Journal of Electrical Engineering and Information Technologies, Vol. **9,** No. 1, pp. 21–31 (2024)
Article 216
In print: ISSN 2545–4250
Received: November 11, 2023
On line: ISSN 2545–4269
Accepted: December 30, 2023
UDC: 621.311.243:004.891.023
https://doi.org/10.51466/JEEIT2491216021sh

Original scientific paper

FORECASTING PV PRODUCTION USING FUZZY REASONING APPROACH

Donard Shaliu, Arlind Çota, Andi Hida, Raimonda Bualoti, Marialis Çelo

Faculty of Electrical Engineering, Polytechnic University of Tirana, Albania
donard.shaliu@gmail.com

A b s t r a c t: In recent years, many studies have been done related to the implementation of methods for PV generation forecasting. The PV generation depends on several factors. Since Artificial Intelligence methods have a greater advantage than other methods, in this paper the construction of a PV energy predictive model of using Fuzzy Logic Approach has been considered. In this paper, a fuzzy reasoning approach is used for prediction of the PV generation. In the proposed method, the fuzzy inferences knowledge-based on IF-THEN rule is developed using MATLAB fuzzy software. Using fuzzy logic, the mathematical representation of influential variables on the prediction of solar power is defined. Three variables influencing the prediction of solar power are taken in consideration as fuzzy logic inputs. These variables are: hours of the day, clouds, tilt angle. The detailed analysis of the fuzzy system surfaces shows that the factors taken in consideration are mutually related. A set of different values of inputs are defined and then PV energy production forecast is made applying the fuzzy approach. The constructed rules based in engineering experience accurately represent forecast of PV generation.

Key words: fuzzy reasoning; influential variables; physical approach; PV generation; statistical approach

ПРОГНОЗА НА ПРОИЗВОДСТВО ОД ФОТОВОЛТАИЧНИ ЦЕНТРАЛИ СО ПРИМЕНА НА ПРИСТАП ЗАСНОВАН НА ФАЗИ РЕЗОНИРАЊЕ

А п с т р а к т: Во текот на последниве години се спроведени голем број истражувања за примена на различни методи за прогноза на производството од фотоволтаичните електрични централи. Производството од овој вид електрични централи зависи од неколку фактори. Земајќи предвид дека методите засновани на вештачка интелигенција имаат предност пред другите методи, во овој труд е прикажан модел за прогноза на производството кој се темели на фази логика. Всушност, со примена на пристапот заснован на фази резонирање се врши прогноза на производството од фотоволтаична електрична централа. Предложениот метод користи фази резонирање засновано на правилото „ако – тогаш“ и е развиен со примена на фази функционалности во програмскиот пакет MATLAB. Користејќи фази логика, се формира математичка репрезентација на величините кои влијаат врз прогнозата на производството од фотоволтаичната централа, а во кои спаѓаат часовите во денот, појавата на облаци и аголот на поставување на модулите. Анализите со примена на фази површини покажуваат дека наведените фактори се заемно зависни. Методот е применет за множество различни влезни величини, при што резултатите покажуваат дека формираните правила кои користат и инженерско искуство можат да дадат точна прогноза на производството од фотоволтаичните централи.

Клучни зборови: фази резонирање; величини кои влијаат на прогнозата; физички пристап; производство од фотоволтаична електрична ценнтрала; статистички пристап

1. INTRODUCTION

The photovoltaic (PV) system generation is an area that is gaining great importance, as the major technology for converting solar energy into electricity, which is reliable, stable and affordable. The effects of the energy crisis that the world experienced since 2021 are still felt, and in the future many challenges are expected. The rise in energy prices and the inflation impact on all energy-consuming sectors shows time dependence to conventional resources. Many countries have realized the need to focus on solar energy and have undertaken policies that support it via subvention packages. Repower EU is one of the policies created by the European Commission with the aim, among others, to increase the production of renewable energy to 45 % from the current 40 % [1]. Furthermore, the objective is to double the PV installed capacity in the next three years, and the target by 2030 is adding 600 GW PV installed capacities [1]. On the other hand, legal initiatives have also been taken that force constructors to install roof top solar panels for new buildings, commercial and residential ones. Italy is an example where a public program provided financial support, up to 75% of the total capital costs, to install a PV system with peak power between 1 and 20 kWpp [2]. The similar approach has significantly increased the amount of energy produced by rooftop PV panels in many countries [3]. Energy from PV panels has dominated the renewable energy industry for many years. At the end of 2018, the installed on-grid capacity reached a power of 480 GW, i.e., an increase of 20% from the previous year (386 GW). According to IRENA's studies, they show that the production from PV panels can increase to a staggering 2,840 GW capacity globally in 2030 and 8,519 GW in 2050. Globally, 60% of the total capacity will be for mass use and 40% rooftop [4]. As the major technology that converts solar radiation into electricity through PV cells, photovoltaic energy is also reliable, sustainable and affordable for everyone. Many authors see the production of electricity from PVs as a solution for the environmental effects caused by fossil energy sources [5]. Furthermore, it also has positive economic and social effects [6].

In addition, PV power in Albania is gaining even greater importance because the power system it based on hydro power plant (HPP) production, which depends on yearly hydrologic factors and dry summer periods [7]. On the other hand, the amount of PV generation is affected by various factors such as the tilt angle, irradiation, altitude, temperature, cloudiness, day hours, etc. [8].

Therefore, for the efficient planning and operation of a PV system, accurate forecast of the electricity production is essential. In recent years, many studies have been done for the implementation of methods of forecasting the PV generation. Since Artificial Intelligence methods have a greater advantage than other methods, this paper considers the construction of a PV energy predictive model of using a Fuzzy Logic approach.

The paper is organized as follows: Section 2 provides an overview of Albanian Electrical Power System. PV power forecasting approaches and methods are described in Section 3. Section 4 describes the proposed fuzzy approach. In addition, Section 5 shows the application of the proposed fuzzy approach. The conclusions are provided in Section 6.

2. ALBANIAN POWER SYSTEM OVERVIEW

Albania is a net importer of electricity, as presented in Figure 1 [7], and approximately 100% of the energy is produced by HPPs.

