Journal of Energy Technology

JET Volume 17 (2024) p.p. 32-47
Issue 2, 2024
Type of article: 1.01
http://www.fe.um.si/si/jet.htm

CONFIGURATION OF A FLAT ROOF SOLAR POWER PLANT FOR MAXIMUM ELECTRICITY PRODUCTION

KONFIGURACIJA SONČNE ELEKTRARNE NA RAVNI STREHI ZA MAKSIMALNO PROIZVODNJO ELEKTRIČNE ENERGIJE

Neja Hadžiselimovićℜ

Keywords: solar power plant, flat roof, optimal tilt angle, maximum power density, maximum electricity production

Abstract

Commercial solar power plants are often installed on larger industrial, warehouse and commercial buildings. Modern prefabricated constructions of such buildings dictate architectural solutions involving flat roofs, which are particularly suitable for the installation of larger solar power plants. This research investigates which configuration of solar module installation and which inclinations are suitable for implementation on a flat roof to achieve maximum annual electricity production. It aims to determine the maximum annual production per unit area and per installed power of the solar modules. The simulation results are conducted for all months of the year, and for the geographic latitude and longitude of the town of Lenart in Slovenia.[1]

Povzetek

Komercialne sončne elektrarne se velikokrat postavljajo na večje industrijske, skladiščne in trgovske objekte. Moderne montažne konstrukcije tovrstnih objektov narekujejo arhitekturne

ℜ 1 Corresponding author: Neja Hadžiselimović, II. gimnazija Maribor, Trg Miloša Zidanška 1, 2000 Maribor, Slovenia, Tel.: +386 40 349 536, E-mail address: neja.hadziselimovic@druga.si

rešitve v izvedbi ravnih streh, ki so posebej primerne za postavitev večjih sončnih elektrarn. Tako je cilj članka raziskati optimalno konfiguracijo sončnih modulov na ravni strehi z namenom doseganja maksimalne proizvodnje električne energije. V tem delu je izvedena raziskava glede tega, katera orientacija sončnih modulov in kateri nakloni so primerni za izvedbo na ravni strehi s ciljem, da bo dosežena maksimalna letna proizvodnja električne energije. Gre za določitev maksimalne letne proizvodnje na površino in na inštalirano moč modulov. Simulacijski rezultati so izvedeni za vse mesece leta ter za geografsko širino in dolžino mesta Lenart v Sloveniji.

1 INTRODUCTION

As indicated by the study "The Limits to Growth" from 1972 *[1]*, modern society faces global problems that lead increasingly to an imbalance between the ecosphere and the socio-technosphere, essentially leading to an ecological crisis. Consequently, within the framework of sustainable development, the central focus of modern society has become the green transition *[2,3]*, which does not rely on excessive consumption of natural resources and overburdening the environment. The goal is sustainable development, which aims to meet the needs of the present without compromising the environment and ability of future generations to meet their own needs.

In this millennium, green technologies that utilise renewable energy sources are becoming increasingly popular in practice. These sources include sea energy, bioenergy, hydro-, wind, geothermal-, and, notably, solar energy. Due to the development of society, the increased standard of living and because of facts regarding global warming *[4,5]*, the need for electrical energy is increasing, especially for cooling and heating buildings as well as the introduction of electric mobility. Thus, society also harnesses solar energy through solar power plants, which represents one of the possible green solutions, provided the power grid infrastructure is upgraded appropriately with smart solutions and adequate storage systems. However, it is a fact that such power plants cannot be installed just anywhere, as this would lead to harmful environmental consequences, including habitat loss, threats to biodiversity, and loss of agricultural land intended primarily for food production *[6]*. Agrovoltaics, which combines food and electricity production while adding value to agriculture, is emerging as one of the solutions *[7,8]*. In agrovoltaics, solar modules are installed above crops, providing favourable conditions for the growth of certain plants compared to full sunlight, which will be extremely important in the future, because of the increase in temperatures due to global warming, especially for rational use of water in agriculture. In the desire to reduce pressure on the environment, it will, therefore, be very important to use areas already designated for the purpose of the additional production of electricity. In this context, the best possible placement of solar power plants with minimal environmental impact is on the roofs of existing buildings, which can be categorised as residential and industrial. In the case of single-family and multi-family buildings in Slovenia, roofs are most commonly gabled, or, more recently, mono-pitched, which is often used in modern construction. For industrial buildings, particularly large warehouses and production halls, flat roofs are used predominantly. Since there are many such large buildings, they present an excellent opportunity for installing solar power plants. The question that arises and the primary issue addressed in this paper is how best to utilise large flat roofs to electricity production. Proper placement of solar modules on flat roofs can maximise electricity production. In studying the problem of maximising solar power production on a flat roof, it is necessary to consider that flat roofs are not entirely flat, but have a minimal slope for proper drainage of meteorological water. The minimum recommended slope of a flat roof is at least 1.19° *[9]*. In seeking the ideal placement of solar modules, it is essential to consider their tilt relative to the flat roof, their orientation, and the spacing required to avoid shading between rows of solar modules. All these factors depend on the basic principles of solar radiation and the microclimatic conditions at a specific latitude, as presented in the following sections.

