USE OF SOLAR RADIATION DATA FROM HELIOCLIM DATABASE FOR SHORT-TERM PV SYSTEM POWER OUTPUT PREDICTION FOR POLISH LOCALIZATION

M. Chwieduk

Instytut Techniki Cieplnej, Wydział Mechaniczny Energetyki i Lotnictwa,
Politechnika Warszawska, Warszawa, Polska

ABSTRACT

Installed power of photovoltaics systems in Poland grow systematically. Annual contribution of energy produced from PV systems in Polish power system is still on the low level. Due to irregular and stochastic characteristic of solar radiation distribution during the year in specific weather conditions power supplied by PV system might have impact on operation of electric grid. Such situations occur more often in European countries that developed solar energy sources in their power system. Due to power grid balancing and its stability, prediction of power generation in renewable energy sources become more important. On the other hand development of earth observation techniques give new tool for accurate solar radiation data acquisition and its prediction.

Article presents model of energy production of PV system based on data from HelioClim database. HelioClim database stores solar radiation data obtained from Meteosat images received from Eumetsat. It also contains 24 hour solar radiation prediction model. PV system model is validated for historical data and used to predict energy output from a specific system. Received prediction of energy production is compared with real output power of a system.

INTRODUCTION

Energy production forecast plays an important role in implementing smart grid idea. Effective management and control of a grid requires reliable information about energy demand and energy production from renewable energy sources to reduce energy losses in grid and avoid breakdowns. Management of controlled energy production units requires planning based not only on actual energy balance in grid but also changes that will appear in near future. All components of energy balance in grid should be controlled or predicted to manage it effectively.

Power of renewable energy sources connected to grid systematically rises in all of European countries. That trend is strictly connected with global PV systems price decrease and its financial impact on investment return time. Speed of growth of installed PV systems power different for different countries depends on one hand on solar condition on the other on specific for each country financial support mechanism for PV/RES systems. Increasing role of PV systems in some national power systems and in many local power grids forces to find accurate forecast solution which might be used for a wide range of applications and in local grids where renewable energy sources are significant energy suppliers.

PV SYSTEM POWER OUTPUT FORECASTING

Energy production forecast form PV system typically consist of two parts: weather prediction model and PV system power output model. Weather prediction model provides weather data from which most important is irradiance. Additional data depends on PV system power output model and typically consist of air temperature and wind velocity. Accuracy of irradiance prediction directly influence accuracy of energy production forecast.

There are number of techniques used for irradiance forecast, below most common are listed. Depending on forecast horizon prediction model can be divided as follows (Pelland et al. 2013)(Kleissl 2013):

- Whole sky imaginary – technique that is based on sky photography and analysis of clouds movement. It can provide very short time forecast up to 10-30 minutes. Irradiance is predicted based on current value and cloud shadow change calculated form cloud velocity and direction.
  Sampling rate depends on frequency of sky imaging and imagines processing time, all this processes can take up to 30 seconds. Spatial resolution of this technique may vary from 10

up to few hundred meters. Whole sky imaginary provides accurate irradiance forecast for a specific location form which sky photographs are taken;

- Satellite imagery – satellite images are used to predict cloud movement and to calculate cloud transmissivity. Techniques used for providing forecast are very similar to those used in whole sky imaginary. Large area covered by satellite image provide information for much longer forecast horizon, which might be up to 5 hours. On the other hand sampling ratio depend on frequency of new satellite images supply. Forecast might be updated every 15 minutes when geostationary satellite is used. Spatial resolution for this method also depends on quality of satellite images and it can be around 1 km;
- Stochastic learning techniques – model provides prediction based on analysis of historical and actual weather data and identifying similarities, patterns. Forecast horizon depends on applied algorithms, typically it is not longer than a day ahead. Sampling rate is connected with weather data update frequency and can also vary form few minutes up to one hour. Spatial resolution depends on available actual weather data, it can vary from hundred meters for data taken from single location up to few kilometers if satellite images are used for estimating irradiance. Biggest disadvantage of stochastic learning technique is forecast accuracy. Accuracy strongly depends on weather changes, all changes in clouds presence gives significant error increase (Perez et ak. 2010);
- Numerical Weather Prediction (NWP) – advanced mathematical models of atmosphere and oceans are used to predict weather basing on current weather conditions (inter alia: satellite images). NWP can provide forecast for up to 10 days, it spatial resolution can vary from 2 to 50 km. Weather forecast is usually updated every hour. NWP provides forecast for longest horizon but its accuracy for intraday forecast has lower accuracy than Whole sky imaginary and Satellite imagery.

