PREDICTION OF PHOTOVOLTAIC SYSTEMS PRODUCTION USING WEATHER FORECASTS

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Abstract

In this paper weather prediction production data model of photovoltaic (PV) systems is presented and compared with experimental data. The predicted PV system daily energy production and peak power output is becoming more important due to increasing technology penetration, the trading with electricity, and to establish the necessary back up capacities. Two forms of weather forecast were utilized. Forecast with 5-day horizon and day time step including data for cloudiness and temperatures, and 3-day horizon forecast with hourly time step prediction of solar radiation. Homer simulation tool was used for determination of hourly PV system production based on forecasted solar radiation. Simulation results were compared to the measured data for 14 kW_p grid connected system and 1,5 kW_p off-grid system.

1. Introduction

Distributed electricity production is rapidly inclining worldwide. Utilization of solar enegy with PV technology is among the frontrunners, but has some disadvantages such as time variability of production due to solar radiation variability. In order to manage electrical systems optimally, combine different production facilities in penetrating smart networks and above all trading with electricity, the forecasting of electricity production of PV systems is needed. This can be done regarding to needs such as desired time horizon. Various authors [1,2] utilize neural networks for forecasting short and also long term production. Even though neural networks utilization in PV production forecasts have high accuracy, they have important down side, which is that measurements are needed in very diverse conditions for learning the network for individual facility due to largely stochastic local meteorological conditions. Therefore we examine the possibility of utilizing available weather forecast for PV production prediction.

Some authors even predict the daily global radiation based on air temperature variation and rainfall [3]. Even though these methods show higher accuracy in prediction of air temperatures, we concluded that they are not relevant for prediction of solar radiation in our application therefore we do not utilize them. Forecasts usually, beside temperatures and phenomena, predict sky cloud cover or solar radiation. Without radiation prediction, like in the example of 5 day forecast utilized in this work, it has to be calculated from available parameters. We utilized the commonly used Kasten&Czeplak model.

2. Availability and content of weather forecasts

Base for all forecasts are results generated by the numerical model ALADIN which is widely applied. Weather forecast is available (in Slovenia forecasts are published by National Environmental Agency ARSO) for 3 days with hurly frequency and 5 days in advance with daily frequency. The data for 5 day forecast is presented in figurative form, and can be accessed automatically via XML/RSS/HTML services.

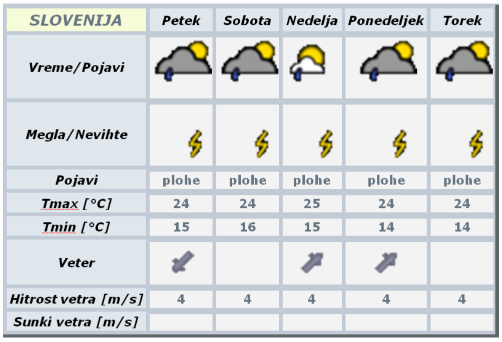


Fig. 1. Example of 5 days forecast for central Slovenia from forecasters [4]

Crucial values for prediction of solar radiation are share of the sky covered with clouds called oktas. Additional parameters can be included as well such as fog, thunderstorm with hail with; with its intensity and minimal and maximal temperature.

Table 1. Example of processed automated weather forecast for 5 days

Time of issuing	Forecast for day of the week	Consecutive day	Forecast for the date	Cloud coverage	Phenomena	Phenomena intensity	Min. T	Max. T
12.9.2011 8:00	Monday CEST	1	12.9.2011 12:00	6	4	1	17	28
12.9.2011 8:00	Tuesday CEST	2	13.9.2011 12:00	2	0	0	15	29
12.9.2011 8:00	Wednesday CEST	3	14.9.2011 12:00	4	4	1	16	28
12.9.2011 8:00	Thursday CEST	4	15.9.2011 12:00	4	0	0	15	29
12.9.2011 8:00	Friday CEST	5	16.9.2011 12:00	4	0	0	13	25

Parameters in the *Table 1* were obtained automatically with developed script. A phenomenon 4 in the table above stands for partly cloudy.

2.1. Prediction of solar radiation from cloud cover forecast

Because solar radiation is considered as the main influential parameter for PV system production , we are focusing on its forecast only. We are not taking in to account the losses of productivity due to the rise of temperature modules because analyses of PV systems done by International Energy Agency showed [5], that freestanding and flat roof systems, such as ones used for verification in this work, have the yearly temperature losses of energy yield between 1,7 and 5 % which is below the weather forecast accuracy of prediction.

