IMPACT OF DAILY VARIATION OF SOLAR RADIATION ON PHOTOVOLTAIC PLANTS ECONOMY AT THE OPEN MARKET
A Case Study "Bavanište" (Serbia)

by

Iva M. BABIĆ* * *and Željko R. DJURIŠIĆ

School of Electrical Engineering, University of Belgrade, Belgrade, Serbia

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The main purpose of this paper is to propose a correlation index between average time diagram of photovoltaic power plant production and a typical diagram of the price of electrical energy at the open market. The basic idea is to define correlation index, which is of key importance for assessing the economy of a photovoltaic power plant under open market conditions. This index may be useful for investors during evaluation of economic parameters of a photovoltaic power plant project which will one part of its lifetime operate at the open market. In this paper, a case study for the project Bavanište, Serbia, is been presented. The estimated value of correlation index shows that each of the produced MWh at prospective photovoltaic power plant Bavanište will realize a price at the Germain electricity market, which is on average 20.8% higher than the average annual price of an MWh. By taking example of the prospective photovoltaic power plant located in Bavanište in Serbia, the proposed methodology has been used to show that the average MWh of electrical energy produced by a photovoltaic power plant at the open market, can be over 20% better valued compare to wind power plant in the same region.

Key words: *photovoltaic power plants, variation of solar radiation, electricity market, correlation index*

Introduction

The present day technology of renewable energy sources (RES) is considered the technology, which can contribute to solving energy problems of the 21. century, as well as to reducing CO_2 emissions from fossil fuels. European Union (EU), through the rules and regulations, has set up the goal of 20% participation of energy obtained from RES in the total energy consumption in EU by 2020 [1]. Within various RES technologies, photovoltaic (PV) today attracts considerable attention due to its potential to contribute a major share of RES in the future [2]. PV installation has seen remarkable growth since 2005 in EU countries [3].

In order to support and motivate producing electrical energy from PV and to encourage the development of the PV sector [3, 4] the present day policies of RES are implemented through subventions [5-7]. The feed-in tariff (FIT) is the most widely used incentive program [8]. Figure 1 shows the example of the levels of subvention prices of electrical energy produced

* Corresponding author; e-mail: iva@etf.rs

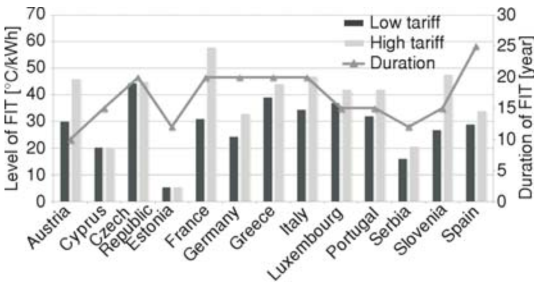

Figure 1. The example of level and duration of FIT of PVPP in several European counties

by photovoltaic power plants (PVPP) and example of duration of FIT for PVPP in several European countries, including Serbia, [3, 5, 9] during the period 2009-2012.

The fixed period of the guaranteed price and disposal of the electrical energy produced in PVPP in majority of EU member countries is 10 to 25 years [9]. This fixed period is considerably shorter than lifetimes of PVPP. They are usually designed for 25 to 35 years. It can be concluded that upon the expiration of the period of guaranteed price, in this case FIT, a PVPP will offer the produced electrical energy to the open market where the price of electrical energy is usually formed on one-hour basis, depending upon demand and supply. The prices of electrical energy at the open market mainly follow consumption diagram and they may vary considerably within one day compared to the corresponding average daily price [10, 11].

The PVPP production profile will predominantly depend on many factors, it is largely predictive, but it cannot be completely planned. In order to estimate average annual PVPP production, typical time diagram of the expected PVPP production power at the daily level for the targeted region have to be analyzed. In this paper targeted region is Bavanište in Serbia.

The correlation index estimation, can be applied to all intermittent sources of electrical energy. In order to assess the economy of PVPP production under open market conditions, it is necessary to estimate a correlation index between average time diagram of PVPP production and a typical diagram of the price of electrical energy at the open market. This index may be useful during the evaluation of economic parameters of a PVPP project, which will one part of its lifetime operate under the open market conditions. It is reasonable to expect that this correlation index will also have a very positive impact on the distribution network.

