Mapping the potential of photovoltaic systems in urban areas of Slovakia

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Abstract

Photovoltaic (PV) systems generating electricity from solar radiation are foreseen as a technology option significantly contributing to the sustainable energy supply. The action plan of the European Commission as outlined in the White Paper “Energy for the Future: Renewable Sources of Energy” can be greatly added by a map-based inventory of the most suitable areas for the installation of PV systems. The quantification of the solar energy resource and an assessment of a potential PV electricity production in the urbanised area of Slovakia is presented. The methodology is based on the use of a digital elevation model with grid resolution of 500 metres and the CORINE land cover database within a GIS application. The spatial patterns of monthly and annual means of daily sums of global irradiation are calculated using the digital elevation model and climatic data. The potential PV production is calculated for the Slovak urbanised areas. The building-integrated horizontal panels and south-facing panels inclined at angles of 15, 25 and 40 degrees are considered, based on the technical capabilities of the current PV systems. The resulting map shows the most suitable urbanised areas, considering different array geometries of the grid-connected household installations. The calculation of PV production potential is a basic step for further analyses and forecasts of energy demand/supply taking into account other socio-economic data.

Introduction

The direct conversion of the solar energy into electrical energy has a promising future due to continuous technological progress and dramatic cost reduction.
There are still barriers to the widespread use of the photovoltaic (PV) systems namely due to the initial capital costs that make them uncompetitive with conventional systems. Therefore, the design and location of PV systems must be precisely planned and calculated. Integration of PV systems into decentralised systems constitute a major priority for the European Union and Candidate Countries. One of the basic prerequisites of the application action plans is a map-based inventory of the most suitable areas for the installation of PV systems. The major emphasis has been put on the grid-connected PV systems installed on roofs and/or walls of individual households in residential areas that are considered as one of the most prospective. The grid-connected PV system produces electrical energy for the system owner but it takes advantage of the grid connection both to export excess energy to the grid or to compensate, from the grid, for a possible lack of power at other periods.

The optimisation procedure basically aims to maximise a given PV configuration to give the highest possible energy yields over a planned period. Methods for optimisation of the performance of PV systems are described for both stand-alone or grid-connected alternatives [1].

The PV simulation programs such as PVFORM [2] and PVSYST [3] are developed to provide all necessary tools at the planning and design stages. Finding the optimum angle of the inclined solar panels is one of the most important steps in the PV system design procedure. The input radiation values are generally the weakest point of the design procedure when considering mountainous regions or those not satisfactorily covered by the radiation measurements. The regional planning has to take into account a spatial pattern of the solar radiation resource. Some approaches related to the regional aspects can be found in [4, 5].

The essential solar radiation input needed for this method is the annual mean of daily sum of global irradiation on the panel surface. Long-term measurements are available only for a limited set of meteorological stations. To obtain the irradiation values for the region either the data from the closest station are used or spatially-distributed data are computed using interpolation techniques and satellite data. At present for Europe the spatially-distributed solar radiation data are available at a continental level, computed within a EC-funded projects ESRA and Satellight [6, 7]. These data for Slovakia have a grid resolution of approximately 10x10 km and 5x10 km, respectively. For regional studies, namely in mountainous regions, better spatial detail is needed as the solar radiation is significantly influenced by terrain effects of slope angle, aspect and topographic shading. Solar radiation models integrated within geographical information systems (GIS) provide a cost-efficient means for understanding the spatial and temporal variation of radiation over regional scales [8]. The GIS is a combination of computer hardware and software that is designed to manage, process, analyse and visualise georeferenced data. The precision of estimated solar radiation is determined mainly by the grid resolution of a digital elevation model and availability of climatic data.

This paper presents a GIS-based estimation of global irradiation using a solar radiation model and a clear-sky index. Estimated irradiation is used in a
calculation of the spatial pattern of potential energy output of PV systems in the urbanised areas of the Slovak Republic (Figure 1), considering different array geometries of the grid-connected household installations.