To discuss radiation, we must first mention the sun. It is a star that enables our existence and is the source of almost all the energy received by the Earth. The reason for such a large amount of solar radiation is the nuclear fusion reaction, which converts hydrogen into helium, releasing an enormous amount of energy. Of this, only 49% of the radiation is absorbed by the ground, while the rest is reflected by clouds, back into space, or from the surface *[10]*.

All the radiation received by the Earth from the sun is called global radiation, which consists of two components - direct and diffuse radiation. The first comes directly from the sun, while the latter comes from all parts of the sky. The amount of radiation on the earth's surface depends on the angle of incidence of the sun's rays. This is the angle between the sun's rays and the normal to the inclined surface. It depends on the time of year and the geographic latitude of the observed location. It is a factor that influences the amount of electricity produced by a solar power plant directly. The angle of incidence of the sun's rays α depends directly on the hour angle *h*, declination δ and longitude *L*. All these angles are marked in Fig. 1 *[11]*.

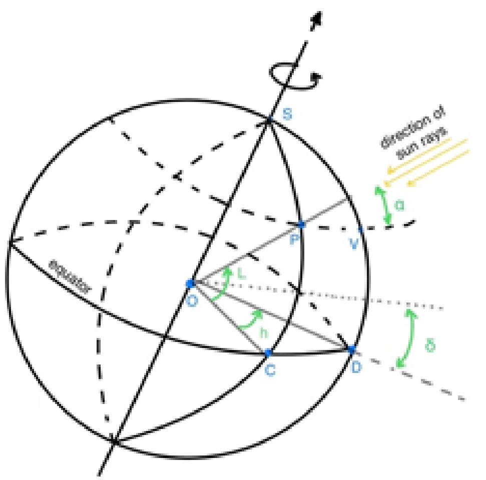


Figure 1: *Definition of hour angle, latitude and declination [12]*

If those angles are known, it is possible to calculate the incident angle of the sun's rays using the cosine theorem (triangle SPV Fig. 1) according to the following equation *[12]*:

$$\cos(90° - \alpha) = \cos(90° - L)\cos(90° - \delta) + \sin(90° - L)\sin(90° - \delta)\cos(h) \quad (1.1)$$

The equation can be simplified further:

$$\sin(\alpha) = \sin(L)\sin(\delta) + \cos(L)\cos(\delta)\cos(h) \quad (1.2)$$

All other correlations between the laws of solar radiation and the production of electricity from a solar power plant, such as daily declination, longitudinal correction, hour angle, local zenith, sun altitude, sun azimuth, etc., are already generally known from different literature *[11]*. The essence of the above is that the angle of incidence of the sun's rays changes over the months, which means that the amount of electricity produced by the solar power plant also changes. However, the focus of this paper is to maximise the total annual electricity production, and to determine the optimal placement for achieving this goal.

Nonetheless, the first step in finding the configuration of the solar power plant is determining the orientation of the solar modules, with three main options: horizontal placement, orientation towards the south (in the northern hemisphere), and east-west orientation. If the solar modules are placed on the roof and oriented south, the maximum electricity production occurs in the middle of the day when the sun's rays are perpendicular to the solar modules, with reduced electricity production in the morning and evening. An East-West orientation enhances energy production during the morning and evening hours, while also allowing for the installation of additional solar modules on the roof, thereby maximising the use of available space. Solar modules placed horizontally on a large flat roof are not used commonly in practice, because snow, pollen, dust and other particles accumulate on them, reducing the amount of produced electricity significantly. To avoid this issue solar modules are tilted at an angle, to maximise annual electricity production. The optimal tilt angle varies between winter and summer, due to the changing angle of the sun's rays throughout the year. In fixed solar power plants the tilt angle cannot be adjusted, so the optimal orientation is generally achieved by choosing an angle close to the geographic latitude and azimuth angle, facing north in the southern hemisphere and south in the northern hemisphere. Therefore, the tilt angle must be determined according to the location where the solar power plant will be installed. In this paper, all simulations are related to the location of Lenart, Slovenia, with the coordinates 46.5834° N and 15.8262° E. Due to the angle of incidence of the sun's rays, the distance from the equator, i.e., geographic latitude, is a significant factor. For the location of Lenart, a tilt angle of 38,5° is optimal for south-orientated solar modules to achieve maximum annual electricity production in a fixed solar power plant *[13]*.