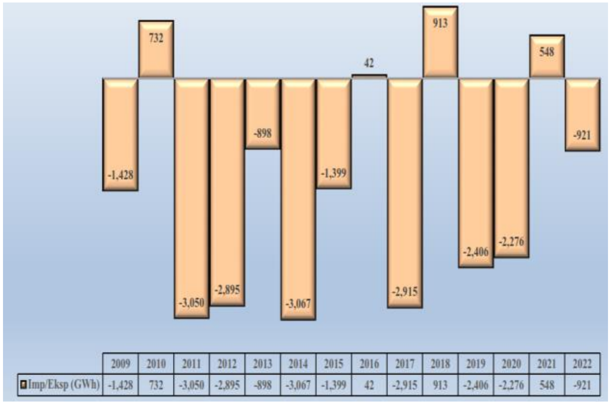


Fig. 1. Import-export balance of electricity in years 2009–2022 (GWh)

Albania has a great potential of solar energy. Due to its geographical position, the solar irradiation in some areas reaches between 1,185 kWh/m^2 per year to 1,700 kWh/m^2 per year. In optimal meteorological conditions, each square meter can absorb 2200 kWh per year [9].

The total electric production capacity installed until 31st December 2022 is 2,614 MW. Albanian Power Corporation (KESH), a public company, shares 1,448 MW or about 55.4% of the total installed capacity, while the other producers share 1,166 MW or 44.6% of the total installed capacity. The installed capacity of PV is only 23 MWpp or 0.73% of the total capacity [7].

The diversification of electric production capacity is one of the objectives that Albanian government has established in the Strategy of Development of Electric Power System [9]. Albanian policies go in the line with European directives for harmonization of legal framework of energy sector. According to the current policies, small and medium-sized businesses as well as household consumers can install a total capacity of up to 500 KWpp for the production of electricity from renewable sources, such as wind or solar, to cover part or all of the energy needed and inject the excess into the distribution network [10]. For year 2023, the new PV capacity should increase about 255.2 MWpp [7]. This new scenario of Albanian energy production and the obligation of ALPEX for accurate day-ahead energy forecast require that PV power plants improve their power generation forecasts.

3. PV POWER FORECASTING APPROACHES AND METHODS

Accurate forecasting of PV electricity production is essential for efficient operation and planning of a PV system. The forecasts of PV power output can refer to short terms which include the very short time horizons from few seconds to few minutes, the “intraday” time horizons from 0 to 6 hours ahead, and the day ahead time horizon, which is up to 24 hours ahead. The medium horizon starts from several hours to several days ahead, and the long term begins from several days to several months ahead. The short-term forecasts are used for load control and monitoring in power system operation and in electricity markets [16].

The selection of appropriate forecasting approaches is essential for the forecasting process. In this case, the methods are classified into three approaches: i) the physical approach which is based on the PV power model, ii) the statistical approach which is based on the artificial intelligence and machine learning methods, iii) the hybrid approach, which is based on the mix of the techniques of the same approach or techniques belonging to the other approaches [20].

In physical methods, energy forecasting is based on the use of meteorological parameters (solar radiation and air temperature) predicted by numerical weather prediction (NWP) models. These parameters are used as inputs to a PV system model to forecast the expected power output.

Statistical methods are based on data series measured in the past and are suggested for short time forecasting. In [11] statistical models based on weather data are used. Regression models are discussed in [12]. These models describe the relationship between solar radiation prediction from NWP and PV power production directly from statistical time series analysis from historical data, without considering the physics of the system.

In [13], [14] and [15] statistical models like Artificial Neural Network (ANN) or fuzzy logic are used. ANN is a simple biological analogy of the brain. ANN techniques are based on the neural system and have been widely used to solve PV energy forecasting problems. Fuzzy logic can be interpreted in two different ways. In a narrow perspective it is a logical system. In a broader sense it is synonymous with fuzzy set theory, which refers to communities of objects that have undefined boundaries, and being part of these communities is determined at quantitative levels.

In this paper, fuzzy logic is used in relation to fuzzy set theory. This logic is characterized by the use of linguistic variables, which have words and not numbers as values or parameters. A particularity in the use of fuzzy logic is the use of fuzzy rules. Although words are less precise than numbers, their use is closer to human intuition.

4. PROPOSED FUZZY APPROACH

Fuzzy logic methodology has been in the focus of many researchers which is due to the fact that it operates with a non-linear element [15]. A fuzzy system is characterized by the following elements:

1) input membership function,
2) fuzzy rules, and
3) the output membership function.

The fuzzy reasoning approach involves following steps:

1) Compile the heuristic rules.
2) Perform fuzzy reasoning.

The next step is to decide which inputs will be included in the membership function design and in the fuzzy rules design. We have selected three input variables: hours of the day, cloudiness and the PV module tilt angle. Figure 2 presents the framework of the proposed fuzzy approach.

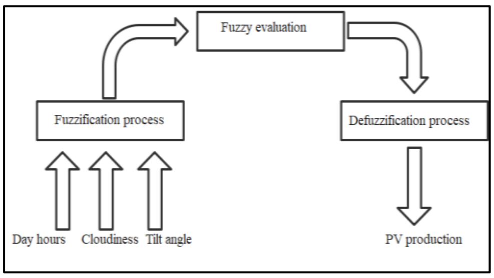


Fig. 2. The framework of the proposed fuzzy approach

a) *Membership functions of input variables*

The input variables are represented by trapezoidal (trapmf) and triangular membership (trimf) function. In the following subsections, the fuzzy model for each variable is presented.

1) Hours of the day

In Figure 3 a typical energy production of PV module during hours of the day [16] is presented. This production is characterized by three parts, the first part is an increase in production, then a constant production, and the third part is a decrease in production [17].

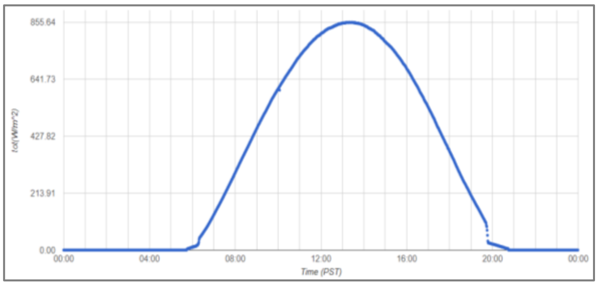


Fig. 3. Typical energy production of PV module during hours of the day

Therefore, the curve can be divided in three sections. Then, the range of each function is defined. Namely, the variable *hours in the day* is designed with three linguistic variables, defined as "AM", which refers to the period between the 7:00 and 10:00, "P" (peak), which is between 9:00 and 15:00 and "PM", which refers to the period between 15:00, and 19:00, as indicated in the Table 1.