Figure 1: The urbanised areas in the Slovak Republic

Methods

Estimation of global irradiation

The estimation of the primary solar resource is based on the clear-sky (potential) global irradiation on a horizontal plane. The real global irradiation on a horizontal plane is estimated by multiplying the clear-sky values by the clear-sky index. These values are then used in the model for computation of global irradiation on inclined planes.

The computation was done using the solar radiation model \textit{r.sun} implemented in the GRASS GIS. The previous version of the model [9] was significantly re-engineered by Hofierka and Šúri [10], based on the work undertaken for development of European Solar Radiation Atlas [6]. The model estimates beam, diffuse and reflected components of the clear-sky global irradiance and irradiation on a horizontal and inclined surfaces. The total daily irradiation values [kWh.m\(^{-2}\).day\(^{-1}\)] are computed by the integration of the irradiance values [W.m\(^{-2}\)] calculated with 30-minute interval between the sunrise and sunset. The model accounts for sky obstruction by shadowing effects of the local terrain features. Below a brief overview of the irradiance calculation scheme of the model is provided, more details can be consulted in [10].

Step 1 Clear-sky irradiation on a horizontal plane
The normal beam (direct) solar irradiance \(B_0\) is estimated from the extraterrestrial irradiance \(G_0 = I_0 \varepsilon\) that is modified by the atmospheric beam attenuation under cloudless sky [11]:

where \( \varepsilon \) is the solar eccentricity, \( I_0 \) solar constant (1367 W.m\(^{-2}\)), \( T_{LK} \) is the air mass 2 Linke turbidity factor, \( m \) is the relative optical air mass [12] and \( \delta_R(m) \) is the Rayleigh optical thickness at air mass \( m \) [13]. The beam irradiance on a horizontal plane \( B_{ch} \) is calculated as:

\[
B_{ch} = B_{cl} \sin h_0
\]

where \( h_0 \) is the solar altitude (an angle between sun and horizon).

The estimate of the diffuse clear-sky irradiance on a horizontal plane \( D_{ch} \) is made as a product of the normal extraterrestrial irradiance \( G_0 \), a diffuse transmission function \( T_n \) dependent on the Linke turbidity factor \( T_{LK} \), and a diffuse solar elevation function \( F_d \) dependent on the solar altitude \( h_0 \) [11]:

\[
D_{ch} = G_0 \cdot T_n (T_{LK}) \cdot F_d (h_0).
\]

The clear-sky global irradiance on a horizontal plane \( G_{ch} \) [W.m\(^{-2}\)] is given by the sum of its beam \( B_{ch} \) and diffuse \( D_{ch} \) components. By the integration of the half-hourly irradiances for a representative day of each month [6, p. 108] the 12 data layers of the monthly means of daily sums of horizontal global irradiation [kWh.m\(^{-2}\).day\(^{-1}\)] were computed together with the 13th layer representing the annual mean of daily sums.

\[
G_{ch} = k_c \cdot G_{ch}.
\]

\[
k_c = G_h / G_{ch}.  \quad (5)
\]

The spatial pattern of the monthly means of the daily sums of the global irradiation for horizontal planes were calculated using the formula:

\[
G_h = k_c \cdot G_{ch}.  \quad (6)
\]
This approach enables to estimate the solar energy resource at the high spatial detail, considering the shadowing effect of the terrain features which significantly determines its spatial pattern mainly in the mountainous landscape that dominates in the Slovakia.

