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Economic Assessment of a Concentrating Solar Power Forecasting System for Participation in the Spanish Electricity Market

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Economic Assessment of a Concentrating Solar Power Forecasting System for Participation in the Spanish Electricity Market

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Abstract

Forecasts of power production are necessary for the electricity market participation of Concentrating Solar Power (CSP) plants. Deviations from the production schedule may lead to penalty charges. the mitigation impact on deviation penalties of an electricity production forecasting tool for Therefore, the accuracy of direct normal irradiance (DNI) forecasts is an important issue. This paper elaborates the 50 MW_{el} parabolic trough plant Andasol 3 in Spain. A commercial DNI model output statistics (MOS) forecast for the period July 2007 to December 2009 is assessed and compared to the two-day persistence approach, which assumes yesterday’s weather conditions and electricity generation also for the following day. Forecasts are analyzed both with meteorological forecast verification methods and from the perspective of a power plant operator. Using MOS, penalty charges in the study period are reduced by 47.6% compared to the persistence case. Finally, typical error patterns of DNI forecasts and their financial impact are discussed.

Keywords: direct normal irradiance; DNI; irradiance forecast; model output statistics; production forecast; CSP-FoSyS; CSP; Andasol; plant simulation; renewable energy

1. Introduction

Concentrating Solar Power (CSP) plants’ advantage relative to wind turbines and photovoltaic cells is the possibility to implement thermal energy storage systems and generate dispatchable energy. But still, the predictability of electricity production from CSP plants is limited by the forecasting accuracy of direct normal irradiance (DNI). Therefore, they cannot operate on day-ahead electricity markets without bearing the risk of paying penalties for deviating from the scheduled generation, diminishing the expected profit of the plant and thus reducing the competitiveness of this renewable energy technology. In Spain, electricity markets are divided in day-ahead and intraday market sessions whereas day-ahead market participation requires a power production forecast for the following day. This forecast has to be in hourly resolution and must be announced to the market operator before 10 AM each day. For a CSP station, this means that a 38 hour site-specific weather forecast is required to calculate the electricity production for sale on the market by means of a power plant model. Deviations from the production schedule may lead to deviation penalties.

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Therefore, the accuracy of DNI forecasts, which is the resource and main input factor for CSP facilities, is an important issue.

The development of an electricity production forecasting tool for the Andasol 3 power plant is currently ongoing. Andasol 3 is a 50 MW_{el} parabolic trough power plant near Guadix in Andalucía, Spain, combined with a molten salt thermal storage for 7.5 hours of full-load operationa. Based on solar irradiance forecasts this system is intended for the electricity market participation use case. This paper elaborates the estimated economic profitability of such a tool. In particular, the aim is to reveal whether a DNI forecasting tool would enhance the profitability of operating at the electricity market by avoiding penalty charges and thus make the CSP technology more competitive compared to conventional power generation.

Simple irradiance forecasting methods are persistence and climatological forecasts. Persistence forecasts assume that future weather conditions (e.g. solar radiation) at a certain time are just like in a fixed period (e.g. one day) before. Following Wilcox and Marion (2008), a climatological forecast means using meteorological data of a typical meteorological year. These methods, especially the latter, tend to be inaccurate and lead to large prediction errors, as demonstrated by Cerni and Price (1997).

Numerical weather prediction (NWP) models simulate the development of atmospheric conditions in a specific geographic region over time by imposing a three-dimensional grid to the modeled region and by calculating the alteration of variables for each grid point and time step, resulting from interactions with neighboring points. These interactions are described by thermodynamic and other physical laws, together forming a system of non-linear differential equations that can be numerically solved with a satisfactory precision. A simulation is starting with a given initialization state, determined mostly by distributed measurements or measurements combined with previous forecasts (possibly also from other, larger scale NWP models) and/or satellite data. The result of a simulation run is a forecast for the specified set of parameters. Some NWP models already include solar irradiance forecasts, but usually this is limited to global horizontal irradiance (GHI), from which DNI still has to be derived. Existing NWP irradiance is found to be fairly precise for clear sky conditions without large atmospheric turbidity, but the performance is significantly reduced in the case of cloudy situations (e.g. Zamora et al., 2005; Girodo, 2006; Breitkreuz et al., 2009). Based on validation studies in the US and Europe, the overall relative root mean squared error (rRMSE) for GHI forecasts is stated to be in the range of 30-50%.

