Energy production estimation for Kosh-Agach grid-tie photovoltaic power plant for different photovoltaic module types

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Abstract. This paper is devoted to calculation of yearly energy production, demanded area and capital costs for first Russian 5 MW grid-tie photovoltaic (PV) plant in Altay Republic that is named Kosh-Agach. Simple linear calculation model, involving average solar radiation and temperature data, grid-tie inverter power-efficiency dependence and PV modules parameters is proposed. Monthly and yearly energy production, equipment costs and demanded area for PV plant are estimated for mono-, polycrystalline and amorphous modules. Calculation includes three types of initial radiation and temperature data—average day for every month from NASA SSE, average radiation and temperature for each day of the year from NASA POWER and typical meteorology year generated from average data for every month. The peculiarities for each type of initial data and their influence on results are discussed.

1. Introduction

Russian Government Bylaw No. 449 from May 28, 2013 was the first law action to widely promote renewable energy application in large grid-tie power systems. In case of solar power it means that capital expenses for photovoltaic (PV) grid-tie power plant from 5 MW (peak) can be compensated to owner in case he wins competition for renewable energy generation which is held by Russian Energy Ministry every year. Low capital expenses and large share of made-in-Russia components (50% from 2014 and 70% from 2016) are important conditions to win the competition.

PV modules are the most important components of a PV plant, which define its energy production, lifetime, costs and area covered by the plant. Nowadays the only PV module producer exists in Russia, which can propose PV modules those are fully meeting the competition conditions. This company that is named HEVEL produces tandem amorph-micromorph thin-film silicon modules based on Oerlikon technology. Some companies compose their modules from purchased abroad mono- or multi-Si PV cells. These modules are also can be mounted on grid-tie PV plants in frames of the Bylaw No. 449, but only in 2014–2015. Several companies are also planning to produce crystalline PV cells and modules in Russia after 2016.

Different types of Si PV modules have different efficiency, different tolerance to temperature and solar radiation conditions and different prices [1–4]. So proper module choice is very

Table 1. Key parameters of PV modules used in calculations.

No.	PV module type and parameters	YL 250 P	HEVEL	Sun Power E20/327
1	Materials and technology	Multi-Si	Tandem a-Si/mc-Si	IBC based on high-purity mono-Si
2	Surface area (m^2)	1.63	1.43	1.68
3	Peak power (W)	250	125	327
4	Cost (₽1000)	17.3	5.50	34.3
5	Power temperature coefficient (%/°C)	−0.45	−0.29	−0.38
6	NOCT[a] (°C)	46	47	45
7	Length (m)	1.65	1.30	1.60
8	Width (m)	0.99	1.10	1.05
9	Specific price (₽/W) (₽80/$)	69	44	105
10	Open circuit voltage (V)	46.7	120	64.9
11	Operation (MPP) voltage (V)	37	90	54.7
12	Operation (MPP) current (A)	8.37	1.39	5.98

[a] Nominal Operating Cell Temperature.

important from the point of view further PV plant operation. The Koch-Agach power plant that is considered in this study was built in the south of Altay Republic and put into operation by Avelar Company in the autumn of 2014. The plant is based on multi-Si modules, which are quite popular over the world for different solar energy application (including grid-tie PV plants) due to their relatively low cost and relatively high efficiency [5].

2. Key parameters of modules and initial climatic data for calculations

In this study, multicrystalline PV modules from Yingli Solar are considered. Another type of PV modules that can be used in PV plant is the tandem-type of amorphous-micromorph silicon thin-films modules produced by HEVEL Company. This type of modules was enough popular up to 2008–2009 due to the lack of crystalline silicon at those time and much higher prices for crystalline PV modules. It has less efficient and less temperature coefficient of power value than crystalline modules. On top of that, the thin-films PV modules can convert wider part of solar spectrum. Introduction of micromorph layer allowed to increase efficiency up to 9–11% [6] and to significantly decrease performance degradation compared to pure amorphous silicon thin-film PV modules [7].