The cloudiness, as a main indicator for solar radiation, is given with 8 levels in classical meteorological form. Where 0/8 means clear sky and 8/8 is sky full covered with clouds. Additional parameters forecasted are also the prediction of phenomena, from fog to thunderstorm with hail with its intensity, minimal and maximal temperature. The correlation between cloudiness and solar radiation is considered to be high according to various studies found in literature review [6,7].

This is used for the case of 5 day weather forecast utilization due to the fact, that solar radiation is not forecasted and needs to be calculated with model. In the case of 3 day forecast this is not necessary, because solar radiation is forecasted directly.
Determination of solar radiation from cloud cover is done by algorithm based on Kasten&Czeplak model [6]. This simplified weather forecast was compared to hourly forecast in order to evaluate its usability for PV production forecasting. In this case solar radiation on horizontal surface is predicted for every hour for next 3 days. Additional parameters in this forecast are the air temperature, relative humidity, velocity and direction of the wind and cloudiness.

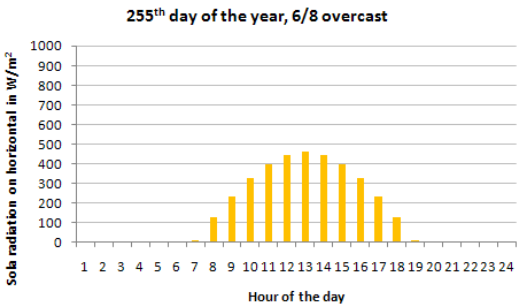


Fig. 2. Example of average hourly solar radiation prediction from cloud cover by Kasten&Czeplak model

Radiation estimation based on cloud cover was based on work of Kasten&Czeplak according to following algorithm [6]. For every hour of analyzed period the azimuth and height of the sun was calculated in order to get real sun paths over the year..

$$I_{GC} = 910 \sin\alpha - 30 \quad \text{Eq. 1}$$
$$I_G = I_{GC} \left(1 - 0{,}75 \left(N/8\right)^{3{,}4}\right) \quad \text{Eq. 2}$$
$$I_D = I_G \left(0{,}3 + 0{,}7 \left(N/8\right)^2\right) \quad \text{Eq. 3}$$

Where I_{GC} is clear sky global solar radiation on horizontal surface, α is solar altitude, I_G represents global horizontal irradiance, N is cloud cover in oktas and I_D represents diffuse pat of horizontal irradiance.
The model is relatively simple, and has some limitations. It underestimates maximal radiation in some cases.

2. 2. Three day time horizon forecast with hourly frequency

Five days horizon daily forecast was compared to the three days hour-by-hour forecasts.
We obtained them from ARSO generated by the ALADIN model with spatial resolution of 10 by 10 kilometres and time resolution of one hour. The height of the point in the model was approximately 300 meters above the terrain.

Table 2. Example of part of 3 day hourly model forecast for Zagorje ob Savi

Forecast for date	**Hour (UTC)**	**Temperature in °C**	**Rainfall in mm**	**Short wave radiation in J/m^2**	**Relative humidity in %**	**Wind velocity in m/s**	**Direction of wind in °**	**Overcast in %**
20120402	0	-3,6	0	0	76,2	1,3	250	0
20120402	100	-3,7	0	0	75,7	1,6	245	0
20120402	200	-3,8	0	0	74,9	1,6	240	0
20120402	300	-3,9	0	0	74,3	1,5	230	0
20120402	400	-4	0	0	74,1	1,7	220	0
20120402	500	-3,9	0	3	74,1	2	220	0
20120402	600	-2,7	0	80	72,2	2	220	10
20120402	700	0,3	0	233	66,8	1,8	225	10
20120402	800	3,2	0	400	63,8	1,9	235	10
20120402	900	5,2	0	548	62,1	2,5	240	10
20120402	1000	6,8	0	657	60,6	3,4	245	10
20120402	0	-3,6	-99	-99	76,2	1,3	250	0

The forecast in the *Table 2* was obtained from ARSO data

2.3. Forecast validation

Forecasts accuracy was verified by showing its variation for same target interval but different time horizons. This inaccuracy is shown in Figure 3 where cloud coverage forecasts issued on different days is presented. We observed how forecasts are in some cases corrected every day, because more data is obtained for prediction of target time horizon.