The main issue with tilting solar modules on a flat roof is shading, which results in only the first row producing the maximum possible electricity. If the distance between the rows is too small, each preceding row will shade the subsequent ones at certain times. Although the tilt angle can increase electricity production, it simultaneously causes shading, making it essential to find an optimal balance between the tilt angle and spacing. Increasing the distance between the solar modules reduces shading, but also reduces the number of solar modules on the roof, which, again, decreases electricity production.

2 METHODOLOGY

2.1 The main components of the solar power plant and used software package

As emphasised repeatedly, the primary goal of this research is to determine the optimal placement of solar modules on a large flat roof, to ensure that the solar power plant produces the maximum amount of electricity annually. To explore the optimal spacing, orientation and tilt of the solar modules, it was necessary to create a simulation model. There are many different solar plant design software tools available, such as Aurora Solar, OpenSolar, Helioscope, Solo and SolarEdge, the latter of which was chosen for the research in this paper. SolarEdge is a global company which provides smart energy technology, especially in seeking opportunities to harness renewable energy sources. Since its inception, SolarEdge has been at the forefront of developing new solar technologies that enhance the efficiency and reliability of photovoltaic systems *[14]*. With its comprehensive services, it offers support to both planners and users, with their free solar design tools being particularly useful for this research. Among these tools is SolarEdge Designer, which provides users with satellite HD images, AI-assisted 3D modelling, irradiance mapping, shading analysis, automated electrical calculations to enhance electricity production, and energy simulations and forecasts *[15]*.

The above reasons explain the choice of SolarEdge Designer, in which the simulation model was created. Subsequently, it was necessary to select the main components of the solar power plant within the program, which were used consistently across all configurations of the solar power plant, and are presented below.

A solar module type Himalaya G10 Series from Huasun Manufacturer with 108-cell bifacial with hetero junction technology *[16]* was used for all the simulations. The modules are 1722 mm long, 1134 mm wide and 30 mm high. The nominal data of the solar module used in this paper are presented in Table 1, where P_{max} represents the maximum power of the solar module, *EFF* is the efficiency, U_{mp} is the optimum operating voltage, I_{mp} is the optimum operating current, V_{oc} is the open circuit voltage, I_{sc} is the short circuit current, *m* is the solar module mass and IP is the ingress protection.

Table 1: *Nominal data of solar module HS-182-B108 D430*

P_{max} (W)	*EFF* (%)	U_{mp} (V)	I_{mp} (A)	V_{oc} (V)	I_{sc} (A)	*m* (kg)	IP
430	22,02	33,49	12,84	40,3	13,3	26	68

Furthermore, the nominal data of the three-phase inverter type SE16 *[17]* from the SolarEdge manufacturer used in this paper are presented in Table 2.

Table 2: *Nominal data of the three-phase inverter SE16*

P_N (kW)	U_N (V)	I_N (A)	*EFF* (%)	*m* (kg)	IP
16	400	25,5	97,7	33,2	65

2.2 Simulation model of a flat roof

For the calculation of electricity production in this paper, a flat roof with dimensions of 52 x 52 metres was used for the simulation model. With the solar modules orientated to the south, 26 solar modules were placed in each row. In Fig. 2 there is a model of the south-orientated solar modules, which are tilted for angle β relative to the flat roof and apart by a distance *d*. In the summertime the angle of incidence of the sun's rays is bigger than in the winter, causing less shading for each subsequent row due to the first. In winter there is evidently a lot more shading present, except for the first row. To conclude, it is evident from Fig. 2 that the greater the distance *d*, the less shading there is, but, at the same time, less modules can be placed on the roof.

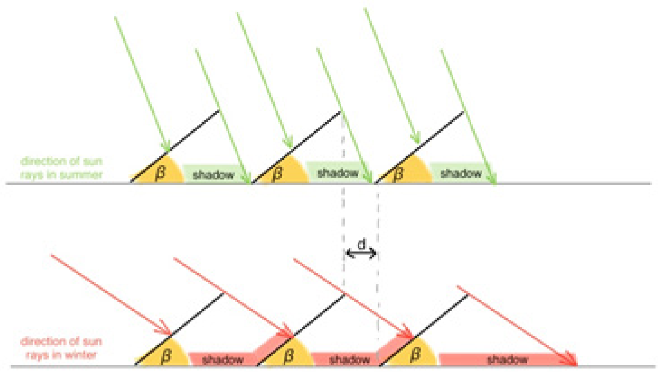


Figure 2: *South orientation of solar power plant modules with the influence of shadowing [18]*

For East-West orientation 2 x 26 modules were placed in each column inside the simulation model, according to Fig. 3. In the simulation model it was investigated how the distance and slope of the solar modules affected the mutual shading of the solar modules.