Considering Russian Government Bylaw No. 449 this type is the only one in Russia to date, which can satisfy modern and prospective localization demands. Serious drawbacks for these modules are concerned with low efficiency that leads to more area and mounting poles compared with crystalline modules, high open-circuit and operation voltage, string boxes, frameless construction, special measures and equipment for transporting and mounting.

The third considered PV module type is highly efficient IBC (interdigitated back contact) technology based product from Sun Power Corporation. These modules are one of the most efficient in the world, but this efficiency is based on thin and high-purity n-type silicon wafers and sophisticated multi-stage production technology [2], providing p–n junction formation on back surface of the PV cell and free from any contacts frontal surface. So prices for these modules are quite high. Key parameters of considered PV modules are given in table 1.

Economic estimation of PV plant is based on capital costs and energy production estimation. Energy production can be estimated basing on climatic data. There are several ways to obtain such data. The most efficient and expensive one is to monitor solar radiation in place of planned

plant construction for different PV modules tilt angles for several years. But demanded time and costs are high, so this way is usually never used in real practice. Data on solar radiation can also be taken from ground-based weather station, which is near the future construction site. There are two main problems for this approach. First, precision of data obtained will be less in case when weather station is quite far from construction site. So, in Russia a distance between site and weather station can reach several hundreds of kilometers. Second, weather station usually monitors solar energy on horizontal surface and the further approximation and mathematical processing for possible PV modules tilt angle are required.

So climatic specialized databases for estimation of PV power plants production are widely used in scientific and engineering approaches due to their availability and wide spatial coverage. NASA SSE [8] database is one of the most adequate for such calculations. NASA SSE is based on the satellite measurements data and their further mathematical processing. For chosen location it gives an averaged data (for 30 years) about solar energy for different tilt of PV modules, daylight hours, temperature of air and earth skin and many other useful parameters. Spatial resolution is 1° by 1°, time resolution is typical (averaged) day for every month of the year. For Russia in 2007–2009 verification for this data was conducted using data of ground-based weather stations [9]. This verification showed quite good agreement between database and averaged ground data on horizontal surface. Later study of small PV plant in Cheboksary including direct experimental measurements of solar radiation on tilted surfaces and theoretical estimates for energy production based on NASA SSE data showed very low deviance between calculated and measured energy production for spring and summer time and quite high for winter and late autumn [10]. NASA SSE data are used in well-known programs for PV power units configuration such as NREL HOMER [11] and PVSyst [12].

Nowadays another database, called NASA POWER [13], also has become available. It contains daily averaged solar radiation on horizontal surface (from 1981/1983 through near real-time), temperature and etc. Use of this data can make calculations more precise due to higher time resolution, but a calculation for solar radiation on the tilted PV modules is needed. In this study for every month this data is obtained using monthly averaged solar radiation on tilted surface and solar radiation on horizontal surface taken from NASA SSE for given location. This is quite simple but raw calculation mainly used for further estimations of energy production per month but not per day. More precise approximation, for example basing on empiric formulas from [14] needs more time and more calculation resources.

One more calculation approach is concerned with generation of typical meteorology year (TMY) for given location [15]. This typical meteorology year is generated using averaged satellite data [16] and presents temperature, solar radiation on tilted surface and other meteorological data sequence with time resolution of one hour. So calculation accuracy can be further improved using such data source, but it also can bear additional calculation errors, it needs time, calculation resources and additional efforts to generate typical meteorological year. Therefore one of this study purposes is to compare 5 MW PV grid-tie plant averaged month and year energy production, obtained in calculations using all three approaches relative to initial climate data (NASA SSE, NASA POWER, TMY). Another one purpose is to compare different types of PV modules in application for such object from the technical and economic point of view.