Table 1

The linguistic variables of the hours of the day

Linguistic variables	Range
AM	7 – 10
P	8–15
PM	13–19

The membership function for the hours in the day is shown below, in Figure 4. A triangular type (trimf) is selected, and the range of the abscissa values is [7:19], while the range of ordinate values is [0:1]. From Figure 4 it can be observed that the functions interfere.

2) Cloudiness

The numerical values of the *cloudiness* inputs are divided into groups named "Low" (slightly cloudy), "MC" (moderately cloudy), "VC" (very cloudy) and "TC" (totally cloudy), as indicated in the Table 2.

Table 2

The linguistic variables of the cloudiness

Linguistic variables	Range
Low	–36 – 30
MC	15 – 50
VC	40 – 80
TC	70 –145

After determining the range of function on the abscissa axis, we build the membership functions of the cloudiness input in the interval fuzzy system. All four membership functions extend to the interval [0:1] on the ordinate axis, while on the abscissa axis to the interval [0:100]. From Figure. 4 it could be noticed that the functions interfere between one another and in addition to the triangular type, the trapezoidal type (trapmf) is also used. The Figure 5 shows the membership functions of the cloudiness input.

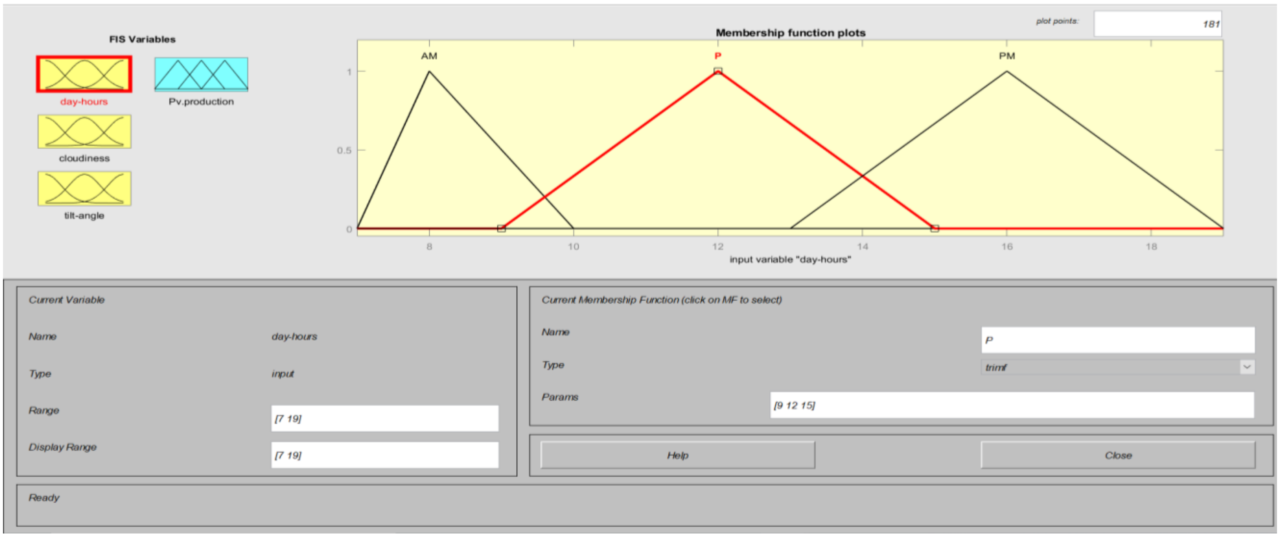


Fig. 4. Membership functions indicator for the hours in the day input

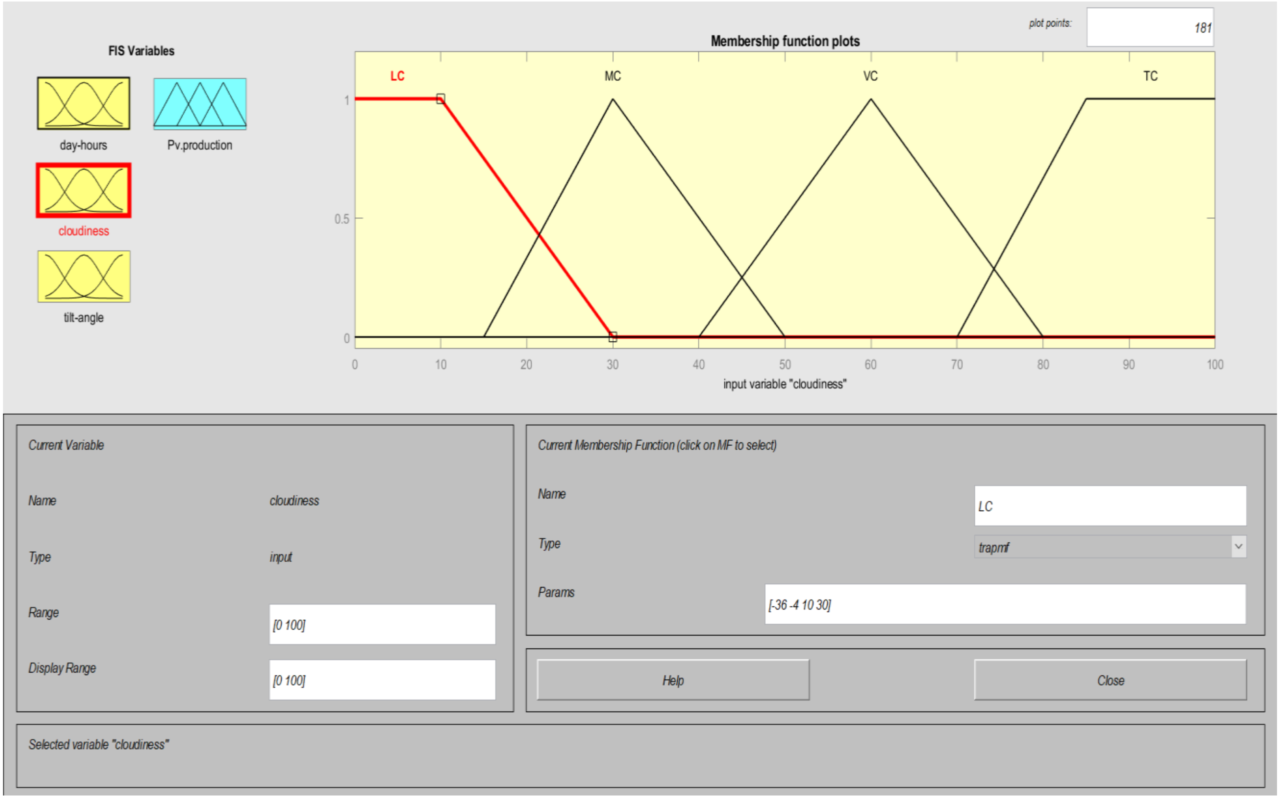


Fig. 5. Membership functions indicator for the cloudiness input

3) Tilt angle

The *tilt angle* and orientation of the panels are determining factors in the production of photovoltaic panels [5, 18]. In Figure 6 the dependency of the PV energy production from the tilt angle is presented [19]. We have referred to this graph as a model to help us determine the intervals of the tilt angle variables in the fuzzy system in Matlab.

