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Francis M. Lopes, Ricardo Conceição, Hugo G. Silva, Rui Salgado, Paulo Canhoto, and Manuel Collares-Pereira

Predictive Value of Short-Term Forecasts of DNI for Solar Energy Systems Operation

Francis M. Lopes[1,2,a)], Ricardo Conceição[1,2,b)], Hugo G. Silva[1,2,c)], Rui Salgado[2,d)], Paulo Canhoto[2,e)], Manuel Collares-Pereira[1,2,f)]

[1]*Renewable Energies Chair, University of Évora, IIFA, Palácio do Vimioso, Largo Marquês de Marialva, 7002-554, Évora, Portugal.*
[2]*Institute of Earth Sciences, University of Évora, Rua Romão Ramalho, 7000-671, Évora, Portugal.*

[a)]Corresponding author: fmlopes@uevora.pt
[b)]rfc@uevora.pt
[c)]hgsilva@uevora.pt
[d)]rsal@uevora.pt
[e)]canhoto@uevora.pt
[f)]collarespereira@uevora.pt

Abstract. Solar power forecasting plays a critical role in power-system management, scheduling, and dispatch operations. Accurate forecasts of direct normal irradiance (DNI) are essential for an optimized operation strategy of concentrating solar thermal (CST) systems, particularly during partly cloudy days, due to solar intermittency. In this work, short-term forecasts from the radiative scheme *McRad* (Cycle 41R2) included in the Integrated Forecasting System (IFS), the global numerical weather prediction model of the European Centre for Medium-Range Weather Forecasts (ECMWF), together with in-situ ground-based measurements, are used in a simulated linear focus parabolic-trough power system through the System Advisor Model (SAM). Results are part of a preliminary analysis concerning the value of DNI predictions from the IFS for operation improvement of a CST system with similar configurations as the Andasol 3 CST power plant. For a 365-day period, the present results show high correlations between predictions of energy to grid based on measurements and IFS forecasts mainly for daily values (≈0.94), while lower correlations are obtained for hourly values (≈0.88), due to cloud representation of the IFS during overcast periods, leading to small deviations with respect to those from measurements. Moreover, to measure the forecasting skill of the IFS, daily and hourly skill scores based on local measurements and a persistence model are obtained (≈0.66 and ≈0.51, respectively), demonstrating that the IFS has a good overall performance. These aspects show the value that forecasted DNI has in the operation management of CST power systems, and, consequently, in the electricity market.

INTRODUCTION

Accurate predictions of DNI, i.e. the solar direct irradiance that is received on a plane normal to the sun's rays over the total solar spectrum [1], are essential for CST power systems particularly during partly cloudy days [2, 3], allowing to reduce the uncertainty of a solar plant outputs due to solar irradiance intermittency [4]. Forecasts of DNI can contribute for an efficient CST operation and management, which convert solar energy into thermal energy and then into electric energy. Such information is important for the operators of CST power plants, since it allows to know, with a certain level of confidence, the energy output into the electrical grid for a given day and to anticipate the corresponding production price in the electricity market. Consequently, this allows the increase of the economic return during more demanding and valuable periods [5], reaching a higher level of profitability.

Current state-of-the-art numerical weather prediction (NWP) models have inaccuracies in the representation of clouds (cloud cover and type) and atmospheric aerosols. This modeling issue leads to deviations in DNI forecasts, since clouds and aerosols are the primary parameters that affect the variation of DNI in space and time due to the

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processes of scattering and absorption of irradiance, including those that result from the interaction with cloud microphysical and dynamical processes [6]. For instance, high altitude clouds, such as cirrus, can suppress DNI almost to zero [7], while in the case of aerosols, DNI reductions in the order of 80-90% can be observed, due to extreme desert dust events [8, 9]. However, such inaccuracies can be corrected through the use of post-processing bias-correction procedures, such as the one performed in [10], in which DNI predictions from the IFS are shown with satisfactory results. Moreover, accurate solar forecasts also have a dependency on the forecast horizon, since forecasting uncertainty tends to decrease with the reduction of the latter. For electrical grid operators, intra-day and day-ahead forecasts are essential to ensure stable grids and to enhance the power supply quality by reducing energy losses and energy fluctuations. This has been a recent standard practice in Europe (e.g. Spain and Germany), as one example being the 11 MW_e commercial solar thermal power plant in Sevilla, Spain [11].

