THE INFLUENCE OF METEOROLOGICAL PARAMETERS ON THE ENERGY YIELD OF SOLAR THERMAL POWER PLANTS

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Abstract

Financing Concentrating Solar Power (CSP) projects is highly dependent on plant performance. Yields of CSP plants depend strongly on site-specific meteorological conditions. Meteorological parameters that can influence the performance of CSP plants are Direct Normal Irradiance (DNI), wind, ambient air temperature, and humidity. The sensitivity study shows that DNI is the parameter with highest influence on energy yield of CSP plants. However, the annual sum or average of DNI is often thought as the value giving already a good indicator for Annual Energy Production (AEP) of CSP plants. This thesis is proven wrong, as the study finds that for years with same DNI annual averages AEP could vary as much as ± 9 % due to differences in DNI frequency distribution. Further the beneficial effect of lower latitudes is not expressed in the long-term average of DNI. For parabolic trough plants it is found that with a 10° increase in latitude, decrease in the ratio of AEP to DNI could be around 10 % for the Northern Hemisphere. Due to less favourable irradiance during winter the effect is even stronger for the Southern Hemisphere and is around 14 % per 10° of latitude, which often is counterbalanced by higher DNI annual averages compared to the Northern hemisphere.
Keywords: Concentrating Solar Power (CSP), solar resource, Direct Normal Irradiance, DNI frequency distribution, plant performance, influence, latitude-effect, ambient meteorological conditions.

1. Introduction

The local meteorological conditions at the site of a solar thermal power or Concentrating Solar Power (CSP) plant have considerable impact on its performance. The meteorological parameter that has the strongest influence on performance of a CSP plant is clearly Direct Normal Irradiance (DNI). Hoyer et. al [1] show that uncertainty of available annual DNI compared to typical uncertainty of technical parameters of a CSP plant is the input parameter that has the strongest influence. But not only the annual average of DNI, but also its frequency distribution and its annual cycle may influence the performance of CSP plants. Due to non-linear response of CSP plants to DNI changes, it is assumed that distribution of DNI values can significantly affect the annual energy yield. It is also assumed that the latitude of a CSP plant has an effect on its output, as angular losses are greater at high latitudes due to lower sun position and also due to reduced duration of available solar radiation during winter.

Also, other meteorological parameters that affect performance of CSP plants include ambient temperature, wind speed and relative humidity conditions at the site. Many studies have been done such as [2] and [3], which determine the influence of cooling technology and the effect of monthly DNI on energy yield of CSP plants respectively. But these studies do not quantify the influence of meteorological parameters on energy yields This paper systematically analyses the influence of various meteorological parameters obtained from 4 different data providers and their time-series characteristics on the annual energy yield.

2. Methodology

The flowchart (Figure 1) explains methodology followed. To achieve the goals mentioned above Parabolic Trough (PT) and Central Receiver (CR) type of CSP technologies are considered. Meteorological data for various test sites from various data sources is used as input to performance simulation software. Reference plant configurations are defined in performance simulation software used and simulations are carried out. The results of simulations (performance metrics) are analysed and the influence of meteorological parameters on energy yield of CSP plants is determined.

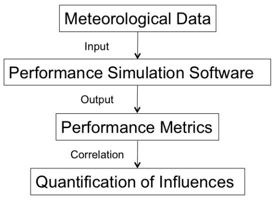

Figure 1: Flow-chart explaining methodology followed to determine the influence of meteorological parameters on the energy yield of CSP plants.

3. Meteorological Input Data

3.1. Test Sites

The decision of selecting test sites is based on various criteria like:

- Availability of high quality data from measurements
- Long temporal coverage of measured data-as many years as possible
- Test sites should have different DNI long-term averages
- Test sites should be on different latitudes
- Test sites should be in different climates

Based on these criteria three main test sites and three additional sites are selected as given in Table 1, which represents the long-term averages of various meteorological parameters at the test sites.