Statistical models attempt to make predictions for future events based on historical time series. Operational and commercially available products in the segment of DNI forecasts are based on Model Output Statistics (MOS). These need historical time series of both site-specific measurements and (in most cases) NWP forecasts to create a prediction equation for any desired variable by multiple linear regressions derived from historical time series data. MOS models correct systematic NWP biases and phase angles and also take into consideration local effects and conditions, but according to Girodo (2006), amongst other disadvantages they fail to predict extreme weather phenomenons. Typically, MOS models can be provided only for locations with existing long-term measurements available for the training of the system. In Girodo's validation study in a region of northern Germany, relative RMSE for a MOS-based GHI prediction with hourly resolution forecasts, growing from about 25% in the first 24h to 30% on the second day.

Satellite observations have the potential to be used for short-term forecasting with high temporal resolution because clouds have a significant impact on irradiance. Type, height, optical depth and the three-dimensional structure of clouds influence the extinction as described in radiative transfer theory. Modeling of global solar irradiance from satellite images is a well-known and fairly well-investigated procedure. Satellite-based short-term forecasting mainly grounds on cloud motion extrapolation and can be applied a few hours in advance according to Hammer et al. (1999). Cloud patterns are linked with a vector field by their motion identifiable from at least two consecutive images. Similar to the results from NWP models, the forecasting error is higher for low sun elevation and high cloud variability and on a low level for clear sky conditions. Up to now cloud motion-based forecasts have only been applied to global irradiance forecasting resulting in a rRMSE of below 20% for 30 min-forecasts, growing with forecast lag to almost 40% for a 3 hour horizon.

For all solar irradiance forecasting methods it has to be noted that they have been used mainly with respect to global irradiances, while CSP technologies request a DNI forecasting scheme. Therefore, this paper uses only the operationally available DNI forecasting method based on MOS technology.

For power plant modeling a variety of different modeling tools is available. Well-known models are TRNSYS of the University of Wisconsin (2010), PCTrough of Solar Millennium’s technology subsidiary Flagsol and the Solar Advisor Model of NREL (2011). These models enable quasi-steady or dynamic modeling of the power plant’s thermal system and calculate heat flows and the turbine’s electricity generation. They take into account all energy flows within and out of the plant. The heat from the concentrated solar radiation is absorbed at the absorber tubes, heat is then transferred with a heat transfer fluid to the heat exchanger which is producing the steam driving the turbine. In the turbine, heat energy is converted to mechanical energy which is again turned into electricity by a generator, while waste heat is emitted via a cooling system. Heat losses through transmission and convection, conversion losses and other energy consumption (e.g. for pumps) are also modeled, so that in the end all relevant energy flows as well as the turbines electricity production are calculated.

Simulating the economic results of forecast utilization for renewable energy producers has been done mostly for wind energy. For example, Barthelmie et al. (2008) examine the economic value of wind speed forecasts for wind farm operators in Great Britain. In the CSP-related literature, irradiance forecasts have so far been addressed by Wittmann et al. (2008, 2009) as a variable of an optimization problem formalizing the optimum operation strategy in case of market participation in Spain, but studies utilizing forecasts that cover more than a few consecutive days are unavailable so far.

Section 2 represents the datasets used in the study, while section 3 provides results on the irradiance forecast quality. Section 4 deals with a simulation of the market participation based on a historical forecast dataset. Finally, section 5 summarizes and concludes the findings of the study.

2. Data and models used

2.1. Ground measurements

Ground measurements have been performed at 37.21° N and 3.07°W at the site of the Andasol power plants in the Spanish province of Andalucia. Solar radiation, temperature, humidity, wind speed and direction have been recorded in one minute resolution according to the recommendations of the World Meteorological Organization (WMO, 2008), using a Vaisala 50Y sensor for temperature and humidity, a NRG 40H anemometer for wind speed and a NRG 200 wind direction sensor for wind direction. Solar radiation was measured utilizing a rotating shadowband pyranometer (RSP). These sensors have a typical error of below 2.5% with proper correction functions and calibration procedure developed by Geuder et al. (2008). Hourly resolved measurements have been obtained by averaging all minutes in the preceding hour.

2.2. Two-day persistence forecasts

A day-ahead two-day persistence forecast is obtained by perceiving the recorded data from the day before (DNI or electricity production) as the forecast for the following day. Basically the recorded data is shifted by 48 hours. They act as the reference case providing the trivial solution of the problem being available for free and without developing any forecasting system. A time lapse of two days is necessary since tomorrow's production forecast has to be announced to the market at 10:00 a.m. when the one-day persistence forecast is not completely available.

2.3. Model output statistics forecast

For our study, a site-specific historical model output statistics (MOS) forecast was used, covering the period from July 2007 to December 2009. Historical NWP forecasts and measurements are used to derive empirical site-specific connections between different weather parameters, thereby including local effects and large-scale atmospheric situations. In our case, forecasts have been obtained from the commercial provider Meteológica. They are based on both the ECMWF and the HIRLAM forecast of the Spanish national meteorological center and have been trained by Meteológica with ground measurement data for the period October 2005 to August 2008 from the measurement station near the power plant.

