THE SPATIAL DISTRIBUTION OF PHOTOVOLTAIC POWER PLANTS IN RELATION TO SOLAR RESOURCE POTENTIAL: THE CASE OF THE CZECH REPUBLIC AND SLOVAKIA

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Abstract

Over the last few years, many European countries experienced a rapid growth of photovoltaic (PV) power plants. For example, more than 20,000 new PV power plants were built in the Czech Republic. The high spatial and temporal variability of the solar resource and subsequent PV power plant production, poses new challenges for the reliability and predictability of the power grid system. In this paper, we analyse the most recent data on PV power plants built in the Czech Republic and Slovakia, with a focus on the spatial distribution of these installations. We have found that these power plants scarcely follow the solar resource potential and, apparently, other factors affect decisions for their location. Recent changes in the support schemes for solar applications also influence these patterns, with new installations mostly confined to built-up areas. These changes will require new tools to assess the appropriate locations of PV systems.

Shrnutí

Prostorové rozložení fotovoltaických elektráren ve vztahu k potenciálu solárního zdroje: případové studie České a Slovenské republiky

V mnohých evropských zemích byl v posledních několika letech zaznamenán rapidní nárůst počtu fotovoltaických elektráren. V České republice bylo například vybudováno více než 20 tisíc fotovoltaických elektráren. Velká prostorová i časová variabilita solárního zdroje a následná produkce fotovoltaických elektráren přináší pro spolehlivost a předvídatelnost systému elektrovodné sítě nové možnosti. Příspěvek analyzuje nejnovější údaje o fotovoltaických elektrárnách vybudovaných v České republice a na Slovensku, přičemž se soustřeďuje na prostorové distribuční systémy těchto instalací. V rámci našeho výzkumu jsme zjistili, že se tyto elektrárny jen velmi zřídka řídí možnostmi zjištěného potenciálu solárního zdroje a že rozhodování o jejich lokalizaci je ovlivňováno dalšími faktory. Systémy nových instalací jsou nedávnými změnami ve schématech podporujících solární aplikace většinou omezovány na zastavěná území. Tyto změny budou vyžadovat pro posuzování vhodných lokalizací fotovoltaických systémů nové nástroje.

Keywords: *solar energy, photovoltaic power plant, geographic information systems, Czech Republic, Slovakia*

1. Introduction

Solar energy plays an increasingly greater role in the production of electricity in many countries around the world. Leaders in using solar energy for photovoltaic (PV) applications include Germany and Italy, the United States of America and several Asian countries (EPIA, 2013). The rapid development of these applications has been supported by various support schemes such as guaranteed feed-in tariffs, tax incentives, etc. The European Union supports the use of renewable energy including solar energy via its commitment to increase the share of renewables in the electricity production of its member states. Many countries have adopted this policy through a feed-in tariff support scheme that fixes the buy-back price of electricity produced by the solar power plant for a specific period (e.g. 15–20 years). The rapidly decreasing costs of PV power plant construction and relatively high buy-back price levels guaranteeing profits have led to a PV power plant construction boom. In the period from 2009 to 2012, more than 2,100 MWp (megawatt-peak) of new PV power capacity was built in the Czech Republic, and more than 491 MWp in Slovakia. The nominal power capacity of installed PV power plants varies from 1 kWp to tens of MWp. The Czech Regulatory Office (ERÚ) has approved more than 20,000 PV power plants (October 2013), and 1,179 PV power plants were approved by the Slovak Regulatory Office for Network Industries (ÚRSO) (September, 2012). This resulted in 17,754 locations with such power plants in the Czech Republic and 635 locations in Slovakia. With the ever-increasing installed power capacity of PV power plants, it has become increasingly important to understand the spatial distribution of these installations and the consequences for power grid management, as well as for electricity production and consumption in various parts of the countries.

