GOCE DELCEV UNIVERSITY, SHTIP, NORTH MACEDONIA
FACULTY OF ELECTRICAL ENGINEERING

ETIMA 2021

FIRST INTERNATIONAL CONFERENCE

19-21 OCTOBER, 2021

TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

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ЕЛЕКТРОТЕХНИЧКИ ФАКУЛТЕТ

UNIVERSITY „GOCE DELCHEV” - SHTIP
FACULTY OF ELECTRICAL ENGINEERING

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FIRST INTERNATIONAL CONFERENCE

ЕТИМА / ETIMA 2021

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PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA.***
ETIMA has a goal to gather the scientists, professors, experts and professionals from the field of technical sciences in one place as a forum for exchange of ideas, to strengthen the multidisciplinary research and cooperation and to promote the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.
Conference ETIMA was held as online conference where contributed more than sixty colleagues, from six different countries with forty papers.
We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA'21 by presenting the results of their current research activities and by launching the new ideas through many fruitful discussions.
We invite you and your colleagues also to attend ETIMA Conference in the future. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information in direct contact, as well as to enjoy the social events together.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот Гоце Делчев.
ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да представува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живеењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.
Конференцијата ЕТИМА се одржа online и на неа дадоа свој допринос повеќе од шеесет автори од шест различни земји со четириесет труда.
Сакаме да ја искажеме нашата благодарност до сите колеги кои допринесоа за успехот на ЕТИМА'21 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Ве покануваме Вие и Вашите колеги да земете учество на ЕТИМА и во иднина. Веруваме дека следниот пат ќе имаме можност да се сретнеме, да размениме идеи, знаење и корисни информации во директен контакт, но исто така да уживаме заедно и во друштвените настани.

Организационен одбор на конференцијата

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INVESTIGATION OF EFFICIENCY ASPECTS IN 3×3 PHOTOVOLTAIC PLANT USING MODEL OF SHADING

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Abstract

Solar irradiation is the most affordable renewable energy source, implementable even on household level. The considerably lower cost of setup and maintenance compared to the other renewable energies makes it a preferable choice in regions with lot of sunny days throughout the year. One of the main R&D aspects of interest of the Photovoltaic (PV) technologies is the efficiency of the PV conversion, which is dealt with on material level. Additional efficiency aspects could be a field of research in support to higher energy production. One of them is the land use efficiency of the utilized plot surface. Namely, the usual approach in populating the plot used by the plant is with row and column distances that guarantee no inter-shading among the panels. This paper presents results of research proposing use of denser panel population in the plot, with allowed inter-shading which under some approximation provides calculations of lower individual panel efficiency but much higher overall land use efficiency. The research project proposes an inter-shading model in a 3×3 PV plant, which can be validated in CAD applications. A clear-sky irradiation model is then used to estimate plant's power at certain moment in the year, and calculation of energy production. Sun position and its incidence angle are calculated using a verified model. The analytical software uses the following input parameters - plant geo-location (latitude, longitude, time zone); panel geometry (width, height); plant geometry (inter-row and inter-column distances, panel inclination angle); and date and time. The inter-shading model results in total plant exposed PV surface to direct solar irradiation, as well as in the total shaded PV surface receiving diffuse (and reflected) radiation. The energy model can then be used for power and energy calculations, as well as optimal inclination, inter-row and inter-column estimations. If panel technologies allow small segmentation with protective diodes implementing approximation that whole directly exposed surface performs PV conversion, then allowed inter-shading and thus denser panel populated plant plot may prove cost-effective.

Key words
solar irradiation, photovoltaic conversion, intershading, land use efficiency.

Introduction

The energy consumption overall is in continuous increase with the increasing world population, so the energy issues raise major and fundamental challenges for the technological trends. The nonrenewable energy sources are depleting, and mankind needs to switch to the renewable sources, which can be defined as geothermal (resulting from earth's core activity), sun related (direct solar irradiation, wind) and gravitationally related (tide, water flow) [1,2,3]. From all renewable sources, the Sun is one of the most used. Photovoltaic cells are devices that use semiconductor materials to convert sunlight into electricity. Photovoltaic technologies offer a large number of advantages which include producing clean energy; offering high reliability, because it does not employ moving/rotating parts; operating cost is very low due to non-demanding maintenance and because it does not require fossil fuel; modular structure allowing simple and flexible assembly [4].