Test site		Plataforma Solar de Almeria	Tamanrasset	De Aar	Sede Boqer	Crucero	Cocos Island
Country		Spain	Algeria	South Africa	Israel	Chile	Keeling
Site Code		ESPSA	DZTAM	ZADAA	ILSBO	CLCRO	COCOS
latitude	[°]	37.09	22.78	-30.67	30.91	-22.28	-12.15
longitude	[°]	-2.36	5.51	23.99	24.8	-69.55	96.83
elevation	[m]	492	1385	1287	500	1176	0
DNI	[W/m²]	243	275	317	271	327	195
	[kWh/m²/a]	2129	2406	2777	2375	2867	1710
GHI	[W/m²]	211	269	235	239	268	234
	[kWh/m²/a]	1846	2537	2062	2090	2349	2048
Ambient temp	[°C]	16.7	21.7	16	19	13.3	26.7
Wind speed	[m/s]	3.5	3.6	5	3.2	5.8	6.3
Rel. Humidity	[%]	57	30	62	89	59	78

Table 1: Overview of meteorological conditions at the selected locations, which include BSRN stations from which high quality measured data is available, that can be used as reference for comparison with satellite data sources.

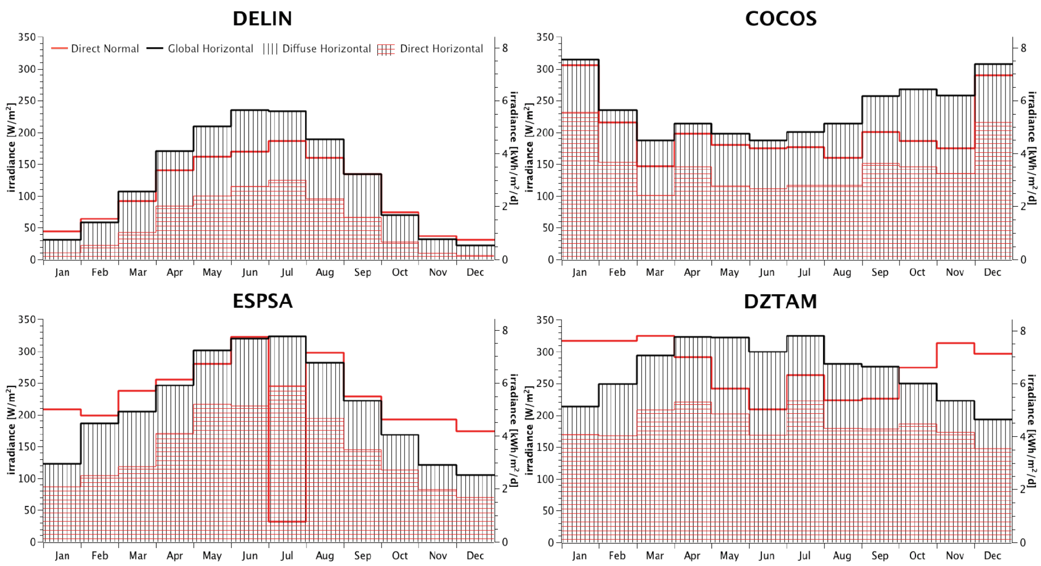

Figure 2: Annual pattern of solar radiation at various test sites.

3.2 DNI data sources

Multiple sources of data for solar radiation are used for analysing the influence of parameters like DNI frequency distribution and latitude effect on energy yield of CSP plants. These data sources for main test sites include ground-based measurements of very high quality and satellite-derived values from various data providers.

Test site	Data source	From-To
ESPSA	BSRN	2002-2009
DZTAM	BSRN	2001-2009
ZADAA	BSRN	2002-2004
ESPSA, DZTAM, ZADAA	DLR-SOLEMI	1991-2005
	EnMetSOL	2005-2008
	GeoModel	2004-2010
	HelioClim-3	2004-2010

Table 2: List of various DNI data sources used with their corresponding temporal coverage.

Table 2 shows data sources used for main test sites and their temporal coverage. Baseline Surface Radiation Network (BSRN) is ground-measured data source while all other data sources are satellite-derived. It should be noted that meteorological parameters like ambient temperature, wind speed, relative humidity, dew-point temperature, pressure, etc. are always obtained from Meteonorm [4] for all the test sites and all the data sources.