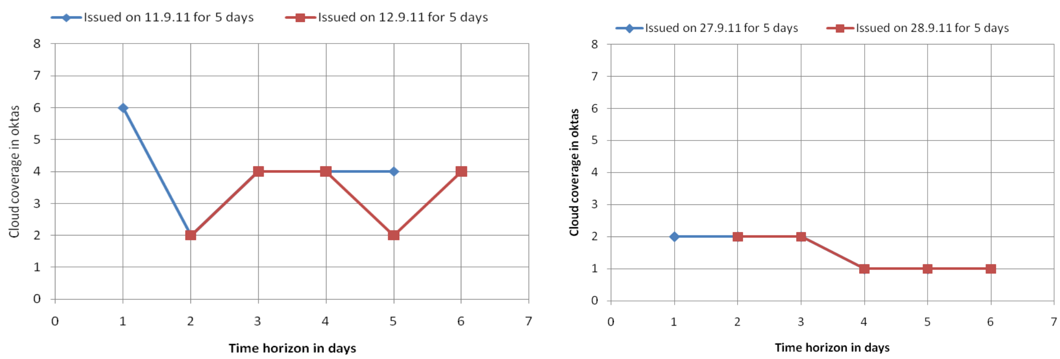


Fig. 3. Example of the differences between 5 day daily forecasts concerning the day of issuing

Fig. 3 shows the variation of forecasted cloud coverage index, used for determination solar radiation by utilizing Kasten&Czeplak model. Three - day time horizon hourly forecast issued on 2 consecutive days are shown in Figure 4.

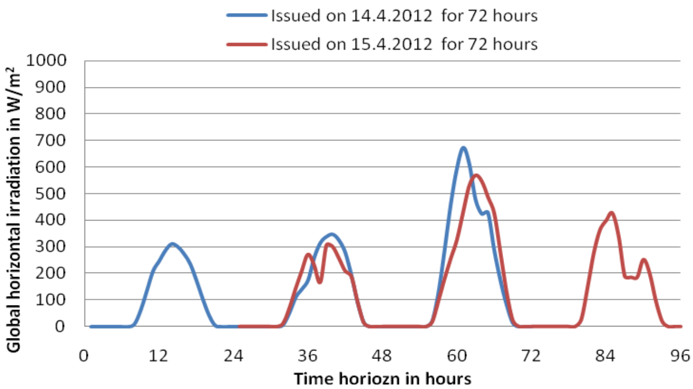


Fig. 4. . Example of the differences between 3 day hourly forecasts concerning the day of issuing

One can observe the variation in forecasted radiation for the same target time but different time horizons. This demonstrates the forecast uncertainty even on shorter time horizon such as one or two days. From this we can conclude, that forecast of PV system operation will be at least this inaccurate, because of we base our prediction on weather forecast. We cannot say how accurate the weather forecast is precise because this validation is substantial task and out of the domain of this research. The uncertainty will be imbedded in our forecasts.

3. PV system output modelling

PV modules are installed having certain orientation and declination. Solar radiation is forecasted for horizontal surface and hast to be converted to fit the analyzed PV system properties.
PV systems hourly output is modelled with Homer simulation tool [8]. Meteorological data obtained from weather forecast is integrated in to software input files. Hourly simulations of PV system operation based on weather forecasts are run for the periods of 3 and 5 days for various weather conditions that occur during the year.
Simulated data is compared with the field measurements from two PV systems, and adequacy of each weather forecast is analyzed based on daily electricity production, daily peak power and the time of daily peak occurrence.

4. Validation of prediction

4.1. Grid connected 14 kW_p PV system

This grid connected facility sell all produced power to public utility grid and is located in central Slovenia on a cultural centre in Zagorje ob Savi. It was build in the frame of FP6 Remining-lowex project. Its operation is monitored via SCADA based community utility monitoring and management system, therefore all historical high resolution production data is available.

It consist of 60 modules with total area of 98,2 m^2, azimuth 0° and slope 30°. Its maximal DC power is 14,3 kW and AC 13,5 kW and maximal DC voltage of 900 V. PV modules are silica polycrystal Perlight Solar PLM- P230 with silica nitride coating. Inverter is Power One type Aurora PVI – 12,5.