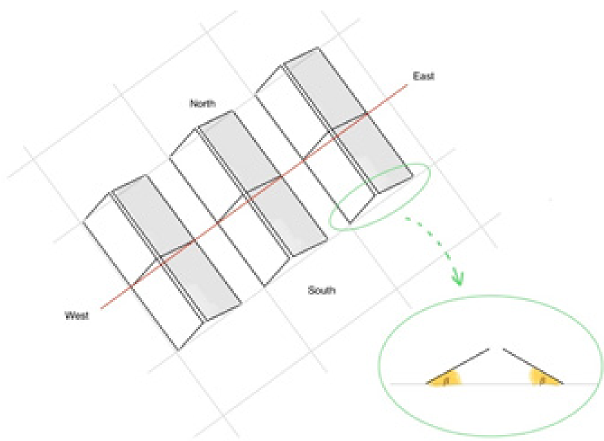


Figure 3: *East-West orientation of solar power plant modules – concept for a flat roof [18]*

3 RESULTS

3.1 South orientation of solar modules on a flat roof

When analysing the placement of south-oriented solar modules on a flat roof, it is necessary to consider the geographical latitude and longitude where the roof with the solar power plant is located. The geographical latitude affects the optimal tilt of the solar modules, at which the power plant produces the maximum amount of electricity annually. The electricity production results for the first row of 26 south-oriented solar modules at different tilt angles are presented in Table 3. The red cells represent at which tilt angle of the modules β the production is the lowest for each month. On the contrary, the green cells show the highest production at a certain tilt angle of the modules. It is evident that, in the winter months, a, bigger tilt is optimal, whereas, in the summer, there is more production with a smaller tilt.

***Table 3:** Electricity production W in MWh for different tilt angles and months for the first row*

β (°)	W_{jan}	W_{feb}	W_{mar}	W_{apr}	W_{may}	W_{jun}	W_{jul}	W_{aug}	W_{sep}	W_{oct}	W_{nov}	W_{dec}	W_{Σ}
3	0,38	0,58	0,95	1,38	1,66	1,73	1,82	1,46	1,16	0,74	0,41	0,31	**12,57**
10	0,46	0,67	1,03	1,44	1,69	1,74	1,85	1,51	1,25	0,83	0,48	0,38	**13,33**
20	0,56	0,79	1,12	1,50	1,70	1,73	1,85	1,55	1,34	0,94	0,57	0,47	**14,12**
30	0,64	0,89	1,18	1,53	1,67	1,68	1,81	1,55	1,40	1,02	0,64	0,54	**14,55**
40	0,71	0,96	1,21	1,51	1,60	1,60	1,73	1,52	1,42	1,08	0,69	0,60	**14,63**
50	0,75	1,00	1,21	1,47	1,50	1,48	1,61	1,45	1,40	1,10	0,73	0,64	**14,33**
60	0,77	1,02	1,18	1,38	1,37	1,33	1,46	1,35	1,36	1,10	0,74	0,66	**13,72**
70	0,78	1,01	1,12	1,26	1,20	1,14	1,27	1,21	1,27	1,07	0,74	0,66	**12,72**

Fig. 4 shows the dependence of annual production on the tilt of the modules for the first row of 26 south-oriented solar modules.

The simulation results show in Fig. 4, that the optimal tilt angle for the location of Lenart city in Slovenia (46.5834° N and 15.8262° E) is 38,5° for maximum annual electricity production of a solar power plant. In the installation of the power plant, the rows are spaced apart by a distance *d* based on the tilt angle, as shown in Fig. 2, where the shading must be considered of the previous row of modules on the next. Table 4 presents the electricity production results of the second row of solar modules compared to the first row for different distances *d* between the rows at a tilt angle of 38,5°. The production of the blue cells of the shaded row of modules is less than 10 percent lower than that of the unshaded 1st row of modules with southern orientation (the green cells in Table 4).

Fig. 4 shows the dependence of annual production on the tilt of the modules for the first row of 26 south-oriented solar modules.

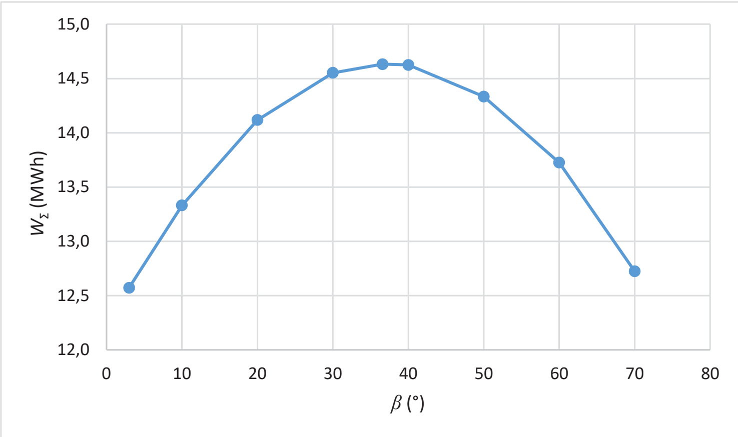


***Figure 4*:** Annual electricity production W_Σ in dependency of tilt angle β for the first row

***Table 4:** Electricity production W (MWh) for different distances between the 1st row and 2nd shaded row, with 26 solar modules in the 2nd row at a tilt angle of 38,5°*