Irradiance forecast (and additionally temperature and wind velocity) is only a part of prediction of power output form PV system. Second part connects weather conditions forecast and PV system specification. There are three most common approaches for PV system output modelling (Pellad et al. 2013):

- Statistic methods – provides PV system output power based on historical data, booth weather and energy production;
- Physical methods – starting from physical model of PV module (or PV cell) and other system components using weather data gives information about produced energy or system power in specific solar conditions;
- Artificial intelligence methods – uses neural networks to connect weather conditions with PV system output power taking in to account several parameter influencing energy production. This method requires historical data for learning process.

SODA HELIOCLIM3 DATABASE

SODA (SOlar radiation DAta) is a satellite-derived solar radiation database. SODA has been developed by Centre Observation, Impacts, Energy, which is laboratory of MINES ParisTech and ARMINES. SODA Service connects a list of services provided by 6 different institutions: NASA(USA), ISAC(Italy), MINES ParisTech (France), METEOTEST (Switzerland), NCEP (USA) and ENTPE (France). SODA offers simple access to a large set of data related to solar radiation.

SODA database storage irradiance values obtained from Meteosat images and additionally weather conditions data. Meteosat images are updated every 15 minutes. Values of irradiance can be interpolated for every location in Europe and can be recalculated for different orientation of solar energy receiver – azimuth and tilt of receiver plane. Historical data for years since 2004 up to 2006 are available for free. Recent model developed for obtaining accurate results of irradiance from Meteosat images is called HelioClim-3 version 4.

Forecast made by SODA portal is based on statistical analysis of HelioClim-3 irradiation database. Forecast is called similarity forecast because its mechanism uses similar to current day irradiance data searched in database for preparing forecast. Current day irradiance is compared with historical data from last 4 years, 10 days with similar irradiance values and day profile are searched. Basing on irradiance data of days following choose dates, average values are calculated and used as a forecast for current day. Regarding to different forecast methods listed in chapter - PV system power output forecasting - forecast prepared by SODA portal can be counted as Stochastic learning technique (SODA portal).

HISTORICAL SODA AND IN-SITU SOLAR IRRADIATION DATA COMPARISON

SODA portal provides historical solar irradiation and meteorological data interpolated for every location in Poland. Data used for comparison was measured in city Falenica near Warsaw (latitude 52.161, longitude 21.212). PV installation and measuring devices from which data was obtained are described in different papers (Pietruszko et al. 2009, Pietruszko Gadzki 2004) and where provided by authors of these papers. Data measured in situ and obtained from SODA are combined in Table 1.

Table 1. Data measured in situ and provided by SODA portal

In situ measurement data		SODA data	
Parameter	Unit	Parameter	Unit
Solar irradiance – global horizontal	W/m²	Irradiation – global horizontal	Wh/m²
		Irradiation – direct horizontal	Wh/m²
		Irradiation – diffuse horizontal	Wh/m²
Solar irradiance – global tilt[1]	W/m²	Irradiation – global tilt[1]	Wh/m²
		Irradiation – direct tilt[1]	Wh/m²
		Irradiation – diffuse tilt[1]	Wh/m²
		Irradiation – reflected tilt[1]	Wh/m²
Wind sped	m/s	Wind speed	m/s
		Wind direction	-
Ambient temperature	°C	Ambient temperature	°C
Module temperature	°C	Relative humidity	%
Time step	5 minutes	Time step	5 minutes