The objective of this paper is implementation of a standard shading model used for a plant of photovoltaic panels to optimize its geometry for more efficient use of the land. The standard shadow model is applied to a plant consisting of nine photovoltaic panels, arranged in three rows and three columns (3×3). The goal is to determine analytically the inter-shading and consequently how the shading affects energy production emphasizing the efficiency of the land utilization. This paper is organized as follows. In section 1 overview of solar geometry and shading model is given, while in section 2 the used methodology is given. In Section 3 the analytical algorithms are described and presented. Section 4 presents results, and Section 5 concludes this paper.

1. Model of shading

The model of inter-shading among the PV panels in the 3×3 configuration as detailed in [5] determines how each panel shades the columns behind, after which the total exposed plant surface S_{dir} and the total shaded plant surface S_{dif} are calculated.

The inter-shading model uses a sun position model [6] that provides required momental sun seasonal altitude and daily azimuth along with the sun incidence angle based on a geolocation (latitude and longitude) as well as date and time.

The model of shading is based on trigonometric functions that determine the geometry of inter-shading. These mathematical relations are verified with CAD software.

Parameters taken for shadow calculations are the angle of inclination β, the panel width Px, the panel length Py, the inter-row distance r_y and the inter-column distance r_x.

Typical shaded moment is depicted in figure 1:

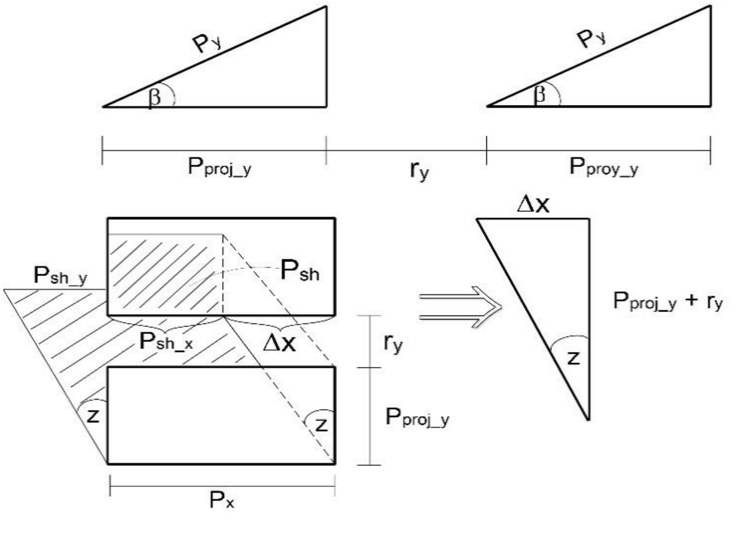

Fig. 1. Elements of inter-shading

This algorithm determines the total area S_{dir} directly exposed to solar radiation G_b, as well as the total area S_{dif} which is exposed to diffuse solar radiation G_d.

2. Calculation of power using Clear-sky irradiation model

After calculation of the solar parameters, the shadow geometry and consequently the exposed and shaded surfaces, the power output of the entire power plant can be calculated for every moment in time with the following equation [1,2]:

$$P_i = (G_b \cdot S_{dir} + Gd \cdot S_{dif}) \cdot \eta \quad (2.1)$$

G_b is direct solar radiation, G_d is diffuse solar radiation, S_{dir} is surface of the panel exposed to direct radiation and S_{dif} is surface of the panel under shadow.

The proposed irradiation model simplifies the context with the assumption that all days of the year are sunny. Even on sunny days, there is some diffuse radiation, mainly due to the refusal of direct radiation by the molecules of the air. The total solar radiation is a sum of the direct, the diffuse and the ground reflected component of radiation. In this model the ground reflected component is insignificant because the location of the solar power plant is assumed to be in isolated rural areas [6,7,8,9].

The effects of the atmosphere in scattering and absorbing radiation are variable with time as atmospheric conditions and air mass change. It is useful to define a standard "clear" sky and calculate the hourly and daily radiation which would be received on a tilted surface under standard test conditions. Hottel (1976) has presented a method for estimating the beam radiation transmitted through clear atmospheres which considers zenith angle and altitude for a standard atmosphere and for four climate types.

Correction types are applied to a_0, a_1, nm to allow changes in climate types. The correction factors are given in Table 1.

