration features in Linear Fresnel Reflector arrays". *Energy Conversion and Management*, Vol. 54, pp. 133–144. doi:10.1016/j.enconman.2011.10.010.

Agyekum, E.B. and Velkin, V.I., 2020. "Optimization and techno-economic assessment of concentrated solar power (CSP) in South-Western Africa: A case study on Ghana". *Sustainable Energy Technologies and Assessments*, Vol. 40, p. 100763. doi:10.1016/j.seta.2020.100763.

Almeida, T.E.G., 2018. *Energia termossolar como alternativa na geração de vapor e água quente no setor agroindustrial*. Master's thesis, Federal University of Santa Catarina, Florianópolis, Brazil.

Bai, Z., Liu, Q., Lei, J., Wang, X., Sun, J. and Jin, H., 2017. "Thermodynamic evaluation of a novel solar-biomass hybrid power generation system". *Energy Conversion and Management*, Vol. 142, pp. 296–306. doi:10.1016/j.enconman.2017.03.028.

Bellos, E., Vellios, L., Theodosiou, I.C. and Tzivanidis, C., 2018. "Investigation of a solar-biomass polygeneration system". *Energy Conversion and Management*, Vol. 173, pp. 283–295. doi:10.1016/j.enconman.2018.07.093.

Binotti, M., Astolfi, M., Campanari, S., Manzolini, G. and Silva, P., 2017. "Preliminary assessment of sCO2 cycles for power generation in CSP solar tower plants". *Applied Energy*, Vol. 204, pp. 1007–1017. doi:10.1016/j.apenergy.2017.05.121.

Boukelia, T., Mecibah, M., Kumar, B. and Reddy, K., 2015. "Investigation of solar parabolic trough power plants with and without integrated TES (thermal energy storage) and FBS (fuel backup system) using thermic oil and solar salt". *Energy*, Vol. 88, pp. 292–303. doi:10.1016/j.energy.2015.05.038.

Burin, E.L.K., 2015. *Plantas de cogeração do setor sucroalcooleiro assistidas por concentradores parabólicos*. Phd Thesis, Federal University of Santa Catarina, Florianópolis, Brazil.

Cabello, J., Cejudo, J., Luque, M., Ruiz, F., Deb, K. and Tewari, R., 2011. "Optimization of the size of a solar thermal electricity plant by means of genetic algorithms". *Renewable Energy*, Vol. 36, pp. 3146–3153. doi:10.1016/j.renene.2011.03.018.

Cardemil, J.M. and Colle, S., 2010. "A base de dados SWERA como suporte para análises técnico-econômicas de plantas termo-solares". In *Anais CBENS 2010*. ABENS, Belém, p. 10.

Casella, F., Casati, E. and Colonna, P., 2014. "Optimal Operation of Solar Tower Plants with Thermal Storage for System Design". *IFAC Proceedings Volumes*, Vol. 47, pp. 4972–4978. doi:10.3182/20140824-6-ZA-1003.02622.

Chen, R., Rao, Z. and Liao, S., 2018. "Determination of key parameters for sizing the heliostat field and thermal energy storage in solar tower power plants". *Energy Conversion and Management*, Vol. 177, pp. 385–394. doi:10.1016/j.enconman.2018.09.065.

Cocco, D., Migliari, L. and Petrollese, M., 2016. "A hybrid CSP–CPV system for improving the dispatchability of solar power plants". *Energy Conversion and Management*, Vol. 114, pp. 312–323. doi:10.1016/j.enconman.2016.02.015.

Desai, N.B. and Bandyopadhyay, S., 2015. "Optimization of concentrating solar thermal power plant based on parabolic trough collector". *Journal of Cleaner Production*, Vol. 89, pp. 262–271. doi:10.1016/j.jclepro.2014.10.097.

Desai, N.B., Kedare, S.B. and Bandyopadhyay, S., 2014. "Optimization of design radiation for concentrating solar thermal power plants without storage". *Solar Energy*, Vol. 107, pp. 98–112. doi:10.1016/j.solener.2014.05.046.

El Hamdani, F., Vaudreuil, S., Abderafi, S. and Bounahmidi, T., 2021. "Determination of design parameters to minimize LCOE, for a 1 MWe CSP plant in different sites". *Renewable Energy*, Vol. 169, pp. 1013–1025. doi:10.1016/j.renene.2021.01.060.

ESMAP, 2019. "Map and data downloads". `https://globalsolaratlas.info/download/world`. Washington, DC: World Bank.