Solar radiation available on the Earth's surface is highly variable, spatially and temporally. Therefore, exploring the true potential at particular locations is a complex task requiring knowledge and expertise in various disciplines. This variability also affects the predictability and manageability of national power grids. The PV systems can be connected to a power grid supplying electricity to various customers, or off-grid when the producer consumes the electricity directly. In both cases, the operation of the national power grids is affected. Šúri et al. (2011) analysed the stability of the Czech power grid system using a hypothetical random distribution of PV power plants with a total nominal capacity of 1,000 MWp under various meteorological scenarios. They concluded that temporal variations are manageable at the national level. Problems may arise locally, though. Thus, accurate data on the spatial distribution of PV power plants are needed for this type of analysis.

Hofierka and Kaňuk (2011) analysed the correlation between the spatial distribution of power plants built in Slovakia and the actual solar potential assessed from the solar radiation database derived by Hofierka and Cebecauer (2008). It was shown that the installations of PV power plants built before 2012 took into account the solar potential of the country only partially. It was concluded that the profitability of the PV project under the support scheme valid at the time of installation was sufficient, even at locations with a lower solar potential. The economic efficiency of these projects and supporting schemes, however, is rather low. The criticism of high electricity costs for consumers has led to a substantial reduction of support in many European countries, eliminating the development of new large solar power plants. The support for new PV power plants is limited only to smaller installations mounted on a roof or a building facade. For example, Slovakia has recently limited the support to systems of up to 100 kWp power capacity and a lower limit of 10 kWp is also considered. It is clear that future PV installations will be smaller and confined mostly to built-up areas.

Assessing and planning PV installations in built-up areas is much more complex than in open areas. Various methodologies have been developed. Some of them are coupled with geographic information systems (GIS) to address the complex urban environment (Littlefair, 2001; Pereira et al., 2001; Gadsden et al., 2003; Compagnon, 2004; Robinson and Stone, 2004). Hofierka and Kaňuk (2009) proposed a methodology for assessing the PV potential in built-up areas using the r.sun solar radiation model and PV GIS online estimation utility (http://sunbird.jrc.it/pvgis/). Recently, findings relevant for the analysed sample areas were extrapolated to other built-up areas identified using the Corine Land Cover database (Kaňuk et al., 2009). Residential areas with blocks of flats and industrial areas were identified as the most effective.

This summary emphasizes the importance of analysing the spatial distribution of existing PV power plants in two neighbouring countries, in which similar changes in legislation recently caused different behaviours in locating the power plants and in the use of the electric energy they produce. Therefore, the aim of this paper is to analyse the spatial distribution of existing PV power plants in the Czech Republic and Slovakia in relation to the solar resource potential and land cover classes identified by the Corine Land Cover 2006 (CLC, 2006) database, and to present future trends in the sector.

2. Spatial and temporal variations in the solar resource potential

Incident solar radiation at any location on the Earth's surface results from the complex interactions of energy between the atmosphere and land or ocean surfaces. On a global scale, the latitudinal gradients of radiation are caused by the geometry of the Earth and by the Earth's rotation and revolution around the Sun. On regional and local scales, the land surface creates strong local gradients that modify the basic pattern of global radiation fields (Hofierka, 2012).

Seasonal and daily variations primarily caused by well-predictable astronomic factors (via solar altitude) are strongly modified by changing atmospheric conditions (e.g. clouds, aerosols, water vapours and ozone). In Central Europe, for example, the monthly sum of global solar radiation striking a horizontal surface in December is about five times lower than in July, which is the month with the highest monthly sum of solar radiation. During the winter season, clear-sky radiation is greatly reduced by cloudiness, especially at lower altitudes. More rain (and cloudiness) in June usually also lowers the monthly sum of solar radiation in spite of the fact that solar altitude in this month is higher than in July (Hofierka and Kaňuk, 2011).

Detailed knowledge of the primary solar energy resource is needed for any solar power system including a PV power plant. Clearly, the analysis of available solar energy resources is a part of the efforts to integrate solar energy into energy systems in many countries. For example, Šúri et al. (2007) created a database of solar radiation maps and other climatic parameters for Europe. To account for the spatial variations of solar irradiation in different geographical conditions, solar radiation models integrated with GIS were developed. The solar radiation models use ground-based or satellite data and digital elevation models as inputs into physically-based empirical equations to provide estimates of irradiation over large regions, while considering terrain inclination, orientation and potentially also shadowing effects. New web-based tools, such as PVGIS, were developed to provide an access to solar databases and to assess the performance of PV systems (Šúri et al., 2005; Šúri et al., 2007; Huld et al., 2012).

