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Orientation and Tilt Dependence of a Fixed PV Array Energy Yield Based on Measurements of Solar Energy and Ground Albedo – a Case Study of Slovenia

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1. Introduction

In the last decade solar photovoltaic (PV) systems have become available as an alternative electrical energy source not only in remote locations but even in densely populated areas as their price decreases and their performance increases. The chapter discusses fixed PV array potential in Slovenia with great geographical and topographical variety, which is a reason that the climate, and also PV potential, changes rapidly already on short distances. The study is based on the meteorological measurements of solar irradiance, air temperature and albedo from the MODIS satellite data. Simulations for four meteorological stations were employed to determine combinations of azimuth and tilt angle for fixed PV arrays that would enable their maximum efficiency. As expected, large tilt with southern orientation is optimal during winter and almost flat installations are optimal during summer. The optimal PV gains are compared also with the results obtained by using the rule of a thumb tilt angle showing some significant differences in some cases.

2. Theoretical background

PV system users can define the orientation of their PV arrays: their azimuth angle (angle measured clockwise from North) and the tilt angle (the angle above the horizontal plane). Previous studies show that, if local weather and climatic conditions are not considered, the optimal fixed tilt angle of PV modules depends only on geographical latitude φ (and the optimal azimuth is always south in the northern hemisphere). Considering only direct solar irradiation, the optimal tilt angle during the year can be calculated as $\varphi - \delta_s$, where δ_s is the declination of the Sun. For example, for latitude $\varphi = 46°$ N the maximal direct irradiation on 21 March and 21 September is achieved at a tilt angle of 44°. On 21 June and on 21 December the tilt angle is changed by the declination of the sun (± 23.5°) to 20.5° and 67.5°.

Due to the diffuse light the optimal tilt angles differ from those in reality. Since modules are frequently incorporated into the architecture of some objects, often some "rule of thumb" is applied. By taking such an approach a certain "yearly optimum" is obtained – as suggested by Duffie and Beckman (1991) – the tilt angle should be 10°–15° more than the latitude during winter and 10°–15° less than the latitude during summer. The lower values are originally based on the classical report by Morse & Czarnecki (1958) from the mid-20th century. Their suggestion for the annually optimally fixed tilt angle is a value 0.9 times the latitude, which results in 40° for Slovenia. Other authors (Lewis, 1987; Heywood, 1971; Lunde, 1982; Garg, 1982) have concluded that the optimal tilt differs from the latitude in a range between ±8° and ±15°. An analytical equation to find the daily optimal tilt angle at any latitude has also been used (El-Kassaby & Hassab, 1994). For example, the average optimal tilt angle on Cyprus (latitude $\varphi = 35°N$) equals 48° in the winter months ($\varphi + 13°$) and 14° ($\varphi - 21°$) in the summer months (Ibrahim, 1995). The optimal tilt was estimated for Brunei Darussalam on the basis of maximising the global solar irradiation reaching the collector surface for each month and year (Yakup & Malik, 2001). The tilt optimised for winter in Poland equals 50°–65°, for summer 10°–25°, and the PV module does not necessarily have to be oriented directly to the south – a range in the azimuth angle of -60° to +60° from the South also provides good results (Chwieduk & Bogdanska, 2004). The optimal tilt angle in Turkey varies from 13°–61° from summer to winter (Kacira et al., 2004), while the monthly optimised tilt in Ireland can vary from 10° to 70° (Mondol et al., 2007).

The optimal tilt for the whole of Europe (PVGIS) shows that climate characteristics have a huge influence on the optimal tilt (Huld et al., 2008). In this contribution we particularly emphasise local weather and climatic conditions when computing the optimal orientation and tilt. As we will show in Section 3, these may differ considerably from the "maximum noon direct irradiation" as well as from the "rule of thumb" results.

2.1 Solar irradiance on a tilted plane

The most important parameter for computing the solar irradiance reaching the Earth's surface is cloud coverage. In clear-sky conditions the next most important factor is the optical path length as the transmissivity of the atmosphere exponentially depends on it, which implies the position of the Sun in the sky (its zenith angle ϑ_s and azimuth A_S that may be aggregated into unit vector $\vec{s}\left(\vartheta_s, \alpha_s\right)$ towards the Sun) changing over the course of a day and year. The **true solar time** (considering the geographical latitude and the equation of time) has been used for accurate computations and not the zonal time.

Actual irradiance on the tilted plane varies significantly with its orientation geometry (tilt τ– angle of inclination between the horizontal surface and the PV module's receiving plane, and orientation A – the azimuth angle between the North and the azimuthal component of the normal to the PV's plane; both may be aggregated into a unit normal vector of the plane $\vec{n}(\tau, A)$.

Solar irradiance is usually measured on a horizontal plane as global irradiance E_{gl}. The direct component $E_{gl,\,dir}$ and diffuse component $E_{gl,diff}$ of global irradiance must be considered separately because of their very different dependences on the tilted irradiance. When knowing the two components one can compute irradiance E_{tilt} on the tilted plane (in the meteorological community this is called quasi-global irradiance). The effect of the PV module's tilt and azimuth angle on the **direct part of solar tilted irradiance** $E_{tilt,dir}$ is described by a scalar product of the two unit vectors:

$$E_{tilt,dir} = \vec{s} \cdot \vec{n} \frac{E_{gl,dir}}{\cos \vartheta_s} \tag{1}$$