3.3. Preparation of Input Files and Characterization of data

Strict quality control procedures are applied to data in order to remove errors. Typical Meteorological Years (TMYs) are created for each data source and each location. TMYs can be created by several procedures. In the context of present work the method of Hoyer et. al [5] is used for creating TMYs, which are created in such a way that for a particular location TMYs from all sources have same DNI annual average. In last step, TMY files are created inTMY3 format used by performance simulation software.

Characterisation of datasets is done with respect to DNI values using statistical parameters like Mean Bias (MB), Root Mean Square Error (RMSE), KSI & OVER [6] (Table 3). MB and RMSE are calculated from parallel periods of data with ground-based data as reference in yearly resolution. KSI & OVER are calculated from the TMYs with ground-based TMY as reference in hourly resolution.

Parameter		Average	RMSE		MB		KSI		OVER	
Test site	Data source	[W/m^2]	[W/m^2]	%	[W/m^2]	%	[W/m^2]	%	[W/m^2]	%
ESPSA	BSRN	243	Reference							
	DLR	269	19	8%	-19	-8%	45	156	38	133
	EnMetSOL	233	12	5%	11	4%	30	104	24	85
	GeoModel	243	7	3%	0	0%	28	98	23	80
	HelioClim-3	268	27	11%	-26	-10%	46	160	43	151
DZTAM	BSRN	275	Reference							
	DLR	263	16	6%	12	4%	31	86	21	58
	EnMetSOL	194	73	27%	73	27%	-	-	-	-
	GeoModel	255	19	7%	18	7%	40	111	36	101
	HelioClim-3	313	47	17%	-46	-17%	-	-	-	-
ZADAA	BSRN	317	Reference							
	DLR	309	11	3%	6	2%	23	82	15	53
	EnMetSOL	300	17	5%	17	5%	29	103	23	82
	GeoModel	315	9	3%	-1	0%	17	60	8	27
	HelioClim-3	300	10	3%	10	3%	33	120	26	95

Table 3: Overview table showing statistical parameters for DNI at main test sites from all data sources.

4. Performance simulation software and reference CSP plant configurations

System Advisor Model (SAM) (version 2010.11.9) [7] is used for simulating performance of CSP plants. SAM typically uses hourly input data. It is based on TRNSYS model, and is widely accepted for pre-feasibility studies. A Parabolic Trough (PT) power plant with 50 MW_e capacity and 7.5 hours of thermal energy storage (similar to Andasol type plants) is used as the reference plant configuration. Similarly, a Central Receiver (CR) power plant with 100 MW_e and 7.5 hours of thermal energy storage is used as the reference plant configuration. The configuration of both power plant types is modelled in SAM (Table 4). PT Empirical model of SAM is used for determining the influence of DNI frequency distribution and latitude effect on the energy yield. SAM PT physical model is used for calculating the effect of ambient temperature, relative humidity and wind speed because in the present SAM version used the empirical model could not consider these effects realistically.

Component	specifications	Unit	Value
Solar Field	solar field area	m^2	510120
	no. of SCAs	-	624
	SCA's per loop	-	4
	no. of loops	-	156
	distance between SCAs in row	m	1
	Row spacing: center to center	m	17.2
Solar Collector Assembly (SCA)	SCA length	m	148.5
	SCA aperture	m	5.77
	SCA aperture area	m^2	817.5
	average focal length	m	2.12
	incidence angle mod coeff 1	-	1
	incidence angle mod coeff 2	-	0.0506
	incidence angle mod coeff 3	-	-0.1763
	tracking error and twist	-	0.99
	geometric accuracy	-	0.98
	mirror reflectance	-	0.935
	mirror cleanliness factor	-	0.95
	dust on envelope	-	0.98
	concentrator factor	-	1
	solar field availability	-	0.99
Heat Collecting Element (HCE)	bellows shadowing	-	0.963
	envelope transmissivity	-	0.963
	absorber absorption	-	0.96
	HCE optical efficiency	-	0.752
	HCE heat losses	[W/m]	155
Heat Transfer Fluid	solar field inlet temp	°C	293
	solar field outlet temp	°C	393
	solar field initial temperature	°C	100
	piping heat losses at design temperature	W/m^2	10
	piping heat loss coefficent 1	-	0.00169
	piping heat loss coefficent 2	-	-1.683 e -05
	piping heat loss coefficent 3	-	6.78 e-05
	solar field piping heat losses	W/m^2	11.3
Power Plock	design turbine gross output power	MW_e	49.9
	design turbine net output power	MW_e	46
	design turbine gross efficiency	%	39.5
	cooling type	-	wet
	design turbine thermal input	MW_t	126.4
Thermal storage	thermal storage (equivalent full load hours)	h	7.5
	thermal storage type	-	2 tank molten s
	tank heat losses	MW_t	0.32