d (cm)	W_{jan}	W_{feb}	W_{mar}	W_{apr}	W_{may}	W_{jun}	W_{jul}	W_{aug}	W_{sep}	W_{oct}	W_{nov}	W_{dec}	W_Σ
0	0,21	0,29	0,44	0,84	0,98	0,98	1,07	0,87	0,57	0,37	0,23	0,19	**7,01**
10	0,23	0,31	0,59	0,89	1,04	1,08	1,13	0,92	0,77	0,38	0,25	0,20	**7,77**
30	0,24	0,36	0,74	1,00	1,39	1,46	1,55	1,12	0,86	0,52	0,26	0,22	**9,71**
50	0,25	0,50	0,78	1,37	1,49	1,50	1,61	1,40	1,00	0,65	0,32	0,23	**11,07**
70	0,32	0,57	0,97	1,41	1,51	1,52	1,64	1,43	1,28	0,68	0,38	0,24	**11,92**
90	0,39	0,60	1,11	1,43	1,53	1,54	1,66	1,44	1,34	0,80	0,42	0,32	**12,54**
110	0,42	0,73	1,14	1,45	1,55	1,55	1,67	1,46	1,35	0,94	0,45	0,36	**13,05**
130	0,45	0,83	1,15	1,45	1,56	1,56	1,68	1,47	1,36	0,99	0,51	0,37	**13,35**
150	0,49	0,92	1,16	1,47	1,57	1,57	1,70	1,48	1,37	1,01	0,56	0,37	**13,64**
1st row	0,69	0,94	1,20	1,52	1,63	1,64	1,76	1,53	1,41	1,06	0,68	0,58	**14,63**

Fig. 5 shows the normalised electricity production of the 2nd shaded row relative to the 1st unshaded row for different distances between both rows. The purple portion of the surface curves on the 3D graph is useful for adequate production at a solar module tilt of 38.5°. The annual electricity production with a 90 cm distance between the shaded rows is 14.3 percent lower compared to the production of the first unshaded row. At 30 cm, the electricity production of the shaded row is 33.6 percent lower.

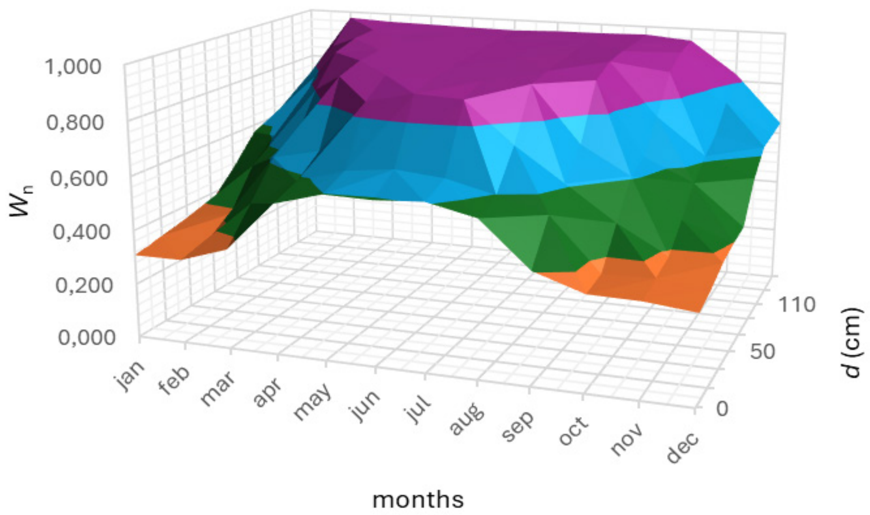


Figure 5: *Electricity production of the 2nd shaded row normalised to the production of the 1st row ata tilt angle of 38,5°*

3.2 East-West orientation of solar modules on a flat-roof

When analysing the installation of East-West oriented solar modules on a flat roof, it is not necessary to consider the geographical latitude and longitude where the roof with the solar power plant is located. The tilt angle of the solar modules relative to the flat roof in an East-West orientation does not affect electricity production significantly. The electricity production results for 26 east-oriented and 26 west-oriented solar modules (2x26 solar modules included in each column, as shown in Fig. 3) at different tilt angles β are presented in Table 5. Due to self-cleaning of the solar modules during rain and the sliding of snow in the winter, an angle β between 12 and 15 degrees is recommended.