Šúri and Hofierka (2004) developed a comprehensive GIS-based methodology to compute solar radiation for any geographical region and for any time moment or period. This solar radiation methodology was implemented in the r.sun module of GRASS GIS (Neteler and Mitasova, 2004). The r.sun module can be used to compute clear-sky or real-sky radiation using several basic input data sources. These include digital elevation models, measured global and diffuse solar irradiation from ground stations and a map of the Linke turbidity coefficient. The measurement of global and diffuse solar irradiation is needed to assess the ratio of real-sky and clear-sky radiation represented by the clear-sky index and its direct and diffuse components used to derive real-sky irradiation on inclined planes. The clear-sky irradiation can be computed relatively easily using the r.sun model; however, the real-sky irradiation is more dependent on local meteorological conditions (cloudiness) which reduce the amount of available irradiation for energy applications.

Hofierka and Cebecauer (2008) applied this methodology to derive a solar radiation database for the territory of Slovakia. The database consists of spatially distributed raster-based maps representing monthly and annual long-term averages of daily radiation sums in $kWh/m^2/day$. While the long-term averages of solar radiation provide valuable information on the available solar radiation for energy applications, the annual, seasonal and intra-day variability may still pose a major problem for the reliable planning and use of solar energy.

The solar radiation database developed by Hofierka and Cebecauer (2008) can also be used effectively to assess the solar resource potential for PV installations. The efficiency of solar radiation conversion by solar cells ranges from 10% to 20% depending on the solar cell technology. In the case of Slovakia, the annual electricity yield from the standard 1 kWp PV system ranges from 850–1,050 kWh (Hofierka and Kaňuk, 2011). The optimum tilt angle of solar panels maximizing the energy yield ranges from 36 ° to 44 °. However, the actual inclination of the panels also depends on the preferred energy output. For example, a standard PV system with the inclination of panels optimized for annual production generates four times more electricity in summer than in winter (Hofierka and Kaňuk, 2009).

The territory of the Czech Republic is covered by several solar databases such as the free PVGIS online solar database with a spatial resolution of 1 km, or the commercially available SolarGIS database with a spatial resolution of 80 m. The methodology used in these databases is based on the satellite-to-irradiance model developed by Perez et al. (2002), as further enhanced by Šúri and Cebecauer (2010). In this study, we used the solar database developed by Hofierka and Cebecauer (2008) for the territory of Slovakia and the SolarGIS database for the territory of the Czech Republic, to evaluate the correlation of solar resource potential with installed power capacity for the locations of PV power plants.

3. Spatial distribution of photovoltaic power plants

The massive development of PV power plants in the Czech Republic and Slovakia started in 2009, with the highest capacity installed in 2010 and 2011. The boom resulted from the generous governmental support in the period from 2008 to 2009, which was later gradually reduced to levels that were more reasonable. For example, the feed-in tariff in the Czech Republic was 13,460 CZK/MWh (about 538 EUR/MWh) in 2008 for any new installation, 7,500 CZK/MWh in 2011 for new installations up to 30 kWp, 5,900 CZK/MWh for installations 30–100 kWp and 5,500 CZK/MWh for above 100 kWp of installed capacity (ERÚ, 2013). Since 2012, no new installations above 30 kWp have been supported. Moreover, the Czech Republic introduced a so-called solar tax in 2011 for PV power plants with a power capacity over 30 kWp installed in 2009 and 2010, and similar measures were considered in Slovakia in 2013. In Slovakia, the highest support in 2009 with the feed-in tariff set to 448.12 EUR/MWh for any new installation was later gradually reduced to 119.11 EUR/MWh in 2013, only for new installations mounted on buildings with an installed power capacity of up to 100 kWp (ÚRSO, 2013). The main difference in the regulation policies of the two countries affecting the installations has been the restricted number of approved licences in Slovakia that were capped by the announced limit of total available capacities. No such restrictions had been imposed in the Czech Republic.