In this paper the practical mathematical expression of correlation index is proposed and defined.

Methodology

The model of PVPP electrical energy valorization at the open market

A very important element during estimate of PVPP project economy is the estimate of the gross income during the projected PVPP lifetime. In accordance with that, the following relation can mathematically define average yearly gross income of a PVPP under open market conditions:

$$W = \mu P_{\mathrm{OMavg}} AEP\, C_{\mathrm{PVPM}} \tag{1}$$

where W [Euro per year] is the estimate of average yearly gross income of a PVPP, P_{OMavg} [Euro per MWh] is the expected average annual price of electrical energy at the electricity market, AEP [MWh] – the annual electricity production of PVPP for an average year, C_{PVPM} – the correlaion photovoltaic market index, and μ – the reduction coefficient ($\mu < 1$).

Value of the reduction coefficient μ is dependent on the quality of production forecast and quality of the forecast of hourly prices at the market.

C_{PVPM} is the index of correlation between time diagram of variation of the price of electrical energy at the electricity market and diagram of electrical energy production of PVPP. Correlation index C_{PVPM} is a unique parameter for each PVPP at an electricity market. Its estimated value can be determined on the basis of available data on hourly solar irradiation at the targeted site for a period of at least one year and historical data on hourly prices of electrical energy at the market where the energy generated by PVPP is intended to be sold.

The following relation can determine quantitative estimate of this index:

$$C_{\mathrm{PVPM}} = \frac{1}{24}\frac{\sum_{j=1}^{24} E_j P_{\mathrm{OMj}}}{E_{\mathrm{avg}} P_{\mathrm{OMavg}}} = \frac{1}{24}\sum_{j=1}^{24} e_j\, p_{\mathrm{OMj}} \tag{2}$$

where E_j is the average hourly PVP production for *j*-th hour of an average day expressed, E_{avg} [MWh] – the electricity production of PVP of an average day, P_{OMj} – the price of MWh produced during *j*-th hour of an average day, and P_{OMavg} – the expected average price of electrical energy at the electricity market.

Values $e_j = E_j/E_{avg}$ and $p_{OMj} = P_{OMj}/P_{OMavg}$ are the corresponding normalized values of E_j and P_{OMj}, respectively.

Equation (2) defines the practical mathematical expression of correlation index. This equation, which is used for correlation index estimation, can be applied to all intermittent sources of electrical energy. In [12], the correlation index for wind power plants (WPP) has been analyzed. Unlike the WPP, the dispersibility of the time diagram of a PVPP production is significantly lower. The comparative analyses of correlation index for PVPP and for WPP will be explained in the section *Results and discussion*.

For mathematical model implementation to assess the correlation index C_{PVPM} it is necessary to know the production profile of $PVPP_{ej}$ and the profile of the price of electrical energy at the open market p_{OMj}. In the two next sections, it will be described how to estimate the production profile of $PVPP_{ej}$ and the profile of the price of electrical energy at the open market p_{OMj}.

Estimate of the time diagram of a PVPP production

Production of electrical energy by a PVPP is largely predictive, but it cannot be completely planned. In addition to day-night shifts, there are unpredictable daily and/or annual weather variations causing variations of the level of solar irradiation at the site of a PVPP [13]. The PVPP production profile will predominantly depend on the time of day, geographical location, cloudiness, and ambient temperature. PVPP production profile will also depend on azimuthal and altitude angles of PV systems.

The estimate of the diagram of production of a PVPP is carried out on the basis of the measurements of solar irradiation and ambient temperature. Power that can be injected by PV panels in a distribution network (*Ej*) per each hour of an average day is estimated in accordance with the relation:

$$E_j = \eta_{\mathrm{inv}} E_{\mathrm{PVSTC}} \frac{I_{\mathrm{PVj}}}{I_{\mathrm{STC}}}[1+\alpha_{\mathrm{TPV}}(T_{\mathrm{PVj}} - T_{\mathrm{STC}})] = \eta_{\mathrm{inv}} E_{\mathrm{PVSTC}} \frac{I_{\mathrm{PVeqj}}}{I_{\mathrm{STC}}} \tag{3}$$