Fig. 5. Site (left) and modules of grid connected facility (right)

4.2. Off grid 1,5 kW$_p$ system

Island facility in installed on OLEA research demo unit in Zagorje ob Savi. OLEA is self sufficient mobile facility for presentation of new concepts of low exergy technologies based on renewable sources and low energy construction. PV system consist of 6 silica mono crystal modules Sinodeu ZD245 – 20m with total area of 9,2 m^2, azimuth 0° and slope 70°. Total peak power is 1,47 kW. OLEA is equipped with SMA Sunny Boy 1700 inverter 5ith 1550 W and peak DC power of 1850 W and voltage of 400 V. as a backup source a EFOY COMFORT E80 methanol fuel cell is installed. Produced and used electricity is managed by Sunny Island 2012 and stored in TAB lead batteries with nominal capacity of 1200 Ah at 12 V. system is monitored via SMA web box, and crucial parameters are measured by SMA sensor box equipment. Also its all key operational parameters are publicly accessible via SMA sunny portal

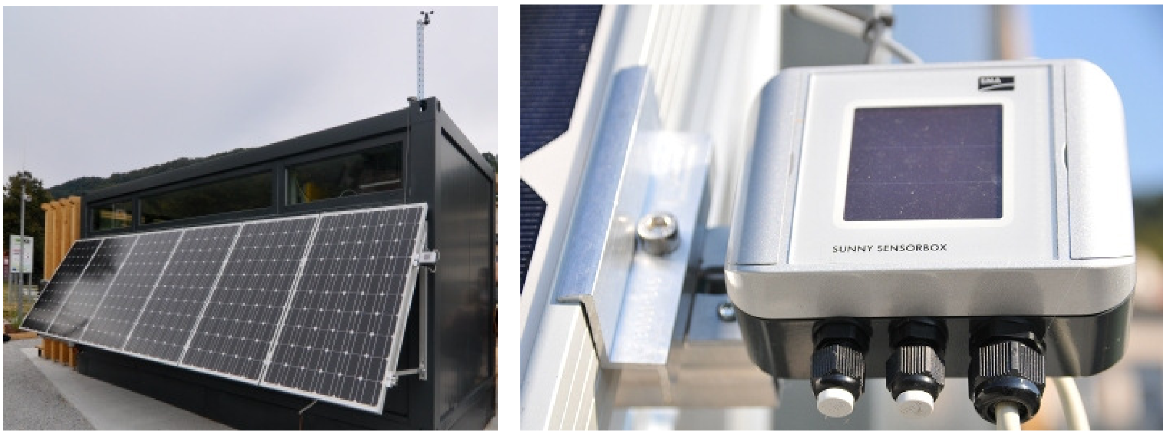


Fig. 6. OLEA off grid system (left) and its radiation sensor (right)

5. Verification of the model

Measurement form both systems were compared with two forecasts with different spatial and time resolution (3 and 5 days daily and hourly) for different weather conditions. In order to measure the prediction accuracy, various statistical parameters can be used. In this work we followed most commonly used method for accuracy measurement [9], which is root mean square error (RMSE).

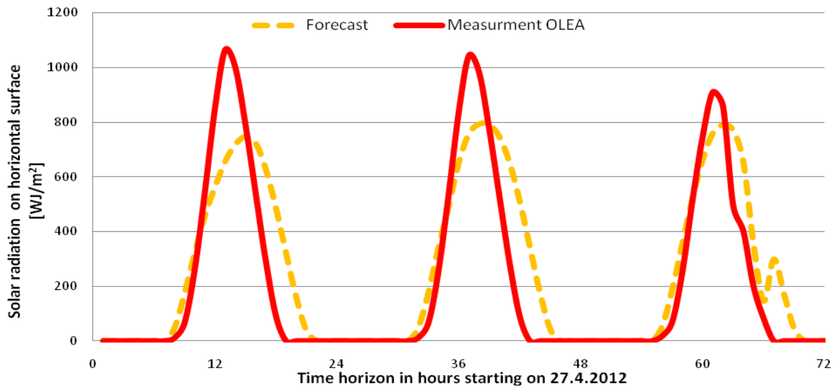
$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - x_{true}}{x_{true}}\right)^2}$$

Eq. 2.

Where n is the number of pairs of measurement and calculation/model evaluated, and the variable x represent the measured (index *true*) and forecasted (index *i*). The accuracy measure of RMSE is calculated for hourly values. Only hours with daylight are considered for the calculation of RMSE. We present results in relative values of error measures (rRMSE).