Fuqiang, W., Ziming, C., Jianyu, T., Yuan, Y., Yong, S. and Linhua, L., 2017. "Progress in concentrated solar power technology with parabolic trough collector system: A comprehensive review". *Renewable and Sustainable Energy Reviews*, Vol. 79, pp. 1314–1328. doi:10.1016/j.rser.2017.05.174.

Hou, H., Wu, J., Yang, Y., Hu, E. and Chen, S., 2015. "Performance of a solar aided power plant in fuel saving mode". *Applied Energy*, Vol. 160, pp. 873–881. doi:10.1016/j.apenergy.2015.01.092.

Hou, H., Xu, Z. and Yang, Y., 2016. "An evaluation method of solar contribution in a solar aided power generation (SAPG) system based on exergy analysis". *Applied Energy*, Vol. 182, pp. 1–8. doi:10.1016/j.apenergy.2016.08.109.

Hou, H., Yang, Y., Hu, E., Song, J., Dong, C. and Mao, J., 2011. "Evaluation of solar aided biomass power generation systems with parabolic trough field". *Science China Technological Sciences*, Vol. 54, pp. 1455–1461. doi:10.1007/s11431-011-4366-4.

IEA, 2014. "Technology Roadmap - Solar Thermal Electricity 2014". Technical report, IEA, Paris. `https://www.iea.org/reports/technology-roadmap-solar-thermal-electricity-2014`.

Khalid, F., Dincer, I. and Rosen, M.A., 2015. "Energy and exergy analyses of a solar-biomass integrated cycle for multigeneration". *Solar Energy*, Vol. 112, pp. 290–299. doi:10.1016/j.solener.2014.11.027.

Leiva-Illanes, R., Escobar, R., Cardemil, J.M. and Alarcón-Padilla, D.C., 2017. "Thermoeconomic assessment of a solar polygeneration plant for electricity, water, cooling and heating in high direct normal irradiation conditions". *Energy Conversion and Management*, Vol. 151, pp. 538–552. doi:10.1016/j.enconman.2017.09.002.

Liu, J., Zeng, Z., Liu, G. and Li, Y., 2018. "Proposition of a critical design direct normal irradiance for solar thermal power plant". *International Journal of Energy Research*, Vol. 42, pp. 4108–4119. doi:10.1002/er.4138.

Liu, Q., Bai, Z., Wang, X., Lei, J. and Jin, H., 2016. "Investigation of thermodynamic performances for two solar-biomass hybrid combined cycle power generation systems". *Energy Conversion and Management*, Vol. 122, pp. 252–262. doi:10.1016/j.enconman.2016.05.080.

Malagueta, D., Szklo, A., Soria, R., Dutra, R., Schaeffer, R. and Moreira Cesar Borba, B.S., 2014. "Potential and impacts of Concentrated Solar Power (CSP) integration in the Brazilian electric power system". *Renewable Energy*, Vol. 68, pp. 223–235. doi:10.1016/j.renene.2014.01.050.

Marugán-Cruz, C., Serrano, D., Gómez-Hernández, J. and Sánchez-Delgado, S., 2019. "Solar multiple optimization of a DSG linear Fresnel power plant". *Energy Conversion and Management*, Vol. 184, pp. 571–580. doi:10.1016/j.enconman.2019.01.054.

Mihoub, S., Chermiti, A. and Beltagy, H., 2017. "Methodology of determining the optimum performances of future concentrating solar thermal power plants in Algeria". *Energy*, Vol. 122, pp. 801–810. doi:10.1016/j.energy.2016.12.056.

Milani, R., Martins, J.H.S., Velasquez, R.M.G., Pozzatti, L.F. and Meyer, B.T., 2020. "Análise de competitividade e penetração de plantas CSP de coletores cilindro-parabólicos no mercado de energia brasileiro". In *Anais CBENS 2020*. ABENS, Fortaleza. `https://anaiscbens.emnuvens.com.br/cbens/article/view/798`.

Milani, R., Szklo, A. and Hoffmann, B.S., 2017. "Hybridization of concentrated solar power with biomass gasification in Brazil's semiarid region". *Energy Conversion and Management*, Vol. 143, pp. 522–537. doi:10.1016/j.enconman.2017.04.015.

Moghimi, M., Craig, K. and Meyer, J., 2017. "Simulation-based optimisation of a linear Fresnel collector mirror field and receiver for optical, thermal and economic performance". *Solar Energy*, Vol. 153, pp. 655–678. doi:10.1016/j.solener.2017.06.001.