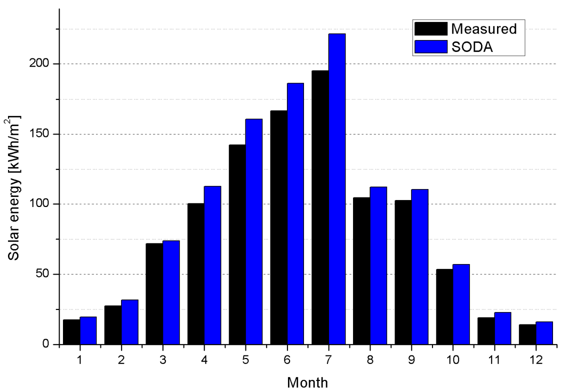
[1]Azimth 0°, Tilt 30°

Irradiation data from both sources where compared - global horizontal irradiation and global tilt irradiation. Month irradiation data are compared on graph 1 and 2, representing global horizontal irradiation and global tilt irradiation. Additionally root mean square error (RMSE) was calculated using following formula:

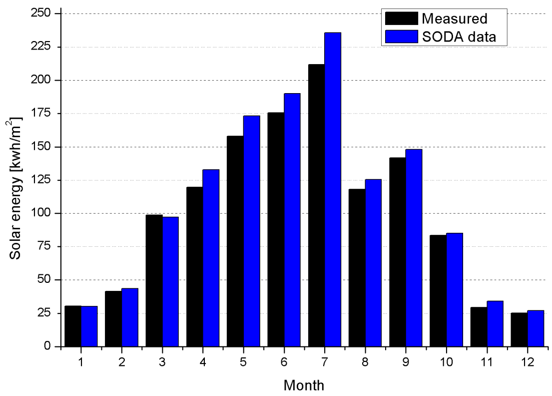
$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}\left(\overline{y}_t - y_t\right)^2}{n}} \qquad (1)$$

Where: n – number of measurements (data for every day - only data from sunrise to sunset); t – measurement data number; $\overline{y}_t$ - irradiation data form SODA database; y_t - irradiation in situ data.

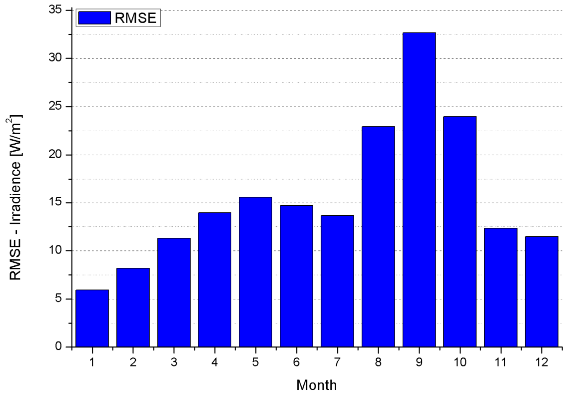
Results of RMSE value for every month for horizontal and tilt data are presented on graph 3 and 4.



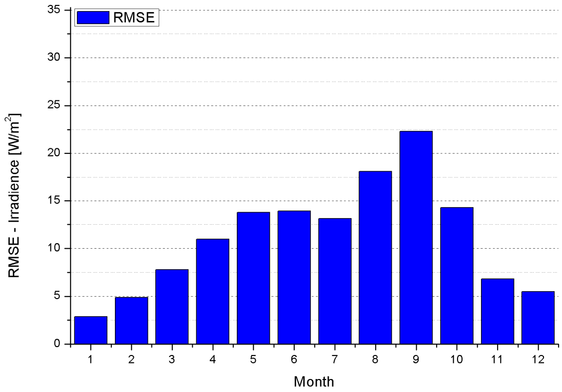
Graph 1. Horizontal month irradiation measured and provided by SODA database [kWh/m²]