The effect of **diffuse tilted irradiance** ($E_{tilt,dif}$) can only be considered to be isotropic when there are no obstacles (e.g. mountains, buildings) on the horizon and the whole sky is covered by clouds of uniform brightness (Fig. 1). Many anisotropic models have therefore been developed: e.g. Brunger & Hooper (1993); a good overview is included in Kambezidis et al. (1994) but they mostly have an empirical background and thus their use is only suitable when a calibration of the model with measurements on the tilted surface is possible. Therefore, simplified isotropic models based on the parameter called the **sky-view factor** (*svf*) are mostly used. The sky-view factor is defined as the hemispherical fraction of unobstructed sky. There are several isotropic models of *svf* for inclined receivers. The 2D one: $svf = (1 + \cos \tau)/2$ (Mondol et al., 2007; Huld et al., 2008; Liu & Jordan, 1963), the improved one with a more realistic 3D consideration: $svf = (1 + \cos^2 \tau)/2$ (Badescu, 2002; Brunger & Hooper, 1993), as well as the 3D linear model by Tian et al. (2001):

$$svf = (\pi - \tau)/\pi. \tag{2}$$

Besides diffuse radiation from the sky, reflected (multiple scattered) radiation from the ground can also be important, especially for modules with a larger tilt and in areas of high ground reflectivity, like in a snow-covered landscape. Ground reflection is defined by the **ground-view factor** (*gvf*) that is a complementary parameter to the sky-view factor:

$$gvf = 1 - svf. \tag{3}$$

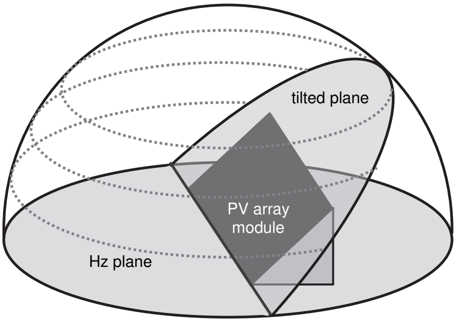

Fig. 1. a) 3D approach to estimating the sky-view factor – the visible sky is limited by the horizontal plane and tilted plane of the PV module, thus only that part of the hemisphere between these planes is visible.

For the diffuse irradiation coming from the ground is beside the geometry important also the ground reflectivity, characterised by the **albedo (reflectivity) of the surrounding surfaces a_{gr}**. A constant albedo of 0.2 (typical grassland) was used in most previous studies. Some other approaches as Gueymard (1993) also suggest a seasonal albedo model. Such an albedo changes over the year according to the latitude and land cover of the observed area or to anisotropic approaches (Arnfield, 1975). These models are mainly appropriate for areas where a direct reflection is possible.

Tilted solar irradiance E_{tilt} of a tilted plane is written by many authors as the sum of the abovementioned contributions. The diffuse component coming from the sky decreases with the tilt angle while at the same time the ground diffuse part of the irradiance increases:

$$\mathrm{E_{tilt}} = \mathrm{E_{tilt,dir}} + \mathrm{E_{tilt,dif}} = E_{tilt,dir} = \vec{s}\cdot\vec{n}\,\frac{E_{gl,dir}}{\cos\vartheta_s} + \mathrm{E_{gl,dif}}\cdot \mathrm{sfv} + \mathrm{a_g}\cdot(\mathrm{E_{gl,dir}} + \mathrm{E_{gl,dif}})\cdot \mathrm{gfv}. \qquad (5)$$

Just recently the first two authors of this contribution have elaborated a more exact and conceptually proper approach based on the integration of isotropic radiance of sky L_{sky} that gives, when integrated over the whole hemisphere, the diffuse irradiance of horizontal receiving surface $E_{gl,dif} = \pi L_{sky}$. Integration over the hemisphere, for which part of it has the radiance of sky L_{sky} and the other part has a different radiance of ground L_{gr} results in irradiation of the tilted surface E_{tilt}. If the albedo a_{gr} and the coefficient k describing the contribution of the diffuse irradiation to the global irradiation ($E_{gl,dif} = k\cdot E_{gl}$) are also considered, an alternative, more accurate estimate of irradiation of the tilted receiving surface is obtained:

$$\mathrm{E_{tilt}} = \mathrm{E_{tilt,dir}} + \mathrm{E_{tilt,dif}} = \vec{s}\cdot\vec{n}\,\frac{E_{gl,dir}}{\cos\vartheta_s} + E_{gl,dif}\,\frac{1}{2}\left(1+\cos^2\tau+\frac{a_{gr}}{k}\sin^2\tau\right) \qquad (5)$$

Expressions (4) and (5) differ only as regards diffuse irradiation; the difference depends on reflectivity a_{gr} and on contribution k of the diffuse irradiance to the global irradiance. For example, for $a_{gr} = 0.2$ and $k = 0.5$ the results differ by up to approximately ±6% for the diffuse irradiance, and up to approximately ±3% for the whole irradiance of tilted irradiance E_{tilt}. Here a more appropriate expression (5) was applied; more details about this are found in a submitted paper (Rakovec & Zakšek, n.d.).

2.2 Performance of PV modules and arrays

The energy conversion efficiency of a PV module or array as a group of electrically connected PV modules in the same plane is defined as the ratio between electrical power P_{PV} conducted away from the module, and the incidence power of the sun: $P_{PV}(t)/SE_{tilt}(t) = \eta$. Normally, their efficiency is defined under standard test conditions η_{STC} (STC – module temperature: $T_{STC} = 25$ °C, irradiance: $E = 1000$ W/m², spectrum: AM1.5; IEC 61836-TR/Ed.2:2007; IEC 60904; http://www.iec.ch). The output power of a PV module depends on several parameters, including the irradiance, incidence angle and PV cell temperature T as the most influential. Namely, the PV cell **efficiency also depends on its temperature** as in solar cells based on the p-n junction diode principle the efficiency decreases with increasing temperature due to the higher dark current (Green, 1982). The efficiency temperature dependence is normally expressed by a linear equation:

$$\eta(T) = \eta_{STC}[1+\gamma(T - T_{STC})]. \tag{6}$$

The value of γ is approximately -0.004/K for polycrystalline silicon cells and modules (Carlson et al., 2000).