2.4. Power plant model

In this study, the proprietary plant model PCTrough, a quasi-steady-state simulation model, has been used, since the original Andasol-3 power plant configuration files from the company Flagsol (responsible for the engineering and construction of the plant) were made available allowing a realistic modeling of the plant. The power plant model was used to perform independent simulation runs with historical day-ahead MOS-based irradiance forecasts, two-day-persistence forecasts and measurement data, which generated the net electricity production fed into the grid in each hour of the simulation period as output. Assumptions had to be made regarding power plant details and the storage and co-firing operation strategies. The storage was used to buffer irradiance gaps during the day and to extend the production into the night, while there was no further optimization of the storage use with respect to the electricity prices implemented. Co-firing was used during the day for production assistance in July and August (because in these months the effect on power generation is largest) and otherwise only to speed up the start-up procedure during morning hours. The amount of gas co-firing is limited to 15% according to the Spanish law (2007). The same operation strategy was chosen for all simulation studies to obtain comparable results for the different meteorological inputs. Days with missing measurement or forecast data were excluded by scheduling maintenance tasks in the software to avoid distortions in the comparison. The difference between the simulation results of forecasted and measured weather data is interpretated as the deviation between forecasted and real electricity production and later used to calculate the deviation penalties that would have been charged by the transmission system operator if the forecasts had been sent to the electricity grid operator one day before.

2.5. Market conditions and penalty information

Trading at the Spanish electricity market is explained in detail in the operation procedures of the Spanish market operator (OMEL, 2011). It takes place for the following day on a day-ahead market (the focus of this paper) and in several intra-day market sessions. Besides the option of a fixed feed-in tariff, the Royal Decree (2007) allows renewable energy producers to take part in this market and to receive an additional premium tariff. Producers must place bids for each hour, containing at least the hour and amount of electricity production. These bids are matched with purchaser's bids in an iterative procedure until the market is cleared. The price for each hour is the marginal price, that means the price of the last matched purchase and sales bid of the session. The tariff paid to the producer is at least the market price plus an additional premium, which has a minimum and maximum level between which the premium depends on the market price.

Independent of the remuneration option choice, forecasts of production have to be provided to the transmission system operator (TSO). In case of deviations from the scheduled production, the transmission system operator may have to add or withdraw power from auxiliary service units as stabilization measures, depending on the status of the transmission grid. The costs of these interactions are distributed via penalty charges among those who caused the interference. Falling penalties are defined as charges for an electricity production below the schedule, rising penalties accordingly for a production above the schedule. In this study, it has been evaluated which penalty charges would have been caused if the electricity production forecasted is entirely sold on the day-ahead market and not traded on the intraday market. Penalty information was received from Red Eléctrica de España, the Spanish TSO (REE, 2010).

3. Verification of historical irradiance forecasts

3.1. Forecast verification

In this study, forecast verification measures are defined following the MESOR standard (2009) as:

- Forecast error for each hour t:

$$\epsilon_{\mathrm{t}} = \mathrm{DNI}_{\mathrm{FC,t}} - \mathrm{DNI}_{\mathrm{meas,t}}\epsilon_{\mathrm{t}} = \mathrm{DNI}_{\mathrm{FC,t}} - \mathrm{DNI}_{\mathrm{meas,t}} \tag{1}$$

- Relative forecast error:

$$\epsilon_{rel,t} = {}^{\epsilon}/_{\overline{DNI_{meas}}} \tag{2}$$

- Root Mean Square Error (RMSE):

$$RMSE \;=\; {}^{1}/_{\sqrt{n}}\,\sqrt{\textstyle\sum_{i=0}^{n}\left(DNI_{FC,t} - DNI_{meas,t}\right)^2} \tag{3}$$

- relative Root Mean Square Error (rRMSE):

$$rRMSE = {}^{RMSE}/_{\overline{DNI_{meas}}} \tag{4}$$

- Mean Bias Error (MBE):

$$MBE = \frac{1}{n}\textstyle\sum_{i=0}^{n}\left(DNI_{FC,t} - DNI_{meas,t}\right) \tag{5}$$

- relative Mean Bias Error (rMBE):

$$rMBE = {}^{MBE}/_{\overline{DNI_{meas}}} \tag{6}$$

- Skill score based on RMSE:

$$SC_{RMSE} = {(RMSE_{FC} - RMSE_{persist})}\Big/{(RMSE_{perfect} - RMSE_{persist})} \qquad (7)$$

DNI_{meas} stands for measured and DNI_{FC} stands for forecasted values. $\overline{DNI_{meas}}$ is the average of all recorded DNI hourly values. $RMSE_{FC}$ means the RMSE of the MOS forecast, $RMSE_{persist}$ stands for the RMSE of the two day persistence forecast and $RMSE_{perfect}$ for the fictional perfect forecast's RMSE. Following the standards, only daylight hours with both available measurement and forecast data have been used.