**Step 3 Global irradiation on an inclined plane**

To compute the global irradiation on inclined planes $G_i$ at real atmospheric conditions the beam and diffuse components for average monthly cloudiness have to be estimated. It is obvious that the ratio of the diffuse component to the global radiation is different for clear-sky and (partly) overcast conditions. The monthly mean of daily sum of diffuse horizontal irradiation $D_h$ for partly overcast conditions is then estimated using the Czeplak version of the Aguiar formula proposed in ESRA [6, p. 117]:

$$D_h / G_h = c_0 + c_1 K_T + c_2 K_T^2 + c_3 K_T^3$$

where $K_T$ is the clearness index (a ratio of the daily global irradiation $G_h$ at the earth’s surface level to the corresponding extraterrestrial irradiation $G_o$). The beam component for the overcast sky $B_h$ is estimated then as:

$$B_h = G_h - D_h.$$ (8)

The global irradiance on an inclined plane $G_i$ is a sum of the beam $B_i$, diffuse $D_i$ and reflected $R_i$ components. The beam irradiance on an inclined plane $B_i$ is then calculated as:

$$B_i = B_h \sin \angle_{xp} / \sin \delta_{exp}$$ (9)

where $\delta_{exp}$ is the solar incidence angle (between sun and the inclined plane).

The model for estimating the diffuse irradiance/irradiation on an inclined plane ($D_i$) by Muneer [20] distinguishes between sunlit potentially sunlit and shaded surfaces:

a) for surfaces in shade ($\delta_{exp} < 0$ and $\angle_{xp} >= 0$):

$$D_i = D_h F(\gamma_N)$$ (10)

b) for sunlit surfaces und non-overcast sky ($\angle_{xp}$ in radians):

$$D_i = D_h F(\gamma_N) (1 - K_b) + K_b \sin \delta_{exp} / \sin \angle_{xp}$$ if $\angle_{xp} >= 0.1 \text{ rad}$

$$D_i = D_h F(\gamma_N) (1 - K_b) + K_b \sin \gamma_N \cos A_{LN} / (0.1 - 0.008 \angle_{xp})$$ if $\angle_{xp} < 0.1 \text{ rad}$

where $A_{LN}$ is an angle between the vertical plane containing the normal to the surface and the plane passing through the centre of the solar disc. In this context the $K_b$ is a measure of the amount of beam radiation available and $F(\gamma_N)$ is a function accounting for the diffuse sky irradiance distribution.

The diffuse ground reflected irradiance received on an inclined surface ($R_i$) is proportional to the global horizontal irradiance $G_h$, to the mean ground albedo $\rho_g$ and a fraction of the ground viewed by an inclined plane $r_g(\gamma_N)$:

$$R_i = \rho_g G_h r_g(\gamma_N)$$ (11)

The spatial data of the monthly means of the daily sums of the global irradiation for inclined planes were estimated for the planes inclined at angles of 15, 25 and 40 degrees, each consisting of 12+1 data layers.
Calculation of PV potential production

In the calculation the basic technical capabilities of the grid-connected PV systems and the irradiation values are considered. The calculation is intended for the preliminary design by providing an order of magnitude estimate of the system production. The essential input is the annual average daily global solar irradiation on solar panels. With the aim to maximise the annual electricity production the optimal panel slope angle at south orientation is determined from the maximum annual global solar irradiation computed at 0, 15, 25 and 40 degrees. To compute the annual electrical energy output from the PV system $E$ [kWh] the following equation can be used [6]:

$$E = 365 P_k \eta_p G_{i,h}$$

(12)

where $P_k$ (in kW) is the peak power installed (1.5 kW in our case), $\eta_p$ is the system efficiency (typical value 0.75) and $G_{i,h}$ is the annual mean of daily global irradiation on the horizontal or inclined solar panel facing to the south.

The results of this stage consist of four maps (Figures 2-5) of the annual potential PV production in Slovakia [kWh], considering the defined array geometries of the grid-connected household installations. The overlay of these – spatially continuous – data with residential areas mapped in CORINE Land Cover database [21] as a class discontinuous urban fabric (class 112) provides an estimate of the mean energy resource in the residential areas for each of 79 Slovak districts.

Results

The spatially-distributed solar energy resource for four alternatives is estimated for Slovakia at a grid resolution of 500 metres. The data reveal significant regional differences given by the available global radiation, which cannot be identified on the contemporary available data sources [6, 7, 18].

