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GEOSPATIAL ESTIMATION OF ROOFTOP SOLAR PHOTOVOLTAIC TECHNICAL POTENTIAL IN SERBIA

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Abstract: Rooftop photovoltaic (PV) systems are essential for meeting the increasing demand for electricity while reducing reliance on fossil fuels, thereby enhancing overall air quality. Yet, for many countries, the geospatial distribution of rooftop PV potential remains poorly quantified, constraining the design of effective policies and grid planning. This study delivers the first nationwide, building-level assessment of rooftop PV in Serbia, integrating Microsoft machine-learning building footprints with Global Solar Atlas irradiance data and a calibrated performance-ratio model on the Google Earth Engine platform. The findings show an upper-bound technical potential of 41.1 GW and 51.5 TWh/year, which is around 40% more than Serbia's current electricity consumption. In Serbia, spatial heterogeneity is present, as cities such as Novi Sad and Leskovac surpass 1 TWh annually, while municipalities in rural areas fall below 20 GWh. The comparison of per-area yield intensity (~250 GWh/km^2) in this study exceeds previous estimates in Serbia, while still aligning with global upper-bound studies. Novel contributions include municipal-level mapping across 197 units, integration of prosumer registries, and a social case study demonstrating the role of rooftop PV in alleviating energy poverty. This study takes a novel approach, based on unconventional data, to estimate rooftop PV potential at the level where decisions actually happen. It enables a bottom-up shift in energy policy, empowering local authorities to drive the energy transition independently from centralized energy policy. These findings support the development of more effective local energy plans that align with residents' needs and overcome bureaucratic delays in project approvals.

Keywords: rooftop photovoltaic; prosumer; technical potential; solar energy; Serbia

1. Introduction

Increasing renewable energy globally is now a practical necessity rather than just a policy goal. With a global capacity of about 1.5 TW by 2023, solar photovoltaics (PV) have taken the lead in this shift (International Renewable Energy Agency, 2024). Among different applications, rooftop PV is particularly attractive because it makes use of existing infrastructure, reduces competition for land, and allows households and communities to participate directly in the energy system. Several studies (e.g., Baruch-Mordo et al., 2019; Gernaat et al., 2020; Joshi et al., 2021; Yeligeti et al., 2023; Zhang et al., 2025) show the

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potential and role of rooftop PVs in increasing electricity supply and creating decentralized electricity systems all over the world. In the literature, recent trends focus on the use of ML-based, building-level frameworks for city-scale rooftop PV mapping (Li et al., 2024), multi-source deep-learning pipelines at urban scale (Long et al., 2025), and nation-wide bottom-up assessments that highlight the value of building-level footprints for scaling potential estimates (Winkler et al., 2025).

The role of rooftop PV is set in Europe's 2030 climate and energy framework. The Renewable Energy Directive now sets a binding target of at least 42.5% renewables in gross final consumption by 2030, with the ambition of reaching 45% (European Parliament, Council of the European Union, 2023). To support this, detailed assessments of rooftop PV have been carried out across the EU. Bódis et al. (2019) provided a continental-scale geospatial analysis at 100 m resolution, while Molnár et al. (2022, 2024) refined these approaches to building-level modelling. National, regional, and urban case studies, such as those conducted for Germany (Mainzer et al., 2014), Switzerland (Assouline et al., 2017), Spain (Gómez-Exposito et al., 2020), the Piedmont Region in Italy (Bergamasco & Asinari, 2011), mid-sized town of Bardejov in eastern Slovakia (Hofierka & Kanuk, 2009), a group of buildings in a suburb of Lisbon (Brito et al., 2012), and urban area of Maribor (Srećković et al., 2016), show that spatially explicit estimates are indispensable when designing incentives and planning grid integration. The experience of Valencia (Gómez-Navarro et al., 2021) is especially relevant, as it demonstrates how rooftop PV mapping can support local programs and strengthen public participation.

Due to its significant dependence on fossil fuels, Serbia remains highly vulnerable to fluctuations in the price of imported fuels (Batas Bjelić & Đukić, 2018) and the unsustainable environmental impacts of lignite mining (Batas Bjelić, 2024). Serbia introduced its National Energy and Climate Plan (NECP; Government of the Republic of Serbia, Ministry of Mining and Energy, 2025) to address these issues and comply with the EU's decarbonization vision. Despite acknowledging that solar and wind are the primary forces behind the growth of renewable energy, its objectives remain modest: only roughly 3.5 GW of additional capacity is planned by 2030 (Aleksić & Batas Bjelić, 2021). This is surprising, given the country's favorable natural conditions – Serbia is receiving approximately 1,400 kWh/m^2 of annual solar radiation, around 40% above the European average (Pucar & Nenković Riznić, 2009). Additionally, applications totaling 5.8 GW of capacity have already been submitted to the distribution operator, demonstrating strong investor interest (Elektrodistribucija Srbije [EDS], 2023). But things have moved slowly. Only 166 MW of the installed capacity had been reached by the end of 2023 (Spasić, 2024), falling significantly short of regional peers such as Hungary, Bulgaria, and Romania (International Renewable Energy Agency, 2024).