Component	specifications	Unit	Value
Heliostat Field	solar field area	m^2	1003405
	no. of heliostats	-	6950
	radial step size	m	116
	min. distance from tower	m	154
	max. distance from tower	m	1310
Heliostat	heliostat width	m	12.2
	heliostat height	m	12.2
	ratio of reflective area	-	0.97
	heliostat area	m^2	144.4
	mirror reflectance and soiling	-	0.88
	heliostat availability	-	0.99
Receiver	external receiver	-	-
	receiver height	m	18.8
	receiver diameter	m	12.44
	no. of panels	-	24
	coating emmitance	-	0.86
	coating absorptance	-	0.96
	tube outer diameter	mm	40
	tube wall thickness	mm	1.25
Heat Transfer Fluid	required HTF outlet temp.	°C	574
Power Plock	design turbine gross output power	MW_e	110
	design turbine net output power	MW_e	100
	design turbine gross efficiency	%	0.425
	cooling type	-	wet
	design turbine thermal input	MW_t	270.6
	design HTF outlet temp.	°C	290
Thermal storage	thermal storage (equivalent full load hours)	h	7.5
	thermal storage type	-	2 tank molten salt

Table 4: Left: Parabolic Trough reference plant configuration used as base case for all simulations. Right: Central Receiver reference plant configurations used as base case for all simulations.

5. Results: Influence of meteorological parameters on energy yield of CSP plants

Parabolic Trough (PT) and Central Receiver (CR) models of SAM defined in Chapter 4 are used as the base case for simulating plant performance. By using different meteorological files as input to the base case model in SAM, various simulation runs are carried out. The main metric considered for performance simulation of CSP plants is their annual net energy yields. The results of performance simulations are analysed and the influence of meteorological parameters on the energy yield of CSP plants are systematically analysed and quantified. For ease of understanding, in the following sub-chapters results are first presented and discussed for PT technology and for site ESPSA.

5.1 DNI Frequency Distribution

The most important parameter that affects performance of solar thermal power (CSP) plants is DNI. For site ESPSA, 5 TMYs are used as input to empirical PT model and results from performance simulation are shown in Figure 3. It is clear that even though all the TMYs have quite similar DNI annual average values and same meteorological parameters, AEP is different for all TMYs. This is mainly related to the difference in DNI frequency distributions of these TMYs. It can be also seen that deviation in AEP for TMYs from different data sources is quite high. At site ESPSA using data sources shown, deviation in AEP from that of ground-measured TMY is found to be 8.7 % to -4.2 %.

CSP plants are designed to operate within specific range of DNI values. If instantaneous DNI values are outside this range, the plant could not utilise such DNI values and hence energy incident is lost. The design range of DNI values within which a plant could operate are generally determined from long-term frequency distribution of DNI. Frequency distribution of DNI describes the expected number of occurrences of DNI values at a particular site.

Dump ratio, defined as the ratio of thermal energy dumped to that absorbed is calculated for all the 5 TMYs. Analysis shows that there is a correlation between AEP and dump ratio. AEP and dump ratio of ground-measured TMY is taken as reference and comparisons are made between different TMYs. It is found that if dump ratio for a TMY is higher than that for ground-measured TMY, AEP for that TMY is less than AEP for ground-measured TMY and vice-versa.