Table 1 compares the forecast verification of the MOS approach versus a 2-day persistence model based on measurements taken at the power plant location. Except for the period July to December 2007 MBE for the MOS is always larger than the persistence model. For July to December 2007 MBE is around zero while for the complete years of 2008 and 2009 MBE is negative, with values of -33 and -38 W/m^2. For all other measures RMSE, rRMSE and the linear correlation coefficient the MOS forecasts show a better performance than the 2-day persistence model except of the correlation coefficient in 2008 which is nearly the same.

Table 1
Verification measures for both MOS and 2-day persistence forecasts for different years

	2d-persist (7-12/2007)	MOS (7-12/2007)	2d-persist (2008)	MOS (2008)	2d-persist (2009)	MOS (2009)
MBE [W/m^2]	0.3	0.2	-3	-33	-2	-38
RMSE [W/m^2]	333	257	366	347	371	266
rRMSE [%]	73	56	81	77	80	58
Correlation coefficient	0.52	0.71	0.47	0.49	0.45	0.7

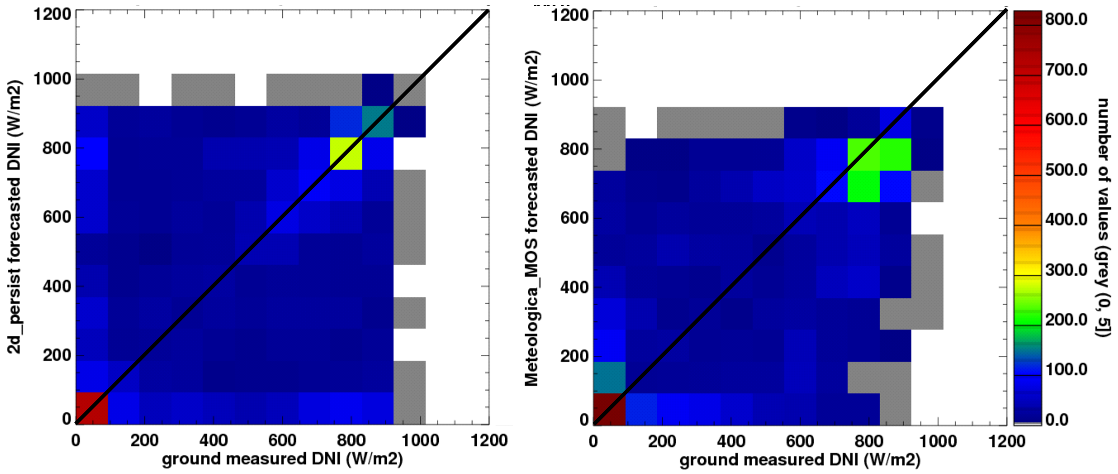

Fig. 1. Two-dimensional frequency distribution of hourly 2-day persistence (left plot) and MOS (right plot) forecast DNI values versus the ground measured DNI for the year 2009.

A comparison of two-dimensional frequency distributions (Fig. 1) shows that the 2-day persistence model stays centered around the 1:1 line, but provides extremely erroneous forecasts (clear atmosphere instead of fully cloudy with low DNI or vice versa) more often than the MOS model. The MOS model, on the other hand, underestimates values above 700 W/m² and overestimates values below 100 W/m².

The skill score based on the RMSE as score parameter describes the relative improvement of the forecast over a reference forecast – here taken as the 2-day persistence forecast. Positive skill scores are found for the period between 9 and 17 hours UTC (Fig. 2) indicating a relative improvement of MOS with respect to the persistence forecast. The year 2008 is an exception showing a positive skill score only until 15 hours UTC. For early morning and late afternoon hours close to sunrise and sunset the 2-day persistence forecast performs better than the MOS forecast. This period is characterized by a strong non-linear behavior of the DNI daily curve where small forecast errors result in large errors in hourly DNI values.

