ECMWF Forecasts of DNI Towards a more Efficient Management of Concentrated Solar Thermal Plants

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MOTIVATION

- **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, allowing **to reduce the uncertainty of solar plant outputs due to solar irradiance intermittency**.

- Current state-of-the-art Numerical Weather Prediction (NWP) models still require **further validation over DNI forecasts**, mainly due to **cloud representation** during overcast periods.

- <u>Objectives</u>: Use of the Integrated Forecasting System (IFS), the global NWP model from the European Centre for Medium-Range Weather Forecasts (ECMWF), **to assess short-term forecasts of DNI in southern Portugal and integrate these in the operationalization of CST systems**.

I) Solar Assessment

II) Operationalization

SOLAR ASSESSMENT

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Short-term forecasts of GHI and DNI for solar energy systems operation: assessment of the ECMWF integrated forecasting system in southern Portugal

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SOLAR ASSESSMENT

- Ground-observations at Mitra (MIT), Évora (EVO), Portalegre (PRT) and Alcoutim (ALC).
- Period of analysis: **1 year** (starting in April 1st 2016).
- **In-situ hourly averages of DNI and GHI** (global horizontal irradiance) were used for analysis.
- Model setup:
  - **McRad (cycle 41R2) radiative scheme;**
  - Forecast issue time was set at 0 UTC;
  - Spatial resolution of 0.1º (~ 11km in latitude);
  - Output is hourly accumulated values (i.e., time step values integrated in an hourly basis);

ECMWF

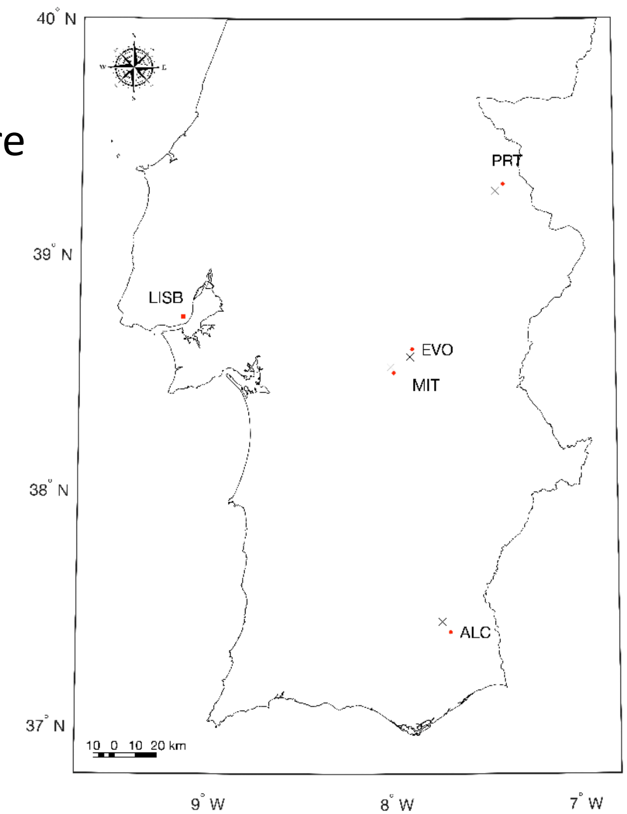

Figure 1. Geographical location for measurements (black crosses) and model (red dots)