Table 1 Correction factors for climate type

Climate type	r_0	r_1	r_k
Tropical	0.95	0.98	1.02
Midlatitude summer	0.97	0.99	1.02
Subarctic summer	0.99	0.99	1.01
Midlatitude winter	1.03	1.01	1.00

The atmospheric transmittance τ_b for beam radiation and the other factors a_0, a_1, k are given in the following form:

$$\tau_b = a_0 \cdot r_0 + a_1 \cdot r_1 \cdot \exp\left(\frac{-k \cdot r_k}{\cos(\Phi)}\right) \quad (2.2)$$

$$a_0 = 0{,}4237 - 0{,}00821 \cdot (6 - nm)^2 \quad (2.3)$$

$$a_1 = 0{,}5055 - 0{,}00595 \cdot (6.5 - nm)^2 \quad (2.4)$$

$$k = 0{,}2711 - 0{,}01858 \cdot (2 - nm)^2 \quad (2.5)$$

where *nm* is the altitude of the targeted geolocation in kilometers.

The clear sky beam normal radiation is then:

$$G_{bn} = G_{atm} \cdot \tau_b \quad (2.6)$$

where G_{atm} is extraterrestrial solar radiation given in the following form:

$$G_{atm} = G_{sc} \cdot (1 + 0{,}033 \cdot \cos\left(\frac{360 \cdot n}{365}\right)) \quad (2.7)$$

and G_{sc}= 1367 W/m^2 is a ***solar constant,*** *n* is the day in a year**.**

Similarly, the τ_d factor can be calculated, which tells the amount of diffuse radiation on a sunny day at the same location.

$$\tau_d = 0.271 - 0.294 \cdot \tau_b \quad (2.8)$$

The clear-sky diffuse normal radiation can be calculated as:

$$G_{dn} = G_{atm} \cdot \tau_d \quad (2.9)$$

Direct radiation changes throughout the day and is calculated according to the cosine rule:

$$G_b = G_{bn} \cos\theta \quad (2.10)$$

The diffuse solar radiation is:

$$G_d = G_{dn} \frac{1+\cos\beta}{2} \quad (2.11)$$

The total solar radiation per m^2 panel is given with the formula:

$$G_t = G_{bn} \cos\theta + G_{dn} \frac{1+\cos\beta}{2} \quad (2.12)$$

where θ is incidence angle, *Gbn* is normal direct solar radiation, *Gdn* is normal diffuse solar radiation and β is tilted angle.

Solar radiation models are essential for predicting average daily, monthly and seasonal radiation, beam radiation and diffuse radiation.

The energy produced for a day is calculated with:

$$Ei = \int_0^{interval} Pi \cdot di \quad (2.13)$$

The model of the solar position, the model of shading and the model of solar radiation (Clear-sky radiation) are mutually connected and implemented into application software for energetic analysis of photovoltaic plant of 3×3 panels. The output power and the cumulative energy for a given period (day, month, year) can be calculated using this software.

5. Methodology

The software is implemented in VBA (Visual Basic for Application). All algorithms which are used in the software are described using diagrams.

The input parameters which are used in the software are given in Table 3.1.

Submodels that are used in software: the model of geometry of solar position, model of a shadow and a model of a solar radiation (Clear-sky radiation). Model of geometry of solar position describes the correct position of the sun at a given moment of the time in relation to geolocation of the photovoltaic grid. The algorithm which describes the model of the solar position takes into consideration the following parameters: The geolocation of the photovoltaic plant (L, LOD), the day in the year, the moment in the day (N, LMT) and the geometric relations which are calculated from them. The parameters of the solar position are calculated on the basis of these relations: the altitude angle α, the angle of solar azimuth z and the incidence angle θ.

Table 3.1 Input parameters used in software for energetic analysis

Input parameters	Symbol
Geographic latitude (º)	*L*
Geographic longitude (º)	*LOD*
A day in a year	*N (1~365)*
Local standard time in a day (min)	*LMT*
Width of a panel (m)	*Px*
Length of a panel (m)	*Py*
Efficiency of a panel (PV conversion)	η
Angle of inclination (˚)	β
Azimuth angle of the panel orientation (˚)	*azp*
Distance between rows (m)	r_y
Distance between columns (m)	r_x
Height above sea level (km)	*nm*
Time interval for integration of energy (min)	Δt

The model of shading considers the solar angles (α, z), the panel geometry (Px, Py), the plant geometry (r_x, r_y, β и azp). The whole illuminated area S_{dir} of the plant and the whole shadow area S_{dif} are determined on the basis of them.

If we know the areas S_{dir} and S_{dif} we can make an analytic valuation of the energetic aspects of the photovoltaic grid using the model of solar radiation (Clear-sky model).