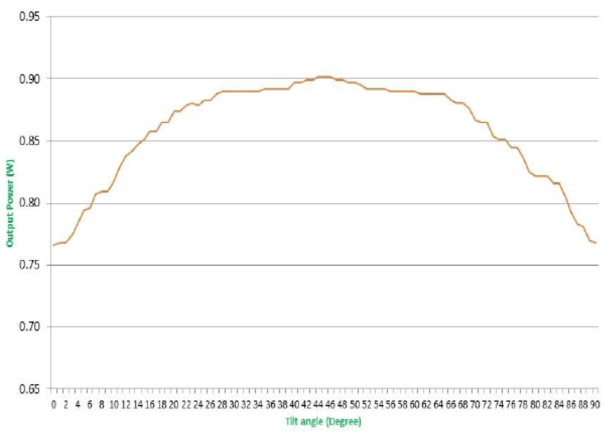


Fig. 6. Graph of the PV power output panel as a function of the tilt angle

The numeric values of the tilt angle input are divided into three units, i.e., "H" (horizontal), "Az" (azimuth angle, optimal), "V" (vertical), and the limits of each interval have been determined. The intervals belonging to each community are shown in the Table 3.

Table 3

The linguistic variables of the tilt angle

Linguistic variables	Range
H	–36 – 30
Az	15 – 50
V	40 – 80

Once the range of each function on the abscissa axis is determined, the membership functions of the inputs to the fuzzy system are constructed. Figure 7 shows the membership functions of the input tilt angle. When a numerical value of the input tilt angle is written to the system, the system automatically defines which function the numerical value belongs to. As mentioned before, the tilt angle input contains the three membership functions, i.e. "H", "Az", and "V". The extent limits in 2-dimensional space are defined in the white field labelled "Params". In the "Type" section, the triangular type (trimf) is selected. The interval of abscissa values is 0:90, while the interval of ordinate values is 0:1.

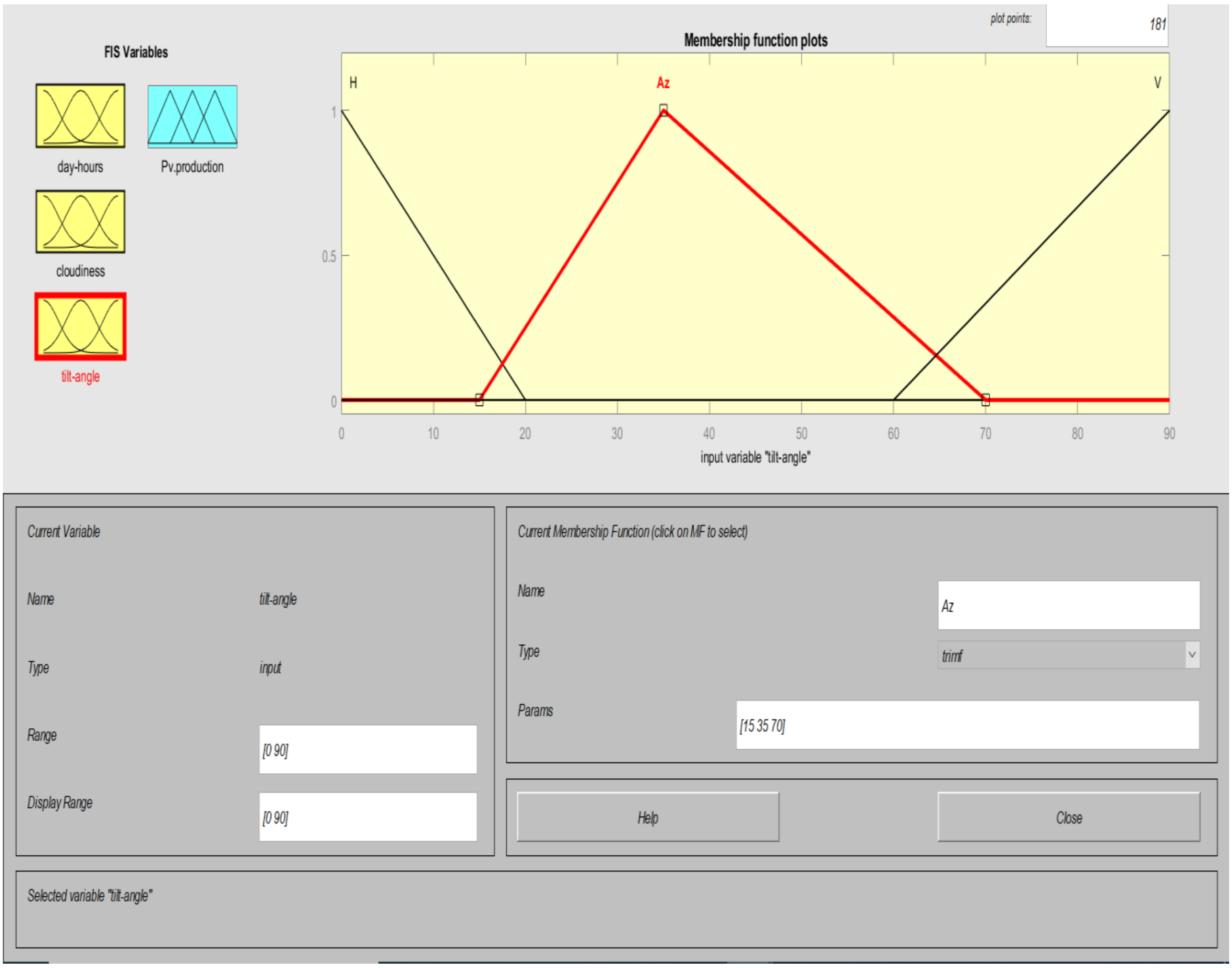


Fig. 7. Membershi functions indicator tilt angle input

From the Figure 7 it could also be observed that the functions interfere with one another.

b) *Output fuzzy membership function*

The *PV production* is used as an output variable. PV production is designed with four linguistic variables defined as "Zero" (zero production), "LP" (low production), "MP" (medium production), "HP" (high production). We first defined the range of each function as indicated in the Table 4.