$k_t = GHI_{obs}/GHI_{TOA}$
$k_b = DNI_{obs}/DNI_{TOA}$

SOLAR ASSESSMENT

$K_t = E_t^{obs}/E_t^{TOA}$
$K_b = E_b^{obs}/E_b^{TOA}$

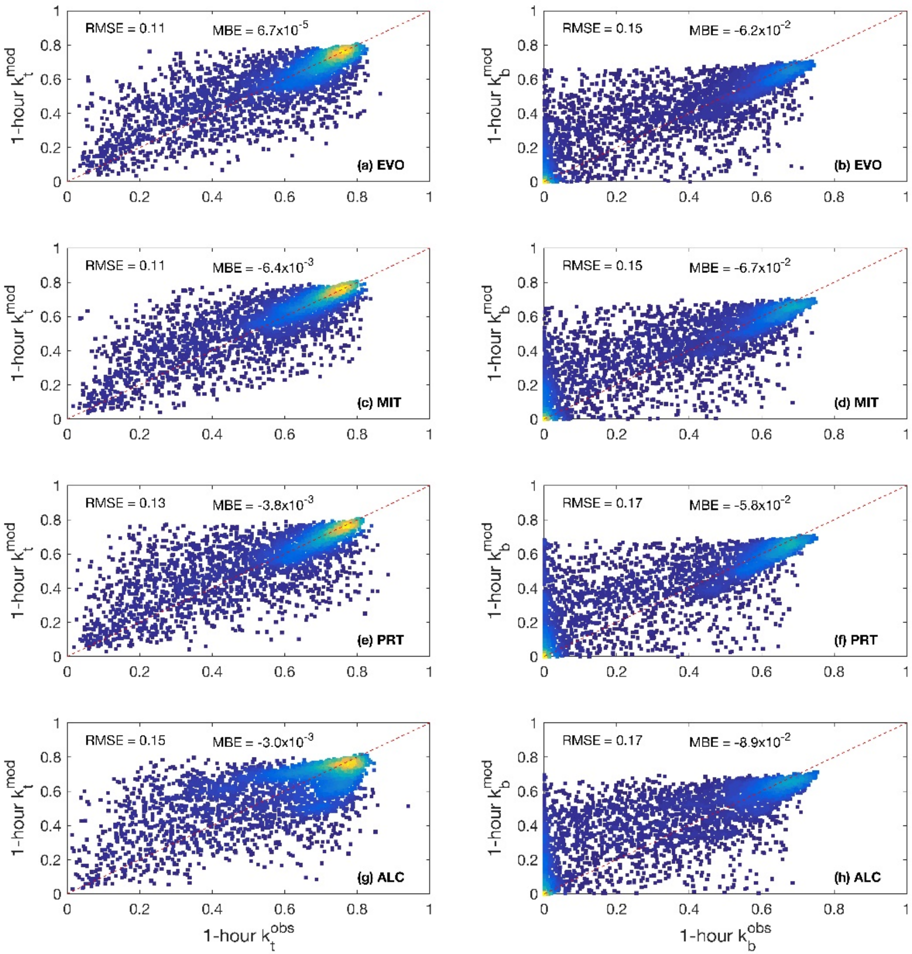

Figure 2. Hourly clearness indices for GHI (k_t) and DNI (k_b) in four ground-measuring stations during one year (April 1st 2016 to March 31st 2017).