Beside the irradiance, incidence angle and temperature dependence of the PV module, the output power of the PV system also depends on system losses: Joule losses in wirings of PV modules into PV arrays and inverter losses. These additional losses do not influence the tilt and azimuth dependence of the output energy since they only depend on the output power and on irradiance and not on time like the module's temperature. To obtain the system energy output from the PV module output energy we used a typical system performance factor of 85% in our study.

2.3 Thermal model of PV modules

How the temperature of the absorbing material of the receiving PV module increases depends on the energy exchanges between the absorber and its environment. Different assumptions can be made as regards the PV module energy balance equation. To explain only the basic energy exchange here we consider the PV module as a whole: cells with temperature T_c, the covering plate with its temperature T_p, eventually with the temperature on the surface (where it exchanges energy with the environment) also different from the one on the inner side of the plate are all considered to be one object with temperature T and with heat capacity c, having mass m and a receiving area S. Such a simplification neglects all the energy flows between the separate parts of the PV module, but on the other hand emphasises only the most important features of PV module energetics, without entering into particular details. In this paper we will also focus only on outdoor conditions. We also suppose, again to simplify the explanation, that all the surroundings have the same temperature as environmental air T_{env}. In principle, for both PV modules and solar thermal (ST) solar collectors the energy flows are the same (Petkovšek & Rakovec, 1983). The divergence of all these energy flows results in cooling (normally during the late afternoon and night), while convergence (i.e. negative divergence) results in a warming of the absorber (normally during morning and early afternoon hours). The result expressed as $(mc)\mathrm{d}T/\mathrm{d}t$ can be written as:

$$\begin{aligned} mc\frac{dT}{dt}(t) &= P_s(t) + P_{conv}(t) + P_{cond}(t) + P_{IR}(t) + P_{lat}(t) - P_{PV}(t) = \\ &= (1-a)SE_{tilt} - (K_{conv} + K_{cond})(T - T_{env}) + \sigma\varepsilon S(\varepsilon_{env}T_{env}^4 - T^4) + P_{lat} - P_{PV} \end{aligned} \tag{7}$$

The terms in the equation are as follows: absorbed solar power $Ps = (1\text{-}a)SE_{tilt}$, the (turbulent) convective heat exchange between the absorber and its atmospheric environment $P_{conv} = -K_{conv}(T - T_{env})$, heat conduction between the absorber and the surrounding neighbouring parts of the module (e.g. supporting) $P_{cond} = -K_{cond}(T - T_{env})$, the infrared radiation energy exchange (in the "terrestrial" wavelengths interval, centred at about 10 μm) $P_{IR} = S\varepsilon(\varepsilon_{env}\sigma T_{env}{}^4 - \sigma T^4)$, eventually latent heat exchanges, due to condensation or evaporation at the module, due to precipitation falling upon it etc: P_{lat} and, of course, the flow of energy away from the absorber – the yield of the useful energy P_{PV}. For the meaning of some of the symbols, see the main text; the others are: a – albedo of the module for solar radiation, S – the area of the module, K_{conv} and K_{cond} are the heat exchange coefficients, σ is the Stefan-Boltzmann constant and ε and ε_{env} are the IR emissivities of the module and its environment, respectively. As regards the IR irradiation from above: for clear sky is IR emissivity ε_{env} of approximately 0.7, while for overcast sky it approaches one – the emissivity of the black body.

An analytical solution of equation (7) needs input data in analytical form; the two most important forms of environmental data are tilted irradiance E_{tilt} and environmental (air) temperature T_{env}. The climatological values exhibit an excellent similarity to the sinusoidal course and the same similarity is found for individual cases (see the example for Etilt in Fig. 3a) as shown in Fig. 2. But an equation in which some other coefficients also change in time differently from case to case can only be precisely integrated numerically for each of the governing conditions to give $T(t)$ and with that also $\eta[T(t)]$. The numerical approach is used to calculate PV characteristics – and $\eta[T(t)]$ – on the basis of the measured data.

For example, an increase in the module's temperature from the morning hours until noon $\Delta T \approx 47$ K (Fig. 3d) leads to a negative relative change in the module's conversion efficiency $\gamma \cdot \Delta T = \Delta\eta \;/\; \eta_{STC} \cong -0.19$, which is confirmed with measurements ($\eta = 10\%$ at noon in Fig. 3c compared to $\eta_{STC} = 12.3\%$).

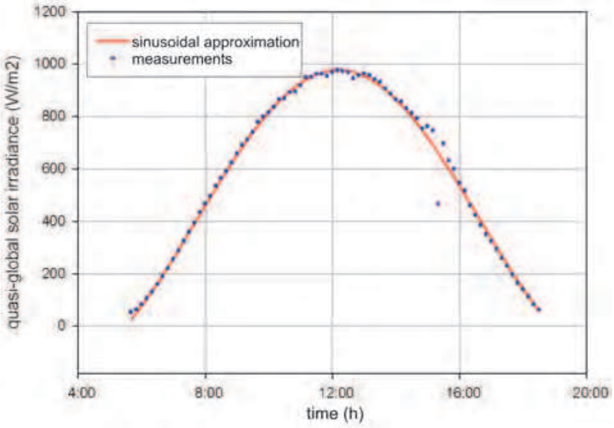

Fig. 2. Quasi-global solar irradiance fitted with a section of the sinusoidal function $E_{tilt0} + E_{tilt1} \sin \omega(t - t_0)$ (with $E_{tilt0} = 405$ W/m², $E_{tilt1} = 572$ W/m², $\omega = 8.46$ h⁻¹). The correlation coefficient between the data and the analytical function is 0.996.