where E_{PVSTC} is the declared power of a PV panel under standard test conditions (STC), I_{PVj} – the average solar irradiation on the surface of a PV panel during hour *j* of an average day, I_{STC} – the solar irradiation that corresponds to STC (I_{STC} = 1000 W/m^2), I_{PVeqj} – the equivalent solar irradiation during hour *j* of an average day, η_{inv} – the efficiency of the inverter, α_{TPV} – the temperature coefficient of variation of power of PV panels, typically α_{TPV} = –0.5%/°C, T_{STC} – the temperature of the panel at STC (T_{STC} = 25 °C), T_{PVj} – the average panel temperature during hour *j* of an average day, estimated by the relation:

$$T_{PVj} = T_{ambj} + \left(\frac{NOCT - 20}{800}\right) I_{PVj} \tag{4}$$

where T_{ambj} is the average measured ambient temperature during the hour *j* of an average day, *NOCT* (normal operation cell temperature) – the cell temperature in a PV module when the ambient temperature is 20 °C, solar irradiation is 0.8 kW/m^2 and the wind speed is 1 m/s. This parameter, *NOCT*, is obtained from the manufacturer of the PV modules.

The time diagrams of the prices of electrical energy at electricity markets

The electrical energy prices at electricity markets are usually defined at hourly level on the basis of demand and supply according to the day-ahead principle. Daily variations of hourly prices mainly follow variations of the daily consumption. This fact is shown in [14] by a comparative analysis of the average hourly prices at the auctions at the Spanish electricity market (OMEL) and at the Germain electricity market (EEX), and the corresponding average hourly loads in Spain and Germany. In addition to the structure of consumption, daily diagram is influenced by the structure of production.

Over the past several years the ever increasing presence of intermittent RES, especially PVPP, has a significant influence on the profile of price of electrical energy at some auctions in the regions having installed significant capacities of RES. These effects have been analyzed in [15-18].

Figure 2 shows average normalized hourly prices of electrical energy at the Germain market EEX for an average day for every year during the period 2007-2011 [19]. On the basis of the average daily diagrams, the corresponding normalized average day over the period of several years has been formed.

During peak hours the electrical energy is on average more expensive by up to 30% compared to the average daily price for an average day, while during minimum load it is on aver-

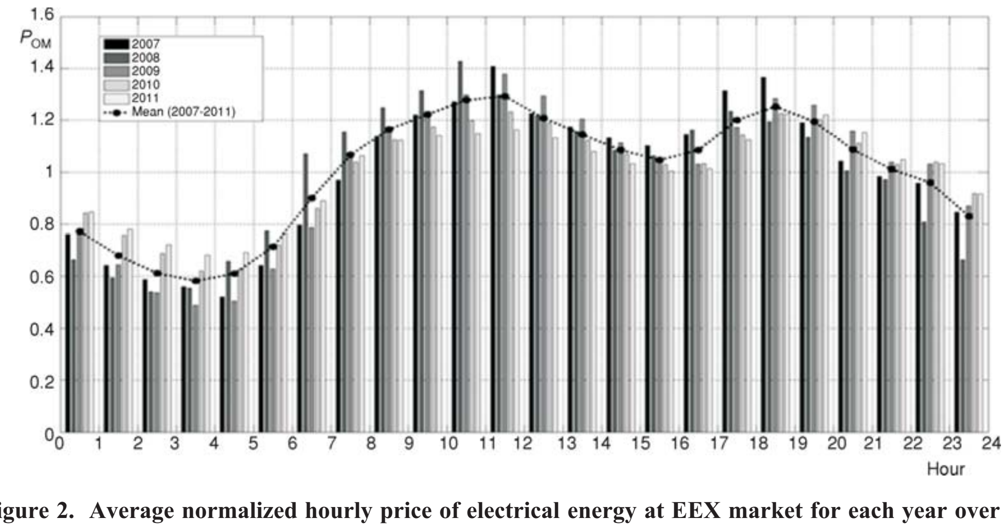

Figure 2. Average normalized hourly price of electrical energy at EEX market for each year over the period 2007-2011

age cheaper by up to 40%. It can be concluded that PVPP in the open market will have larger gross income per MWh under open market conditions compared to the average daily electricity price because the electricity price during lenth of the day is higher than the average. The quantitative evaluation of this effect is contained in the correlation index C_{PVPM} which is defined by the relation (2).