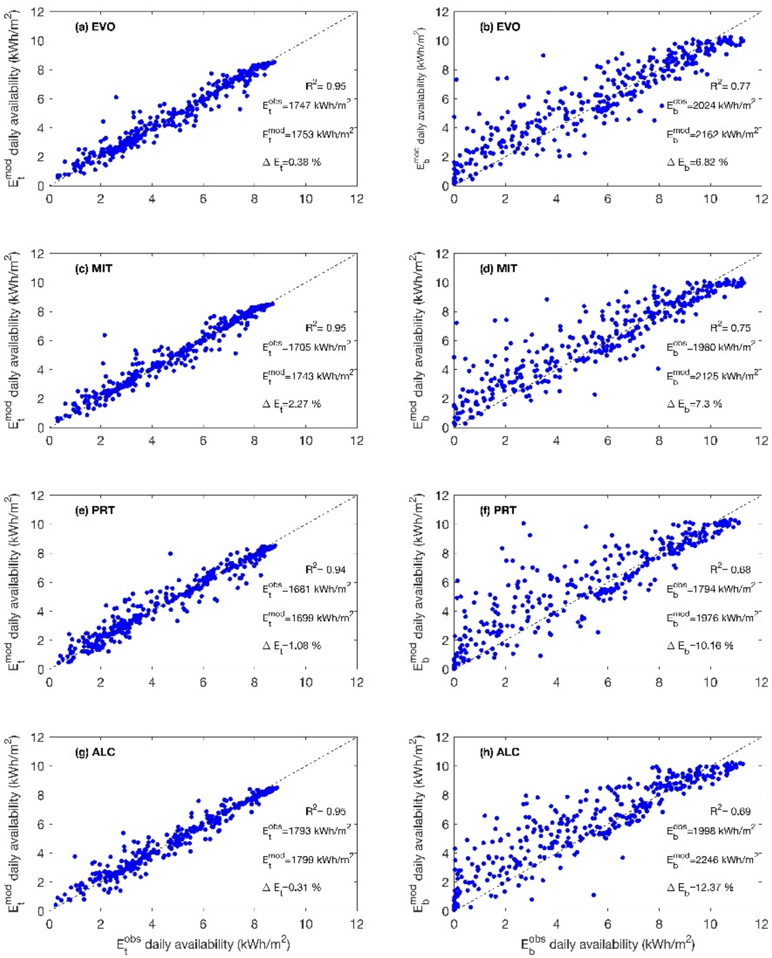

Figure 3. Daily availabilities (kWh/m^2) for GHI (E_t) and DNI (E_b) in four ground-measuring stations during one year (April 1st 2016 to March 31st 2017).

SOLAR ASSESSMENT

Table 1. Statistical summary

	EVO		MIT		PRT		ALC	
	Observation	Model	Observation	Model	Observation	Model	Observation	Model
Longitude (˚)	W7.91172	W7.9	W8.011221	W8.0	W7.442716	W7.4	W7.744901	W7.7
Latitude (˚)	N38.567686	N38.6	N38.530522	N38.5	N39.269221	N39.3	N37.441844	N37.4
Distance (km)	3.73		3.53		5.02		6.11	
Mean DNI (W/m^2)	548.85	587.15	566.19	611.19	559.27	617.79	547.80	611.29
Mean GHI (W/m^2)	474.53	475.41	467.52	477.40	462.40	466.23	489.21	489.72
Median DNI (W/m^2)	651.37	668.12	652.41	682.91	668.18	697.20	629.84	684.84
Median GHI (W/m^2)	452.55	448.96	441.71	453.25	421.34	439.33	468.26	469.83
Std DNI (W/m^2)	335.05	283.75	325.80	267.66	336.35	272.23	333.04	269.71
Std GHI (W/m^2)	258.31	255.53	261.91	255.85	268.63	255.62	270.28	255.50
Skewness DNI	-0.46	-0.69	-0.50	-0.78	-0.49	-0.81	-0.43	-0.82
Skewness GHI	0.22	0.29	0.27	0.28	0.31	0.30	0.23	0.25
Kurtosis DNI	1.73	2.22	1.82	2.44	1.73	2.44	1.74	2.51
Kurtosis GHI	1.98	2.03	1.97	2.02	1.97	2.03	1.96	2.01
N days DNI	181.58	181.58	168.46	168.46	154.63	154.63	181.46	181.46
N days GHI	180.21	180.21	179.71	179.71	179.13	179.13	179.83	179.83
E_b ($kWh/m^2/year$)	2020	2162	1961	2102	1770	1943	2010	2244
E_t ($kWh/m^2/year$)	1750	1754	1708	1744	1685	1699	1797	1800
ΔE_b (%)	**7.02**		7.15		9.78		11.65	
ΔE_t (%)	0.20		2.12		0.85		0.16	
R_b^2	0.77		0.73		0.65		0.69	
R_t^2	0.95		0.95		0.94		0.95	

SOLAR ASSESSMENT

$$SS = 1 - MSE_{for}/MSE_{per}$$

k_t	EVO	MIT	PRT	ALC
SS	0.6975	0.6975	0.5775	0.6400

k_b	EVO	MIT	PRT	ALC
SS	0.6094	0.6094	0.5725	0.5556

Table 2. Skill score (SS) based in the mean square error (MSE) of hourly clearness indices for GHI (k_t) and DNI (k_b) between the ECMWF global model and persistence forecast for one year.