Existing assessments of rooftop PV potential provide only a partial explanation. Earlier studies (Batić & Ivančić, 2023; Doljak & Samardžija, 2017; Đurišić & Škrbić, 2022; Stojkov, 2011) relied mainly on statistical proxies for the building stock and applied several assumptions on usable roof area and efficiency. As a result, they generated aggregated national totals but offered little insight into local variation. On the other hand, Ašonja and Vuković (2018) offered a broad overview of Serbia's solar energy potential, highlighting barriers to deployment such as grid limitations and low realization rates compared with the country's high solar irradiance.

Nevertheless, as several local studies have begun to show, such as analyses for Belgrade (Brankov et al., 2020; Dodig & Djapic, 2023), Vranje (Gradska uprava Vranje, 2022), Inđija (as one of the pilot cities in the i-Scope project; Protić et al., 2018), and selected municipalities

(Batas Bjelic & Ciric, 2014; Batas-Bjelic et al., 2017), the potential for rooftop PV varies substantially across regions. Without spatial detail, it is difficult to design incentives that reflect local opportunities, anticipate where distribution grids might face bottlenecks, or identify municipalities where rooftop PV could be used as a tool for alleviating energy poverty. In short, the lack of geospatially explicit data has become a bottleneck for Serbia's solar transition.

The present study seeks to fill this gap and provide first comprehensive, municipal-level assessment of rooftop PV technical potential in Serbia. Upper-bound of rooftop PV technical potential, in terms of installed capacity and annual electricity generation, across 197 municipalities in Serbia, is estimated by combining irradiance data from the Global Solar Atlas (Solargis, 2024) with Microsoft Global ML Building Footprints (Microsoft, 2022) via a performance-ratio model (Wu et al., 2017). The results were compared with earlier estimations made for Serbia (Batić & Ivančić, 2023; Doljak & Samardžija, 2017; Đurišić & Škrbić, 2022; Stojkov, 2011) and the EU (Bódis et al., 2019; Molnár et al., 2024), as well as other studies worldwide. More importantly, the obtained results are relevant for the implementation of Serbia's NECP (Government of the Republic of Serbia, Ministry of Mining and Energy, 2025), the design of incentive schemes, and the broader involvement of citizens as energy prosumers. Through this research, Serbia aligns with best international practices and provides policymakers with the spatial evidence they need to transition from national goals to local initiatives.

2. Study area

Serbia is located in Southeastern Europe, at the center of the Balkan Peninsula, defined by the coordinates 41°53′N–46°11′N and 18°49′E–23°00′E. The country covers a total area of 88,499 km² and is divided into 197 municipalities and cities (Figure 1; Statistical Office of the Republic of Serbia [SORS], 2024a). The 2022 Census reports a total of 2,261,051 residential buildings (SORS, 2024b) and 6,647,003 inhabitants (SORS, 2023), excluding the Autonomous Province [AP] of Kosovo and Metohija (the territory under United Nations Security Council Resolution, No. 1244; United Nations, 1999).

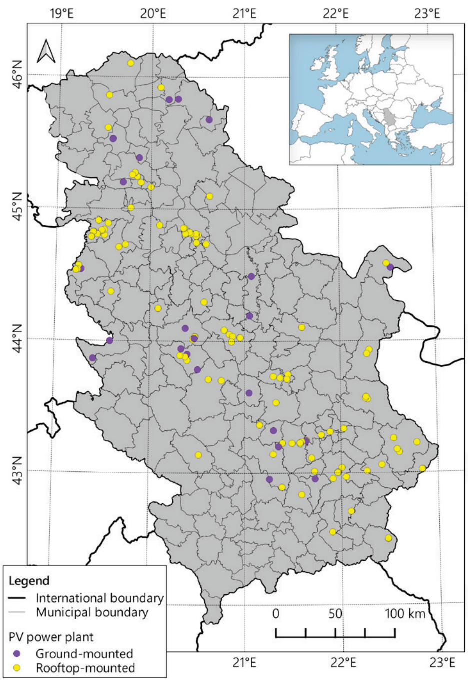

Figure 1. Study area.

The northern region of Serbia features mostly lowlands with an elevation of less than 200 m a.s.l., whereas the remainder of the country consists of mountains drained by the main river valleys of Velika Morava, Zapadna Morava, and Južna Morava. These valleys and lowlands have the highest population density and activity concentration.