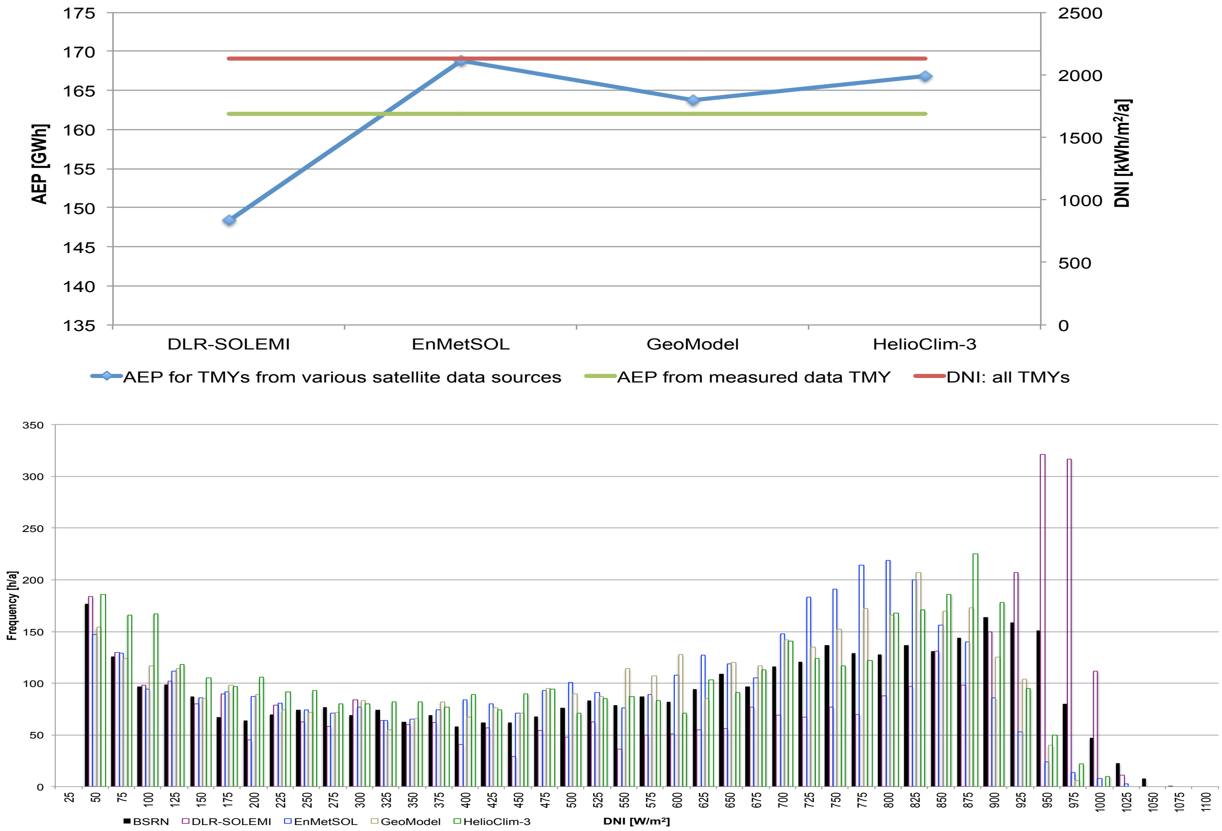

Figure 3: Top: Figure comparing AEP from TMYs created from different data sources for site ESPSA. The green line represents reference AEP from ground-measured TMY. DNI values are almost same for all TMYs. Bottom: Comparison of DNI frequency distributions of TMYs created from different sources with that from ground-measured TMY at site ESPSA. The black bars represent frequency distribution from ground-measured TMY.

Figure 3 explains the reason behind differences in AEP from different TMYs, which is closely associated with DNI frequency distribution. Parameters like KSI & OVER, which give information about differences in frequency distribution are used to relate differences in AEP. While comparing two frequency distributions, the smaller the value of these parameters, the better is the match. So, if two DNI frequency distributions match with each other quite closely, KSI parameter would be small and difference in AEP would also be small. From Figure 4 it is observed that for TMY from GeoModel, the value of KSI is least amongst all and consequently the difference in AEP is also the least. The value of KSI is highest for HC-3 while difference in AEP is highest for DLR-SOLEMI. This is not consistent behaviour and should be checked at other sites. It has been found that there exist shortcomings in the definition of KSI parameter for relating KSI with changes in AEP. Hence, a modified KSI parameter should be defined.