3. The algorithm calculations

A simple linear calculation model, involving average solar radiation and temperature data, grid-tie inverter power-efficiency dependence and PV modules parameters (peak power, power temperature coefficient, normal operation conditions temperature, module surface area) is proposed. There is suppose that grid-tie power plant contains PV modules array, connected to 3-phase grid inverters use a maximum power point tracking (MPPT) technique. In case of high-voltage PV modules total operating current of series-connected PV thin-film modules

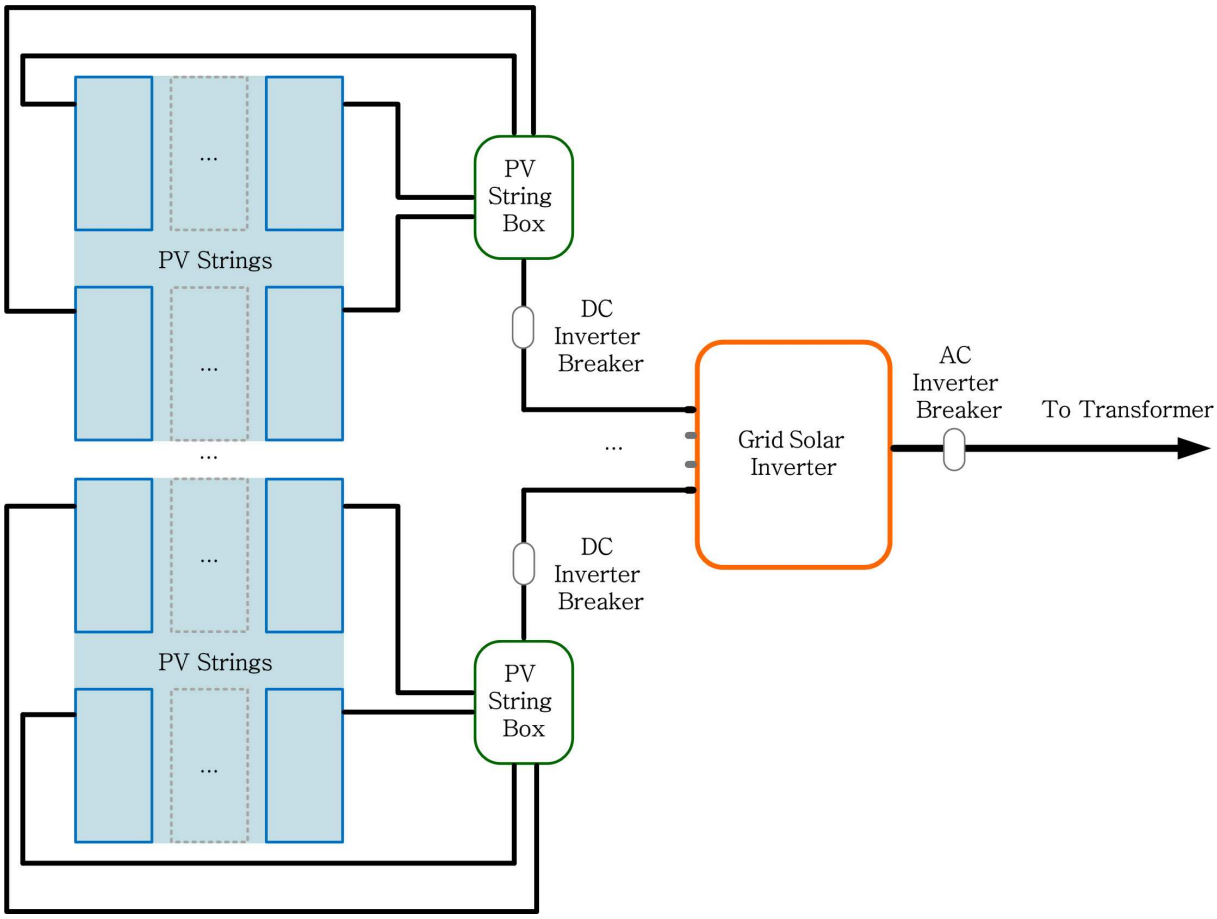

Figure 1. Scheme of grid-tie PV plant for calculation.

strings can be less than inverter operation current. It means that inverter cannot be loaded by all available power and string boxes are needed to connect additional strings of series-connected PV modules to all available MPPT-inputs of inverter to match total current of modules and available inverter current.

This study has not purpose of precise capital costs estimation but only comparison of costs for different PV modules application. Therefore costs and efficiency of transformer connecting PV plant to local transmission grid are not discussed. PV plant structure for the calculation is given on figure 1.