Graph 2. Tilt month irradiation measured and provided by SODA database [kWh/m²]



Graph 3. RMSE for irradiance on horizontal plane [W/m^2]



Graph 4. RMSE for irradiance on tilt plane [W/m^2]

Annual value of irradiance on horizontal plane measured in-situ is equal to 1015 kWh/m^2, corresponding value provided by SODA database is equal to 1125 kWh/m^2. Annual value measured in-situ on tilted plane is equal to 1234 kWh/m^2, corresponding value provided by SODA database is equal to 1322 kWh/m^2.

PV INSTALATION MODEL

To compare possibility of SODA database usage, historical data of irradiance was used to calculate PV system output. Physical model of PV installation based on PV modules and inverter parameters was proposed. Data obtained from this model where compared with real output data from installation. This comparison was made to evaluate accuracy of proposed model and in next step to evaluate forecast provide by SODA database and power output from real installation. Model of PV installation is needed for comparing predicted energy production and real measured in system.

Physical model of PV installation consist of model of PV module and inverter. Equation provided by Skoplaki et al. (Skoplaki et al.2008) was used to evaluate PV module temperature (T_c):

$$T_c = T_a + \frac{1}{G_{NOCT}}\left(T_{NOCT} - T_{a,NOCT}\right)\frac{h_{w,NOCT}}{h_w(v)}\left[1 - \frac{\eta_{STC}}{\tau\alpha}\left(1 - \beta_{STC}T_{STC}\right)\right] \qquad (2)$$

Where:
$h_w = 5.7 + 2.8v_w$ – wind convection coefficient; v_w – wind speed close to PV module; T_a - ambient temperature; G_{NOCT} – irradiance at NOCT conditions (800 W/m^2); T_{NOCT} – cell temperature at NOCT conditions; $T_{a,NOCT}$ – ambient temperature at NOCT conditions (20°C); $h_{w,NOCT}$ – wind convection coefficient for wind speed at NOCT conditions ($v_w = 1m/s$); η_{STC} – efficiency at STC conditions; τ – transmittance of cover system; α – absorption coefficient of cell; β_{STC} – temperature coefficient of maximal power at STC conditions; T_{STC} – ambient temperature at STC conditions (25°C).

Power of PV module (P_{PV}) was obtained from equation (Brihmat Mekhtoub 2014):

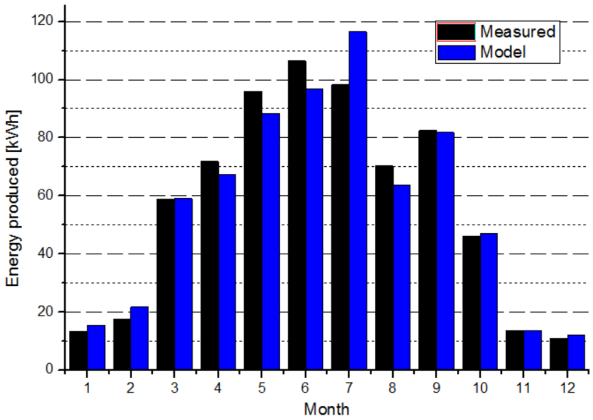
$$P_{PV} = P_{max}\left(\frac{G_T}{G_{STC}}\right)\left[1 + \beta_{STC}(T_C - T_{STC})\right] \qquad (3)$$

Where:
P_{max} – module power at STC; G_T – irradiance at PV module plane; G_{STC} – irradiance at STC conditions.

Parameters of PV module used in model of PV installation in Falenty are: T_{NOCT} - 45,2 °C; η_{STC} – 5%; β_{STC} - 0,4 %/°C; $\tau\alpha$ - 0,9; P_{max} - 50W. Parameters given by SODA database with 5 minutes time step are as follows: T_a, v_w , G_T. Additionally losses in DC wires connecting modules with inverter where taken into account. Inverter efficiency in a function of load was approximated by polynomial approximation. Whole PV system build in Falenica is described in details by Pietruszo et al. (Pietruszo et al.2009).