***Table 5:** Electricity production W (MWh) for different tilt angles and months for an East-West orientation*

β (°)	W_{jan}	W_{feb}	W_{mar}	W_{apr}	W_{may}	W_{jun}	W_{jul}	W_{aug}	W_{sep}	W_{oct}	W_{nov}	W_{dec}	W_{Σ}
3	0,68	1,07	1,82	2,70	3,29	3,43	3,62	2,87	2,24	1,39	0,76	0,55	**24,43**
7	0,69	1,08	1,82	2,70	3,28	3,42	3,61	2,87	2,24	1,40	0,76	0,56	**24,43**
11	0,69	1,08	1,82	2,69	3,27	3,41	3,60	2,86	2,24	1,40	0,76	0,56	**24,39**
15	0,69	1,08	1,81	2,68	3,24	3,39	3,58	2,84	2,23	1,40	0,77	0,56	**24,27**
19	0,70	1,09	1,81	2,67	3,21	3,36	3,55	2,83	2,22	1,39	0,77	0,56	**24,16**
23	0,70	1,09	1,80	2,65	3,18	3,33	3,52	2,80	2,21	1,39	0,77	0,57	**24,00**
27	0,70	1,09	1,78	2,62	3,13	3,28	3,47	2,77	2,19	1,38	0,77	0,57	**23,75**
31	0,70	1,09	1,77	2,59	3,09	3,23	3,42	2,74	2,17	1,37	0,76	0,57	**23,50**
35	0,70	1,08	1,75	2,56	3,04	3,19	3,37	2,70	2,15	1,36	0,76	0,57	**23,22**
39	0,69	1,08	1,73	2,53	2,98	3,13	3,31	2,66	2,12	1,35	0,75	0,56	**22,90**
43	0,69	1,07	1,70	2,48	2,92	3,07	3,26	2,61	2,09	1,33	0,75	0,56	**22,52**

From Fig. 6 it is evident that, in the colder months of the year (January, February, November and December), the tilt angle of the solar modules in the East-West orientation practically does not affect the electricity production. The influence of the tilt angle is more pronounced during the warmer months (May, June, July and August). The question remains as to what happens when additional columns of solar modules are added to the first column in the East-West orientation on a flat roof. Is there mutual shading between the columns in that case? Practically not, because the height of the solar module junctions in one column is fairly low, as shown in Fig. 7, and it affects neighbouring columns minimally according to the electricity production calculations at different spacings between the columns (presented in Table 6).

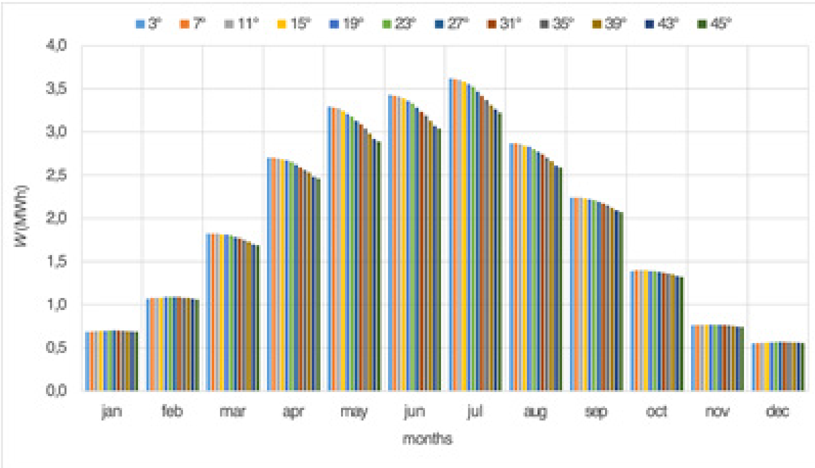


Figure 6: *Electricity production of East-West orientation for different tilt angles and months*

In Fig. 7, there is an example of east-west orientated solar modules used in practice.

Figure 7: *Practical placement of East-West oriented solar modules (own photo)*

In Table 6 the results of the annual electricity production calculations show that the impact of the distance between columns in the East-West orientation due to shading is negligible. The blue cells indicate a decrease in electricity production of less than 1 percent compared to the unshaded column, and the ochre cells indicate a decrease of less than 2 percent. In all other white cells, the electricity production of the shaded columns is less than 4 percent lower compared to the unshaded column. Therefore, in practice, spacings of 25 to 50 cm are used, primarily for maintenance and servicing of the solar power plant.

Table 6: *Electricity production W (MWh) for different distances between the 1st column and 2nd column for 2x26 solar modules in an East-West orientation for a tilt angle of of 15°*