Mohammadi, K., Ellingwood, K. and Powell, K., 2020. "Novel hybrid solar tower-gas turbine combined power cycles using supercritical carbon dioxide bottoming cycles". *Applied Thermal Engineering*, Vol. 178, p. 115588.

doi:10.1016/j.applthermaleng.2020.115588.

Montes, M., Abánades, A. and Martínez-Val, J., 2009a. "Performance of a direct steam generation solar thermal power plant for electricity production as a function of the solar multiple". *Solar Energy*, Vol. 83, pp. 679–689. doi:10.1016/j.solener.2008.10.015.

Montes, M., Abánades, A., Martínez-Val, J. and Valdés, M., 2009b. "Solar multiple optimization for a solar-only thermal power plant, using oil as heat transfer fluid in the parabolic trough collectors". *Solar Energy*, Vol. 83, pp. 2165–2176. doi:10.1016/j.solener.2009.08.010.

Morais, P.H.d.S., Lodi, A., Aoki, A.C. and Modesto, M., 2020. "Energy, exergetic and economic analyses of a combined solar-biomass-ORC cooling cogeneration systems for a Brazilian small plant". *Renewable Energy*, Vol. 157, pp. 1131–1147. doi:10.1016/j.renene.2020.04.147.

NREL, 2020. "System Advisor Model Version 2020.11.29". `https://sam.nrel.gov/download.html?own=0`.

NREL, 2021. "Concentrating Solar Power Projects". `https://solarpaces.nrel.gov/`. Número de chamada: 5.

Oyekale, J., Petrollese, M., Heberle, F., Brüggemann, D. and Cau, G., 2020. "Exergetic and integrated exergoeconomic assessments of a hybrid solar-biomass organic Rankine cycle cogeneration plant". *Energy Conversion and Management*, Vol. 215, p. 112905. doi:10.1016/j.enconman.2020.112905.

Palenzuela, P., Zaragoza, G., Alarcón-Padilla, D.C., Guillén, E., Ibarra, M. and Blanco, J., 2011. "Assessment of different configurations for combined parabolic-trough (PT) solar power and desalination plants in arid regions". *Energy*, Vol. 36, pp. 4950–4958. doi:10.1016/j.energy.2011.05.039.

Pantaleo, A.M., Camporeale, S.M., Sorrentino, A., Miliozzi, A., Shah, N. and Markides, C.N., 2020. "Hybrid solar-biomass combined Brayton/organic Rankine-cycle plants integrated with thermal storage: Techno-economic feasibility in selected Mediterranean areas". *Renewable Energy*, Vol. 147, pp. 2913–2931. doi:10.1016/j.renene.2018.08.022.

Quaschning, V., Kistner, R. and Ortmanns, W., 2002. "Influence of Direct Normal Irradiance Variation on the Optimal Parabolic Trough Field Size: A Problem Solved with Technical and Economical Simulations". *Journal of Solar Energy Engineering*, Vol. 124, pp. 160–164. doi:10.1115/1.1465432.

Sharma, C., Sharma, A.K., Mullick, S.C. and Kandpal, T.C., 2016. "A study of the effect of design parameters on the performance of linear solar concentrator based thermal power plants in India". *Renewable Energy*, Vol. 87, pp. 666–675. doi:10.1016/j.renene.2015.11.007.

Turchi, C.S., Boyd, M., Kesseli, D., Kurup, P., Mehos, M.S., Neises, T.W., Sharan, P., Wagner, M.J. and Wendelin, T., 2019. "CSP Systems Analysis - Final Project Report". Technical Report NREL/TP–5500-72856, 1513197, National Renewable Energy Laboratory. doi:10.2172/1513197.

Velasquez, R.M.G., Martins, J.H.S., Milani, R., Pozzatti, L.F. and Meyer, B.T., 2020. "Análise técnico-econômica comparativa das tecnologias de concentração heliotérmica em localidades brasileiras". In *CIES 2020 - Comunicações*. Lisboa. doi:10.34637/CIES2020.1.2032. Publisher: LNEG - Laboratório Nacional de Energia e Geologia.

Wagner, M.J. and Gilman, P., 2011. "Technical Manual for the SAM Physical Trough Model". Technical Report NREL/TP-5500-51825, 1016437. doi:10.2172/1016437.

Wang, Z., 2019. *Design of Solar Thermal Power Plants*. Academic Press. doi:10.1016/B978-0-12-815613-1.00003-1.

8. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.