PV MODEL VALIDATION BASED ON HISTORICAL DATA

Purposed and described model of PV installation was validate using historical data measured in Falenica. As an input to model irradiance in PV module plane, ambient temperature and wind speed where used to calculate output power of the system. Annual energy production from PV system in Falenica in 2006 was equal to 686 kWh. Annual energy production result from calculations is equal to 678 kWh. Additionally monthly values of energy produced by system and values obtained from calculations are shown on graph 5.



Graph 5. Monthly values of energy produced by PV system in Falenica and values obtained by model [kWh]

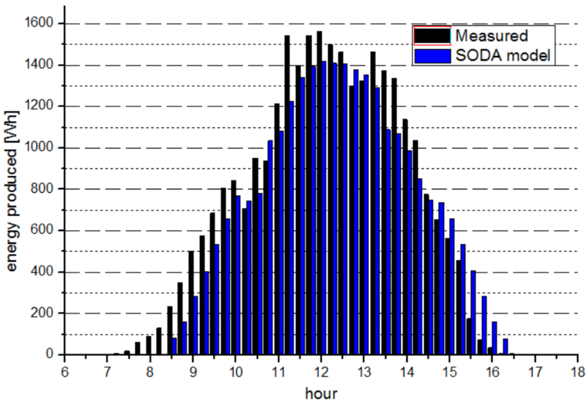
Results from purposed model corresponds with measured values. Relative error for monthly values does not exceeds 20 kWh, absolute maximal error value is equal to 23% (February). Annual energy production is estimated with very good accuracy, but results for each month and day have significant error. PV system in Falenica is based on amorphous silicon (a-Si) modules, which are difficult to model. A-Si modules has narrow spectral response in comparison with crystalline silicone modules and module performance changes with change of solar spectrum (different air mass). Additionally the thermal annealing effect and directly connected light induced degradation effect influence performance of a-Si modules (Skoczek et al. 2011).

PV SYSTEM POWER PREDICTION BASED ON SODA FORECAST DATABASE

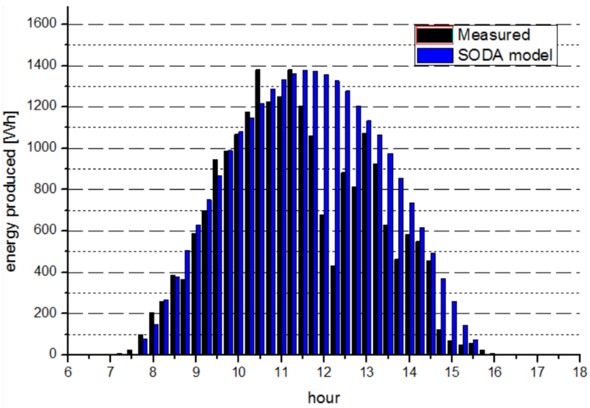
Model described in previous chapter was used to conduct calculation based on SODA irradiance forecast. Results of calculations where compared with measured energy production of PV system placed in Warsaw which nominal power is 10 kWp (9832,5 Wp). System is built from crystalline silicone PV modules and 10kW TL inverter. Parameters of PV module used in model of PV installation in Warsaw are as follows: T_{NOCT} - 45,7 °C; η_{STC} – 14,8%; β_{STC} - 0,5 %/°C; $\tau\alpha$ - 0,9; P_{max} - 230W.