2.4 Some experimental results

The Laboratory of Photovoltaics and Optoelectronics at the Faculty of Electrical Engineering of the University of Ljubljana (latitude: 46.07°N, longitude: 14.52°E) continuously monitors outdoor conditions of several variables and parameters relevant for PV (Kurnik et al., 2007; Kurnik et al., 2008), including E_{tilt}, P_{PV}, module temperature T and air temperature T_{air}.

One example for 20 July 2007 in Ljubljana is presented in Fig. 3. Based on these data the module efficiency was computed and is presented in Fig. 3c. Due to the higher reflection from the module by large incident angles, the efficiencies in early morning and late afternoon hours are quite low. Instead of being some 11 or 12% (as the module's temperature at that time is low!) the calculated values are even below 9%. Between 8:30 and 12:30, when solar rays are more perpendicular to the module (low reflection), the module

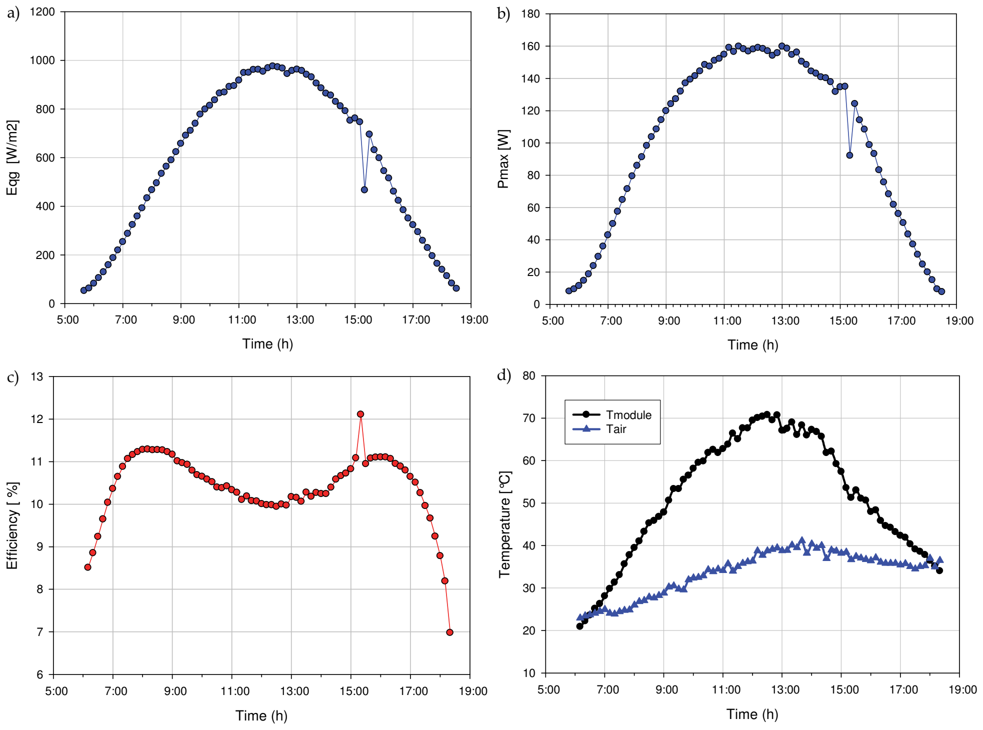

Fig. 3. a) Measured tilted irradiance E_{tilt} in the plane of the PV module (τ=30°, α=180°) oriented to the South on a clear day on 20 July 2007 in Ljubljana – with the Sun being occulted by a cloud at 15:20; b) measured power P_{PV} obtained of a typical polycrystalline module (S=1.634 m^2) with the same tilt and orientation; c) measured efficiency $\eta = P_{PV}/S/E_{tilt}$ (η_{STC} = 12.3%); and d) temperature of module T and of the surrounding air on roof T_{air} being higher than the one measured at the met station (Topič et al., 2007).

temperature increases from 45 °C to 71 °C and the η drops from 11.3% to 10.0%. The empirically estimated relative efficiency temperature coefficient is - 0.0044/K, which is close to the producer's specification of the temperature coefficient of the maximal output power γ = - 0.004/K.

3. Case study

The case study area presented in this chapter is Slovenia – a country on the south-east flank of the Alps between the Mediterranean and the Pannonian plain (approximately 13.5°-16.5°E and 45.5°-47.0°N). The country's great topographical variety significantly influences the climate characteristics, which results in annual solar radiation variations and influences the orientation of PV modules.

3.1 Data

The majority of pyranometers installed at meteorological stations in Slovenia have been functioning since 1993 or even later. The study was therefore done on just 10-year-long data sets (Kastelec et al., 2007) and not on a 30-year period, which is the climatologically established standard. Global solar irradiation was during 1994–2003 measured at 12 meteorological stations (on average, one per approximately 2,000 km^2). Air temperature measurements were also taken from the same meteorological stations.

Map of ten-year average of annual global solar irradiation exposure was done by spatial interpolation of measured data on 12 locations and estimated data of global irradiation exposure on the basis of measured sunshine duration on 15 additional locations using Ångström's formula (Fig. 4).

Annual global radiance exposure changes significantly due to the country's great climatic variety even over short distances. No data across the Slovenian border was taken into account by spatial interpolation, so the accuracy of interpolated values is lower in the regions near the borders especially in the mountainous western and southern parts.