After defining the range of function on the abscissa axis, we build the membership functions of the output *PV production*, as shown in Figure 8 below.

The output *PV production* contains the four membership functions, i.e. "Zero", "LP", "MP", and "HP". The selected membership function type is triangular. The base of each triangle is extended into 2 units. The selected function MP has its base in the interval [20, 70], while the third peak is in the *x-y* coordinates (5, 1). All four membership functions extend to the interval [0:1] on the ordinate axis, while on the abscissa axis to the interval [0:100]. As presented in Figure 8 the functions interfere with one another and in addition to the triangular type, the trapezoidal type (trapmf) is also used.

Table 4

The linguistic variables of PV production

Linguistic variables	Range
Zero	0 – 10
LP	10 – 30
MP	20 – 70
HP	60 –140

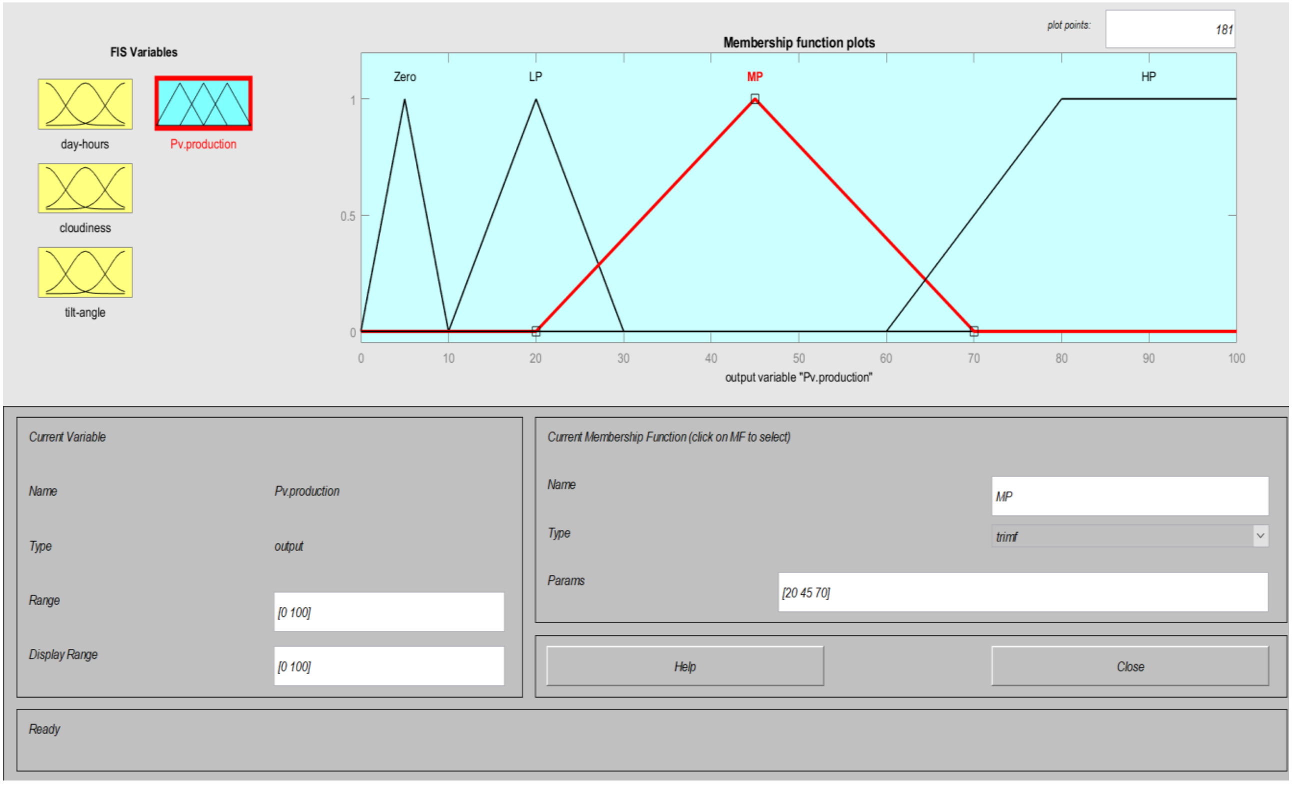


Fig. 8. Membership functions indicator PV production output

5. APPLICATION OF THE PROPOSED FUZZY APPROACH

In the proposed method, a fuzzy knowledge-based approach is developed. To evaluate the PV energy production, the Fuzzy Inference System (FIS) editor of MATLAB Fuzzy Logic Toolbox is used. The component relations of the fuzzy system are shown in the Figure 9. In the last step of the methodology, the fuzzy logic toolbox of MATLAB was applied for introducing the membership functions and the fuzzy rules. Furthermore, the software helped to automate the evaluation of the PV production.

a) *Fuzzy inference rules*

To define the fuzzy inference rules the following steps are taken:

1) Define the total numbers of interactions between the input output variables.

2) The output for each rule was determined by the references and practical experience.

Each rule consists of two components which are the antecedent (IF part) and the consequent (THEN part). With the fuzzy logic technique, partial output membership can be improved by increasing the number of rules. In the process of fuzzy approach, we have used the Centroid methods.

For the fuzzy logic control, Mamdani’s Max-Min composition technique is used. FIS derives output fuzzy sets from judging all the fuzzy rules by finding the weighted average of all 26 fuzzy rules. Using the Fuzzy Rule Viewer, the impact of each input on the output production value can be observed, as shown in Figure 10.

Four cases are considered to determine the influence of each input on the output, where one of the inputs receives four different values, while the other two are kept unchanged. The same process is repeated for each input variable.

From Figure 11 the influence of the input value hours of the day on the value of the output is observed, keeping the other two inputs constant. For different values for the input variable hours of the day (8, 12, 14, 16) we notice that the values of the output increase. Also, it is worth saying that during peak (P) and afternoon (PM) we get higher values of PV production.

From Figure 12, the impact of the increase in the percentage of clouds on the output PV production can be observed. Keeping constant values of the other two input variables, the PV production is decreasing. The less clouds we have, the higher the production will be.