Most of Serbia has a moderately continental climate, except for the northern part, which is characterized by a continental climate, and the southwest, with a modified Mediterranean climate (Milovanović et al., 2023). The average sunshine duration per year (period 1961–2010) ranges from 1,534.8 hours in Požega to 2,142.6 hours in Kikinda (Milovanović et al., 2017). The northwestern part of Serbia receives less than 1,240 kWh/m^2 of global horizontal irradiance annually, whereas the southeast receives more than 1,540 kWh/m^2 (Institute for Multidisciplinary Research, 2004).

Figure 1 illustrates the spatial distribution of 161 solar power plants listed in the *Register of connected power plants that use renewable energy sources* (updated on January 15, 2025; EDS, 2025a) in Serbia. The total installed capacity of these solar power plants is approximately 87 MW, with rooftop systems contributing around 10 MW. Additionally, 4,410 solar power plants are registered in the Prosumer registries with a total installed capacity of 88.8 MW as of February 2025 (EDS, 2025b, 2025c, 2025d).

3. Data and methodology

To estimate the spatial variability of PV potential on building rooftops, various data sets and software were used. Computing was performed on the Google Earth Engine (GEE; Google, n.d.; Gorelick et al., 2017) platform, while the final results, presented as maps of rooftop photovoltaic potential and current installed capacity, were created using QGIS (Version 3.16; 2020) software.

The study applies three spatially explicit datasets: solar resource, building footprint, and borders of administrative units (i.e. municipal boundaries). Solar resource data are obtained from Global Solar Atlas (Version 2.11; Solargis 2024). The average yearly sum of global horizontal irradiation (kWh/m^2) data for the period 1994–2018 was converted to irradiance data (W/m^2), and the mean value was computed for each building. Global ML Building Footprints, i.e. MSBuildings dataset (Microsoft, 2022) was used to derive building footprint vector data for Serbia. The dataset comprises 1.4 billion building footprints worldwide, extracted from Bing Maps imagery between 2014 and 2024, including imagery from Maxar, Airbus, and IGN France. Squares of missing data in the dataset were due to exclusion processes of imagery tiles that were dated prior to 2014 or those with a low detection probability (loosely defined by proximity to roads and population centers). In Serbia, gaps in the data are primarily found in the southern region. Consequently, the municipalities of Vranje, Vranjska Banja, Preševo, Bujanovac, and Trgovište are completely excluded from estimation.

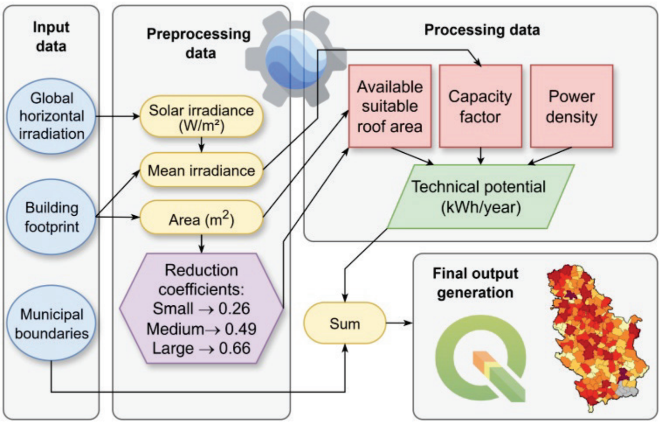

Figure 2. Framework for the estimation of rooftop PV technical potential.

Before assessing the technical potential, the area and average irradiance for each building were calculated. Municipality boundaries were retrieved from the GeoSrbija open data (Republic Geodetic Authority, n.d.) platform and imported as an asset into GEE. The municipal level was used to display the final result of PV technical potential. The whole process model is illustrated in Figure 2.

The hierarchical taxonomy of rooftop PV potential (Izquierdo et al., 2008) is followed, which distinguishes physical (resource), geographical (usable rooftop area after siting constraints), and technical potential (conversion of usable area and irradiance into electricity using performance parameters). Technical potential accounts for three aspects: irradiance on tilted surfaces, module spacing to avoid shading, and efficiency under real operating conditions. The present study explicitly captures the third aspect—module efficiency and system losses—through a performance-ratio model (Equation 2). At the same time, tilt and shading effects could not be resolved due to the lack of 3D roof geometry, and are therefore noted as limitations. Thus, this study reports an upper-bound technical potential, consistent with the international taxonomy and similar to approaches applied in other urban assessments (e.g., Gómez-Navarro et al., 2021), derived from usable rooftop area (building footprints with reduction coefficients) multiplied by a PV performance model that incorporates availability, balance-of-system losses, module efficiency, and long-term irradiance. This corresponds to the "technical" tier of the taxonomy but remains subject to refinement as higher-resolution DSM and building data become available.