It can be concluded that the early support schemes (up to 2010) indirectly supported mainly large ground installations with lower costs per installed kWp capacity, compared to building-mounted systems with higher installation costs. Recent changes in the support schemes of both countries have effectively eliminated the development of new large PV power plants. Since 2012, only small systems have been supported. In some countries with an excellent solar resource potential, such as Spain and Italy, however, solar energy has become increasingly competitive with some other energy sources, even without generous governmental support. This is helped by a substantial reduction of the PV technology costs, especially in the segment of solar cell components (EPIA, 2013).

3.1 The spatial distribution of photovoltaic power plants in Slovakia

Hofierka and Kaňuk (2011) presented the spatial distribution of PV power plants built in Slovakia up to 2011, based on data provided by the Slovak Regulatory Office for Network Industries ÚRSO. The total installed power capacity at that time was 489 MWp in 569 locations. It has been shown that there was only a weak correlation (Pearson's r = 0.24) between the location of installed PV power plants and the actual solar resource potential, identified using the solar radiation database published by Hofierka and Cebecauer (2008). The solar radiation database was derived using the methodology that synthetically expresses the influence of various factors affecting the potential, such as latitude, elevation, land surface forms and long-term atmospheric conditions.

According to slightly updated data provided by the Slovak Regulatory Office for Network Industries ÚRSO, valid for 2012, the installed power capacity increased to 492 MWp in 635 locations (Fig. 1). The textual addresses of the power plants were manually geo-located using aerial orthophotomaps and field mapping. The GIS data were further processed in the ArcGIS v.10.1 software. The

CLC 2006 CODE	CLC 2006 level 2 class	All locations		Locations of <0.3 MWp		Locations of >1 MWp	
		Count	Sum of installed power [MWp]	Count	Sum of installed power [MWp]	Count	Sum of installed power [MWp]
11	Urban fabric	404	93.227	311	12.798	1	2.997
12	Industrial, commercial and transport units	22	19.190	14	0.600	4	14.658
13	Mine, dump and construction sites	2	7.089	1	0.026	1	7.063
14	Artificial, non-agricultural vegetated areas	5	0.225	5	0.225	0	0.000
21	Arable land	148	342.366	28	1.498	86	310.183
23	Pastures	11	2.929	8	0.116	0	0.000
24	Heterogeneous agricultural areas	40	25.694	25	0.662	8	18.394
31	Forests	1	0.004	1	0.004	0	0.000
32	Scrub and/or herbaceous vegetation associations	2	1.022	1	0.009	1	1.013
	Total	**635**	**491.746**	**394**	**15.938**	**101**	**354.308**

Tab. 1: Distribution of PV power plants within the CLC2006 classes in Slovakia
Source: ÚRSO (2013) and EEA (2007)

correlation between the PV power plant locations and the solar resource potential represented by the solar database developed by Hofierka and Cebecauer (2008) was again very weak (Pearson's r = 0.24).

To identify the spatial relation of the PV power plant location to the land cover in a particular location, we used the CLC 2006 database in a raster data format of 100 metres cell size, widely used in many environmental studies, which fully covers the territory of both countries. The advantage is that the CLC 2006 database had been created using a uniform methodology and had recorded the land cover prior to the construction of the first PV power plants in both assessed countries. There are also drawbacks of this database, however, mainly the mapping scale of 1:100 000 (EEA, 2007). This issue is discussed further below. A comparison of the spatial distribution of installations in Slovakia in relation to CLC2006 level 2 land cover classes can be found in Table 1. Most installations (404 locations) are located in built-up areas (code 11: Urban fabric) dominated by smaller PV power plants (below 0.3 MWp), with a total capacity of 93 MWp. Larger power plants (over 1 MWp) are located mostly in agricultural areas (21: Arable land, 23: Pastures, 24: Heterogeneous agricultural areas). PV power plants located in the agricultural areas have a total capacity of 371 MWp (75% of the total PV power capacity in Slovakia). We have also analysed the spatial relationship of PV power plant installations to the solar resource potential within the CLC 2006 land cover classes. Dominant installations in the agricultural areas have a slightly higher correlation (r = 0.26) to the solar resource potential than installations in the built-up areas (r = 0.17). Globally, large installations over 1 MWp follow the solar resource potential (r = 0.3) better than small installations (r = 0.08).