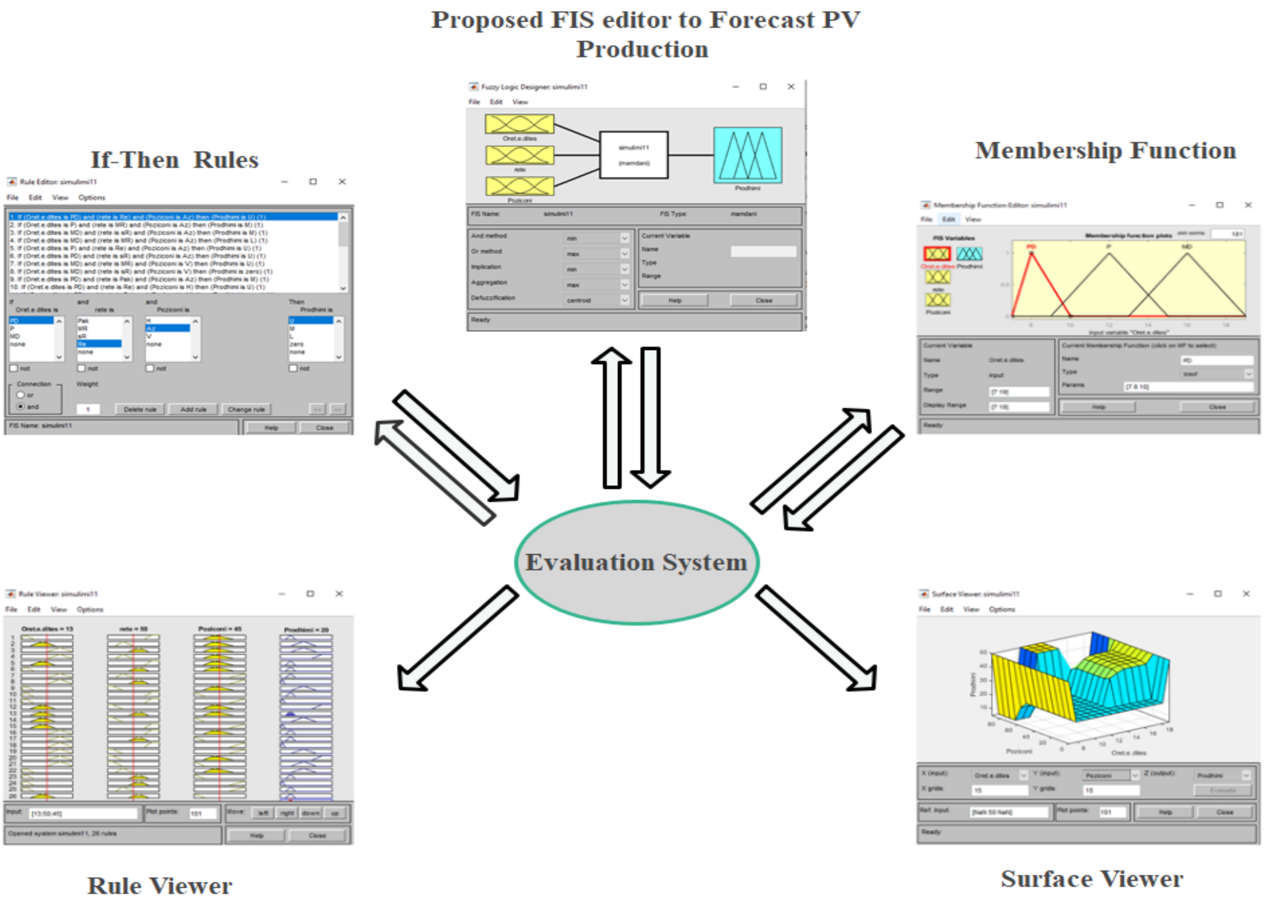


Fig. 9. Interaction of system tools with each other

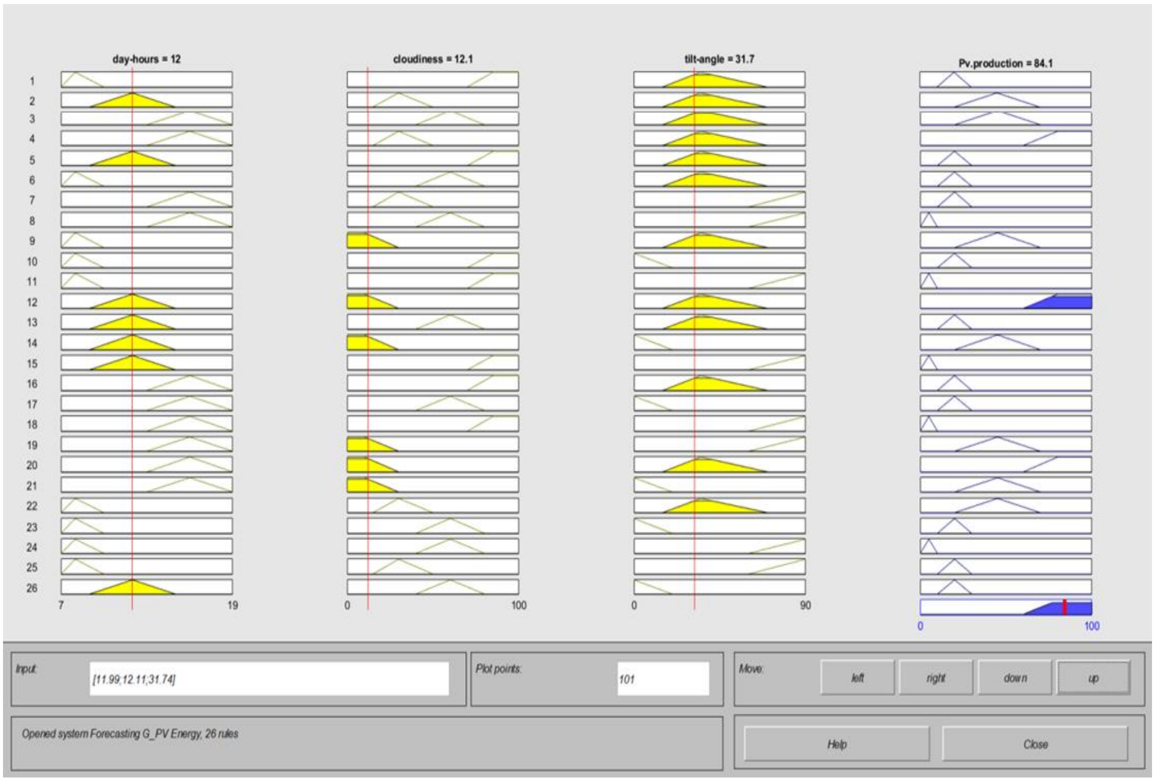


Fig. 10. The impact of each input on the output value

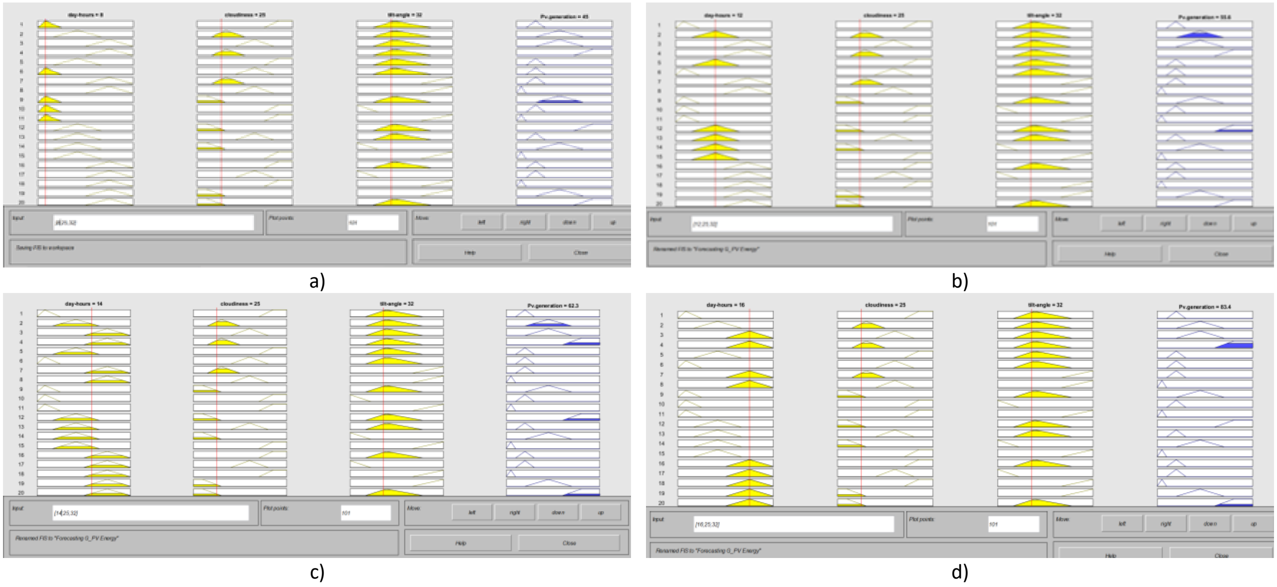


Fig. 11. The influence of the input hours of the day on the value of the output PV production on fuzzy inference rules a) "hour of the day" is 8 and all other inputs are constant; b) "hour of the day" is 12 and all other inputs are constant, c) "hour of the day" is 14 and all other inputs are constant; d) "hour of the day" is 16 and all other inputs are constant

Fig. 12. Fuzzy inference rules, the influence of the input cloudiness on the output PV production value

In the same way we changed the values of the tilt angle variable, it can be observed that for positioning of the PV panel at the optimal angle Az, the PV production is higher than in the horizontal or vertical positioning. When comparing the horizontal and vertical position of the panel, there is only a slight difference of the output.