Technical potential for the *i*th rooftop PV (P_i; kWh/year) is estimated using Equation 1 (Baruch-Mordo et al., 2019):

$$P_i = A_i \cdot CF_i \cdot E \cdot 8{,}760 \tag{1}$$

where for each building i, Ai *is* available suitable roof area for installation of PV, CF_i is the capacity factor, and E is the power density (W/m^2). Available suitable roof area for building i is calculated as a product of total roof area and reduction coefficient depending on the building size. Initially, it was assumed that the building footprint area directly corresponded to the rooftop area. Reduction coefficients for small (< 465 m^2), medium (465–2323 m^2), and large (> 2,323 m^2) buildings were taken from a study by Gagnon et al. (2016): 0.26, 0.49, and 0.66, respectively.

The capacity factor represents the ratio of actual to the highest feasible electricity generation of a power plant over a given period. To estimate capacity factor, Equation 2 (Wu et al., 2017) is used:

$$CF_i = \frac{(1-\eta_0)-(1-\eta_b)\cdot G_i}{1{,}000} \tag{2}$$

where η_0 is outage rate (4%), η_b is the inverter and AC wiring inefficiency rate (4%), G_i is spatially averaged solar irradiance (W/m^2) for *i*th building, and incident solar radiation at standard test conditions of 1,000 W/m^2.

The power density for PV modules with a 15% conversion efficiency ranges from 120 to 150 W/m^2 (Smil, 2015). For this estimation, it is assumed that standard photovoltaic modules with an efficiency of 20% are installed. The power density in Equation 1 is set at 200 W/m^2 (Alhmoud, 2023).

4. Results and discussion

The data analysis reveals a rooftop PV potential in Serbia that is both substantial and unevenly distributed. Using Microsoft building-footprint data, we estimate a total roof area of 655.34 km² nationwide, and it does not align with the 600 km² calculated by the Republic Geodetic Authority (eKapija, 2022). This source does not specify whether the Republic Geodetic Authority included the roof area in the AP of Kosovo and Metohija. After applying size-dependent reduction coefficients, approximately 205.6 km² remain suitable for PV installation. When combined with long-term irradiance values and a performance-ratio model, this corresponds to an upper-bound technical potential of 41.11 GW of installed capacity and 51.47 TWh of annual electricity generation. For comparison, this value is 42.3% greater than Serbia's total electricity consumption in 2023 (SORS, 2025).

Technical potential is unevenly distributed throughout the territory of Serbia. Cities pop out with their potential, with Novi Sad as the single highest contributor (exceeding 1,300 GWh per year), followed by Leskovac, which surpasses the 1,000 GWh per year threshold (Figure 3A). Municipalities in remote areas have a smaller potential, as illustrated by cases such as Crna Trava and Novo Brdo, where estimated annual production is less than 20 GWh. Even more stark differences are shown by normalized values (Figure 3B), where sparsely populated areas continue to fall below the national average of 1,312 MWh/km². In contrast, Vračar, the most densely populated municipality in the City of Belgrade, has an annual PV power generation potential of over 30 GWh/km².

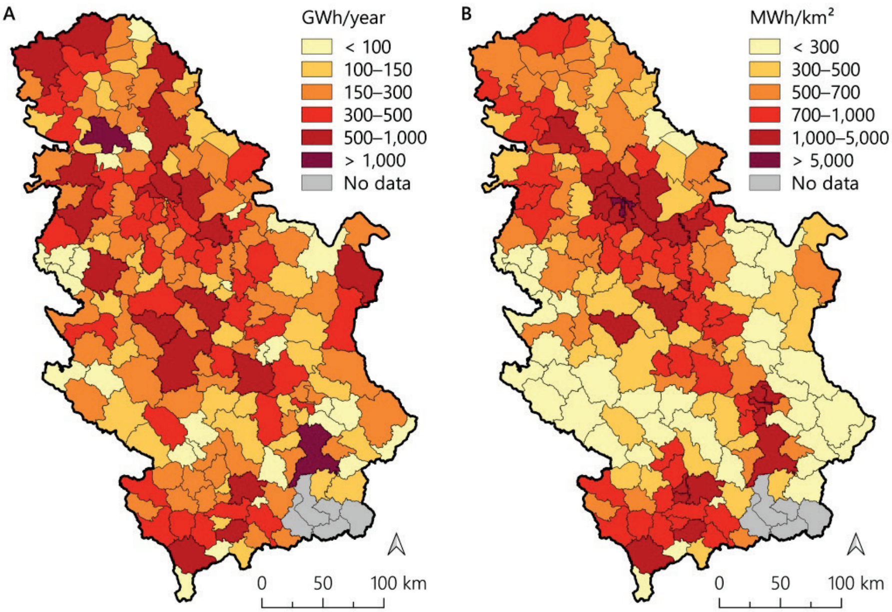

Figure 3. Technical potential of rooftop PV by municipality (A) and per unit area within each municipality (B) in Serbia.