Taking into account the aforementioned aspects, the DNI predictions from the IFS (ECMWF) are compared with in-situ measurements in a 24-hour forecast horizon, which are used to predict the energy output of a CST power plant modeled through the SAM software [12], developed by the U.S. Department of Energy and National Renewable Energy Laboratory (NREL). This exercise can enable the output of the respective annual performance and financial metrics from a CST power plant, which includes the effect that DNI and meteorological variables have in a CST power system efficiency. A case study concerning a linear focus parabolic-trough system with similar configurations as the Andasol 3 CST project power plant (Granada, Spain) is presented. As a first step, this validation method aims to be a contribution to understand how to improve the overall performance of a solar unit, having the potential to be adapted to any other type of power plant system and region in the world.

DATA

A 365-day period of in-situ ground-measured and forecasted data, based in a 24-hour prediction horizon from the IFS, are analyzed from April 1st, 2016 to March 31st, 2017. Both measured and forecasted time-series include irradiance and meteorological data, which are used as input parameters for the SAM power plant model in order to calculate the corresponding energy production.

Continuous measured data gathered from one of twelve radiometric stations of an existing national network in Portugal [13] is used. The network, designed and installed for DNI resource mapping, will also contribute for the operationalization of solar power plants, as part of the DNI-A project (reference ALT20-03-0145-FEDER-000011). The selected measuring station (EVO) is located in Évora city (N38.567686, W7.91172), installed on the top of a research building of the Institute of Earth Sciences (ICT - *Instituto de Ciências da Terra*), in the southern region of Portugal. The climate of this region is of the Mediterranean type (Csa, based on the Köppen classification) with maximum temperatures that generally fluctuate from 31˚C to 35˚C during the summer months, and occasionally reaching values above 40˚C [14]. The region is characterized in general by a clean atmosphere and has exceptional conditions for harvesting of solar energy, since it has one of the highest solar resource potentials in Europe, with a DNI annual availability over 2100 kWh/m^2/year [13]. DNI measurements were performed using a CHP1 pyrheliometer from Kipp & Zonen, being attached to a SOLYS2 Sun-Tracker. The pyrheliometer has been calibrated every 2 years, following the International Organization for Standardization (ISO) 9059:1990 [15], and is a First-Class instrument according to the ISO 9060:1990 [16], with an estimated uncertainty on a daily basis of < 1%. The EVO station is considered to be a reference in the entire national network, since it has been having a regular maintenance protocol with daily cleaning and standard data quality control since February 2015 [17]. Moreover, other relevant meteorological parameters were also measured near the Sun-Tracker with standard high-quality instruments. Measured DNI and local meteorological parameters, such as air temperature (˚C), relative humidity (%), atmospheric pressure (hPa) and wind speed (m/s), were acquired on a 1-minute sampling rate and then averaged. The hourly time-series for atmospheric pressure was obtained from the ground-based measuring station of the Portuguese Meteorological Service (IPMA - *Instituto Português do Mar e da Atmosfera*) near Évora (N38.536542, W7.887958), since no atmospheric pressure data was available for the considered period of study in the EVO station.