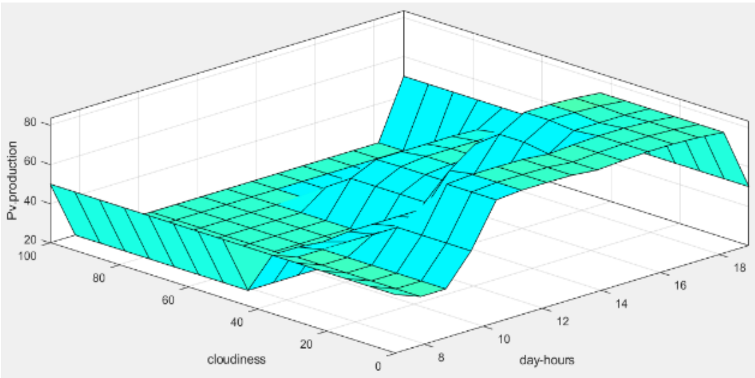
Table 5 provides comparison of the output value of the fuzzy approach with linguistic output variable. It can be observed that the same result is obtained with the value defined by the fuzzy approach and fuzzy output variable.

Figure 13 shows the effect of combination of two inputs on the output value (production), while setting one input constant.

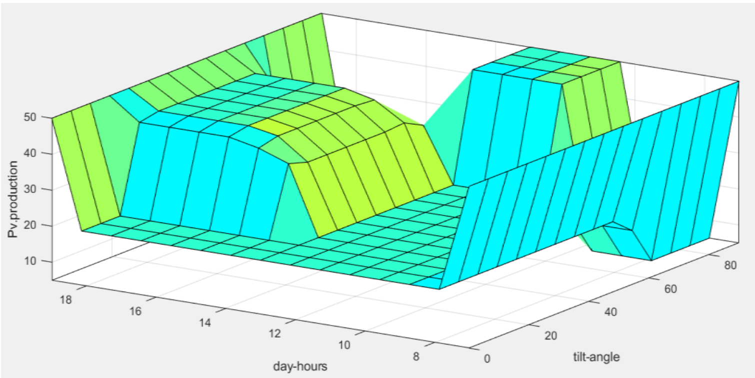
T a b l e 5

Comparison of the fuzzy approach output value and the linguistic output variable

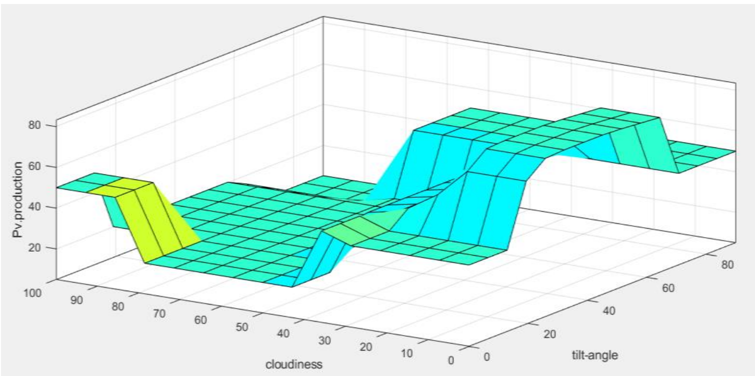
Nr.	Inputs			Output	
	Day hours	Cloudiness (%)	Tilt angle (°)	Production (%)	
1.	8	15	30	45	MP
2.	12	15	30	83.7	HP
3.	8	75	30	20	LP
4.	12	75	30	20	LP
5.	8	15	70	50	MP
6.	12	15	70	50	MP
7.	8	75	70	5	zero
8.	12	75	70	5	zero



a)



b)



c)