The highest potential is found in municipalities that are geographically located on the main development axes of the Danube-Moravian Corridor and larger basins (Kosovo, Metohija, etc.).

It is also the area with the highest population density and activity concentration and, therefore, with the highest energy demand. Utilizing the estimated rooftop PV potential in this study, together with heat pumps, can be a solution to the air pollution problem, especially regarding $PM_{2.5}$ levels from domestic heating in urban areas, as reported in studies by Stanojević, Malinović-Milićević et al. (2024) and Stanojević, Miljanović, et al. (2019).

A comparison between the estimated and actual annual PV production was done in order to validate the results (Figure 4). The selection of existing photovoltaic systems was conducted based on available data regarding the electricity production of eligible producers (Elektroprivreda Srbije, 2015–2024). The systems were chosen to best align with the model's parameters, particularly the available roof area, across three building categories defined by their footprint area. Three existing rooftop solar PV power plants selected for validation with model results are:

- “SE Jajinci” (44°44'39"N 20°29'27"E), with a capacity of 8 kW, developed on the roof of a small building (family house);
- “IMP” (44°48'24.6"N, 20°30'23.7"E), with a capacity of 50 kW, mounted on the roof of a medium-sized building (R&D institution); and
- “ST solarna” (42°50'17"N, 21°35'18"E), with a capacity of 440 kW, installed on the roof of a large building (industrial hall).

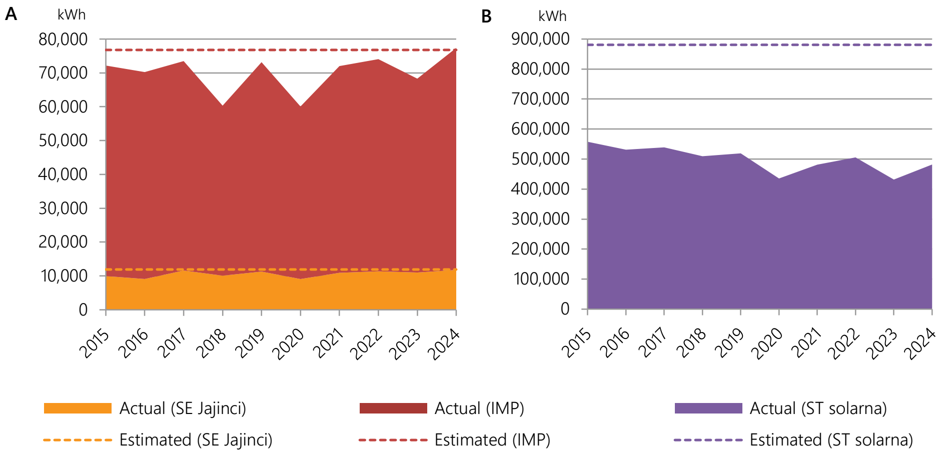

Figure 4. Comparison of actual vs. estimated annual PV production in systems installed on small (A), medium (A), and large (B) building rooftops.

The mean absolute percent error between actual and estimated upper bound for the tested PV power plants is 11.4% (SE Jajinci), 25.3% (IMP), and 55.3% (ST Solarna). Figure 4B shows that the model could be less accurate when evaluating large rooftop PV power plants. Although a suitable rooftop area for PV panel installation matched the real conditions, it was not determined that the same type of PV panels were used as in the assessment model, and which part of the roof has been used to mount PV panels. Also, the estimation did not consider all PV system losses, such as shading, soiling (dirt on panels), temperature-related losses, spectral and angular losses, which can vary from 10% to 25%, as noted by Denholm et al. (2010). Additionally, it is not known if produced energy is used for self-consumption and to which percentage of the production. This suggests a need for deeper investigation into all known technical predictors as part of future studies.

The proposed methodology in this study allows for estimating the potential energy production from rooftop PV systems for a specific group of facilities. To address the energy insecurity faced by low-income households, the social neighborhood of Košutnjak in the Municipality of Čačak, located in southwestern Serbia, was selected as a case study (Figure 5). The settlement consists of 13 buildings with 102 apartments ranging in size from 20 to 50 m^2. According to the study by Vuksanović-Macura et al. (2021), monthly utility expenses, including electricity and gas, vary from 110 to 196 euros depending on the size of the apartment. The total area of roofs that can be utilized in the neighborhood is approximately 442.52 m^2, which permits the installation of 88.5 kW of PV systems. These systems have the potential to generate 108.42 MWh of electricity per year which could have monetization level of support at around 100,000 € per year.