SOLAR ASSESSMENT

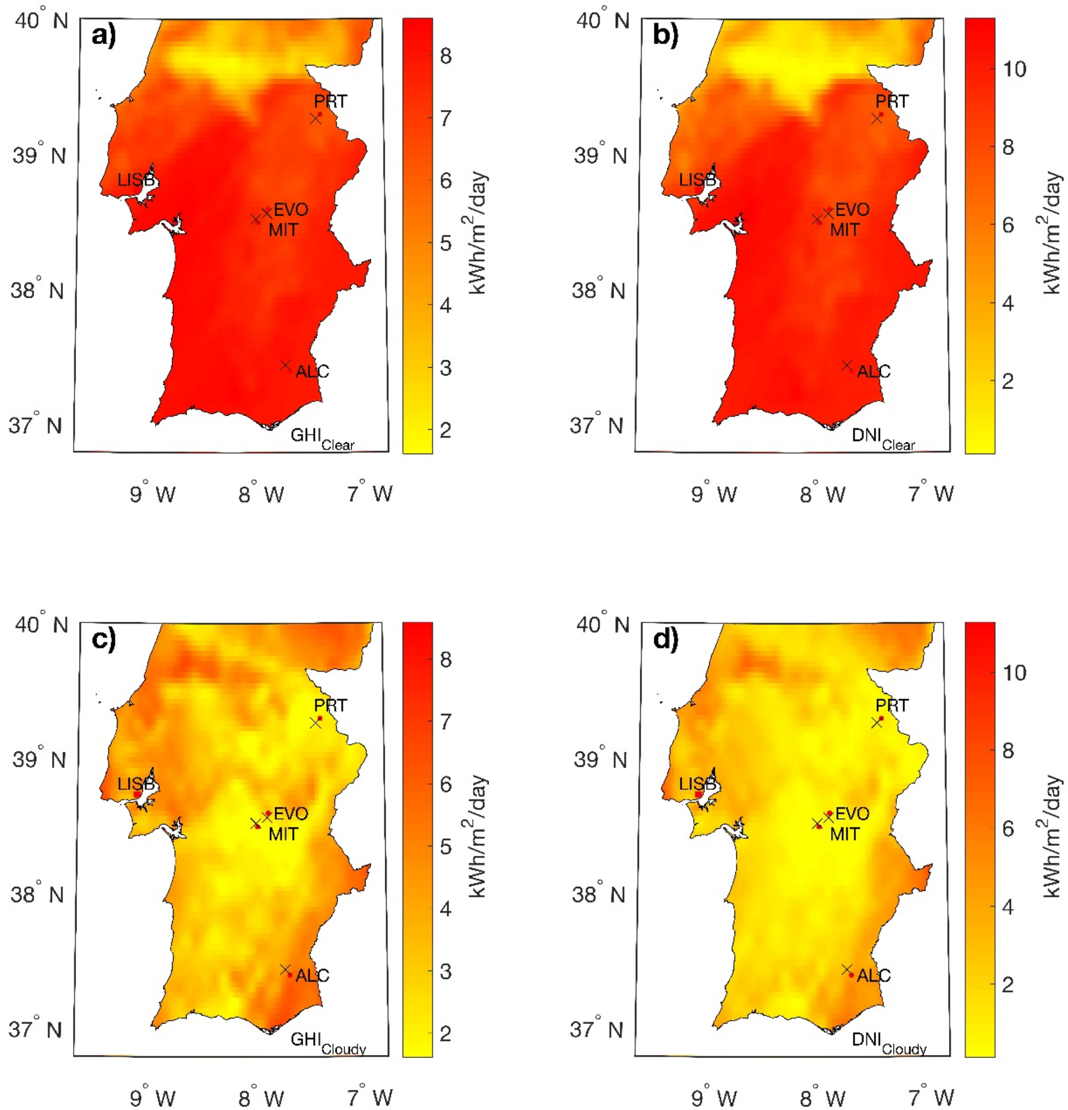

Figure 4 – Spatial distribution of predicted daily irradiation availability (kWh/m^2/day) from the ECMWF model for two test cases in southern Portugal: one clear sky day (July 12th 2016) and one cloudy day (May 8th 2016). Irradiation maps are portrayed as: (a) GHI_{clear}, (b) DNI_{clear}, (c) GHI_{cloudy} and (d) DNI_{cloudy}.

SOLAR ASSESSMENT

<u>Main results:</u>

• DNI simulations are particularly hindered by cloud and aerosol representation (i.e. a cloud effect underestimation during overcast periods and an aerosol effect overestimation during clear sky conditions, respectively).

• The predicted local solar irradiation availabilities are consistent with the measured reference values* for the region although the model tends to generally overestimate GHI and DNI, particularly the latter.