3.2 The spatial distribution of photovoltaic power plants in the Czech Republic

More than 20,000 PV power plants approved by the Czech Energy regulatory office ERÚ are distributed in 17,754 locations across the Czech Republic (Fig. 2). The data provided contained the textual addresses of the power plants but not the exact

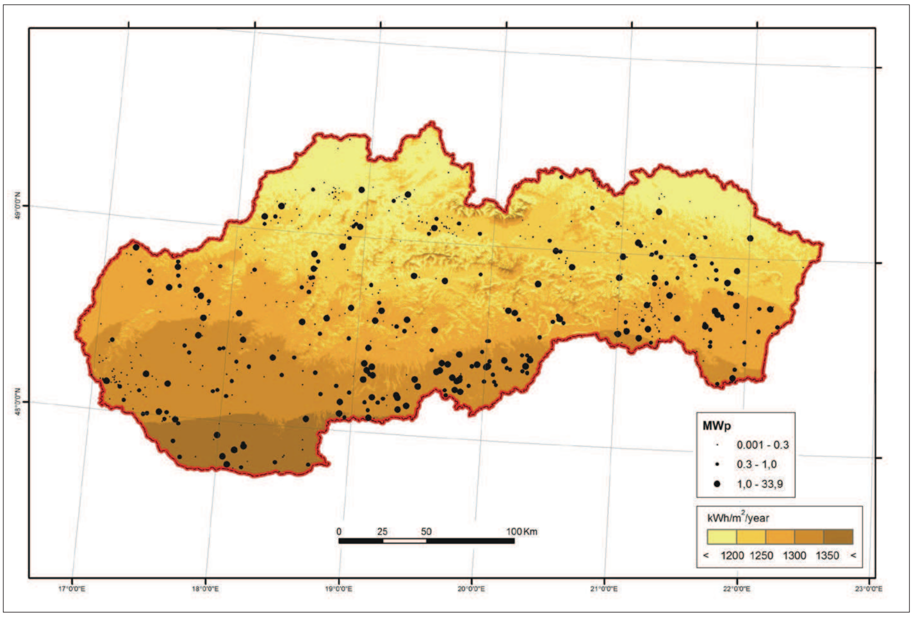

Fig. 1: Spatial distribution of PV power plants in Slovakia in 2012

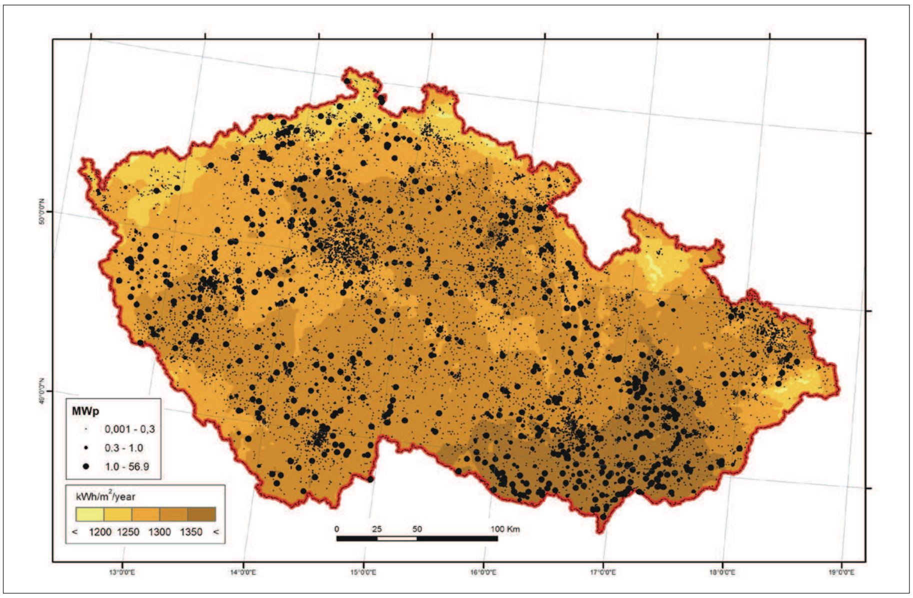

Fig. 2: Spatial distribution of PV power plants in the Czech Republic in 2013

spatial coordinates. The online BatchGeo utility was used to geo-locate these installations. The accuracy of geo-location in built-up areas was very high, but in open space areas only the centroids of the respective villages were identified. The actual positions of larger power plants were verified manually (on-screen) and corrected using orthophotomaps available at www.mapy.cz and the WMS service of the Czech Surveying and Cadastral Office (ČÚZK, http://geoportal.cuzk.cz), and further processed in the ArcGIS v.10.1 software.

The correlation of the PV power plant locations and the solar resource potential represented by the SolarGIS database in the Czech Republic is even weaker than in Slovakia (Pearson's r = 0.093). A closer look at the distribution reveals a few spatial trends, however. Small PV installations with installed capacities less than 0.3 MWp are concentrated in built-up areas dominated by large urban agglomerations, such as Praha (Prague), Brno, Plzeň (Pilsen), České Budějovice and the Ostrava region. The distribution of installations in relation to CLC 2006 level 2 land cover classes and total sums of installed power capacities is shown in Table 2. The highest number of installations can be found in the areas of 11: "Urban fabric" class, with a dominance of very small installations. Some PV power plants in built-up areas are quite large (1 MWp and more), however, mostly located in industrial areas (code 12: Industrial, commercial and transport units). The largest share of the total PV power capacity (70%, 1,348 MWp) is located in agricultural areas (21: Arable land, 22: Permanent crops, 23: Pastures, 24: Heterogeneous agricultural areas) dominated by large PV power plants (more than 1 MWp). Unlike the situation in Slovakia, installations in the agricultural areas have a much higher correlation (r = 0.22) with the solar resource potential than installations in the built-up areas (r = 0.04). However, large installations over 1 MWp follow the solar resource potential (r = 0.02) very poorly, and smaller installations are only marginally better (r = 0.05).