d (cm)	W_{jan}	W_{feb}	W_{mar}	W_{apr}	W_{may}	W_{jun}	W_{jul}	W_{aug}	W_{sep}	W_{oct}	W_{nov}	W_{dec}	W_{Σ}
0	0,67	1,05	1,77	2,63	3,19	3,32	3,51	2,80	2,18	1,35	0,74	0,54	**23,75**
10	0,68	1,05	1,77	2,63	3,19	3,33	3,51	2,80	2,19	1,35	0,75	0,55	**23,78**
30	0,68	1,07	1,78	2,64	3,20	3,33	3,52	2,80	2,19	1,37	0,75	0,55	**23,86**
50	0,68	1,07	1,79	2,66	3,22	3,37	3,56	2,82	2,21	1,38	0,75	0,55	**24,05**
70	0,68	1,07	1,80	2,66	3,22	3,37	3,56	2,82	2,22	1,38	0,76	0,55	**24,09**
90	0,68	1,07	1,80	2,67	3,23	3,38	3,56	2,83	2,22	1,38	0,76	0,55	**24,11**
110	0,69	1,07	1,80	2,67	3,23	3,38	3,57	2,83	2,22	1,38	0,76	0,56	**24,13**
130	0,69	1,07	1,80	2,67	3,23	3,38	3,57	2,83	2,22	1,38	0,76	0,56	**24,16**
150	0,69	1,08	1,81	2,67	3,23	3,38	3,57	2,83	2,22	1,39	0,76	0,56	**24,19**
1st col.	0,69	1,08	1,81	2,68	3,24	3,39	3,58	2,84	2,23	1,40	0,77	0,56	**24,27**

4 ANALYSIS

For the simulation model presented in Section 2.1, the simulation calculations of electricity production were performed for both possible configurations (South orientation and East-West orientation, as shown in Fig. 8) of the solar power plant on the flat roof discussed in the paper.

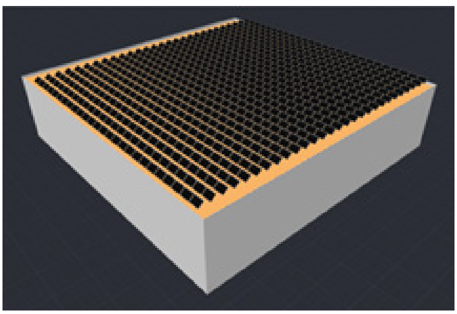
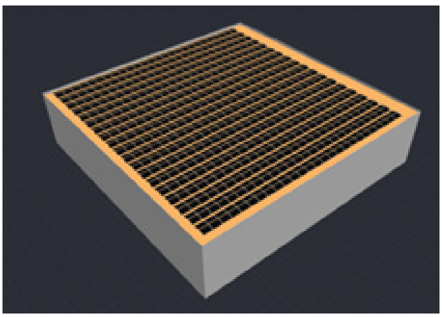
(a)  (b) 

Figure 8: *Simulation model in SolarEdge Designer software; (a) South orientation and (b) East-West orientation.*

In Table 7 there are the calculations` results for a simulation model with dimensions 50x50, in which case the flat roof has 2500 m² of useful area for solar modules` installation. What is important to consider is the fact that, in practice, not all the area of the flat roof is used for solar modules` placement, because there should be space left for service and maintenance access to solar modules, as well as enough place for ensuring fire safety *[19]*. In Table 7 P_i represents the installed peak power of the solar modules, W_Σ is the annual electricity production, *WD* is the energy density in terms of annual electricity production per flat-roof surface, *PI* is the performance index in terms of annual electricity production per installed solar modules peak power, and *PD* is the power density in terms of the installed peak power of solar modules per flat-roof surface. From the results of the calculations presented, it is evident that the best configuration is East-West, because it has far higher values for all the variables listed above. It is especially important to emphasise annual energy production $W_{\Sigma,}$ which, in the East-West orientation is 23,78% higher than in the south orientation at just 7,64% higher power density in terms of the installed peak power of solar modules per flat-roof surface *PD*.

Table 7: *Electricity production for different orientation, distance and tilt angle – simulation model*

Orientation	*d* (cm)	*β* (°)	*No. of modules*	P_i (kW_p)	W_Σ (MWh)	*WD* (kWh/m^2)	*PI* (Wh/W_p)	*PD* (kW_p/m^2)
South	90	38,5	728	313,04	181,31	72,524	579	0,125
South	30	15	910	391,30	348,20	139,28	890	0,157
East-West	30	15	988	424,84	456,82	186,33	1075	0,170

5 DISCUSSION

The research about solar power plant configuration on a flat roof for the highest annual production of electric energy is presented in this article. When placing solar modules on a flat roof at a certain tilt shading occurs, as a problem which should be considered while determining the best configuration. The data show that the optimal tilt angle for Lenart in Slovenia, where the simulation model was located, is 38,5°. However, in practice, it shows up that, at this tilt of solar modules on a flat roof, the annual production is actually the lowest compared to the south and East-West orientation, both at a tilt angle of 15°. The calculations show that it is possible to provide a power density of 0,170 kW_p/m^2 on a flat roof with East-West orientation of the solar modules. This means that we can install 170 W of solar module power per square metre, which produces 186.33 kWh per square metre of flat roof annually.