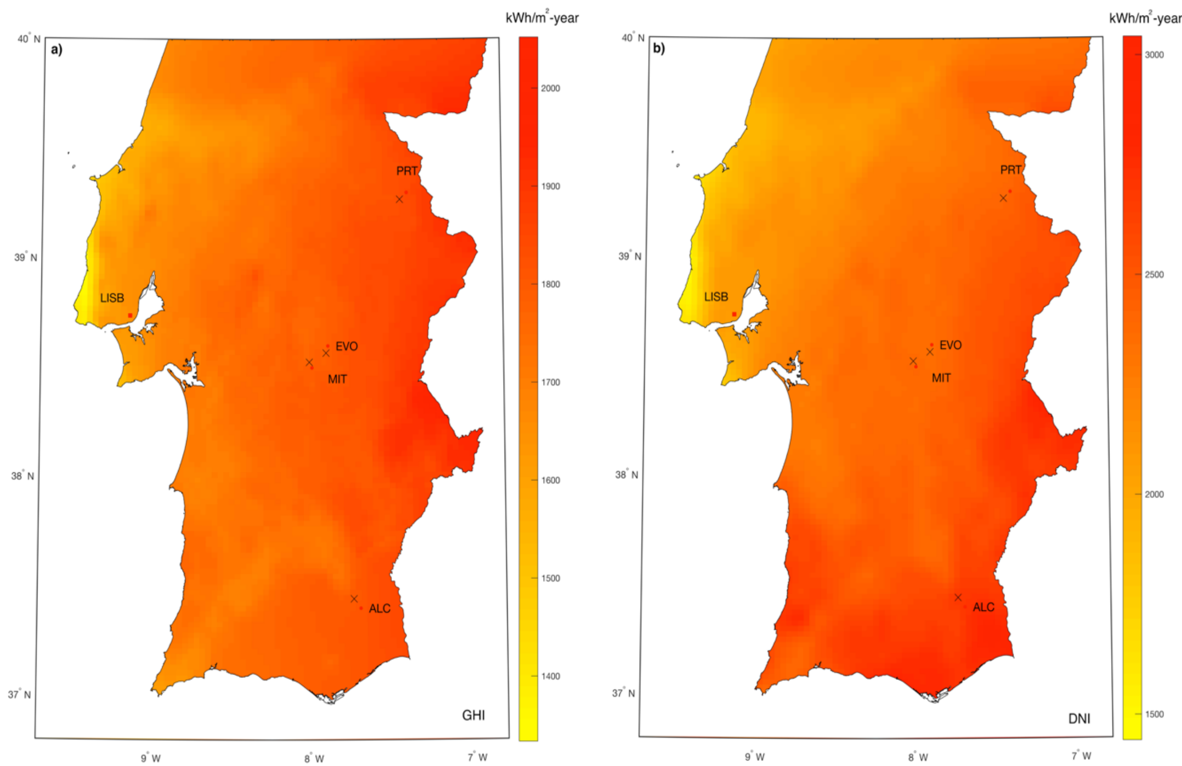

Figure 5. Spatial distribution of predicted annual GHI (a) and DNI (b) availability (kWh/m^2-year) in southern Portugal for 365 days simulated.

*GHI (1900 kWh/m^2); DNI (> 2100 kWh/m^2) in Cavaco et al. 2017

OPERATIONALIZATION

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

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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 under clear-sky conditions during partly cloudy days. 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 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 the improvement of the operationalization 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 the lower correlations obtained for hourly values (~0.89) are due to cloud representation of the IFS during overcast periods, leading to small deviations with respect to those from measurements. Moreover, as means 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 0.53, 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.

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In a preliminary analysis, IFS short-term forecasts, together with in-situ ground-based measurements, are used here in a simulated linear parabolic-trough power system through the System Advisor Model (SAM) software developed by the U.S. Department of Energy and National Renewable Energy Laboratory (NREL).

Conference proceedings + poster

OPERATIONALIZATION

- A case study concerning a linear parabolic-trough system with similar configurations as the **Andasol 3 CST project power plant** (Granada, Spain) was presented as part of a preliminary analysis concerning the value of DNI predictions from the IFS for improvement of the operationalization of a CST system.

- Output of the respective **annual electricity injection** to the grid E_G (MWh) from a CST power plant.

- A validation method is used to understand how to improve the overall performance of a solar unit.

- The selected study location was **Évora city (N38.567686, W7.91172)** in the southern region of Portugal.

- Hourly ground-measured and forecasted data (based in a 24-hour prediction horizon from the IFS) were analyzed for a 365-day period, 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.