The diffuse part of the incoming solar energy was determined statistically by the Meteonorm 5.0 model package (Meteotest, 2003) at the remaining stations. The diffuse part of the incoming energy contributes a relatively smaller proportion to the global radiance exposure during summer (approximately 35–45%), and a relatively greater one during winter when there is even more diffuse than direct radiance exposure (up to 60%).

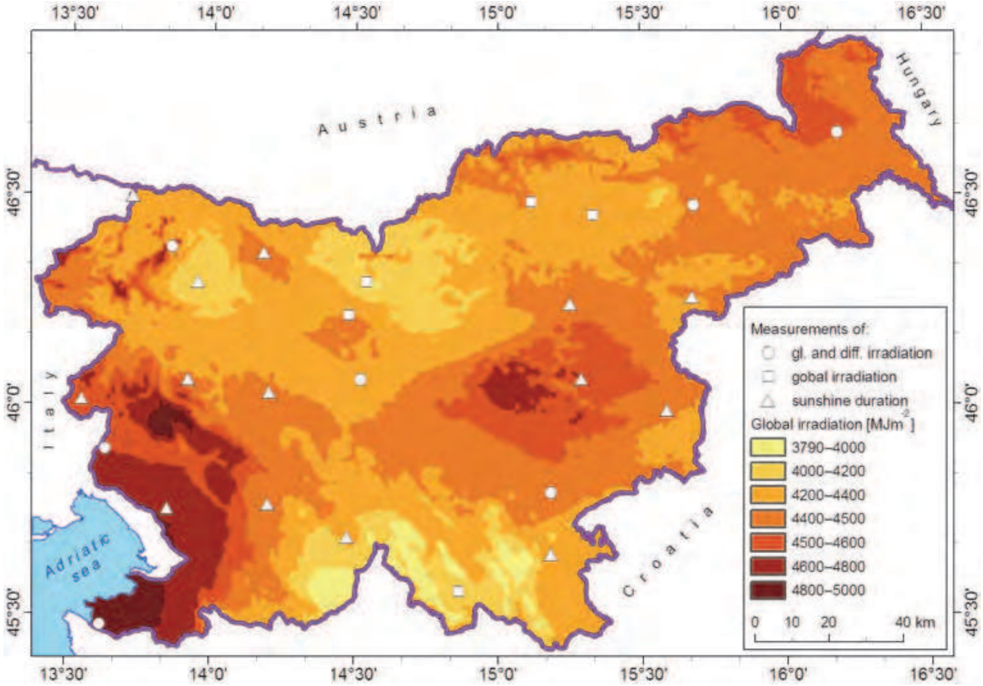

Fig. 4. Interpolated average annual global solar irradiation exposure has a heterogeneous spatial distribution in Slovenia (average for the 1994–2003 period; Kastelec et al., 2007).

The surface albedo was estimated by satellites. MODIS MOD43B3 albedo product (NASA, 2010) was used in the study, more specifically the shortwave (0.3–5.0µm) white sky broadband albedo. The MOD43B3 albedo product is prepared every 16 days in a onekilometre spatial resolution. A reprocessed (V004) MOD43B3 albedo product is available from March 2000 till the present (thus not for the same time interval as used for global radiance exposure). Fig. 5 shows the annually averaged albedo over Slovenia for the 2000–2007 period.

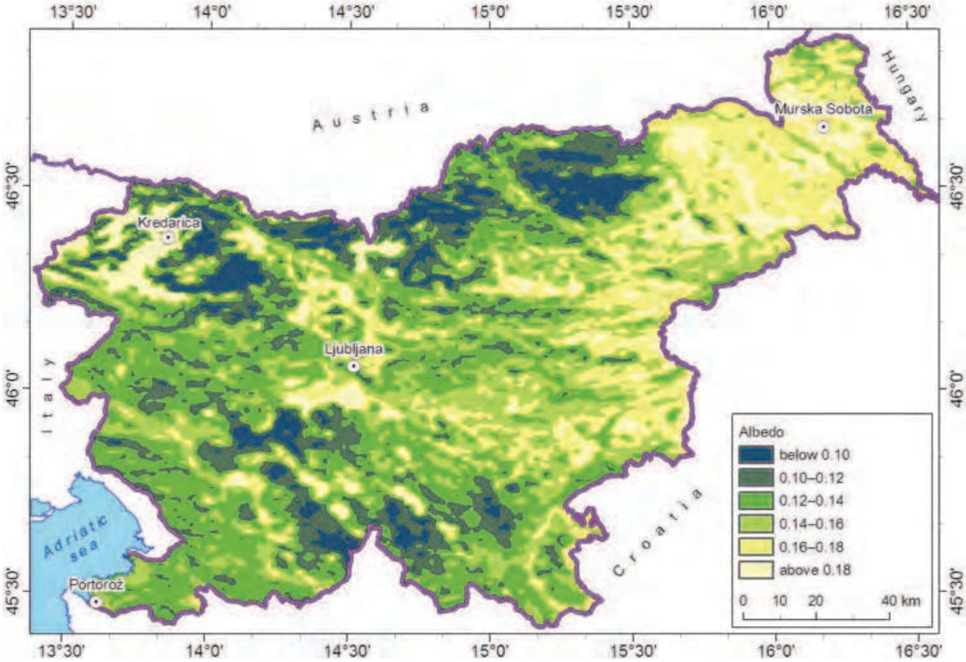

Fig. 5. Yearly averaged albedo (2000–2007) of the surface in Slovenia using MODIS images in a 1,000 m spatial resolution. Locations of four locations whose results are shown in the case study are also marked.