For every month of the year using NASA SSE data it can obtain average energy production of PV array. Possible production can be estimated as:

$$W_{\text{pj}} = N_{\text{mod}} S_{\text{mod}} A_j \eta_j, \tag{1}$$

where N_{mod}—total amount of PV modules in the array, S_{mod}—area of single PV module of given type, A_j—averaged for j-th month daily solar radiation, η_j—daily averaged efficiency of PV module for j-th month typical day. For calculation of N_{mod}:

$$N_{\text{mod}} = \frac{P_{\text{pv}}}{P_{\text{mod}}}, \tag{2}$$

where P_{pv} stands for peak power of PV plant and P_{mod} for peak power of single PV module in the array. Average efficiency of PV module for given month can be estimated through (4),

based on empiric equation from and using PV module average operating temperature in j-th month, calculated by (3):

$$T_{\mathrm{modj}} = T_j + \frac{A_j(N_{\mathrm{oct}} - 20)}{0.8t_{\mathrm{d}j}}, \tag{3}$$

where T_j—average environment temperature, N_{oct}—operating temperature of PV cells of module (at 800 W/m^2 and 20 °C), $t_{\mathrm{d}j}$—the daylight time for given month (empiric equation is based on the value of solar radiation flux, not on energy, so to estimate averaged flux it is necessary to take ratio of averaged energy to averaged daylight time). In case of TMY approach equation (3) doesn't include this value. Coefficient 0.8 comes from the fact that in [14] 800 W/m^2 is used while in NASA SSE all values of solar radiation are given in kWh/m^2/day. For calculation of η_j:

$$\eta_j = \eta_{\mathrm{STC}}(1 + k_t T_{\mathrm{mod}j} - 25), \tag{4}$$

where η_{STC}—module efficiency in standard test conditions (1000 W/m^2 and temperature of module is 25 °C), k_t (1/°C)—power temperature coefficient.

Energy produced can be summarized to obtain month and year energy production in case of using TMY and NASA POWER data.

Capital costs for PV plant and area covered with modules must also be estimated. Estimation of possible amount of operated PV modules per one chosen inverter (in this case Sunny Central 20000 TL from SMA Gmbh is considered) includes calculation of modules, connected in series for one string:

$$N_{\mathrm{ser}} = \frac{U_{\mathrm{ocv-inv}}}{U_{\mathrm{ocv-mod}}}, \tag{5}$$

N_{ser}—number of PV modules connected in series, $U_{\mathrm{ocv-inv}}$—available open circuit voltage on the inverter input, $U_{\mathrm{ocv-mod}}$—open circuit voltage of PV module.

Number of module strings, connected in parallel, is defined by available current of inverter and operation current of module:

$$N_{\mathrm{str}} = \frac{I_{\mathrm{inv}}}{I_{\mathrm{mod}}}, \tag{6}$$

N_{str}—number of PV modules strings, connected in parallel, I_{inv}—maximum inverter operating current, I_{mod}—operating current of single PV module.

Both numbers shall be rounded to the nearest whole number. Multiplication of these values gives the total number of PV modules that work with a frequency converter. Total power of these modules must not be higher than maximum power of inverter. Otherwise one should decrease number of strings or number of modules in one string. Each type of inverter also has several independent MPPT-inputs for strings. In case when number of these inputs is less than number of calculated module strings and the total power of the modules is less than available power of the inverter, one should use string boxes to connect additional strings to inverter. This situation is usually typical for thin-film modules with their high operation and open circuit voltages and low operation currents. Number of string boxes per inverter is equal to ratio of strings to number of MPPT-inputs of inverter.

Total numbers of inverters and string boxes on PV power plant are calculated division of maximum power of PV plant to total power of modules per one inverter and multiplication of this value by number of string boxes per one inverter respectively. Costs of modules and other equipment are obtained by multiplication of prices for one unit by number of these units in the PV plant.