For the region of study, the quality of DNI 24-hour forecasts has been recently assessed in [18]. The IFS (cycle 41R2) results showed a mean annual overall overestimation against measurements for the same period of the present work. It was also demonstrated that DNI predictions are mainly hindered due to the representation of clouds and aerosols used in the IFS, since these two parameters strongly affect the predicted DNI. In the case of partly cloudy days, the IFS tends to overestimate the radiative effect of clouds, while during clear-sky days under very clean atmospheric conditions it shows an underestimation of the radiative effect of aerosols, due to the use of a mean monthly aerosol climatology. Nonetheless, taking these aspects into account, the forecasted DNI showed a general good agreement with ground-based measurements, with relative differences for DNI in various locations within the region raging between ≈7% and ≈12%. Higher deviations are probably due to local aerosols and small scale fogs or low clouds that formed nearby the selected measuring station. In this work, the first 24-hour predictions of the 0000 UTC IFS run were used with an average grid resolution of 9 km (0.125˚ x 0.125˚). Since the DNI was not an available output parameter from the IFS, and in order to obtain hourly values of DNI, the predicted direct horizontal irradiance, i.e. the projection of direct solar radiation on a horizontal surface, represented by the *fdir* parameter of the IFS was used. The *fdir* parameter, which is an accumulated value (irradiation, in J/m^2), was converted to mean irradiance values (W/m^2) and then divided by the hourly averaged local cosine of the solar zenith angle (CZA) in order to compute the DNI (in power) to be used in the SAM.

SAM MODEL

The SAM, version 2017.9.5 [19], from NREL, is used here in a preliminary analysis to validate the predicted value of DNI forecasts from the IFS for CST power systems operation managing. The power plant model can generate hourly calculations through a physical (thermo-electric) and financial model, allowing to compute the respective annual efficiency and financial metrics of renewable energy systems, such as CST systems. Predictions of energy output and cost estimations are generated for a given power plant, parameterized through several input parameters for each run, e.g. type of installation and system design variables. DNI and meteorological parameters at the project location are also needed in order to generate the hourly outputs. These outputs include a wide range of metrics, such as the annual electricity production of a power plant, detailing the respective annual efficiency. It should be noted that the SAM calculates hourly outputs based on the CZA starting at January 1st. In the present work, to overcome this aspect, the period between January 1st and March 31st, 2017 was concatenated at the beginning of the input time-series for the SAM simulation. In this study, a CST physical linear focus parabolic-trough system of a 50 MW_e power plant with a similar configuration as the operational Spanish Andasol 3 CST project [20] is simulated. Real performance input parameters have been used in order to simulate the desired CST system. Additionally, and for reference in the present study, the Andasol 3 CST power plant has an estimated electricity generation of 175.000 MWh/year.

METHODOLOGY

As common practice for data control quality check, adopted filters for the considered local measurements were applied prior to analysis. These include basic filters for solar irradiance records and gap-filling techniques, due to the presence of possible missing periods of data caused by any instrumentation malfunction. A list of data quality filters that were considered for the present analysis is indicated below:

1. DNI ≥ 0.
2. DNI > CZA^+.
3. DNI < DNI_{TOA}.
4. DNI < BSRN-QFPPL [21].
5. Gap-filling with linear interpolation for missing periods less or equal than 2 hours.
6. Gap-filling with data from the nearest station for missing periods above 2 hours.

Considering a 365-day period, measurements showed a percentage of missing data of ≈0.01% and ≈0.05% for the local DNI and meteorological data, respectively. This highlights the high-quality data of EVO station, particularly for DNI measurements. The second filter has also been applied to the IFS data, considering the CZA of the nearest IFS grid point to the corresponding measuring location. In the third filter, the total solar irradiance, defined as the total power from the Sun at the mean Earth-Sun distance, 1361 W/m^2 accordingly to [22], is used to calculate the DNI at the top-of-atmosphere (TOA), as given by Eq. 2.77 in [23]. For the fourth filter, established physical possible limits were used. Regarding the six filter, the nearest measuring station used to fill possible data gaps of the EVO data series for the same period, is located at Mitra (N38.530522, W8.011221), in the outskirts of Évora city, about 13 km apart.