3.2 Computational simulation

We computed the energy output for each combination of a tilt and azimuth angle for all months and for the whole year. This gives us the optimum combination of both geometry parameters for each period. In the same way we get also the increase or decrease of the energy received on any orientation of a PV in the chosen period. Our results are the graphs showing this increase/decrease relative to tilt τ and azimuth angle α are the most important results of this study. We ran the simulation using the IDL language. It took several minutes for each computation using a relatively powerful personal computer.

Solar irradiance changes continuously over time in nature. Therefore, we decided to average the hourly measurements for 10-day periods. This resulted into 16-hourly averaged values (sunrise always after 4:00 and sunset always before 20:00) for each of the 36 periods. As meteorological measurements are performed at observing times according to UTC or to zonal time (CET) and not according to the true solar time, the distribution of the solar irradiance over the day is not symmetrical regarding the zonal noon. This can lead to errors of 20° by estimation of the optimal azimuth angle in March. The hourly data were thus fitted to a 5th order polynomial and then the irradiance and temperature values were estimated for each one hundredth of an hour. These values (at the end 16,000 for each of the 36 periods) were used in the simulation.

The MOD43B3 albedo product was averaged for the 2000–2007 period (this product was not available for earlier years) over each month. Then it was projected to the Slovenian national co-ordinate system into a regular grid of a 1,000 m spatial resolution. Due to cloud coverage, some albedo datasets contain data gaps; these were in our case study removed during temporal averaging.

4. Results

The results are presented for four locations in Slovenia (see their locations in Fig. 5). The graphs (Figs. 6–9) and Table 1 present the relative gain of energy (as a percentage) for the optimal combination of the inclination and orientation (marked by a cross) in comparison to energy on the horizontal surface. The abscise axes correspond to the azimuthal orientation (clockwise from the North) for azimuths from E to W (90° to 270°) and ordinate axes to the tilt (zero when the surface is horizontal and 90° for a vertical receiving surface). There are some differences among the four places, along with some common attributes. It is important to stress that optimal orientations and tilts are strongly affected by local weather and climatic conditions.

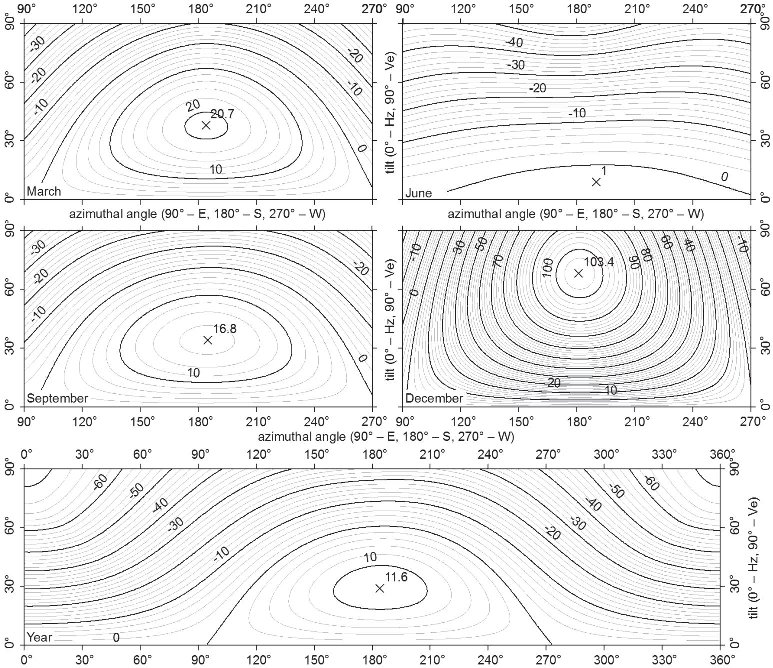

Fig. 6. Contour plots of the relative PV array energy yield regarding the horizontal surface as a function of a fixed orientation and tilt for March, June, September and December as well as the whole year for Portorož in the Mediterranean part of Slovenia.

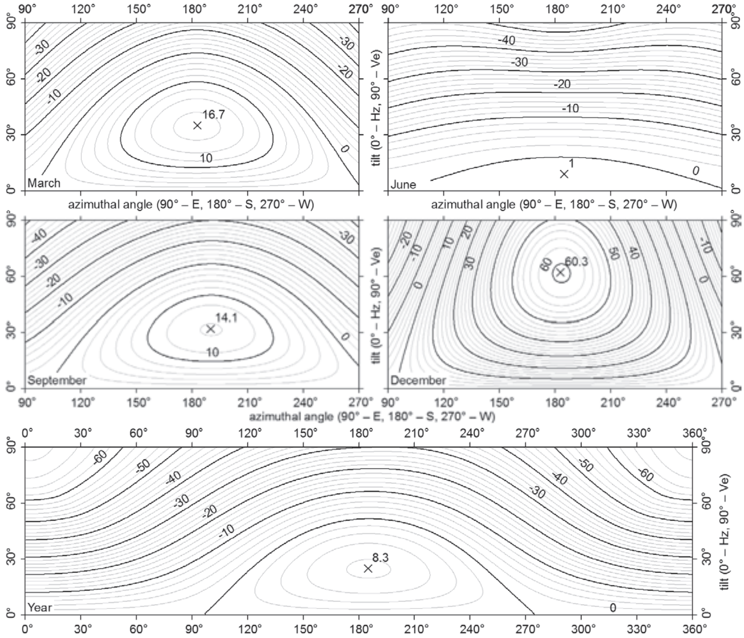

Fig. 7. As for Figure 6, but for Ljubljana in a basin in central Slovenia.