OPERATIONALIZATION

- The E_G based on forecasted data shows an overestimation of ≈17.159 MWh of the total annual energy against E_G based on measurements, i.e. a relative difference of ≈12.16%.

- Deviations in relation to the referenced annual energy generation of the Andasol 3 CST power plant (175.000 MWh/year), which result mainly from not using during the simulation the exact same configurations as the Andasol 3 CST, since such information is not available.

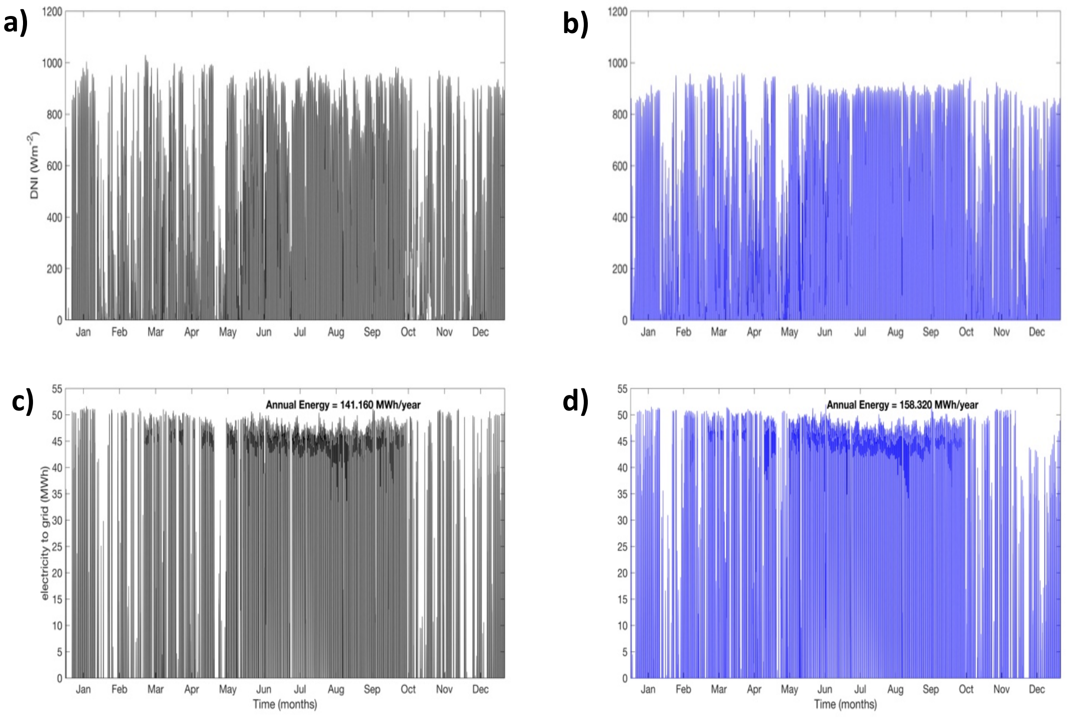

Figure 6. Direct Normal Irradiances, DNI (W/m^2), from measured (a) and IFS forecasted data (b) in Évora (southern Portugal), together with the respective electricity injection to the grid, E_G (MWh), (c) and (d), respectively **~141.160** and **~158.320 MWh/year**, calculated through SAM.

OPERATIONALIZATION

- Significantly higher correlation (r) between E_G based on measured and forecasted data, mainly for daily values.

- Lower correlations (hourly values) are the result of induced errors due to overcast and partly cloudy periods in which NWP predictions still need to be improved regarding cloud representation.

- Zero values found in the hourly results are related to shutdown periods and unusable stored energy. This is evident in E_G based on both measurements and IFS forecasts.