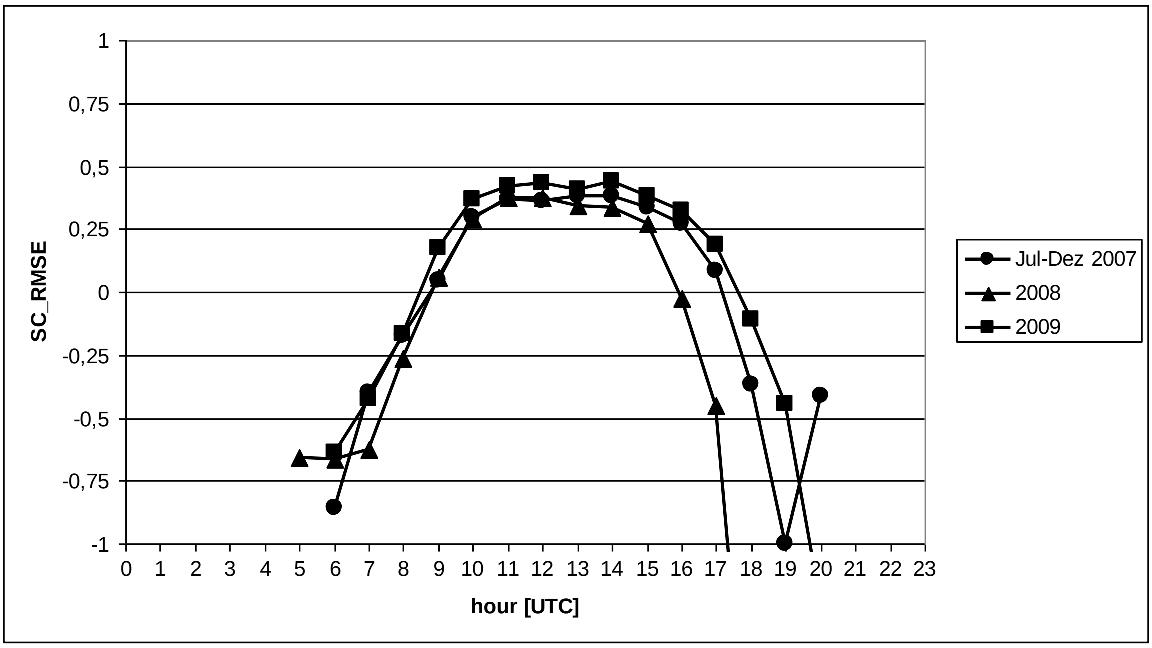

Fig. 2. Skill score over the time of forecast day 2 for different years July-Dez 2007 (circle), 2008 (triangle), and 2009 (square).

3.2. Identification of error patterns from the view of electricity market participation

Like for NWP and satellite forecasts, predicting irradiance in hourly resolution is expected to be less precise under broken cloud conditions, since the distribution of single clouds in the sky is stochastic. Fig. 3 shows the seasonal distribution of the relative forecast error for the MOS approach. Results indicate that during summer, the forecast is generally more reliable than in other seasons, having a percentage of small relative errors (<10%) almost twice as high as in other seasons, and showing much less frequent large errors >100%. Generally, in most cases the irradiance is either underestimated or strongly overestimated (> 100%).

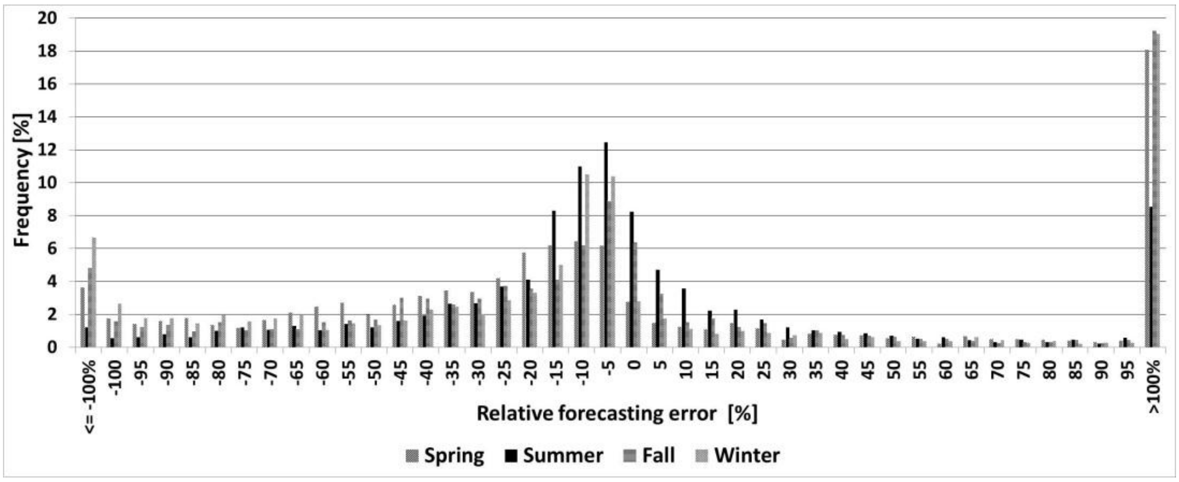

Fig. 3. Seasonal frequency distribution of the relative forecasting error for 2007-2009

Error measures are derived for hourly values as a function of daily DNI sums obtained for the respective day (Fig. 4) and a measure for DNI volatility (Fig. 5). Relative values are also given since absolute values strongly depend on the natural fluctuation of DNI with the day-night rhythm.