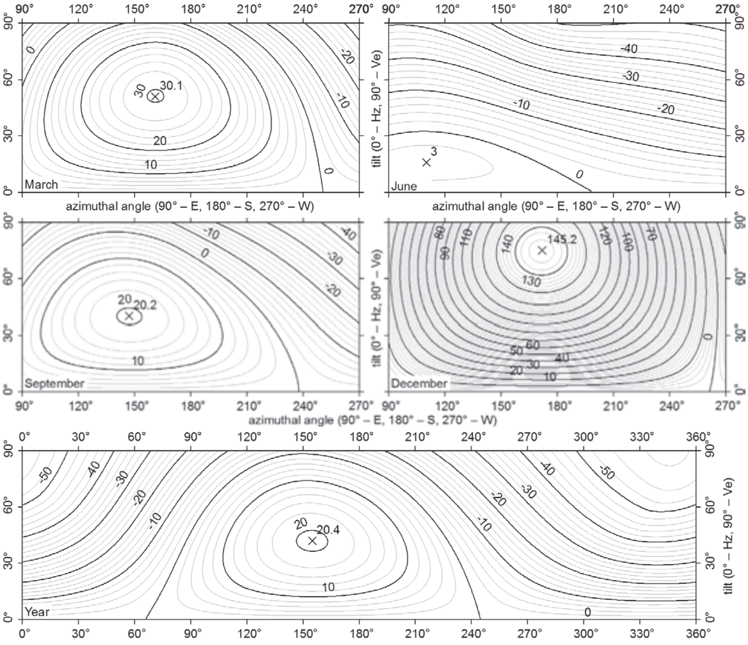

Fig. 8. As for Figure 6, but for Kredarica in high mountains.

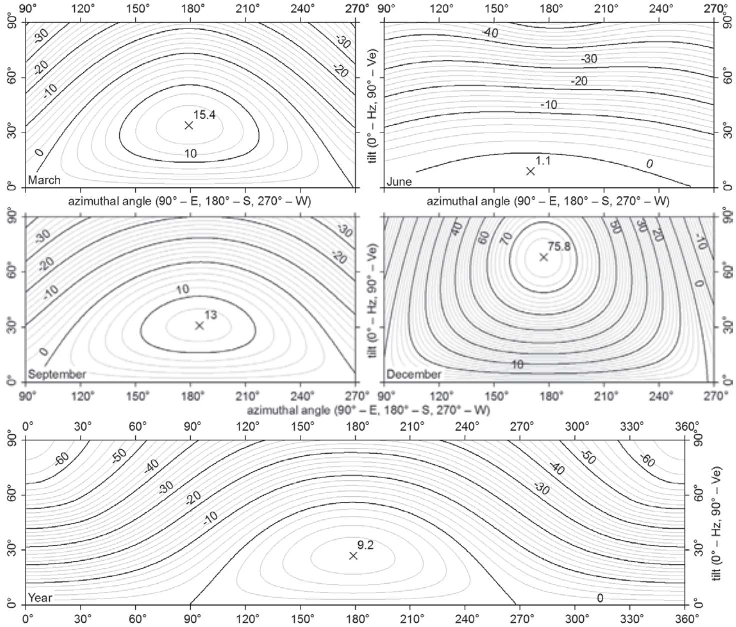

Fig. 9. As for Figure 6, but for Murska Sobota in the Pannonian part of Slovenia

Figures 6–9 and Table 1 show that the PV modules should be oriented more or less towards the South – but not exactly; in Portorož and Ljubljana the optimal orientation is around 5° from the South towards the West. The main reason for this is that the effect of morning fog or low cloudiness, making the irradiance asymmetrical around (true) noon, prevails over the effect of lower efficiency in early afternoon hours due to the higher temperature of the module. The situation at Kredarica in this respect is very specific due to the mountain wall of the top cone of Mt. Triglav to the West of the location. Since there is a lot of shadow in the afternoon, the modules should be considerably oriented towards SE (α=155°). In the Pannonian part of Slovenia, in the warm part of the year a considerable proportion of precipitation is caused by convective cloudiness – and the fact that convective clouds normally develop in the early afternoon is also reflected in radiance exposures in Murska Sobota – especially in June and September the orientation from the South more to the East is clearly expressed. Thus not only monthly but even the optimal fixed annual orientation and tilt perform slightly better than using "a rule of thumb", especially in places with a complex horizon (like at the mountainous Kredarica).

The tilt angles are more season dependent as azimuth angles. For example, in December the optimal orientation for clear sky conditions should be South (180°) and considering only direct irradiation the tilt should be from 67° to 70° (depending on the latitude). However, as there is often fog and low cloudiness on winter mornings, the tilt may change considerably. For example in Ljubljana located in a basin (where such phenomena are most frequent) the optimal tilt is only 62° and the orientation 183°. In contrast, in June it is best to have the module more or less horizontal. The reason for that (at first glance quite unexpected result) is the high solar elevation; in June the Sun rises north from East (at approximately ENE in Slovenia) and also sets north from West (at approximately WNW in Slovenia). So a PV module might be in the shadow (no direct insolation) during early morning hours and late in the afternoon. Further, a tilted surface also receives less diffuse irradiance.