Three day time horizon local hourly forecast of low overcast and measurement for off grid system

We compare forecasted and measured average hourly power, daily peak power size and time. Peak power should occur at solar noon, on the clear days, but may vary when overcastted.
Because measurements take place on off grid facility one cannot compare electricity production, because if is a function of battery state of charge. Once the battery is full, there is no more electricity produced, even if radiation is available. Therefore we compare measured and predicted radiation on surface of PV system which is the main influential parameter for electricity production.



Calculated errors for:		**rRMSE [%]**
Hourly data	1st day	178,1
	2nd	186,3
	3rd	90,6
	All days	157,7
Daily energy	1st day	9,4
	2nd	20,4
	3rd	26,7
	All days	23,4
Peak	1st day	29,9
	2nd	24,1
	3rd	13,3

Fig. 7. Prediction and measurement of hourly values of solar radiation on horizontal surface for 3 day hourly low overcast forecast.

Fig. 7 shows the predicted and measured solar radiation. The daytime rRMSE of hourly horizontal solar radiation for the whole 3 days period is 157,7 % (total measured radiation energy in the period was 15,5 kWh/m^2 and predicted 18,3 kWh/m^2).

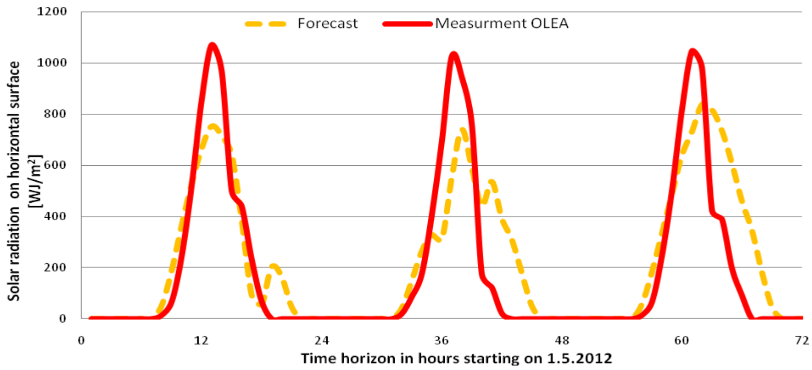
Table 3. Example of measured and predicted total daily solar radiation energy in kWh/m^2

Time horizon in days	1	2	3
Predicted	6,02	6,51	5,76
Measured	5,51	5,4	4,55

When comparing predicted and measured daily peak we calculate the rRMSE values on the range from 13 to 30 %, depending on time horizon. Measured peak for the first day was 1064 W, and predicted 746 W.

Three day time horizon local hourly forecast of mid overcast and measurement for off grid system

For mid overcast we consider variable forecast of sky cloud coverage, which was from 0,8 to 7,2 oktas in the analyzed period.



Calculated errors for:		rRMSE [%]
Hourly data	1st day	105,0
	2nd	540,9
	3rd	180,8
	All days	334,8
Daily energy	1st day	2,6
	2nd	10,2
	3rd	35,2
	All days	26,2
Peak	1st day	29,7
	2nd	27,9
	3rd	20,0

Fig. 8. Prediction and measurement of hourly values of solar radiation on horizontal for 3 day hourly mid overcast forecast.

Prediction of daily radiation energy for first day is very precise (2,6 %) but rRMSE for hourly values is 105 %. Reason is, as we can observe from the Figure 8, that higher peak is compensated with forecasted solar radiation variation in late afternoon that did not occur.

rRMSE of hourly horizontal solar radiation for the whole 3 days period is significant, 334,8 %.This shows high inaccuracy in hourly radiation predictions – for 2nd day rRMSE is 540,9%, but daily energy forecast missed for 35,2 %.

Peaks forecasts are accurate in the range from 20 to 30 %.

Table 4. Example of measured and predicted total daily solar radiation energy in kWh/m^2

Time horizon in days	1	2	3
Measured	4,99	4,43	4,78
Predicted	4,86	4,88	6,46

Three day time horizon local hourly forecast of high overcast and measurement for off grid system

In this analysis we focused on the period where forecasted sky cloud coverage was above 4 oktas most of the analyzed period.