The calculation of the power Pi (equation 3.1) enables calculation of cumulative produced energy at a given period (day, month, year etc.)

The calculation of energy is fundamental for precise determination of the optimal parameters of the photovoltaic grid: angle of inclination β_{opt} and the distances (*opt_rx*; *opt_ry*) between the photovoltaic panels.

The optimal daily inclination of the panels β_{opt} is that for which maximal energy is produced by the panels with optimal orientation of panels (*azp*=0º) towards local noon.

The optimal distances *opt_rx* and *opt_ry* are those for which the photovoltaic grid produces energy at least equal to some predefined reference energy at optimal daily angle of inclination β_{opt} and allowed intershading. According to that, distances between rows r_y and distances between columns r_x are in the range until overcoming the intershading. Algorithm for determining the optimal distances (*opt_rx*; *opt_ry*) is shown in Fig. 2.

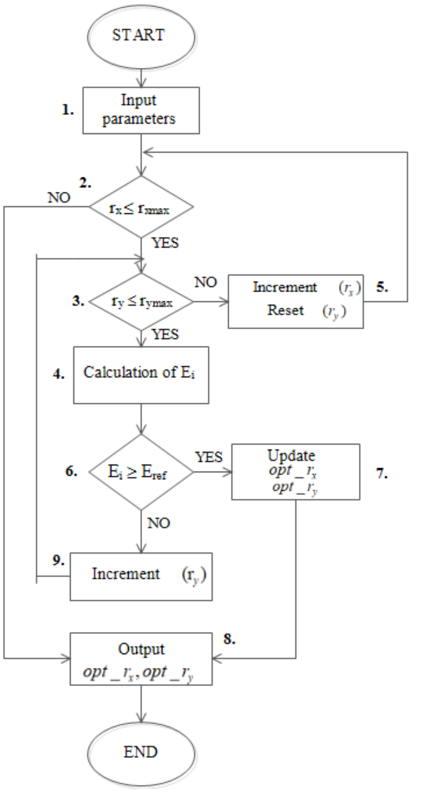

Fig. 2. Algorithm for determining optimal interpanel distances

The software enables energetic analyses for the defined photovoltaic plant and comparative analyses in relation to its essential parameters. The essential parameters which influence the production of electric energy are the parameters that describe the geometry of the photovoltaic plant, in other words, the interpanel distances r_x and r_y as well as the angle inclination of the photovoltaic panels β.

The input parameters in the software for energetic analysis of the photovoltaic plant are the following: width *Px*=1m and length of the panel *Py*=1,64m, efficiency of the panel $\eta=20\%$, angle of panel inclination β, azimuth angle of the panel orientation *azp*=0º, height above sea-level *nm*=0,3 m and time interval for energy integrating Δt_E=15 min.

It is necessary to optimize the inclination angle β to get maximal production of electrical energy. The optimal angle of inclination β_{opt} is defined as inclination for which maximal energy is provided at a certain period (typical date day). In this way, daily tracking can be provided for the panels of the photovoltaic plant.

The tracking of the panels is updated at a daily base for the needs of this research. The optimal angle of inclination is calculated at avoided intershading, by testing the whole interval of the inclination angle β (0° ~ 90°) with selected step 1°. Maximal daily energy production is achieved by choosing the optimal angle of inclination β_{opt} for a specific day. Algorithm for determine optimal angle of inclination β_{opt} is shown on Fig. 3.