Fig. 13. The influence of different factors to the PV production:
a) influence of cloudiness and day hours, b) influence of day hours and tilt angle,
c) influence of cloudiness and tilt angle

6. CONCLUSION

In this paper a fuzzy approach is presented for PV production forecast, taking in to account the day hours, weather conditions and tilt angle.

From the obtained results it can be observed that different combination of input values should be taken into account to define the final result. Fuzzy approach gives us the possibility to take into account these combinations.

Furthermore, this method permits to use the engineering experience and data sets in defining fuzzy rules, enables the interpretation of the different factors that affect the PV production, turning them into logical conditions.

The proposed fuzzy approach gives satisfactory results for the prediction of energy production from photovoltaic. Moreover, helps in the correct decision-making and risk management of the producers that participate in the electricity market timeframes, avoiding penalties.

REFERENCES

[1] https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

[2] Song, A., Lu, L., Liu, Z., Wong, M. S. (2016): A study of incentive policies for building-integrated photovoltaic technology in Hong Kong. *Sustainability* **8** (8), 769. https://doi.org/10.3390/su8080769

[3] Kılıç. U, Kekezoğlu, B. (2022): A review of solar photovoltaic incentives and policy: Selected countries and Turkey. *Ain Shams Engineering Journal*, Volume **13**, Issue 5, 101669. https://doi.org/10.1016/j.asej.2021.101669

[4] IRENA (2019), *Global Energy Transformation: A Roadmap to 2050*, International Renewable Energy Agency, Abu Dhabi. ISBN: 978-92-9260-121-8

[5] Hamed, T. A., Alshare, A. (2021): Environmental impact of solar and wind energy – a review, *J. Sustain. Dev. Energy Water Environ. Syst*. Vol. **10**, Iss. 2, 1090387. DOI: http://dx.doi.org/10.13044/j.sdewes.d9.0387

[6] Changsheng Li, Haiyu Wang, Hong Miao, Bin Ye (2017): The economic and social performance of integrated photovoltaic and agricultural greenhouses systems: Case study in China, *Applied Energy*, Vol. **190**, pp. 204–212. https://doi.org/10.1016/j.apenergy.2016.12.121

[7] https://www.ere.gov.al/en/publications/annual-reports

[8] Hida, A., Kërçi, T., Bualoti, R., Çelo, M., Shaliu, D. (2022): A techno-economic analysis of a photovoltaic plant: an Albanian case study, *International Conference on Renewable Energies and Smart Technologies (REST)*, Tirana, Albania, pp. 1–5. DOI: 10.1109/REST54687.2022.10022337

[9] http://www.akbn.gov.al/wp-content/uploads/2019/05/Renewable-Energy.pdf

[10] https://kpmg.com/al/en/home/insights/2023/05/new-law-on--promotion-of-the-use-of-energy-from-renewable-source.html

[11] De Giorgi, M. G., Congedo, P. M., Malvoni, M. (2014): Photovoltaic power forecasting using statistical methods: impact of weather data. *IET Sci. Meas. Technol*., **8**, pp. 90–97. https://doi.org/10.1049/iet-smt.2013.0135

[12] Karamdel, S., Liang, X., Faried, S. O., Shabbir, M. N. S. K. (2022): A Regression model-based short-term pv power generation forecasting, *IEEE Electrical Power and Energy Conference (EPEC)*, Victoria, BC, Canada, pp. 261–266, DOI: 10.1109/EPEC56903.2022.10000086.

[13] Abuella, M., Chowdhury, B. (2015): Solar power forecasting using artificial neural networks, *North American Power Symposium (NAPS)*, Charlotte, NC, USA, pp. 1–5. DOI: 10.1109/NAPS.2015.7335176.

[14] Ncane, Z. P., Saha, A. K. (2019): Forecasting solar power generation using fuzzy logic and artificial neural network, *2019 Southern African Universities Power Engineering Conference/Robotics and Mechatronics / Pattern Recognition Association of South Africa (SAUPEC / Rob Mech/ PRASA)*, Bloemfontein, South Africa, pp. 518–523, DOI: 10.1109/RoboMech.2019.8704737

[15] Tabish Ansari, M., Rizwan, M. (2022): Solar energy forecasting using fuzzy logic and artificial neural network. In: Palani, I. A., Sathiya, P., Palanisamy, D. (eds): *Recent Advances in Materials and Modern Manufacturing. Lecture Notes in Mechanical Engineering*. Springer, Singapore. https://doi.org/10.1007/978-981-19-0244-4_47

[16] Li. Z., Rahman, S., Vega, R., Dong, B. (2016): A hierarchical approach using machine learning methods in solar photovoltaic energy production forecasting, *Energies*, vol. **9**, no. 1, p. 55. https://doi.org/10.3390/en9010055

[17] Casula, L., D’Amico, G., Masala, G. et al. (2020): Performance estimation of photovoltaic energy production. *Lett Spat Resour Sci* **13**, 267–285. https://doi.org/10.1007/s12076-020-00258-x

[18] Yunus Khan, T. M., Soudagar, M. E. M., Kanchan, M. et al. (2020): Optimum location and influence of tilt angle on performance of solar PV panels. *J Therm Anal Calorim* **141**, 511–532. https://doi.org/10.1007/s10973-019-09089-5

[19] Shareef, M. (2017): The impact of tilt angle on photovoltaic panel output. *ZANCO Journal of Pure and Applied Sciences* **29** (15), 112–118. DOI: 10.21271/ZJPAS.29.5.12

[20] Abdelhakim El Hendouzi, Abdennaser Bourouhou (2020): Solar photovoltaic power forecasting, *Journal of Electrical and Computer Engineering*, vol. **2020**, iss. 1, Article ID 8819925, p. 21. https://doi.org/10.1155/2020/8819925