RMSE reaches 300 W/m² for DNI sums > 1000 Wh/m² and is declining to 200 W/m² with an increasing DNI sum up to 7500 Wh/m² (Fig. 4). For higher values, it remains almost constant. Also, in relative values the forecast is more accurate for clear sky conditions which generally have higher DNI sums. rMBE is positive for DNI sums < 5000 Wh/m² and slightly negative for higher values. Also the daily sums tend to be overestimated for days with lower irradiance and underestimated on clearsky days.

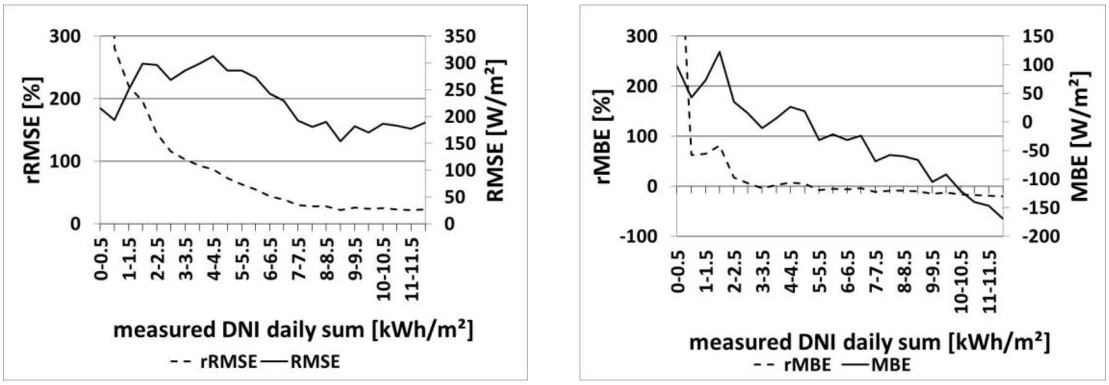

Fig. 4. Absolute and relative root mean square error (left plot) and absolute and relative mean bias error (right plot) depending on DNI day sums

DNI volatility needs to be described by a measure on how often the irradiance changes during a day. The number of direction changes in the hourly resolved DNI day curve is counted for every day. Clear sky days as well as completely overcast days show only one change at noon. The higher the number of DNI direction changes, the more volatile is the DNI, indicating broken cloud coverage with single, moving clouds passing through. Both the rRMSE and the rMBE show higher values for more volatile conditions (Fig. 5). The rMBE is negative for one and three sign changes, which are the days with higher DNI sums. This indirectly confirms the above finding of a negative bias for high DNI sums.

Overall, clear sky and high irradiance conditions can be predicted with a smaller forecasting error than conditions with cloud cover, but also tend to be underestimated.

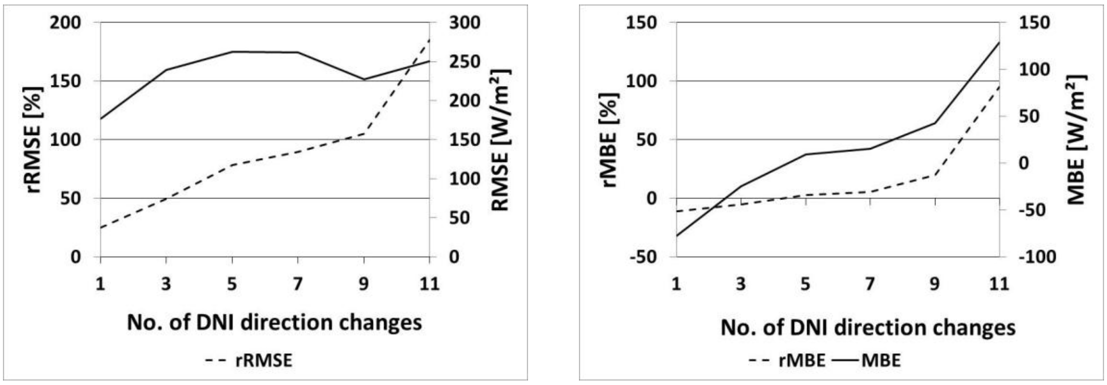

Fig. 5. Absolute and relative root mean square error (left plot) and absolute and relative root mean bias error (right plot) depending on DNI volatility

4. Market participation simulation

4.1. Simulation results

Table 2 shows the results from the day-ahead market participation simulation using both 2-day persistence and MOS forecasts. MOS forecasts significantly reduce penalty charges by 47.6 % compared to the simple persistence forecasts. Rising penalties are higher than falling penalties. This is mostly due to higher average rising penalty prices. The "Avg. penalty sum/MWh" is calculated by dividing the average penalty sum by the simulated electricity production of 404 GWh in the analysis period. It is noted in €/MWh and, therefore, serves as an average "price" for wrong forecasting throughout the year.