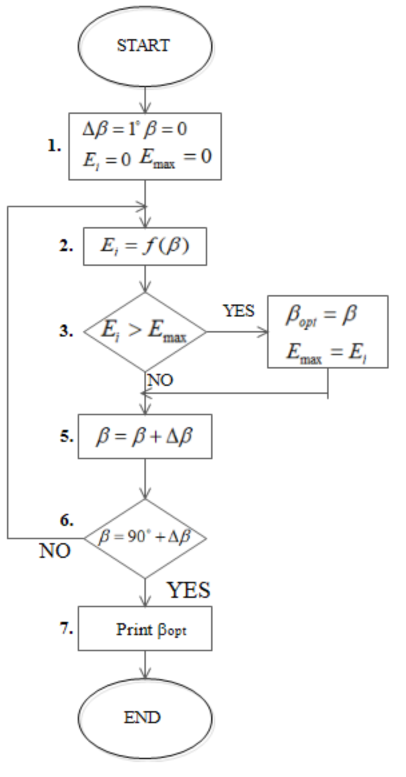

Fig. 3. Algorithm for determination of optimal angle β_{opt}

The following analysis is made for geographic latitudes from 0˚ to 65˚ for the North hemisphere. Comparative analysis for the produced energy is made in relation to the shortest day of the year 21st December, *N*=355th day of the year. This day is chosen because the shadows are the longest. As a result of this there is a need of the greatest values of the distances between the panels in order to avoid them. This day 21st December marked with *N*=355 is taken as reference day. Besides the reference day 21st December other 7 days are selected: 9th February (N=40), 21st March (N=80), 1st May (N=121), 21st June (N=172), 7th August (N=218), 21st September (N=264) and 5th November (N=309).

6. Numerical results and discussion

Analysis for the produced daily energy *E*, comprised area of the land and the surface efficiency of the land *Eff* for the reference day - the shortest day (21st December) is presented in the table 4.1.

Table 4.1 Calculation of reference parameters: the distance between the columns *ref_rx*, the distance between rows *ref_ry*, comprised area of the land *Sref*, daily energy *Eref* and efficiency of the land *Eff_ref* for 21 December (N=355).

L (°)	*ref_rx* (m)	*ref_ry* (m)	*Sref* (m^2)	*Eref* (kWh)	*Eff_ref* (kWh/m^2)
0	3,1	0,3	46,871	12,119	0,259
5	3,3	0,5	50,91	11,877	0,233
10	3,4	0,7	53,693	11,505	0,214
15	3,5	0,9	56,236	11,291	0,201
20	3,4	1,1	56,244	10,852	0,193
25	3,7	1,5	64,769	10,97	0,169
30	4,1	1,9	74,949	10,589	0,141
35	4,2	2,4	83,607	9,943	0,119
40	4,6	3,1	101,953	9,191	0,09
45	5,1	4	128,874	8,305	0,064
50	6,1	5,6	190,853	7,045	0,037
55	6,9	8	284,571	5,578	0,02
60	9,1	11,9	515,463	3,886	0,008
65	9,4	29,9	1305,15	1,805	0,001

According to table 4.1, the following parameters are calculated for the reference day (21st December): The distances between the columns *ref_rx* and the rows *ref_ry*, the comprised area of the land *Sref*, the daily energy *Eref* and the surface efficiency of the land *Eff_ref*.

After calculating the reference and optimal distances between the panels of the defined photovoltaic plant, the annual energy *GE* is calculated for each obtained distance pair: reference distances (*ref_rx*; *ref_ry),* optimal distances *(opt_rx*, *opt_ry*) for each latitude from the range (0° ~ 65°) respectively, as well as surface efficiency of the land *Eff*, with daily setting of the angle of inclination *β* on the optimal obtained angle β_{opt}.

Based on performed analysis, optimal distances (*opt_rx*; *opt_ry*), lowest energy loss *ΔGE* and increased surface efficiency of the occupied land *Eff* are obtained in relation of the reference parameters. Conclusions about the optimal distances for a given value of the latitude with optimal placement of the panels and results provided from the calculated values for optimal distances (*opt_rx*; *opt_ry*) for each geographic latitude from the range (0° ~ 65°) are given in table 4.2.

For all tested dates (corresponding optimal distances) and daily tracking of the *βopt* angle of inclination of the photovoltaic panels, the annual energies *GE* for each latitude of the interval (0º ~ 65º) are calculated. From the comparative analysis with the annual energies, it can be concluded that the relative change of the energy *ΔGE* obtained at optimal distances, in relation to the reference distances, changes and increases with the increase of the latitudes in the range from 1.27% to 15.2% for latitudes (0 ˚ ~ 65˚).

Table 4.2 The values of optimal distances for the given value of the latitude at the optimal placement of the panels

L (˚)	*opt_rx* (m)	*opt_rx* (m)	*GE* (MWh)	*Eff* (MWh/m²)	*Δ GE* (%)
0	0	0	3,962	0,268	1,27
5	0	0,1	4,005	0,26	1,38
10	0	0,2	4,027	0,252	1,54
15	0	0,2	4,006	0,251	2,17
20	0	0,4	3,997	0,233	2,13
25	0	0,5	4,074	0,229	2,72
30	0	1,4	4,094	0,177	0,9
35	0	1,4	3,99	0,172	1,65
40	0	1,4	3,862	0,167	2,57
45	0	1,3	3,695	0,164	3,9
50	0	0,9	3,458	0,172	6,44
55	0	0	3,019	0,205	13,87
60	0	0	2,789	0,189	14,60
65	0	0	2,515	0,17	15,32