To simplify construction and calculation it is taken that single inverter operates with modules, mounted on the single mounting pole. According to possible levels of wind speed in the region,

number of PV modules, mounted vertically in one row, is chosen. After this number of horizontal PV modules rows is calculated as:

$$N_{\text{hor}} = \frac{N_{\text{ser}} N_{\text{par}}}{N_{\text{v}}}, \tag{7}$$

where N_{v} is the number of vertically mounted modules. Using this value one can calculate number of mounting poles in given PV plant and their costs by:

$$C_{\text{mp}} = C_{\text{s}} N_{\text{v}} N_{\text{hor}} S_{\text{mod}}, \tag{8}$$

where C_{s}—specific costs of active area (area, covered with PV modules) for given mounting pole type which can be estimated as division of mounting pole cost to total mounted PV modules area. Costs for mounting poles were obtained through conversation with Schletter GmbH Company. S_{mod} is area of the single PV module. After this area, which is demanded for single mounting pole is estimated as:

$$S_{\text{mp}} = l_{\text{mp}} w_{\text{mp}} = w_{\text{mod}} N_{\text{v}} N_{\text{hor}} l_{\text{mod}} \cos(\theta), \tag{9}$$

where l_{mp} and w_{mp} stands for length and width of mounting poles, l_{mod} and w_{mod}—for length and width of modules and θ is tilt angle of PV modules.

For normal PV plant operation mounting poles must be situated at some distance d from each other to avoid mutual shading morning and evening. To calculate d we estimated position of sun at 11.00 AM for Kosh-Agach on December, 22, because this day is the worst day of the year from point of view of solar radiation level and this day gives the lowest declination angle of the sun. The choice of time is based on an operation experience of small grid-tie PV plant [10] that first two hours after sunrise are not productive:

$$d = \frac{(H - h_0)}{\tan \gamma} \cos(180^\circ - \beta), \tag{10}$$

where H is the maximum height of mounting pole at given tilt angle, h_0 is the height of mounting pole low edge (must be higher, than the maximum possible level of snow for given region), γ—declination angle of the sun for given time and β—azimuth angle. Angle values for γ and β are taken from free solar calculator, available at [17]. So total area of one position, including mounting pole and area with width d can be estimated as:

$$S_0 = N_{\text{hor}} l_{\text{mod}} \big(d + w_{\text{mod}} N_{\text{v}} \cos(\theta)\big). \tag{11}$$

Total PV plant area is obtained by multiplication of single position area from (11) by the total number of inverters in PV plant. Containers with inverters can be situated behind the last mounting pole (inside the last position).

Capital costs are estimated as sum of costs for PV modules (taken from web-site of Russian PV and back-up products retailer, Solarhome LLC [18]), mounting poles, inverters, containers for inverters and construction works. Construction works were estimated as 50% from mounting poles and total costs of PV modules basing on experience of PV plants construction in Yakutia and Altay Republic. Installation of mounting poles and PV modules is the most labor and equipment demanding part of PV plant construction.

4. Results and discussion

Estimation results for all PV modules types and for all initial data sources (averaged for year) are given in table 2. Tilt angle of PV modules is chosen equal to 35° according to data NASA SSE which show the maximum value of solar radiation for the whole year for this angle. Another reason is that Kosh-Agach is in a desert region with very small amount of snow and rain, so these factors can be neglected.

Table 2. Year averaged calculation results for Kosh-Agach. Tilt angle for PV modules is 35°.

PV module types	YL 250 P	HEVEL	Sun Power E20/327
Demanded area (10^3 m^2)	103.4	184.5	81.30
Capital costs without area costs (10^6 ₽)	521.6	490.7	675.2
Yearly averaged energy production NASA SSE (GWh)	8.11	7.94	8.05
Yearly averaged energy production NASA POWER 2014 (GWh)	9.98	9.42	9.73
Yearly averaged energy production TMY (GWh)	8.60	8.51	8.58

Table 3. The capital costs structure estimation for different PV modules (%).