It is important to measure the forecasting skill of the IFS predictions in order to quantify their inaccuracies [24] towards measurements. In this context, the forecasting metric mean square error skill score (*SS*) is used in this analysis, being usually calculated using the root mean square error (*RMSE*). The *RMSE* is a recommended statistical metric for the application of electricity grid management issues [2], since only large errors are significant to the safety of the electrical grid system. Thus, the *SS* is computed as the decrease in the mean square error (*MSE*) of the forecast with respect to a reference, i.e. a persistence model time-series that is obtained here by persisting previous observational values over the 24-hour forecast horizon, as shown by [25]:

$$SS = 1 - \frac{MSE_{for}}{MSE_{per}}, \tag{1}$$

$$MSE = RMSE^2 = \frac{1}{n} \times \sum_{j=1}^{n} [I(j) - \hat{I}(j)]^2 , \tag{2}$$

where MSE_{for} and MSE_{per} are the corresponding error metrics for the forecast and the persistence, while $I(j)$ and $\hat{I}(j)$ are the measured and the forecasted value at time j, respectively, and n the number of assessed pairs. Skill values equal to one state that results are close to a perfect forecast, negative values are related to a lower performance of the IFS as compared to the persistence model, while zero values show that there is no improvement over the reference.

RESULTS AND DISCUSSION

The focus of this work concerns the value of 24-hour horizon forecasts of DNI for a 365-day period, as means to improve the management of operational CST power systems. To this end, an important quantity to know is the daily electric energy demand that an electrical grid operator has to handle on a daily basis. The electricity generated by a CST power plant with similar characteristics as those of the Andasol 3 power plant can be estimated by the software SAM through the output parameter energy injection to the grid E_G ($MW_e h$).

Hourly values of E_G based on measured and forecasted data are depicted in **Fig. 1**, together with the respective DNI. As expected, it is during the summer that more electricity is generated and stored due to: i) higher frequency of clear-sky days with high DNI availability; ii) an increase in the number of sun hours during the day (an important feature for the total energy production); and iii) smaller CZA and a thinner air mass. The opposite case occurs during the winter, where the E_G tends to be lower and, in some cases, almost zero due to a higher occurrence of overcast periods which can prevail during several consecutive days. It is during these periods that the IFS clearly shows difficulties in representing clouds which, consequently, leads to lower values of E_G than the ones obtained with measurements. In general, the total E_G based on forecasted data shows an overestimation of ≈20.000 $MW_e h$ against E_G based on measurements, i.e. a relative difference of ≈12.75%. This is a consequence of the annual DNI overestimation shown by the IFS, which is here transferred to the energy output of a CST power plant through a non-linear transfer function (thermo-electric model) including the effect of other meteorological variables, namely the air temperature and wind speed that affect the system efficiency. Taking in consideration parasitic power consumption during non-production hours, together with a constant derating value of 4% for the simulated plant, the annual energy values generated based in measurements and IFS are ≈153.655 MWh/year and ≈159.795 MWh/year, respectively. Although with small deviations in relation to the referenced annual energy generation of the Andasol 3 CST power plant (175.000 MWh/year), the IFS annual energy based E_G are closer than the ones obtained with measurements. Deviations from the real annual production value are mainly related to the capability of the IFS in representing clouds and aerosols, as well as the adopted energy management schedules that the real Andasol 3 implements daily accordingly to the energy demand in the electricity market. Moreover, a limit for the energy generated in the SAM is also considered, which is clearly seen during summer in both measured and forecasted E_G, meaning that more energy could be produced during this period instead.