![Figure 2: Annual PV electricity output for horizontal plane [kWh]](image-url)
The regional differences in the availability of global irradiation are determined by the latitude, terrain effects and local climatic conditions, namely in the intra-mountaineous basins. Our calculated irradiation values are influenced by the time series of the climatic data used for the interpolation of clear-sky index (1951-1980). On the set of 6 Slovak meteorological stations we have compared our values to those available in the ESRA database (that is based on time series 1981-1990) and the highest differences (up to 8%) were observed for the Sliač and Trebišov stations. This fact could partly reflect the fluctuations of the local climatic conditions in the last decades.

Figure 3: Annual PV electricity output for inclination angle of 15° [kWh]

Figure 4: Annual PV electricity output for inclination angle of 25° [kWh]

The annual means of the daily sums of global irradiation for the horizontal plane in the residential areas are in the interval 2.8-3.6 kWh.m^{-2}. For the inclined planes (15, 25 and 40 degrees) the values are in the interval 3.1-4.0, 3.2-4.1 and
3.2-4.2 kWh.m$^{-2}$. When compared to the horizontal plane this represents the solar resource increase in average about 11, 15 and 17%, respectively.

Based on these elaborations the highest yields for the given configuration (i.e. capital investment) could be reached for the solar panels inclined at angles 25 to 40 degrees. While the inclinations about 25 degrees are feasible for the households with tilted roofs, the solar panels having higher inclination angles can be flexibly installed on the flat roofs that are abundant in many areas.

When considering only the economical criteria related to the PV electricity output, it is noticeable that a large-scale installation of PV systems is the most attractive in the districts located in or near the Danubian lowland (SW Slovakia). The mean potential of the energy production in the residential areas of the “top 10” districts is between 1400-1450 kWh for horizontal panels up to 1630-1700 kWh for the solar panels inclined at the angle of 40 degrees (given the 1.5 kW peak power installation). On the contrary the less feasible districts are located in the northern Slovakia where the mean potential energy output in residential areas is calculated at 1210-1250 kWh for the horizontal panels up to 1400-1450 kWh for the panels inclined at the angle of 40 degrees.

The energy yield is not the only factor taken into consideration in the state policy of support to PV installations. The prioritising of the less-favoured (marginal) areas can help them to overcome some social and economic limits and promote their development based on the sustainable energy production [22]. This is a case of some districts located in the southern parts of the central Slovakia or in the East-Slovakian Lowland, still having high solar energy potential. Even given the lowest yield of 1210 kWh per year for 1.5 kW installation, this is still on average greater then 3 kWh per day for an installation of approx. 12 m$^2$, easily meeting the needs of a typical 4 person house.
Conclusions

The calculation of PV production potential is a basic step for further analyses and forecasts of energy demand/supply taking into account technical and also socio-economic data. In this approach the emphasis was placed on the calculation of the solar radiation resource at higher resolution based on use of the digital elevation model within GIS. The latest equations suggested by the ESRA project were implemented in the calculation of the clear-sky model and we benefited also from the latest progress in estimation of the Linke turbidity factor within the SoDa project. The clear-sky index is a key factor in calculation of the global irradiation. The accuracy of its spatial pattern is determined by the availability of the climatic data where in addition to sunshine and cloudiness, precipitation and temperature could be used. A potential for further improvements to these elaborations could be in further investigation of the multidimensional interpolation methods. The PV output assessment is drafted to provide estimates for preliminary planning period. The results are a good basis for the national PV development programs. These estimates have to be analysed in more detail considering the different modes of energy consumption and production as well as other technical data. For a calculation of the total energy resource in the selected urbanised areas the more detailed data about the roofing is important. The social and economic aspects are also important and must be taken into account.

Acknowledgement

This work has been carried out under the EC JRC Enlargement Action Programme as project number 52 entitled “Environment and the solar energy resource” in a co-operation with GeoModel s.r.o. The authors would like to thank to Lucien Wald and Jaroslav Hofierka for the discussions and helpful comments on solar radiation modelling and spatial interpolation.

References

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