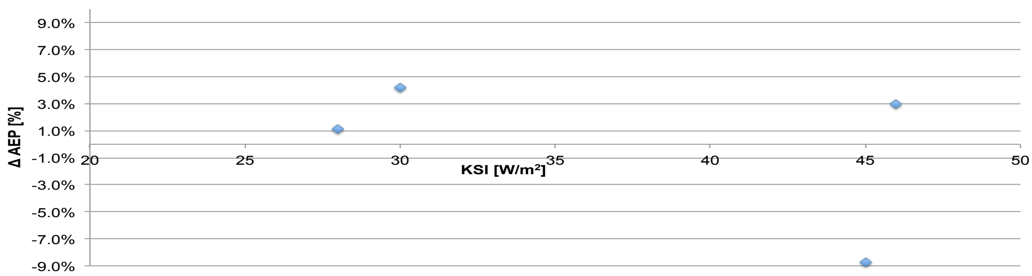

Figure 4: Figures showing the relation between KSI and AEP at ESPSA.

The same procedure of analysis used for site ESPSA to determine the influence of DNI frequency distribution on AEP is used for sites DZTAM and ZADAA for PT technology and for sites ESPSA, DZTAM & ZADAA for CR technology. The overall result is that variation in AEP for years with same DNI annual average but different DNI frequency distribution can be in the range of -9 % to +8 % for PT and -4 % to +9 % for CR technology.

5.2 Latitude effect

To quantify the influence of latitude on energy yield it would be ideal to find locations at different latitudes, which have very similar DNI annual averages. But from Figure 5 it can be seen that test sites on different latitudes have quite different DNI annual averages. To make results inter-comparable, a new variable AEP/DNI is defined, where, AEP is Annual energy production (AEP) at a site in MWh and DNI is long term annual average of DNI at that site in $kWh/m^2/a$.

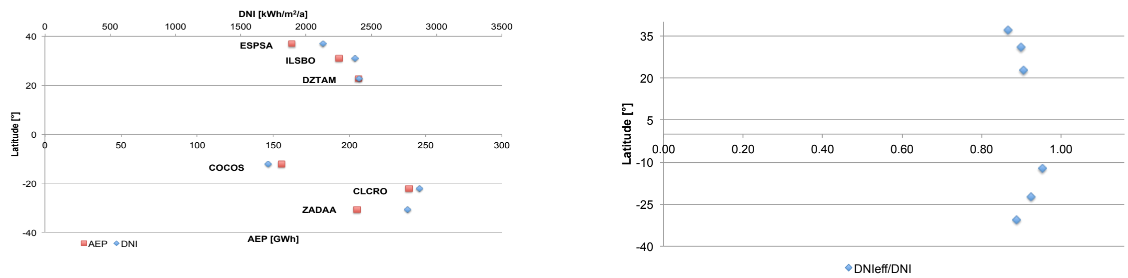

Figure 5: Figure showing DNI resources and AEP at various test sites sorted according to latitude. The primary X-axis represents AEP while the secondary X-axis represents long-term DNI averages.

Using such normalisation of AEP to the annual averages of DNI, it is possible to better compare the performance of CSP plants. The value of effective DNI decreases at higher latitudes and hence the available DNI that can be converted/utilised by collectors decreases. This is because Incidence Angle Modifier (IAM) values decrease with increasing latitude. Thus these factors reduce collector efficiency and hence solar field efficiency.