Table 2 Day-ahead market simulation results for the period July 2007 to December 2009

	Avg. Penalty Sum/Year	Avg. Penalty Sum/MWh	Falling penalties	Rising penalties	Reduction to persistence
Two-day persistence	€ 460,662	2.756 €/MWh	31.3%	68.7%	€ 219,062
MOS Forecast	€ 241,600	1,445 €/ MWh	26.5%	73.5%	47.6%

4.2. Forecast errors in terms of penalty charges

In this section, the error patterns identified above are checked for their monetary consequences. The average penalty per MWh of produced electricity is calculated independently for each range of the independent variable (Fig. 6). The red stacked line represents the period average of penalties per MWh, as indicated in Table 2, serving as a benchmark to compare specific situations with the average.

Penalties per MWh are above the average with increasing relative forecast error. A forecasting error below 10% includes the night hours where the forecasting error for obvious reasons is zero.

Penalties during night hours are always due to forecasting errors during the day, which result in a wrongly predicted storage load status in the evening. Especially for the range of DNI daily sums between 1000 and 7500 Wh/m², which has been identified as critical in section 3.2, penalties per MWh are indeed above the average. Penalties per MWh are below the average for days with a low DNI volatility (one and three direction changes) and above average for higher DNI volatility (> 3 changes).These results show that indeed the weaknesses of MOS (and probably other) forecast models have some financial impact. This is not straightforward as both the power plant simulation and the market prices have non-linear system components, such as the storage capacity in the power plant and the behavior of other market participants.

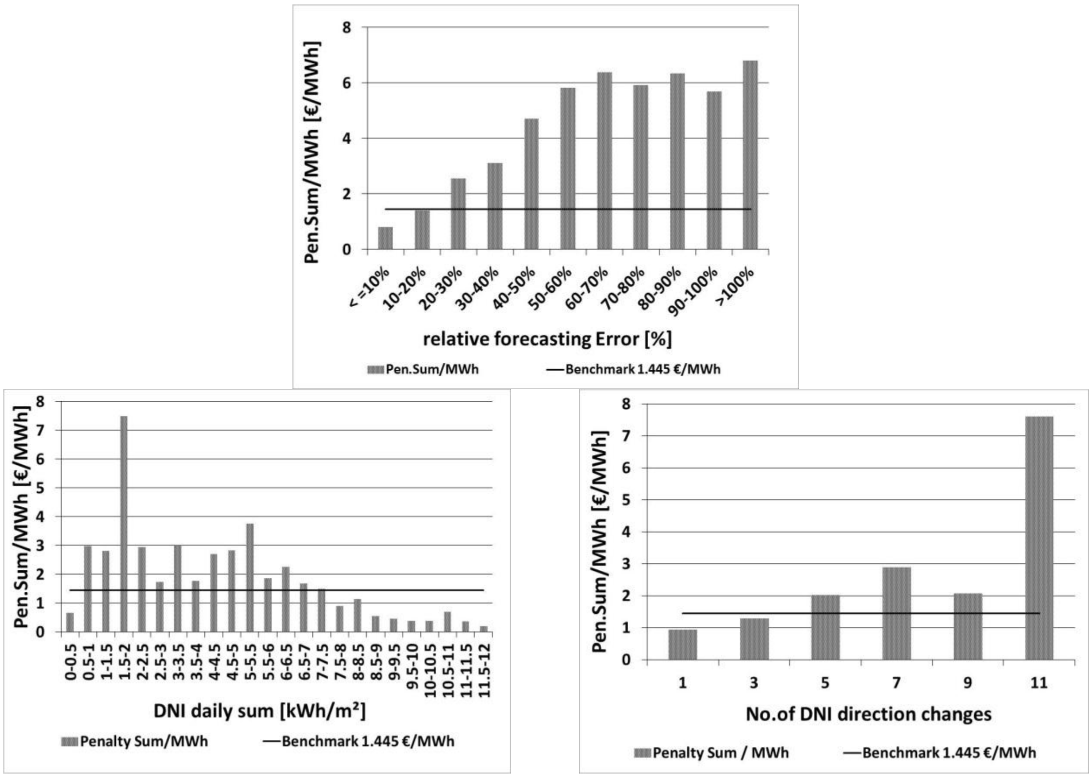

Fig. 6. Penalty/MWh depending on relative forecasting error (upper plot), DNI daily sum (lower left plot), and DNI volatility (lower right plot)