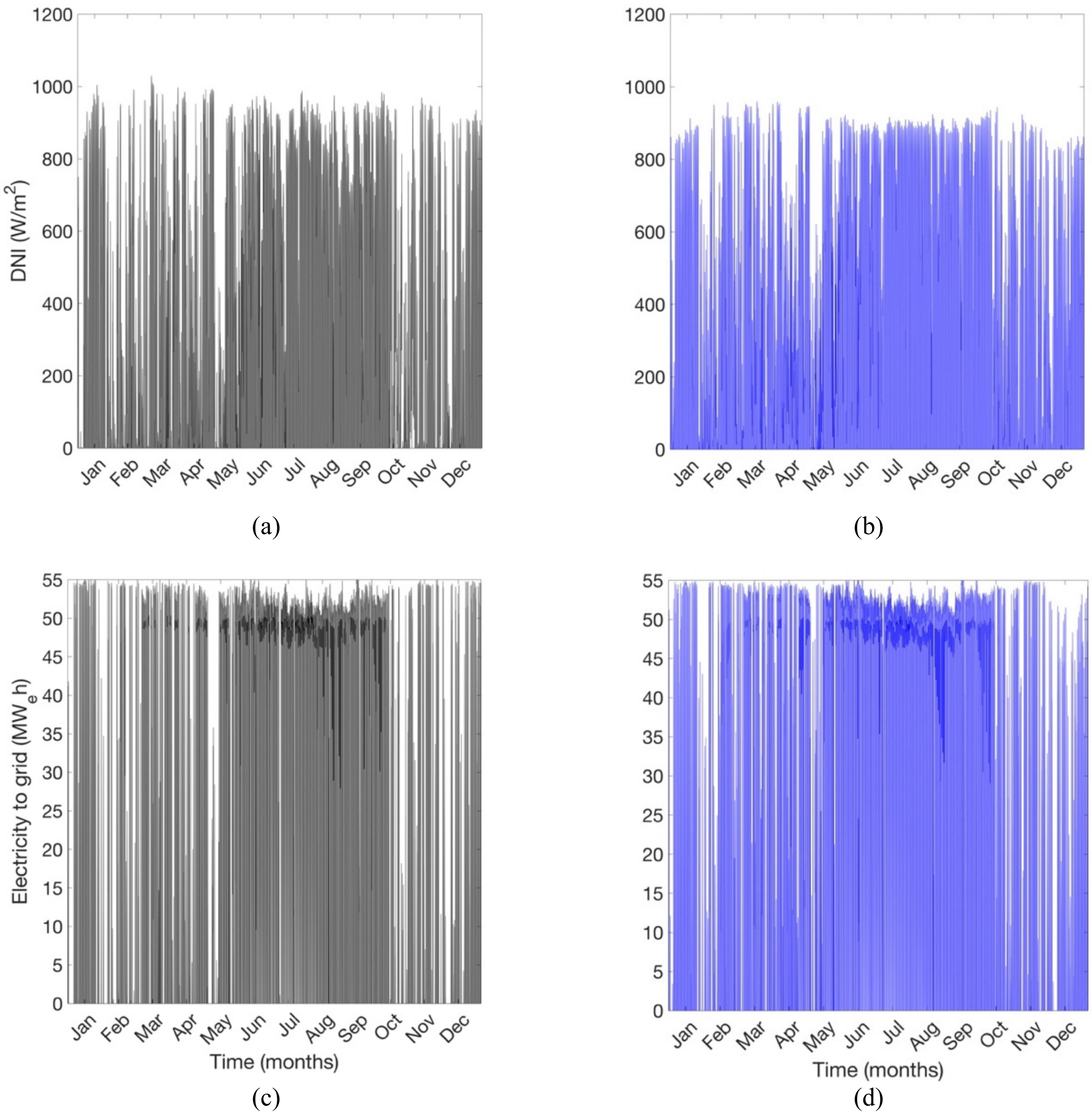

FIGURE 1. Direct Normal Irradiances, DNI (W/m^2), from measured (a) and IFS forecasted data (b) in EVO station (Évora, southern Portugal) together with the respective energy injection to the grid, E_G (MW$_e$h), (c) and (d), calculated through the SAM. Period of study relates April 1st, 2016 to March 31st, 2017.