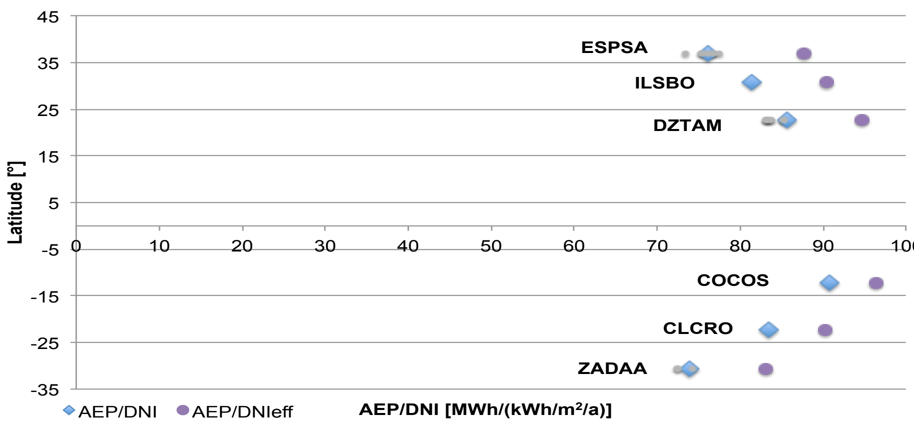

Figure 6: Variation of ratios AEP/DNI and AEP/$DNI_{effective}$ with changing latitude.

The variable AEP/DNI & AEP/$DNI_{effective}$ for all test sites is shown in Figure 6. Just like collector efficiency, solar field efficiency and $DNI_{effective}$, this variable also decreases with increasing latitude. Thus, with the clarification that value of AEP/$DNI_{effective}$ in Southern and Northern Hemisphere being independent of each other, it can be observed that there is a general trend in the behaviour of this variable. In both hemispheres the trend is almost linear. For 10° increase in latitude, the decrease in AEP/DNI is 9 % for Northern Hemisphere and 14 % for Southern Hemisphere. The performance of PT plants decreases by approximately 6 % with 10° increase in latitude and by around 8 % per 10° at latitudes above 30°. It should be noted that the same procedure of analysis used for PT technology is used for all sites for CR technology. For CR it is found that with 10° increase in latitude, the decrease in AEP/DNI is 10 % for Northern Hemisphere and 9 % for Southern Hemisphere.

5.3 Auxiliary meteorological parameters

The influence of meteorological parameters like ambient temperature, wind speed, relative humidity etc. is minor as long as the variations are not too extreme. Therefore, such parameters are termed auxiliary. The influence of such auxiliary parameters on energy yield is determined and summarised in Figure 7.
For Parabolic Trough (PT) it is found that under the assumption of constant relative humidity conditions, with increase of the annual average ambient temperature AEP decreases by 0.14 %/(°C) and for Central Receivers (CR) by 0.15 %/(°C).