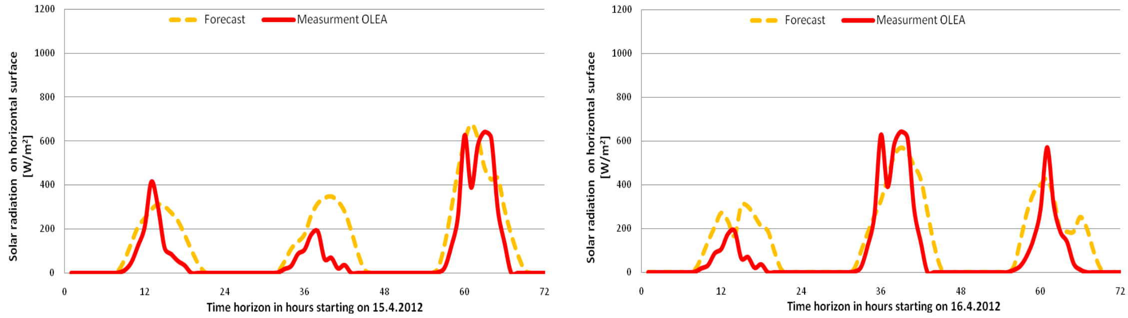


Fig. 9. Prediction and measurement of hourly values of solar radiation on horizontal surface for 3 day hourly high overcast forecast issued on 2 consecutive days.

Table 5: Comparison of accuracy prediction indicators for two consecutive days

Issued on 15 4 (left)			**Issued on 16 4 (right)**		
Calculated errors for:		**rRMSE [%]**			**rRMSE [%]**
Hourly data	1st day	276,4			
	2nd	**525,0**	Hourly data	1st day	**437,6**
	3rd	**213,6**		2nd	**165,5**
	All days	364,1		3rd	638,9
Daily energy	1st day	72,1		All days	457,2
	2nd	**232,1**	Daily energy	1st day	**208,3**
	3rd	**27,3**		2nd	**16,8**
	All days	51,2		3rd	71,9
Peak	1st day	24,7		All days	39,5
	2nd	**84,9**	Peak	1st day	**62,7**
	3rd	**5,3**		2nd	**11,1**
				3rd	25,0

Inaccuracy in high cloud cover period is significant, especially rRMSE for hourly predictions. Peak prediction is more successful in very cloudy conditions, because we know how it is limited. From the *Table 5* we can observe increase of accuracy (lower rRMSE) for most of the values on shorter time horizon. The this is not valid only for 2 (3) day peak forecast, which is problematic in all conditions.

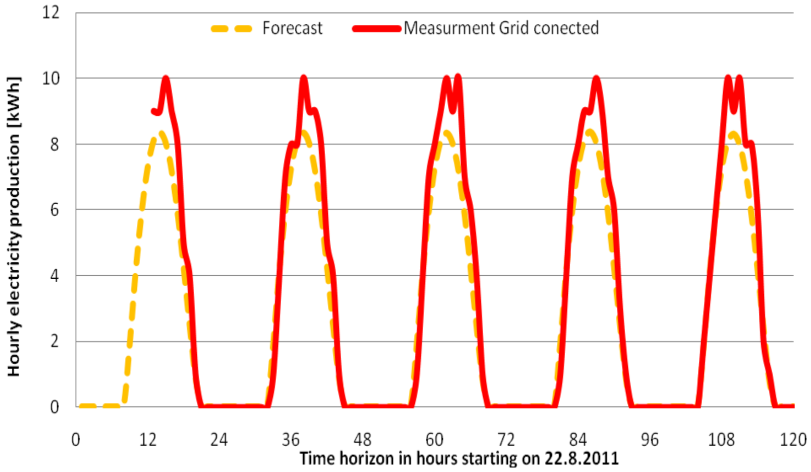
Table 6. Example of measured and predicted time of daily peak occurrence

Time horizon in days	1	2	3
Predicted	13:00	15:00	12:00
Measured	12:00	13:00	15:00

When predicting time of daily peak power occurrence, the precisions cannot be higher than 1 hour, because this is the time step of forecast and simulations. In low overcast period, the peak time can be determined accurately based only geometrical correlations between receiver surface and the sun as the function of time of the year. But for cloud covered sky this cannot be achieved with reasonable accuracy.

Five day time horizon regional daily forecast of low overcast for grid connected system

Solar radiation on horizontal plane for 5 day time horizon regional forecast is calculated by Kasten&Czeplak model from predicted overcast. Output of grid connected PV power plant is modelled with HOMER on hourly basis. System is model in detail and meteo input files are prepared for each period. Simulation of operation are run and presented here. They are compared with measurement of electricity production from grid connected facility.