	Global radiance exposures (kWh/m²)	Optimal orientation (°)	Tilt for maximum E_{dir} at solar noon (°)*	Optimal tilt (°)	Radiance exposures by optimal orientation and tilt (kWh/m²)	Increase by optimal tilt and orientation according to global radiance exposures (%)
Portorož on the Adriatic coast, φ = 45° 28´, λ = 13° 37´ h = 2 m a.s.l.						
March	110.2	184	45.5	38	133.0	20.7
June	202.2	190	22	9	204.1	1.0
Sept	126.4	185	45.5	34	147.6	16.8
Dec	33.6	181	67	68	68.4	103.4
year	1412.3	184		29	1573.1	11.4
Ljubljana in a basin in central Slovenia, φ = 46° 4´, λ = 14° 31´ h = 299 m a.s.l.						
March	97.4	183	46	35	113.8	16.7
June	178.5	185	22.5	9	180.4	1.1
Sept	108.7	190	46	32	124.1	14.1
Dec	23.8	183	69.5	62	38.2	60.3
year	1229.3	185		25	1329.3	8.1
Kredarica in high mountains, φ = 46° 23´, λ = 13° 51´ h = 2514 m a.s.l.						
March	121.3	161	46.5	51	157.9	30.2
June	155.9	110	23	16	160.6	3.0
Sept	107.7	147	46.5	40	129.5	20.2
Dec	44.3	172	70	75	108.7	145.3
year	1282.5	154		42	1538.5	20.0
Murska Sobota on Pannonian flatlands, φ = 46° 39´, λ = 16° 11´ h = 188 m a.s.l.						
March	99.7	179	46.5	34	115.1	15.4
June	184.9	170	23	9	186.9	1.1
Sept	109.8	185	46.5	31	124.1	13.0
Dec	26.8	177	70	68	47.1	75.8
year	1275.3	179		27	1390.0	9.0

* Tilts for maximum E_{dir} at solar noon are rounded to 0.5 of a degree

Table 1. Optimal azimuths and tilts according to months and the whole year and the resulting solar radiance exposures. The orientation for maximum E_{dir} at solar noon is 180° for all cases.

It is also interesting that taking the temperature dependence of the PV module on efficiency into account does not greatly influence the optimal orientation and tilt. A comparison with optima for the solar radiance exposures alone, i.e. the isolation of natural surfaces (Rakovec & Zakšek, 2008), only shows here and there some differences in optimal orientations and tilts. Most of the results are equal (within a degree or two). The main reason for this is evident in Figure 3 where one can notice that although the efficiencies are not exactly symmetrical around noon – they are slightly smaller in the afternoon than in the morning hours – the asymmetry does not influence the optimal orientation essentially – by more than a degree or so.

The albedo of the surrounding landscape influences the gain mainly at greater tilts of the modules when they "see" a considerable proportion of the ground in their half space; with tilts of around 70° the proportion is roughly 40% ground and 60% sky. As high tilts are favourable in winter, and as it is possible that there is snow cover in winter, with a high albedo, the ground may be even brighter than the sky. Such details are not included in our "monthly average" albedo – except for mountainous locations where snow in winter is regular and hence captured by satellite data.

A comparison with some other studies for Slovenia, e.g. PVGIS (Huld et al., 2008) using a yearly averaged albedo and isotropic model proposed by (Liu & Jordan, 1963), shows that the optimal yearly tilts are significantly larger than in our study (PVGIS 35° for almost the whole of Slovenia versus ours e.g. 25° in Ljubljana; Table 1). If in addition the surface albedo is also overestimated (most models use 0.2, while the average yearly albedo equals e.g. 0.14 in Ljubljana) the results overestimate the actual gains by some 2–3%. The difference in gains could also be a consequence of an interpolation inaccuracy – PVGIS interpolated results for the whole of Europe and we estimated our results for chosen locations. The method considers the heterogeneity of the country by using solar irradiance characteristics that have different seasonal and daily courses in different parts of the country. These climatic differences accompanied by the albedo's heterogeneity therefore lead to different optimal azimuthal angles and tilts of the PV modules.

Location	H_{gl} (kWh/m^2)	$maxH^*$ (kWh/m^2)	H_{rt} (kWh/m^2)	$H_{rt}/maxH$ (%)	H_{fix} (kWh/m^2)	$H_{fix}/maxH^*$ (%)	W_{el} (kWh/m^2)
Portorož	1412.3	1641.1	1560.8	95.1	1573.1	95.8	160.2
Ljubljana	1229.3	1367.0	1311.6	96.0	1329.3	97.2	134.6
Kredarica	1282.5	1655.7	1498.5	90.5	1538.5	92.9	158.0
Murska Sobota	1275.3	1442.4	1379.2	95.6	1390.0	96.4	141.0

* maxH – Maximum solar radiance exposure is determined by considering monthly optimal orientations and tilts; such a maximum could even be increased by changing the orientation and tilt daily – but this is not a realistic option; among other reasons also due to the changing weather from day to day.

Table 2. Average annual solar radiance exposures; H_{gl} – solar global radiance exposure, $maxH$ (see the note marked by *), H_{rt} – exposure by a fixed "rule of thumb" orientation 180° and tilt 35°, H_{fix} – by fixed optimal orientation and tilt, and W_{el} – electrical energy from a 215 Wp PV module with 85% system efficiency and with a fixed annual orientation and tilt at selected locations in Slovenia.

On the basis of our simulations, it may be concluded that the best solution would be to change the orientation and inclination of PV modules during the course of the year (monthly, if technically possible; Table 1). But also for a fixed annual orientation and tilt the optimal orientation and tilt perform somewhat better than using "a rule of thumb", especially in places with a complex horizon or specific climatic conditions – up to 3%.

5. Conclusion

To conclude, long-term measured meteorological values should be used to obtain reliable results on PV yield. Only then it is possible to dimension the PV system for yield optimization. We showed that the measured irradiation values are the most important parameter in photovoltaics. If only measurements of global irradiation are available, the diffuse part of irradiation can be simulated. Temperature measurements have merely a small effect on optimal orientation of PV system. Accurate albedo values are also irrelevant for the system orientation during the summer as albedo is usually low and optimal tilt angles are small. However in regions, where the albedo changes significantly during the year, is its accuracy important especially during winter, as the ground covered by snow is often even brighter than the sky.

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