A deeper comparison for the hourly and daily values of E_G obtained through measurements, IFS and the persistence model (**Fig. 2**), shows a significantly higher correlation coefficient (r) between E_G based on measured and forecasted data, mainly for daily values where an r of ≈0.94 (**Fig. 2c**) is found, while for the daily values of the persistence model, a lower r (≈0.77) is obtained (**Fig. 2d**). For the hourly values, r of ≈0.88 (**Fig. 2a**) and ≈0.75 (**Fig. 2b**) are obtained. The lower correlations result from the fact that hourly values can induce more errors, mainly during overcast periods, in which the IFS predictions still need to be improved regarding cloud representation. It is in the range of 40-50 MW$_e$h that there is a better correspondence (**Fig. 2a** and **b**) between the various E_G hourly values. This is shown by the high frequency of occurrences of E_G values, which are related to periods of clear-sky conditions, while a higher dispersion occurs for lower E_G values, corresponding to cloudy periods. It should be noted that the zero values found in the hourly results are due to shutdown periods (highlighted in E_G based on both measurements and IFS forecasts), being related to unusable stored energy.

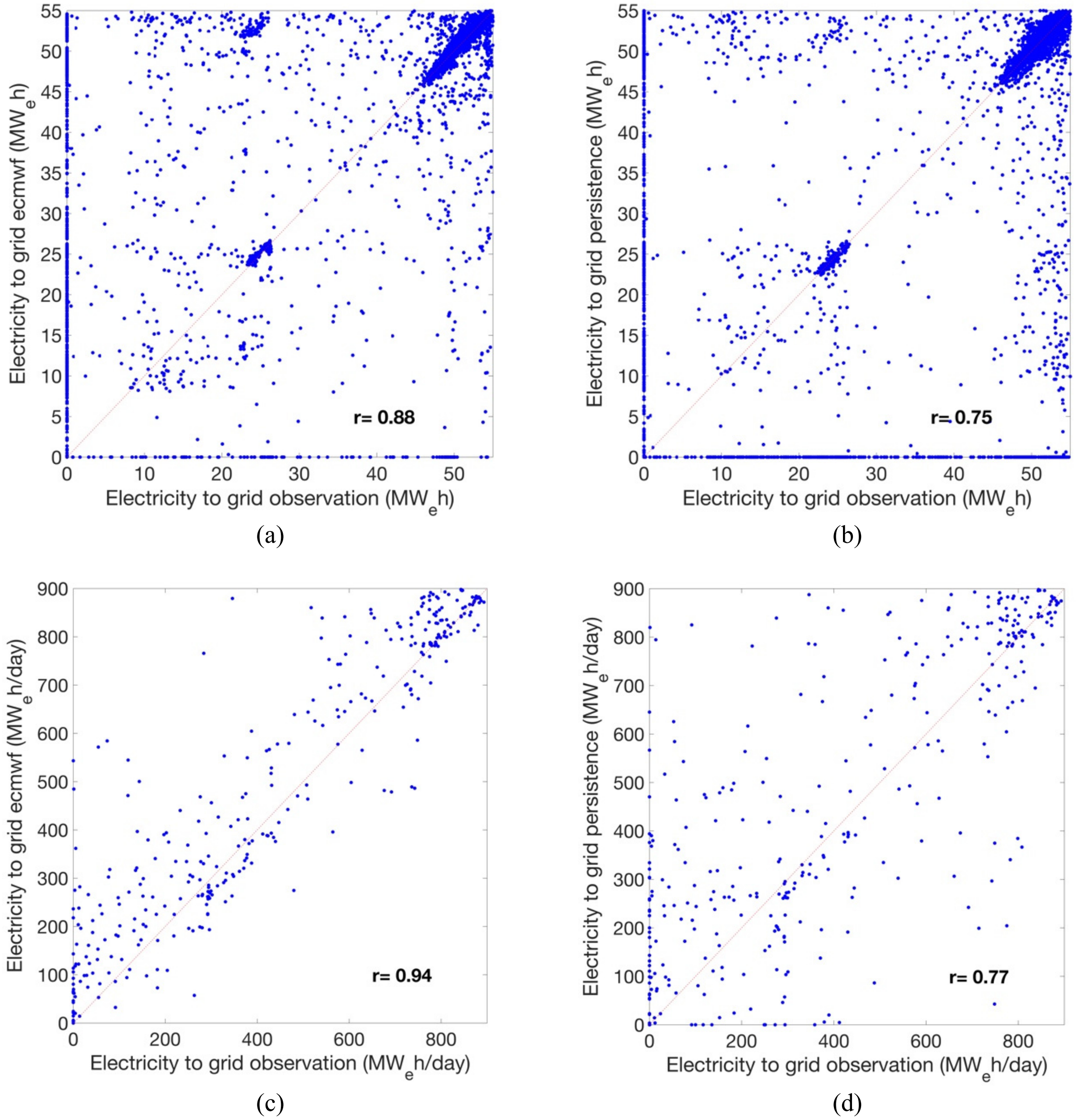

FIGURE 2. Energy injection to the grid, E_G (MW_eh), based on DNI measurements, persistence and IFS forecast models. Hourly (a, b) and daily (c, d) results are shown for EVO station (Évora, southern Portugal). Corresponding correlation coefficient, *r*, and a red-dashed identity line (y=x) are also depicted. Period of study relates April 1st, 2016 to March 31st 2017.

In **Table 1**, a statistical summary for both hourly and daily values of E_G is presented. In general, the IFS forecast model tends to overestimate the E_G, as shown by the negative values of mean bias error (*MBE*). However, the IFS also depicts a better performance than the persistence model, with lower *RMSE* values. The calculated *SS* (based on the *MSE*) are above 0.5, particularly for the daily values (≈0.66), which prove that the IFS forecast model performs better than the persistence model. This means that, with the appropriated post process techniques of forecasted DNI data, the use of NWP modeling in a CST power plant system is potentially a valuable tool for an efficient management of CST power systems operations.