Calculated errors for:		rRMSE [%]
Hourly data	1st day	15,9
	2nd	30,4
	3rd	31,4
	4th	30,0
	5th	17,1
	All days	25,9
Daily energy	1st day	17,6
	2nd	12,9
	3rd	15,5
	4th	12,8
	5th	13,8
	All days	14,6
Peak	1st day	16,3
	2nd	16,4
	3rd	16,6
	4th	16,2
	5th	16,9

Fig. 10. Prediction and measurement of hourly values of electricity production for 5 day daily low overcast forecast.

Forecasted cloud cover for the whole period was 1 okta. We can observe from the *Figure 10*, peaks are predicted to low. rRMSE of hourly power production for the whole 5 days period is 25,9 %. Total measured produced electricity was 353 kWh and we predicted 322 kWh in the 5 day period.
Mean precision of daily energy production prediction in low overcast weather forecast is 14,5 %.
The reason in underestimated peak may lie in the PV modelling in Homer simulation tool, but even though, the precision is in the range of 16 %.

Five day time horizon regional daily forecast of mid overcast for grid connected system

Due to daily time step, all daily profiles are flat, because we use only one value for sky cloud cover from the prediction. Forecasted cloud coverage was 6, 2, 4, 4, 4 oktas.

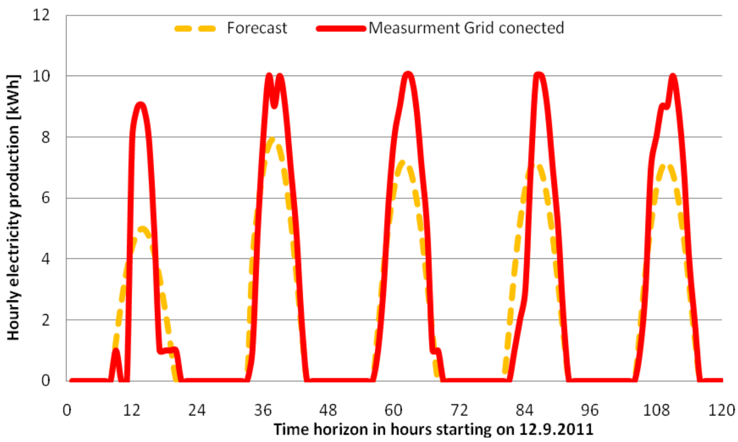


Fig. 11. Prediction and measurement of hourly values of electricity production for 5 day daily mid overcast forecast.

Calculated errors for:		rRMSE [%]
Hourly data	1st day	87,4
	2nd	90,6
	3rd	36,0
	4th	100,7
	5th	32,4
	All days	77,5
Daily energy	1st day	14,1
	2nd	13,4
	3rd	23,5
	4th	4,8
	5th	23,2
	All days	17,3
Peak	1st day	44,5
	2nd	20,4
	3rd	27,8
	4th	28,1
	5th	28,4

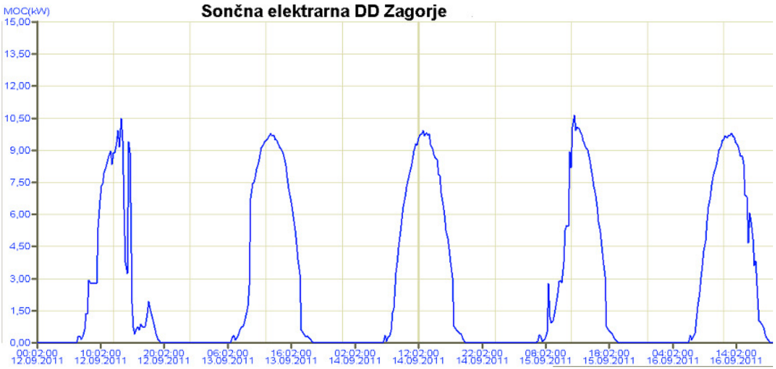


Fig. 12. Measurements of electricity production with 2 min sampling rate from PV plant *Delavski dom* monitoring system for same period as Figure 9.