Module type	YL 250 P	HEVEL	Sun Power E20/327
PV modules	67.4	44.8	77.8
Mounting poles	12.5	23.2	7.40
String boxes	0	5	0
Inverters	8.0	9.9	5.5
Container for inverters	1.6	2.0	1.1
Construction works	10.5	15.0	8.2

We can see in table 2, that the largest area of the plant will be achieved with HEVEL modules, the smallest one—with IBC modules. This result is concerned with different base efficiencies for different module types, which in this case are dominant over other factors, such as power temperature dependence. High increase of USD exchange rate and absence of native production capacities for crystalline modules led to the fact, that application of thin-film PV modules give smaller capital costs than other technologies. But, from analyzing costs structure (table 3) one can see, that in case of multicrystalline modules large share belongs to mounting poles and construction works. So in case of native crystalline modules capital costs can be significantly decreased and smaller occupied area could give more possibilities for PV plants construction not only in deserted, but also in developed regions of the country, where the rent price of area can be much higher than in Altai Republic.

Energy production estimation shows the highest value for multicrystalline modules, smaller—for IBC-based and the smallest—for thin films. But difference in values is not very large. This can be concerned with different number of modules (only total power, 5 MW is constant). Comparison of initial data sources shows, that the largest production is predicted on the base of NASA POWER, approximated to tilt angle, the smallest—on the base of NASA SSE data. The problem can be in the more precise calculation of temperature and radiation in TMY and NASA POWER, in high errors during tilt angle approximation for NASA POWER, and in that fact, that NASA POWER data is taken for 2014, while the other data sources operate with data sequences, averaged over 30 years. So additional calculation using NASA POWER approach (for 2005–2008) is performed. Results are given in table 4.

Difference between years is quite noticeable, but averaged value is higher, than for other calculation approaches. For further analysis the monthly data for all approaches has been taken into account. This results and the real production of energy in Kosh-Agach for several month

Table 4. Calculation results for NASA POWER approach for different years, PV modules YL 250 P, tilt angle 35°.

	2005	2006	2007	2008	2014
Yearly averaged energy production NASA POWER (GWh)	9.14	8.87	8.48	10.01	9.98

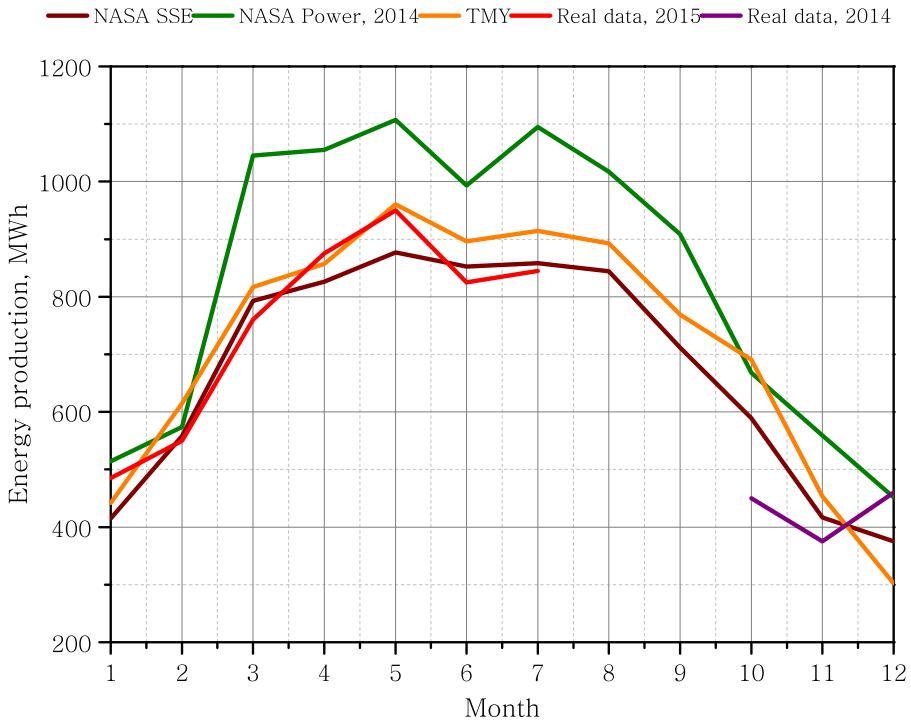

Figure 2. Prediction of energy production in Kosh-Agach under different approaches and the real production of energy; multicrystalline PV modules, tilt angle 35°.

from [19] is shown on figure 2. Data comparison shows, that rude approximation of NASA POWER data is not reliable instrument. Results obtained from calculations based NASA SSE data are in good agreement with real measurements. TMY-approach allows obtaining results, close to data from NASA SSE, but calculation is more sophisticated.