It should be noted that the number of installations found in the particular CLC 2006 classes is slightly influenced by the lower level of detail (a minimum mapping unit of 25 ha) and the spatial accuracy of the CLC 2006 database. In particular, some smaller PV power plants found in smaller settlements can sometimes be classified in agricultural or forest area classes. Such inaccuracies, however, do not substantially affect the overall picture of the distribution of the PV power plants within the major CLC 2006 classes.

4. Transition from large-scale to small-scale installations

Urban areas are very important for solar energy applications. It is assumed that future massive thermal and photovoltaic (PV) applications will involve urban areas primarily. More than 80% of inhabitants of the most developed countries live in an urban environment. In urban areas, energy is consumed and, at the same time, a large portion of green-house gases is produced. Šúri et al. (2007) point out that, in theory, the electricity consumption in many countries could be completely covered by the utilization of solar radiation from a relatively small area (for example, using only 1% of the territory in some countries). This assumption has been corroborated by recent changes in the Slovak support scheme, confining the installation of future PV power plants only to building-mounted systems with a maximum installed capacity of 100 kWp.

The global and regional solar resource databases with spatial resolutions ranging from 100 m to 1 km are of limited applicability in urban areas. The complex nature of the urban environment includes the 3-D morphology of buildings, urban greenery with parks, and isolated trees casting shadows on facades and roofs. All of these factors greatly modify the available solar radiation throughout the day and year. Recently, virtual 3-D city models have become an integral part of many urban studies. Hofierka and Kaňuk (2010) provide an example. The production of 3-D city models is also stimulated by new 3-D mapping technologies such as LiDAR, pictometry and digital photogrammetry, as well as by the development of 3-D tools in GIS technologies that enable 3-D data processing and visualization.