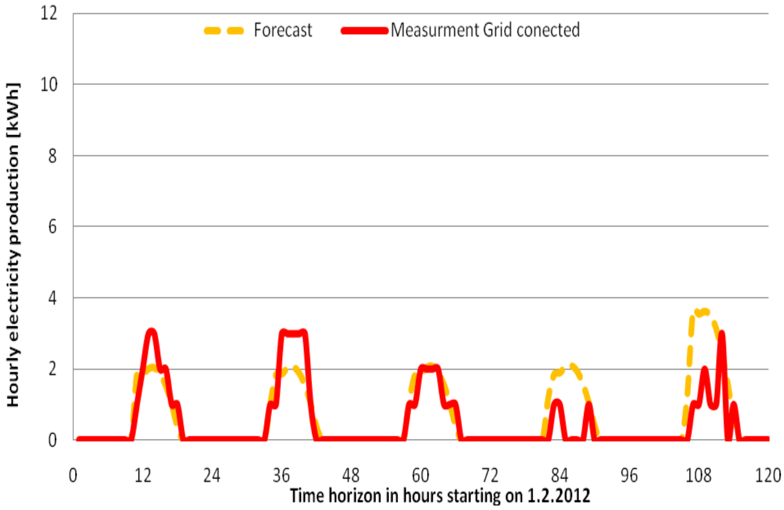
In this mid overcast period rRMSE of hourly power production for the whole 5 days period is 77,5 %. Total measured produced electricity was 305 kWh and we predicted 255 kWh in the whole 5 day period. Total daily energy production precision is up to 23,5 %

Peaks are underestimated in the prediction.

We can observe, that even though the forecasted cloudiness is significantly higher for the region than in previous case, the measured production profile is very similar. The reason is, that the predicted cloudiness does not reflect real condition of PV system site accurately enough.

Five day time horizon regional daily forecast of high overcast for grid connected system

In this scenario we analyzed the period with following forecasted cloudiness: 7,7,7,7 and 6 oktas for the 5th day.



Calculated errors for:		**rRMSE [%]**
Hourly data	1st day	41,7
	2nd	42,3
	3rd	42,0
	4th	43,7
	5th	177,3
	All days	87,9
Daily energy	1st day	16,4
	2nd	24,0
	3rd	6,9
	4th	370,6
	5th	134,0
	All days	176,7
Peak	1st day	32,0
	2nd	31,3
	3rd	4,0
	4th	110,0
	5th	21,5

Fig. 13. Prediction and measurement of hourly values of electricity production for 5 day daily high overcast forecast.

In high overcast period rRMSE of hourly power production for the whole 5 days period is 87,9% where total electricity production in the 5 day period was 59 kWh and predicted 77,6 kWh. Daily peak prediction precision is up or 32 %, except for the 4th day when it was 110 %.

Fig. 14. Measurements of electricity production with 2 min sampling rate from grid connected PV plant

From *Figure 12* we can observe, that values of produced electricity are close to zero, on the fourth day of analyzed period, as it can also be observed form *Figure 11*.

6. Conclusion

We found that prediction accuracy depends heavily on forecasted cloudiness. The accuracy of hourly values, daily energy and peak prediction is the highest in low overcast periods, as would one intuitively expect. In high overcast conditions, the 5 day time horizon daily forecast is more accurate for cumulative daily energy prediction than 3 day hourly, because fluctuations are nullified. Based on analyzed periods, we cannot conclude, that hourly 3 day forecast is more accurate in all conditions than 5 day time horizon daily. Low overcast periods are problematic, because they are heavily site specific. When the cloudiness is higher and fluctuating, the prediction accuracy is significantly decreased, as presented in the appendix. Hourly data comparison of predicted and measured solar parameters in the daytime can have rRMSE over 500 %.Peak prediction is most accurate in low overcast conditions (rRMSE=~20%), followed by mid overcast (rRMSE=~30%). The regional 5 day daily forecast is more accurate in the unstable (high overcast) conditions. It can be utilized for prediction of PV daily production with high confidence (below 20 %) in low overcast periods. When there is low overcast period, the prediction corresponds well with measurements for both types of forecast and is limited mainly by the accuracy of production model itself. Local 3 days hourly forecast has its limits, due to local meteorological and geographical specific condition which are not modelled in the national weather forecast model, such as winter inversion, fog and local air pollution, but it has advantage of forecasting the time and size of the peak (rRMSE=~20%), in mid overcast conditions. Daily cumulative values of electricity production are relatively accurate for low and mid overcast (rRMSE<20%), for prediction of time and size of peaks other methods should be utilized. We conclude that even 5 day time horizon daily forecast could be utilized for prediction of PV systems production parameters on daily basis, but hourly values are still very inaccurate. Future work should include determination of confidence intervals for predicted variables

7. Acknowledgments

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8. Appendix –presentation of results

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