TABLE 1. Statistical summary of the energy injection to the grid, E_G (MW_eh), obtained through the SAM based on measurements (Obs), IFS forecasts (IFS) and persistence models (Per) for EVO station (Évora, southern Portugal). Correlation coefficient (*r*), root mean square error (*RMSE*), mean bias error (*MBE*), mean absolute error (*MAE*) and the (dimensionless) skill score (*SS*) of the hourly and daily results are shown. Period of study relates April 1st, 2016 to March 31st, 2017.

	Hourly		Daily	
	E_G (Obs) – E_G (IFS)	E_G (Obs) – E_G (Per)	E_G (Obs) – E_G (IFS)	E_G (Obs) – E_G (Per)
r	0.88	0.75	0.94	0.77
RMSE	11.58	16.54	124.21	212.34
MBE	-2.28	7.40×10^{-17}	-54.78	3.89×10^{-16}
MAE	4.16	6.77	82.70	142.53
SS	0.51		0.66	

CONCLUSIONS

Measured and IFS forecasted DNI were used to simulate the energy production of a real linear focus parabolic-trough power system with the purpose of contributing to improve the operation of CST power plant systems. Results of energy injection to the grid, E_G, an important quantity to know for the day-ahead energy management, have shown the high potential that the use of the forecasted DNI has such power systems, with correlations of ≈0.89 and ≈0.94 for the hourly and daily predicted energy generation, respectively. A good overall performance by the IFS has been shown despite the current difficulties that NWP models have in predicting DNI during overcast periods.

Future work includes: i) the use of an upgraded version of the radiative scheme, *McRad* (Cycle 41R2), named *ecRad* (Cycle 43R3) which has recently become operational in July 11th, 2017 [26]. This improvement contains a more efficient radiative code to perform deterministic predictions of DNI and also uses an aerosol data assimilation system through the Copernicus Atmosphere Monitoring Service (CAMS) instead of the previous aerosol monthly means; ii) unlike the previous analysis carried out by the authors, the incident radiation on a plane normal to the Sun's direction (*drsp*) will be used as a direct DNI output from the IFS, thus allowing to improve calculations; and iii) a more robust statistical analysis that includes the simulation of different types of CST power systems, e.g. central receiver systems, with higher number of input parameters from real power plants in the SAM software. These aspects will certainly allow for higher levels of confidence to be reached when using forecasted DNI in CST power systems.

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