CLC 2006 CODE	CLC 2006 level 2 class	All locations		Locations of <0.3 MWp		Locations of >1 MWp	
		Count	Sum of installed power [MWp]	Count	Sum of installed power [MWp]	Count	Sum of installed power [MWp]
11	Urban fabric	12,175	363.590	12,000	212.571	41	72.651
12	Industrial, commercial and transport units	1,033	338.795	901	36.646	58	260.113
13	Mine, dump and construction sites	16	8.150	15	0.369	1	7.781
14	Artificial, non-agricultural vegetated areas	91	2.762	89	1.196	0	NA
21	Arable land	1,882	1,069.994	1,437	35.483	310	949.027
22	Permanent crops	29	10.720	23	0.442	3	8.970
23	Pastures	446	116.801	393	8.070	31	94.114
24	Heterogeneous agricultural areas	1,849	150.527	1,778	31.726	35	93.754
31	Forests	211	5.931	210	4.931	0	NA
32	Scrub and/or herbaceous vegetation associations	22	33.291	16	0.300	6	32.991
	Total	**17,754**	**2,101.000**	**16,862**	**332.00**	**485**	**1,519.00**

Tab. 2: Distribution of PV power plants within the CLC 2006 classes in the Czech Republic
Source: ERÚ (2013) and EEA (2007)

Hofierka and Kaňuk (2009) have developed a methodology for assessing the photovoltaic potential of urban areas using the 3-D city model, r.sun solar radiation model and PVGIS photovoltaic estimation utility available at http://re.jrc.ec.europa.eu/pvgis/. The methodology can be effectively used for any urban area with a 3-D city model and known rooftop parameters. The assessment of the urban areas of two towns in Slovakia, Prešov and Bardejov, has shown that urban zones of the blocks of flats and industrial zones have the highest potential for future rooftop PV power plant installations (Fig. 3). A study by Kaňuk et al. (2009) further extrapolated the estimated PV potential for residential areas with the blocks of flats identified using the Corine Land Cover database to 138 cities in Slovakia. The study concluded that the estimated annual photovoltaic potential of these cities is around 960,000 MWh.

It should be noted that this methodology can only be applied to the rooftops (i.e. 2-D surfaces) and many parameters must be assessed manually. Since no real 3-D tools had been available until recently, vertical surfaces such as facades usually had to be excluded. Recently, Hofierka and Zlocha (2012) developed new 3-D tools for assessing the solar radiation distribution in morphologically complex urban areas. The new v.sun module for GRASS GIS is based on the solar methodology developed for the r.sun module. The 3-D surfaces of buildings are segmented using a combined voxel-vector approach, allowing for a more accurate assessment of the solar resource potential even on vertical surfaces such as facades (Fig. 4). The applications of the v.sun module go beyond the PV applications and may include an analysis of light and thermal conditions of buildings and open urban areas.