In calculation description it has been supposed that solar radiation in evening and morning hours is lost due to mutual shadowing of solar batteries. TMY approach, having hourly time resolution, allows direct estimation of the lost radiation in the calculation of the energy production. Estimation has been taken for December, which is the worst month from shadowing point of view. Results are shown in figure 3.

From figure 3 one can see that average share of lost radiation for December is quite small throughout the month. The correlation between total daily solar radiation and influence of morning and evening hours on total energy production is not evident–some gloomy days present low difference between estimations with and without morning and evening hours. So main point for these hours influence is solar radiation distribution throughout the day.

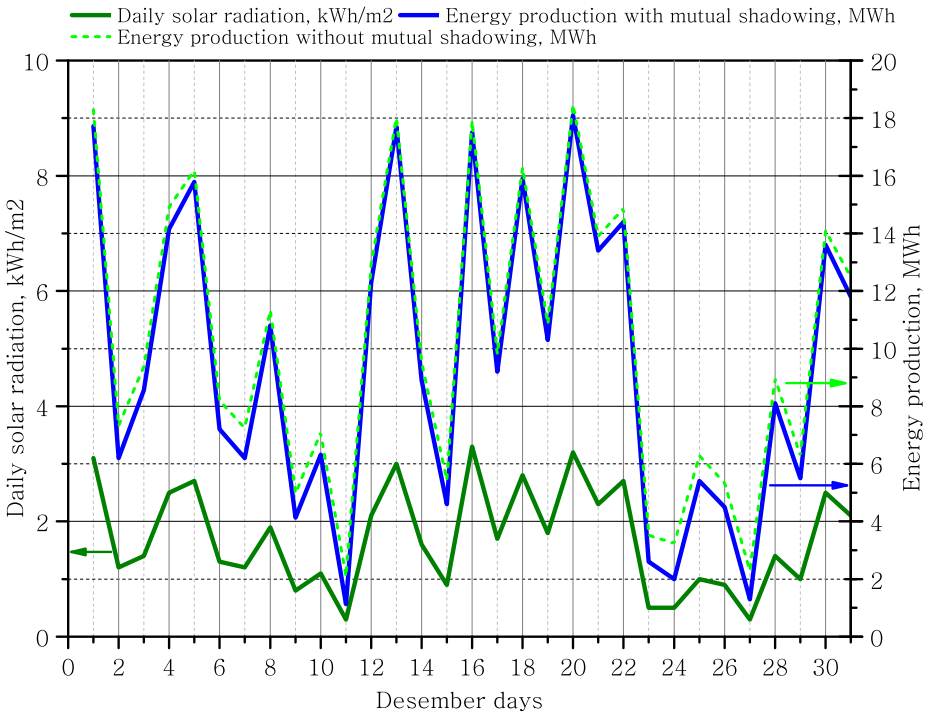

Figure 3. Shadowing influence on energy production estimation for December.

5. Conclusions

Several approaches for PV grid-tie power plant energy production prediction are described and used for case study on the base of PV power plant Kosh-Agach. Calculated results are compared with real measurements data for several months. It has been shown, that approach based on NASA SSE data can be quite simple and efficient tool for technical and economic estimations. NASA POWER data needs accurate approximation for different PV modules angles tilt. TMY approach allows to take into account issues of PV plant operation concerned with mutual PV modules shading in the evening and morning, but share of solar radiation in this periods is quite low.

Technical and economic estimations for Kosh-Agach in case of different types of PV modules have been made. Thin-film tandem-type PV modules showed lowest capital costs, but largest demanded area of the plant and large share of mounting poles, construction works and string boxes in the cost structure. In case of serial production of crystalline modules in Russia the competitiveness of grid-tie PV plants can be increased.

Acknowledgments

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