SODA portal irradiance forecast is made one day ahead. Period form 1 October 2017 to 14 October 2017 was investigated. Each day one day ahead SODA portal forecast of irradiance was prepared for specified location. Next day real measured PV system energy production was compared with forecast. As a result relative error and RMSE for whole time period was calculated. Basing on obtained data and comparing different days two scenarios in irradiance forecast where most popular:

- SODA forecast was very accurate – situation occurred when two consecutive days had very similar irradiance profile during whole day;
- Soda forecast had significant errors – situation occurred when two consecutive days had very different irradiance profile during whole or part of a day.



Graph 6. Energy produced by PV system on 11 October 2017 and forecast of energy production



Graph 7. Energy produced by PV system on 7 October 2017 and forecast of energy production

This two cases result directly from how model of similarity forecast delivered by SODA works. Two cases described above are shown on graph 6 and 7. Energy produced by system every 15 minutes are compared with energy production based on SODA forecast data and PV installation model.

CONCLUSION

In this paper measured historical solar irradiance data were compared with data available with SODA portal for specific location. Solar irradiance data was measured in Falenica near Warsaw. Data form year 2006 was compared and gave small RMSE error. SODA HelioClim database in comparison with measured solar irradiance result in RMSE equal to 17 W/m^2. Purposed in article physical model of PV system does not describe correctly PV system based on a-Si PV modules. Annual energy production simulation gave small - 1% absolute error but monthly and daily calculated values had error a significant error. The same physical model was applied for c-Si PV module installation gave much better accuracy. Calculations using SODA forecast model where conducted for two weeks period. Data from installation place in Warsaw was used as an reference. As a result small relative error for whole prediction period – 4% was achieved. Detailed analysis showed substantial errors in solar irradiance forecast in case of change of solar irradiance profile day by day.

Different techniques of short term PV output power forecast are available, each has its own advantages. Using SODA similarity forecast for short term PV power output prediction does not require and specific measurements done in situ. Prediction can be performed easily for almost every location in Europe. Conducted calculation showed that SODA irradiance database containing historical data corresponds with measured irradiance values. On the other hand SODA similarity forecast does not provide high accuracy prediction for each day. Solution with better accuracy, based on satellite images or NWP would provide more reliable forecast. SODA similarity model can be used as a good approximation, with the awareness of the limitations resulting from the model operation.

LITERATURE

Pelland S., Remund J., Kleissl J., Oozeki T., Brabandere K., "*Photovoltaic and Solar Forecasting: State of the Art*", INTERNATIONAL ENERGY AGENCY, PHOTOVOLTAIC POWER SYSTEMS PROGRAMME - IEA PVPS Task 14, Subtask 3.1, Report IEA-PVPS T14-01: 2013, October 2013

Perez R, Kivalov S, Schlemmer J, Hemker K Jr., Renne D, Hoff TE, "*Validation of short and medium term operational solar radiation forecasts in the US*", Solar Energy, 2010

Kleissl J. (editor), "*Solar Resource Assessment and Forecasting*", Elsevier, 2013

SODA Portal - http://www.soda-pro.com/

Pietruszko S., Fetlinski B., Bialecki M., *„Analysis of the performance of grid connected photovoltaic system"*, Photovoltaic Specialists Conference (PVSC) 34th IEEE, 2009

Pietruszko S., Gadzki M., *„1 kW grid-connected PV system after two years of monitoring"*, Opto-electronic Review 12(1), p. 91-93, 2004

Skoplaki E., Boudouvis AG., Palyvos JA., *„A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting",* Solar Energy Materials & Solar Cells 92: p. 1393-1402, 2008

Brihmat F., Mekhtoub S., *„PV Cell Temperature/ PV Power Output Relationships Homer Methodology Calculation"*, Conférence Internationale des Energies Renouvelables "CIER'13", International Journal of Scientific Research & Engineering Technology, 2014

Skoczek A., Virtuani A., Cebecauer T., Chianese D., *„Energy yield prediction of Amorphous Silicon PV modules using full time data series of irradiance and temperature for different geographical locations"*, 26th European Photovoltaic Solar Energy Conference and Exhibition, p. 3248 – 3254, 2011