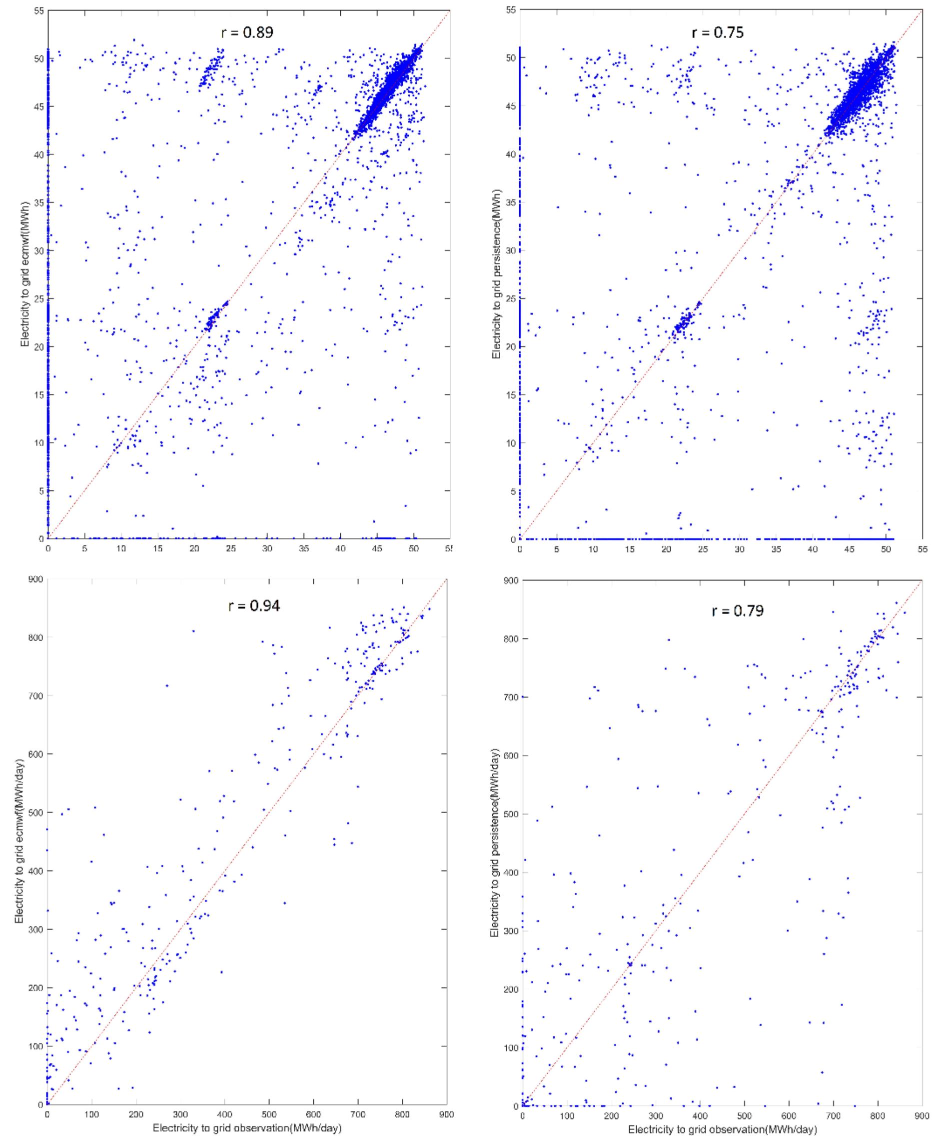

Figure 7. Energy injection to the grid, E_G (MWh). Hourly (a, b) and daily (c, d) results for EVO station (Évora, southern Portugal) during April 1st 2016 to March 31st 2017.

OPERATIONALIZATION

- High correlations between predictions of energy to grid based on measurements and IFS forecasts are obtained mainly for daily values, while hourly values are hindered by cloud representation mainly during overcast periods.

- The forecasting skill (SS) shows that the IFS has a good overall performance despite the current difficulties that NWP models have in predicting DNI during overcast periods.

	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	0.89	0.75	0.94	0.79
RMSE	10.35	15.03	111.18	192.78
MBE	-1.96	-4.88×10^{-17}	-47.01	1.59×10^{-16}
MAE	3.63	6.01	72.82	127.66
SS	0.53		0.67	

Table 3. Statistical summary of the energy injection to the grid, E_G (MWh), obtained through SAM based on measurements (Obs), IFS forecasts (IFS) and persistence model (Per) for EVO station (Évora, southern Portugal).

Table 4

EVO	k_t	k_b
SS	0.6975	0.6094

ON GOING WORK

- The use of an upgraded version of the radiative scheme named ***ecRad*** (Cycle 43R3) which has recently become operational in July 11th 2017 (ECMWF , 2017).

- A more robust statistical analysis that includes the simulation of different types of CST power 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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