An average family house with a footprint area of 80 m^2 can install a PV system on its roof with a capacity of approximately 4.2 kW, generating around 5.1 MWh of electricity per year. A 100 kW PV system can be installed on a 1,000 m^2 multifamily residential roof, generating approximately 120.6 MWh of electricity per year. Furthermore, a supermarket with a 2,500 m^2 footprint could accommodate a 330 kW PV system, producing about 407 MWh of electricity annually.

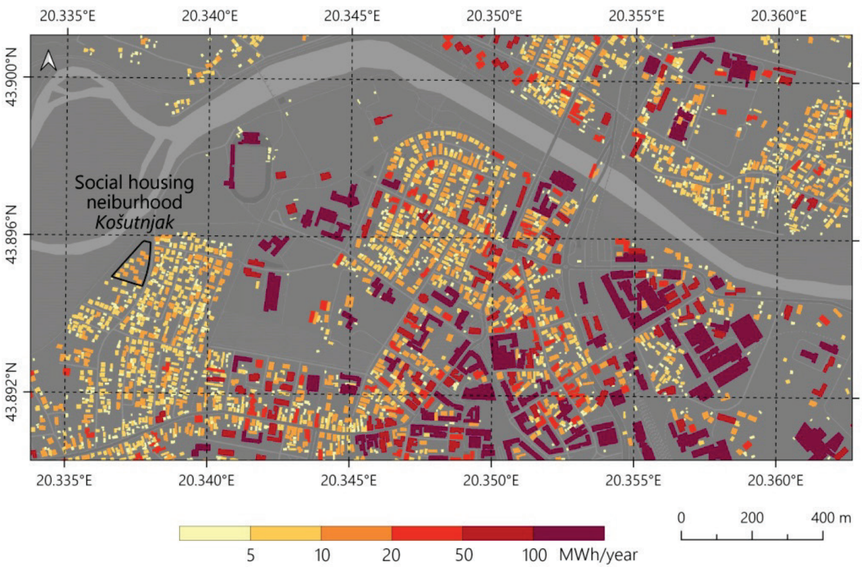

Figure 5. Technical potential for rooftop PV in social house neiborhood Košutnjak in Čačak.

Energy poverty remains a persistent challenge in Serbia, with between 7% and 22% of households struggling to secure essential energy services (Ban et al., 2021). According to SORS (2024c), 9.4% of people live in households that cannot afford to keep their homes adequately warm. Energy bills represent 11.4% of the average household's monthly income. Electricity accounts for 45.7% of this total, while natural gas, solid and liquid fuels, and district heating account for the remaining 54.3% (SORS, 2024d). Low income, high energy expenses, and low energy efficiency are the main causes of energy poverty (Boardman, 1991, as cited in Croon et al., 2024). Old and inefficient heating systems that burn solid fuels, such as coal and wood, are typical in socially vulnerable households. Since they cannot afford to replace these devices, they end up using far more energy to heat their homes (RES Foundation, 2021). Installing solar panels and improving insulation and heating systems directly reduce utility costs for tenants (Croon et al. 2024), ensuring a decent standard of living and protecting our health. Solar systems with 1–5 kW output power are suitable for various consumer needs (Vuksanović–Macura, 2021) and could help in alleviation of energy poverty in low-income households (Avramović & Batas Bjelić, 2024).

In contrast to the technical ceiling presented above, the reality on the ground is modest. Household prosumers (customer who produces electricity from renewable energy sources for personal use and sells any excess back to the electricity supplier; Law on the Use of Renewable Energy Sources, 2024) are growing in number but remain concentrated in a few municipalities (Novi Sad, Zemun, Subotica, Leskovac, Šabac, Pančevo, Kladovo, and Vranje; Figure 6A), and their total installed capacity (26 MW, 3,182 prosumers; EDS, 2025b) represents only a fraction of the upper-bound technical potential.