6 CONCLUSIONS

The green transition of a sustainably oriented society requires the use of renewable resources. Direct use of solar energy is possible with solar power plants, whose installed capacity is increasing rapidly worldwide. In exploiting solar energy, power plants are installed on structures of various sizes and roof topologies. A particular challenge is the installation of a solar power plants on flat roofs, where it turns out that the placement of south-facing modules does not contribute to maximum electricity production. Therefore, this article presents methods and procedures for determining the optimal placement of solar modules on a flat roof of a building to achieve maximum annual production. Commercial software tools were used for the production calculations, which can determine the appropriate configuration of the module layout for maximum production. It turned out that the East-West orientation of the solar modules is the best for a flat roof. One of the advantages of East-West orientation is higher power density, which results in increased electricity production. This is a good solution, because it is more common for buildings to be space-constrained than not. Furthermore, the East-West orientation is the most aerodynamic out of all configurations, which is especially beneficial for flat roofs in windy areas. Because East-West systems are tilted with an angle of 15°, self-cleaning capabilities are increased, which is, again, important for the maximisation of electricity production. Another great thing about this orientation is that the solar modules are installed back-to-back, which reduces the risk of shading, and therefore increases the efficiency of the solar power plant.

References

[1] **D. H. Meadows et al.:** *The Limits to Growth*, Universe Books, 1972

[2] **Directorate-General for Structural Reform Support:** *Technical support for implementing the European Green Deal*, Publication Office of the European Union in Luxembourg, 2020

[3] **M. Borowiecki et al.:** *Accelerating the EU's green transition*, OECD Economics Department Working Papers, No. 1777, 2023

[4] **A. M. Reveshti et al.:** I*nvestigating the effect of new and old weather data on the energy consumption of buildings affected by global warming in different climates*, International Journal of Thermofluids, No. 19, 2023

[5] **A. A. Ahmed:** *Global warming potential, water footprint, and energy demand of shared autonomous electric vehicles incorporating circular economy practices*, Sustainable Production and Consumption, No. 36, 2023

[6] **Editorial:** *Sustainable development of energy, water and environment systems in the critical decade for climate action*, Energy Conversion and Managementtle, No. 296, 2023

[7] **P. Jain et al.:** *Agrovoltaics: Step towards sustainable energy-food combination*, Bioresource Technology Reports, No. 15, 2021

[8] **C. J. Torrente et al.:** *Simulation model to analyze the spatial distribution of solar radiation in agrivoltaic Mediterranean greenhouses and its effect on crop water needs*, Applied Energy, No. 353, 2024

[9] **International Code Council:** *International Building Code*, USA, 2021

[10] **Kastelec et al.**: Sončna energija v Sloveniji, Ljubljana, 2007

[11] **E. Golubovska et al.:** *Analytical estimation of the optimal PV panel tilt based on a clear sky irradiance model*, Journal of Energy Technology, Vol. 16, Iss. 4, 2023

[12] **S. Seme:** *Optimalno sledenje fotonapetostnega sistema soncu ob upoštevanju izgub pogonskega sklopa*, doctoral dissertation, UM FERI, 2011

[13] **Solarific.** Available: https://solarific.co/si (date of last access: 13. 8. 2024)

[14] **A. Dudek:** *Equity research: SolarEdge Technologies, INC.*, University of Algarve, 2023

[15] **Energy Simulation Validation:** *SolarEdge Designer Review*, 2019. Available: https://knowledge-center.solaredge.com/sites/kc/files/se-designer-simulation-validation-dnv-gl-report.pdf (last access: 13. 8. 2024)

[16] **Huasun.** Available: G10-182-108-DS_EN (huasunsolar.com) (last access: 13. 8. 2024)

[17] **Huason.** Available: se-three-phase-inverter-extended-power-datasheet.pdf (solaredge.com) (last access 13. 8. 2024)

[18] [**Y. Yang et al.:** *Potential analysis of roof-mounted solar photovoltaics in Sweden*, Applied Energy, No. 279, 2020

[19] **SolarPower Europe:** *Rooftop PV Fire Safety Factsheet*. Available: https://api.solarpowereurope.org/uploads/Factsheet_Rooftop_PV_Fire_Safety_vfinal_33eaab8bb3.pdf?updated_at=2024-03-18T15:38:06.684Z (last access: 13. 8. 2024)

Nomenclature

α	Incident angle of the sun's rays
h	Hour angle
δ	Declination
L	Longitude
P_{max}	Maximum power of the solar module
EFF	Efficiency of the solar module
U_{mp}	Optimum operating voltage
I_{mp}	Optimum operating current
V_{oc}	Open circuit voltage
I_{sc}	Short circuit current
m	Solar module mass
IP	Ingress protection
β	Tilt angle of the modules relative to the flat roof
d	Distance between the modules
P_i	Installed peak power of the solar modules
W_Σ	Annual electricity production

WD	Energy density of the annual electricity production per flat-roof surface
PI	Performance index of the annual electricity production per installed solar module`s peak power
PD	Power density in terms of the installed peak power of the solar modules per flat-roof surface