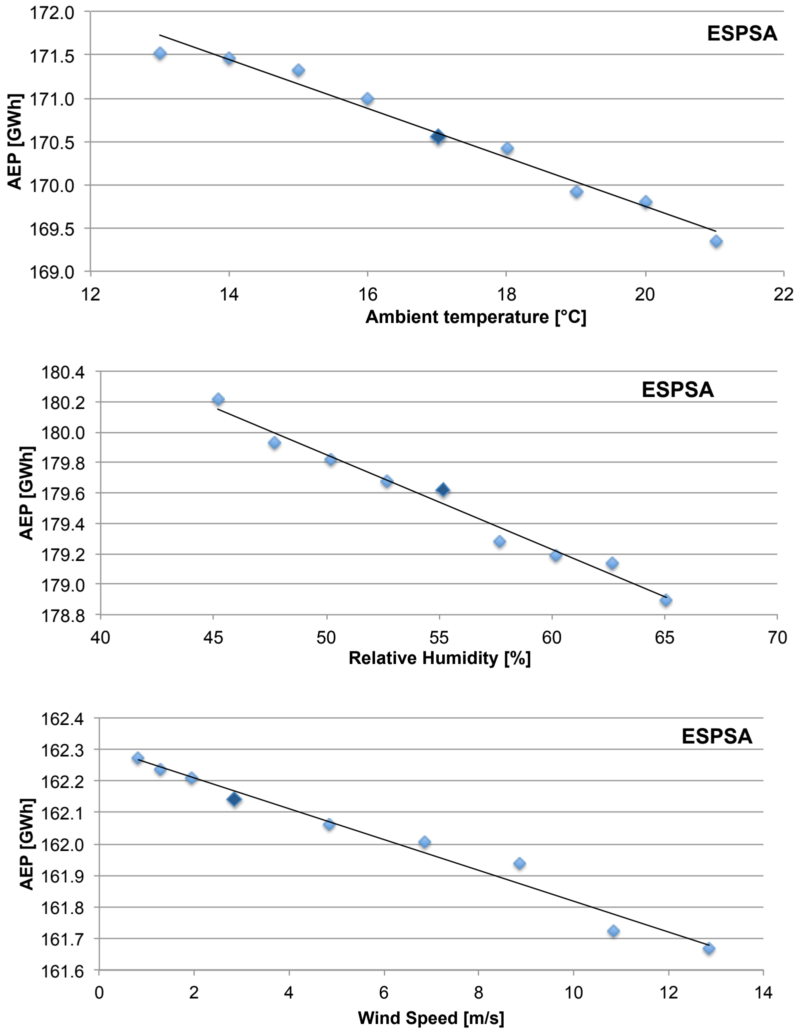

Figure 7: The variation of AEP at site ESPSA for PT with change in meteorological parameters. Top: With increase in ambient temperature, AEP decreases. Middle: As relative humidity increases, AEP decreases. Bottom: Wind speed increase results in decrease in AEP. Large markers represent reference case

Similarly, it is found that with increase in annual average RH, AEP decreases by 0.033 % /(% RH) for both PT and CR technologies. It is found that with increase in annual average wind speed, AEP decreases by 0.02 % /(m/s) for PT and by 1 % /(m/s) for CR technology. Effects of wind speed are expected to be much stronger if the wind speed is frequently close to the shut-off wind speed of plant. Then the derived linear approximation is not valid. Weaker collectors/heliostats would lead to increased effects, stiffer designs or wind protection to reduce dependencies.

6. Conclusions and Outlook

This paper determines the influence of various meteorological parameters like DNI, ambient temperature, relative humidity and wind speed on energy yields of solar thermal power plants. Two types of CSP technologies namely Parabolic Trough and Central Receivers are considered and influences are determined separately for each type. A PT power plant with 50 MWe capacity and 7.5 equivalent full load hours of thermal energy storage has been used as reference plant. A CR power plant with 100 MWe capacity and 7.5 equivalent full load hours of thermal energy storage has been used as reference plant.

It is concluded that the most important factor that influences the performance of CSP plants is frequency distribution of DNI. Using a TMY with unrealistic frequency distribution as input to the performance simulation software leads to unrealistic energy yields. The differences can be as high as ±9 % for sites with same DNI annual average. The influence of latitude shows that the performance of CSP plants already in operation in Spain and the USA should not be used as basis for determining the performance and hence the financial suitability of plants planned in other countries. For CSP plants it is found that for 10° increase in latitude, the decrease in ratio AEP/DNI can be 10 % for Northern Hemisphere and 14% for Southern Hemisphere. Other meteorological parameters do have an influence on the energy yield but it is minor, as long as no extreme weather conditions are prevalent.

It is found that the measure KSI defined by [6] is not able to perfectly relate differences in AEP due to differences in DNI frequency distributions. To compare frequency distributions from satellite sources with that from ground-measured data modified and improved KSI statistic should be defined. Satellite-derived time series that do not match well with ground-based measurements shall be post processed with help of site-specific measurements. Simulations should be carried out using sub-hourly time resolutions to better simulate and represent transient effects as close as possible. In this work all influences on energy yields are calculated for a plant with relatively large thermal energy storage. It is assumed that such a large storage rather dampens the influence of DNI fluctuations. To investigate such influences should be calculated for plants with greater and smaller storage capacities to determine dependency of these influences on thermal storage of power plants. The influence of DNI on energy yields in this paper may be partly overestimated because the layout of plant is not adapted specifically to each site or DNI distribution. To achieve more realistic results, detailed simulation tools should be used that are capable of simulating transient effects and meteorological input files in higher time resolutions.

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