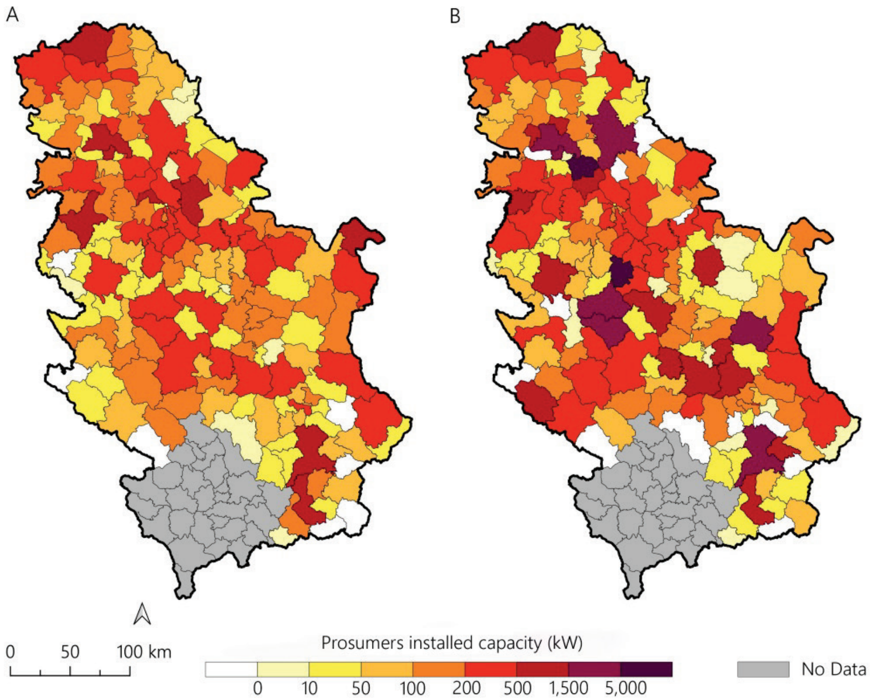

Figure 6. Current installed PV capacity of households (A) and non-household or non-residential communities prosumers (B) at the municipal level in Serbia (data as of February 20, 2025).

The picture looks different in the commercial and industrial sectors. Although they number only 1,224, fewer than the household category, their collective capacity reaches 62.7 MW, more than double when compared to households. Strikingly, this capacity is concentrated: one-fifth of Serbian municipalities host above-average installations (>378.48 kW), yet these account for nearly four fifths of the country's non-household prosumer capacity. Such unevenness reveals both the scale of unrealized opportunity and the structural factors shaping deployment.

A closer look at leading municipalities illustrates this point. In both Aranđelovac and Inđija, the installed capacities in each of them exceed 8 MW, driven by large-scale industrial actors. By installing rooftop photovoltaic systems on twelve production halls in Aranđelovac, the company "Peštan" has reduced its electricity consumption by 20% compared to 2018—an amount equal to the yearly consumption of roughly 2,200 households (Peštan, n.d.). In the meantime, "Toyo Tire" has installed a 7.2 MW ground-mounted system in Inđija that provides 15% of the factory's energy requirements (UNDP Serbia, 2023).

Survey research by Nenković-Riznić et al. (2023) indicates that permitting processes are complex, upfront costs remain high, and many municipalities in Serbia lack sufficient information about solar potential. Additionally, these municipalities are not prepared to accommodate a large number of prosumers. At the same time, while young people generally have a positive attitude toward renewable energy sources, particularly solar energy, there appear to be some shortcomings in the practical application of solar energy (Association RES Serbia, 2025).

On the other hand, good practices in financial support, followed by the transfer of knowledge in installing rooftop PV systems, have led to progress in less developed areas of Serbia, compared to more developed municipalities. In the villages of Temska and Dojkinci, situated in the foothills of the Stara Planina mountain range in southeastern Serbia, the first two cooperative solar power plants, each with a capacity of 5 kW, were installed on the roofs of community buildings as an example of such an initiative (Elektropionir, n.d.). Energy cooperative "Sunčani krovovi Šabac" (n.d.) successfully supported the first prosumer in obtaining their prosumer status through a complex procedure. In addition to cooperative PV power plants, the City of Pirot is proud of several projects aimed at promoting solar energy. These include PV installations on the public facilities: a 15 kW system on the Economic School building, a 30 kW system at the public enterprise Komunalac, a 150 kW system at the secondary waste separation plant within the regional landfill, and another 150 kW system at the Berilovac pumping station (eKapija, 2025). Moreover, several public and private solar projects are underway across the city, all pushing Pirot toward its goal of becoming Serbia's "City of Sun" (Spasić, 2023).

Vranje has an impressive planning and analytical framework for harnessing solar energy. The Spatial Plan of the City of Vranje (JP Zavod za urbanizam Vranje, 2018) identifies 12 potential sites for the construction of ground-mounted solar power plants. Additionally, a roof radiation assessment was conducted for the urban settlement of Vranje, estimating the total geographical potential at 49,173 MWh (Gradska uprava Vranje, 2022). The total installed capacity for the Municipality of Vranje is 525.04 kW for household prosumers (Figure 6A) and 572.16 kW for non-household or non-residential community prosumers (Figure 6B). Unfortunately, the lack of building footprint data in the Global ML Building Footprints dataset has prevented the assessment of rooftop PV technical potential for the administrative unit of Vranje. As a result, there was no comparison with the previously mentioned data regarding the current state of prosumers or other assessments conducted in the area.