Conclusion

The comparative analysis is performed with daily tracking of the angle of inclination β_{opt} of the photovoltaic panels, during which, a protocol is implemented, according to which the analysis of the values obtained on the daily energies is performed. According to the protocol, distances (*max_rx*; *max_ry*) are determined, during which the maximum daily energy *Emax* is obtained and the occupied land area *Smax*. These parameters apply when shading is negligible or completely avoided. In relation to the reference day, certain optimal distances (*opt_rx; opt_ry*) are determined, at which energy *Eopt* is obtained approximately equal to the reference energy *Eref*, and the area of the covered land area is *Sopt*. The ratio between the reference area of the plot *Sref* and the optimal area *Sop*t on it, defines the efficiency of the given land area. Based on the comparative analysis of the reference day, it can be concluded that the distances between the photovoltaic panels r_x and r_y and the optimal angle of inclination *βopt* affects the change in the efficiency of the occupied land. The results show that the optimal parameters i.e., the optimal distances (*opt_rx; opt_ry*) are relative and depend on the selected reference date. If another date is chosen as the reference date or a higher reference energy is set, then the optimal distances in relation to that reference date will be greater than the distances obtained for December 21.

After the energy analyzes are made by days, it is determined that by allowing shading, there is reduction in the production electric energy on the plant and the average efficiency of photovoltaic panels is decreased, but at the expense of the efficiency of the used land containing the photovoltaic panels, which is increased many times.

Based on the obtained values for the annual energies *GE* and the change of the annual energy *ΔGE*, recommendations are given for optimal placement of the photovoltaic panels in the grid, considering the latitude range, according to the most favorable day from the tested dates. One such example is Table 4.2 which gives the optimal distances by latitudes that results from the conducted comparative analysis for the reference day, December 21st.

After the optimization, the efficiency of the given land area is significantly increased, at the expense of the reduced annual electricity production, which means the existing site maximized for the reference date can accommodate many more panels (multiple 3x3 photovoltaic plants) on its surface.

References

[1] J. A. Duffie, W. A. Beckman, "*Solar Engineering of Thermal Processes, Fourth Edition"*, John Wiley and Sons, 2013.

[2] T. Demsar, "Optimisation of quantity of electric energy from solar power plant regarding its layout″, University of Ljubljana, Master Thesis, 2015.

[3] H. Spasevska "Solar energy in Macedonia: policy, perspectives and challenges for application", *Proceedings of World Renewable Energy Congress- XI*, Abu Dhabi, p-p. 1409-1414, 2010.

[4] B. Citkuseva Dimitrovska, R. Golubovski, H. Spasevska, J. Veta Buralieva, "Computational methodology in determining shading among photovoltaic panels″, Balkan Journal of Applied Mathematics and Informatics (BJAMI), 4(1). Pp 41-50. ISSN 2545-4803, 2021.

[5] B. Citkuseva Dimitrovska, M. Cepin, R. Golubovski, H. Spasevska, "Modeling photovoltaic grid inter-shading, Thermal Science, May 2020.

[6] Soteris A. Kalogirou, *"Solar Energy Engineering Process and Systems"*, Elsevier, 2009

[7] C. Stanciu, D. Stanciu, "Optimum tilt angle for flat plate collectors all over the World–A declination dependence formula and comparisons for three solar radiation models", *Energy Conversion and Management*, Elsevier, Volume 81, pages 133-143, 2014.

[8] A. K. Yadav, S. S. Chandel, "Tilt angle optimization to maximize incident solar radiation: A review", *Renewable and Sustainable Energy Reviews*, Elsevier, Volume 23(C), pages 503-513, 2013.

[9] D. Stanciu, C. Stanciui, I. Paraschiv, "Mathematical links between optimum solar collector tilts in isotropic sky for intercepting maximum solar irradiance", *Journal of Atmospheric and Solar – Terrestrial Physics*, Volume 137, Pages 58-65, Elsevier, 2015.

[10] M. P. Mitkovic, J. P. Djekic, M. Z. Igic, P. B. Mitkovic, M. M. Dinic Brankovic, "Analysis of Electric power production in South Serbia: Recommendations for improvement of Operation of First Mini Photovoltaic Power Plants", *Thermal Science,* Volume 22, Pages 1205-1216, 2018.