4.3. Sensitivity analysis of forecast improvement or deterioration

To assess the impact of potential forecast improvements or deteriorations, the hourly forecasting error has been reduced by fixed percentages with a 1% step width in the 0 to 10% range and in 10% steps in the 10 to 50% range. The plant simulation has been repeated with this data. Figure 7 shows how penalty sum and average penalty per MWh change if the hourly forecast error is reduced or increased. For an improvement of 10%, e.g. by evolution of NWP models (i.e., improvement of MOS input data), a penalty reduction of about 7% would be the result. The average penalty per MWh would then decrease from 1.445 to 1.34 €/MWh.

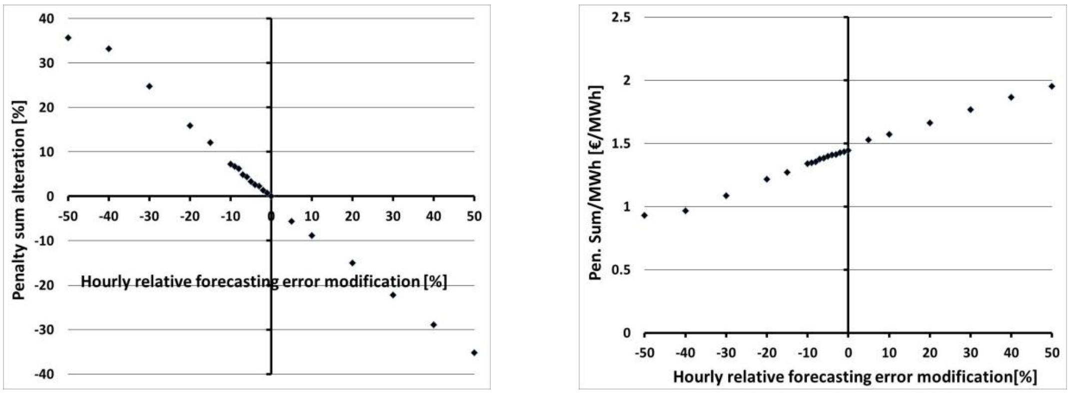

Fig. 7. Alteration of penalty sum (left pot) and of Avg.Penalty sum/MWh (right plot) depending on hourly forecasting error modification

5. Conclusions and outlook

For renewable energy producers, day-ahead market participation bears the risk of incurring penalties by failing to meet the announced production schedule. A reliable prediction of solar generated electricity would minimize these charges and enhance power plant profitability and competitiveness in the market. Different methods of solar irradiance forecasting and their typical accuracy have been presented in general, followed by a description of the data and models used in this study. A historical MOS DNI forecast, meteorological measurement data and a persistence forecast derived from the measurements were used together with the plant model PCTrough to simulate electricity market participation of the Spanish 50 MW parabolic trough plant Andasol 3 and the penalty charges that would have been incurred by forecasting errors.

Relevant forecast error patterns from the view of a solar power plant operator have been identified for the MOS forecast. In more cloudy situations with lower daily DNI sums and more volatile irradiance conditions, the forecasting accuracy is declining and it was shown that this has a financial impact by causing penalty charges above the normal period average. With growing installed solar power capacity, further research in DNI forecasting is needed to meet the demand of the solar industry for a more reliable production forecast enabling participation in competitive electricity markets. A great potential to leverage the identified weaknesses of existing forecasting models to predict irradiance in cloudy situations is expected to be provided by satellite imagery based forecasting and the interpretation and extrapolation of cloud motion.

Present DNI forecasting methods have weaknesses in predicting accurate values in high temporal resolution, particularly in situations with volatile DNI, which are mostly due to broken cloud coverage. This was demonstrated to be valid for a historic time series of a commercially available MOS forecast. With growing solar generated electricity installations capacity, further research in DNI forecasting is needed to meet the demand of the solar industry for a reliable production forecast that enables participation in competitive electricity markets. A great potential to leverage the identified weaknesses of existing forecasting models to predict irradiance in cloudy situations lies in satellite imagery based forecasting and the interpretation and extrapolation of cloud motion. Nevertheless, the present paper has shown that using DNI forecasts has the potential to significantly reduce penalty charges. Using a MOS forecast, savings were almost 50% of the total penalty sum compared to a simple 2-day persistence approach.

The further use of a reliable forecasting system lies beyond market participation. Operation and maintenance planning could be improved. For example, larger maintenance operations could be scheduled to periods with low forecasted irradiance. In plant operation, satellite nowcasting could enhance the temporal resolution from 60 to 15 min, with the potential of further improving solar field and turbine operations.

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