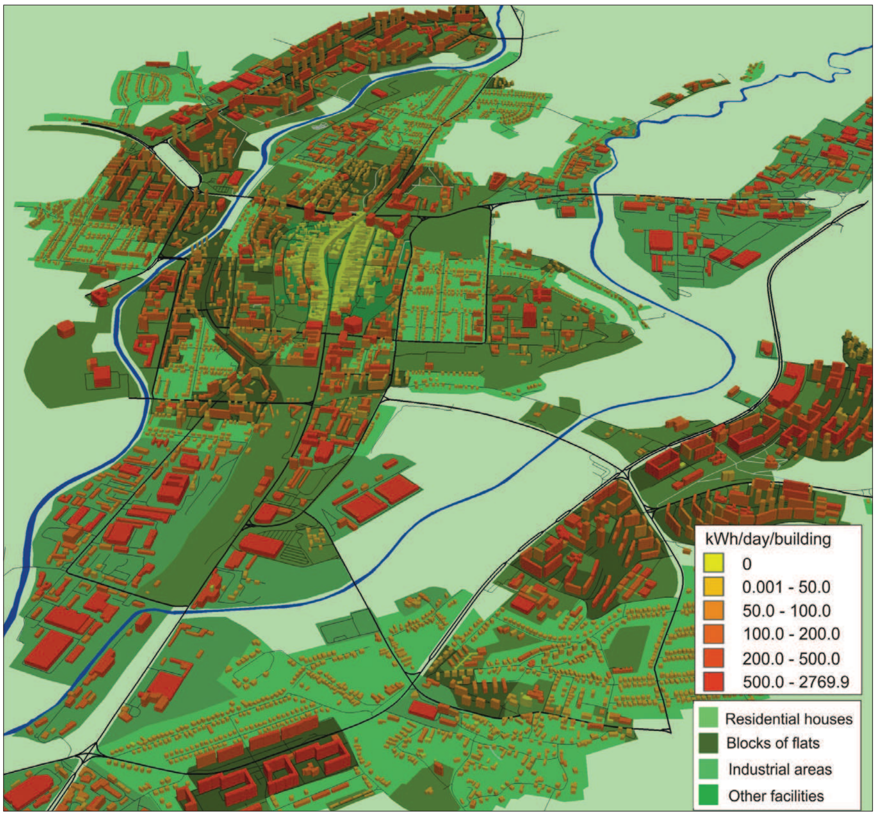

Fig. 3: Assessment of photovoltaic potential in the urban area of Prešov

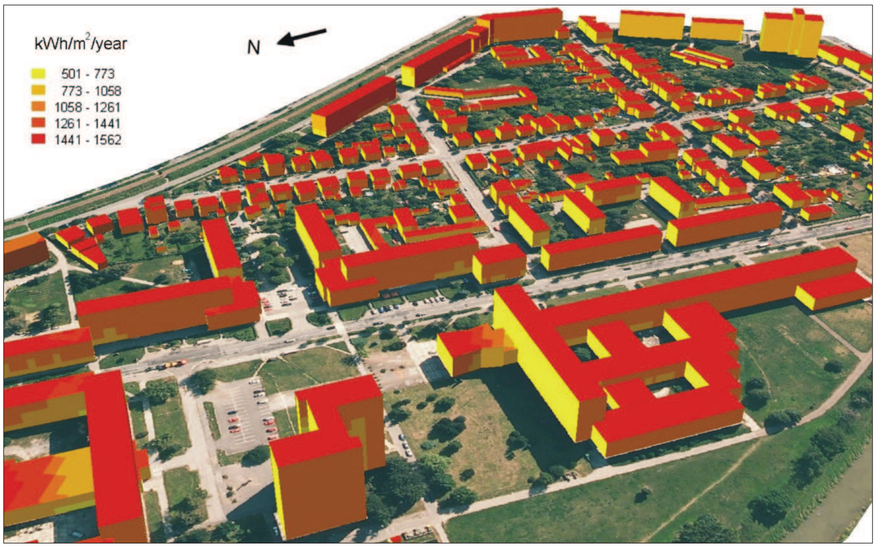

Fig. 4: 3-D solar radiation modelling using the v.sun module

5. Conclusions

Solar energy has become an integral part of energy resource mixes of many countries, including the Czech Republic and Slovakia. The generous support schemes in both countries, as well as the decreasing costs of new PV power plant installations, caused a massive boom in the area of PV power plant construction in the period 2009 to 2012. More than 20,000 new PV power plants were built in the two countries, but the consequences included higher electricity prices paid by consumers. Recent changes in the support schemes for new PV installations, however, will shift the focus to smaller systems in built-up areas. In this paper, we have analysed the spatial distribution of existing PV power plants. We have found that these power plants scarcely follow the solar resource potential represented by solar databases developed by Hofierka and Cebecauer (2008) and the commercially available SolarGIS (Šúri and Cebecauer, 2010). Smaller installations (less than 0.3 MWp) are concentrated mostly in the built-up areas (these are often rooftop installations); larger installations are usually located in open agricultural areas, with a few exceptions found in industrial areas or in quarry areas (former extraction of minerals).

Recent changes in the support schemes for new PV installations will also affect these patterns, with new installations mostly limited to built-up areas. These changes will require new tools to assess the appropriate locations of the PV systems. The complex environment of built-up areas will require new 3-D tools, integrated with the spatial databases and modelling techniques of GIS. Several examples have been presented, assessing the solar resource potential in a built-up area using a virtual 3-D city model and new 3-D solar radiation tools developed for GRASS GIS.

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