Results and discussion

In this paper, as an example, a case study for the project Bavanište, Serbia, has been presented. The correlation index C_{PVPM} for the prospective PVPP at the location Bavanište, is calculated and analyzed. The location Bavanište is situated in the Kovin municipality, in the South Banat, District of Vojvodina province. Developing the project of wind farm "Bavaništansko Polje" in Serbia of rated power 188 MW [20], at this location, the one-year measurements of the solar and wind potential were made during 2009 for the prospective PVPP. These one-year measurements of the soalr insolation was performed using a Li-Cor pyranometer, while measuring the ambient temperature is done by using NRG # 110S thermometer. On the basis of the available measurements of ten-minute average values of solar irradiation and the air temperature at this location, for the period of one year, calculation of the average hourly power of production of PV panels at this location has been performed.

On the basis of one-year-long measurements at the location of perspective PVPP in Bavanište and applying the methodology described in the section *Estimate of the time diagram of a PVPP production*, estimate of the daily profile of the PVPP power production have been obtained. Figure 3 shows concurrently the normalized average hourly diagram of the estimated PVPP production for an average day over 2009.

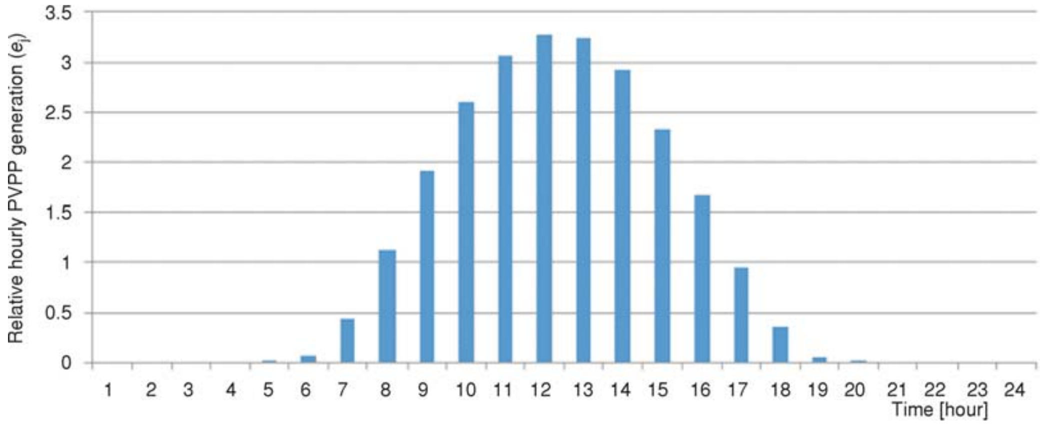

Figure 3. The estimated normalized average hourly productions of prospective PVPP in Bavanište for an average day over 2009

Figure 4 shows concurrently the normalized average hourly diagram of the estimated production of prospective PVPP in Bavanište and normalized average hourly prices of electrical energy at the Germain market EEX for an average day over 2009. On the basis of available average hourly prices of electrical energy during 2009, described in the previous section the normalized average hourly prices of electrical energy have been obtained.

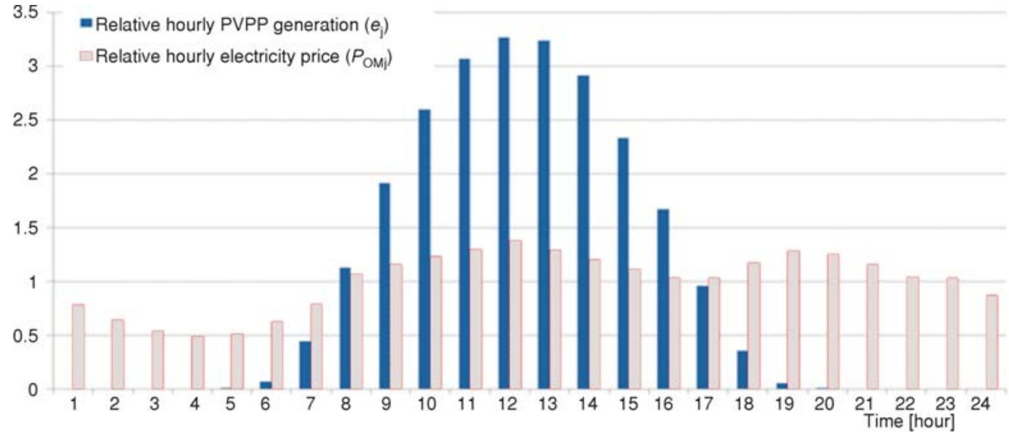

Figure 4. The estimated normalized average hourly productions of prospective PVPP in Bavanište and the normalized hourly prices of electrical energy at EEX market for an average day over 2009

Figure 4 is comparative diagram of the normalized average hourly changes diagram of the estimated production of prospective PVPP in Bavanište and of the normalized average hourly prices of electrical energy at EEX market for an average day over 2009.

Observing the comparative diagram, which is shown in fig. 4, it can be concluded that the correlation between the average daily variation of the production of prospective PVPP in Bavanište and the average daily variation of the price of electrical energy at EEX market is very good.

On the basis of relation (2) the calculated average daily correlation index for prospective PVPP in Bavanište is $C_{\mathrm{PVPM}} = 1.2082$.

The estimated value of index C_{PVPM} shows that each of the produced MWh at prospective PVPP in Bavanište will realize a price at the EEX market, which is on average 20.8% higher than the average annual price of an MWh. This is a significant comparative advantage of PVPP over other types of RES, like WPP for example. Correlation index of the production of a WPP and profile of the price of electrical energy at the open market is usually close to 1 and that is shown in literature [12], where the correlation index for WPP in Bavanište is calculated. This means that an MWh produced in PVPP has a price, which is on average 20% higher compared to the one of the WPP under open market conditions at the same location. In addition, it should be taken into account that prediction of daily production of a PVPP is considerably better for a PVPP than for a WPP. For this reason, it may be conclude that energy produced by a PVPP has a considerably higher value compared to that of a WPP.

It is possible to perform the preceding analysis not only for the Germain market EEX, but for any open market where the energy produced by a PVPP could be sold and then calculate the corresponding correlation index. Under open market conditions, it is possible to sell energy from a PVPP at the market, which has the statistical correlation that matches best the production profile of the PVPP.

The preceding analysis shows that electrical energy produced in a PVPP has the character of peak energy in a daily consumption diagram. This characteristic, in addition to the direct economic effects, possesses a series of positive technical effects on the electric power system and on the distribution network, primarily as regards reducing the losses, relieving the elements of a power system, thus extending their lifetimes, as well as relieving the conventional sources of electrical energy.

Conclusions

In perspective, all sources of electrical energy will be equally treated at the open market of electrical energy. Under such conditions, for economic parameters of a PVPP project, in addition to the annual production of electrical energy, it is required to take into account the profile of the daily diagram of production and the average time diagram of the price of electrical energy.

The analyzes, which are done in this paper, represent a very important aspect of PVPP integration in the power system and the electricity market.

In this paper, the correlation index C_{PVPM} between the average time diagram of the price of electrical energy at the open market and average time diagram of production of certain PVPP is proposed and defined. Correlation index C_{PVPM} may be used as a quantitative measure of the influence of the daily profiles of production to the economy of a PVPP project under the open market conditions. These analyses are very significant for correct perceiving of economy and valorisation of electrical energy produced by PVPP and other intermittent sources of electrical energy.

The estimated value of correlation index C_{PVPM} for the prospective PVPP in Bavanište in Serbia, shows that each of the produced MWh at prospective PVPP in Bavanište will realize a price at the EEX market, which is on average 20.8% higher than the average annual price of an MWh.

By taking example of the prospective PVPP located in Bavanište in Serbia, the proposed methodology has been used to show that the average MWh of electrical energy produced by a PVPP at the open market, can be over 20% better valued compare to WPP under open market conditions in the same region, in this case in region in Bavanište in Serbia.

The prediction of daily production of a PVPP is considerably better for a PVPP than for a WPP, so it is obvious that energy produced by a PVPP has a considerably higher value compared to energy produced by WPP.

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