4.1. Comparison with earlier assessments

A comparison with earlier assessments demonstrates that the estimates obtained in this study are systematically higher than those previously reported for Serbia. Our building-level analysis, based on Microsoft's machine-learning building footprints, identifies an upper-bound technical potential of 41.1 GW and 51.5 TWh per year from 205.6 km² of usable rooftop area. This corresponds to a yield intensity of around 250.5 GWh per km² annually, which is markedly higher than the intensities observed in other Serbian and some international benchmarks.

More modest results were consistently reported for Serbia in previous studies. The study by Batić and Ivančić (2023), which focused exclusively on residential buildings and excluded the AP of Kosovo and Metohija, found 52 km² of usable roof space, accounting for PV potential of 6.9 GW and 7.9 TWh per year, equivalent to 151.9 GWh per km². Doljak and Samardžija (2017), using regional statistical allocations, identified 91.7 km² of usable roofs with 14.4 TWh of generation, giving a yield intensity of 156.7 GWh per km². Similarly, the Spatial Plan of the Republic of Serbia 2010–2020 (Stojkov, 2011) reported roughly 7 TWh of rooftop PV potential, reflecting the cautious assumptions typical of planning documents at that time. The estimates of Đurišić and Škrbić (2022), which rely on NUTS-3 proxies (NUTS 3; Uredba o nomenklaturi statističkih teritorijalnih jedinica, 109/2009, 46/2010) to derive approximately 600 km² of roof area and about 13.2 TWh of rooftop generation, also fall below our results because proxy-based methods tend to underestimate the contribution of large commercial and industrial buildings. Jacobson et al. (2017) found that the rooftop area suitable for PVs on residential, commercial, and government buildings in Serbia is 122 km², with a potential capacity of 29.3 GWp.

Several methodological differences can explain the higher values reported in the present study. First, our analysis encompasses the entire building stock, residential, commercial, industrial, agricultural, institutional, and infrastructural. In contrast, earlier work was limited either to residential roofs or relied on generalized assumptions that downplayed the role of larger non-residential structures. Second, the use of high-resolution building footprints allows us to estimate roof area directly, avoiding the need for indirect proxies that have shown to underestimate available surface systematically. Third, by applying contemporary module efficiencies (200 W/m², equivalent to about 20 percent conversion efficiency) and a performance-ratio model calibrated to Serbian conditions, our assumptions better reflect current technological capabilities than those in earlier studies, which used lower power densities and more conservative derating factors. Finally, the Izquierdo et al. (2008) taxonomy of upper-bound technical potential was adopted in this study, which does not deduct for roof orientation, tilt, or shading, thereby positioning our estimate at the theoretical ceiling.

To substantiate the robustness of estimates, this study contains an international comparison exercise that situates Serbia's rooftop PV potential within a broader global context. Previous studies have reported widely differing outcomes depending on data sources, methodological resolution, and scope. Unlike studies that apply strict geometric suitability filters (e.g., shading, tilt, azimuth), such as Gagnon et al. (2016) for the United States or Bódis et al. (2019) for the EU, our analysis reports an upper-bound technical potential without exclusions for roof orientation or shading, focusing on the roofs and their parts that have most favorable conditions. As a result, the yield per unit area is higher. Other studies, such as McKenna et al. (2022) for Great Britain, produce lower intensities of 128 GWh/km²/yr due to their conservative treatment of roof suitability and efficiency assumptions. However, India produces between 182.5−365 GWh/km²/yr (Sethi et al., 2025), which is even more than our study. The global assessment of sites has an average of ~135 GWh/km²/yr (Joshi et al., 2021), reflecting both averaging across diverse climates and more restrictive suitability criteria and other trade-offs. Gernaat et al. (2020), also on a world level, show a number of 230.6 GWh/km²/yr, which is close to the number in our study as well (Table 1).

By contrast, the Serbian results align with the upper theoretical ceiling of rooftop PV when efficiency parameters are maximized and roof suitability is not heavily constrained. Our estimate should be interpreted as an upper-bound technical potential that can be used for benchmarking each site and municipality rather than an easily deployable figure.

Table 1. A summary of comparison

State/Region	Study	Usable rooftop area (km²)	Capacity (GWp)	Generation (TWh/yr)	Yield intensity (GWh/km²/yr)
Serbia	Present study	205.6	41.1	51.5	250.5
Serbia	Batić and Ivančić (2023)	52	6.9	7.9	151.9
Serbia	Doljak and Samardžija (2017)	91.7		14.4	156.7
Serbia	Jacobson et al. (2017)	122	29.3	n.a.	n.a.
Romania	Bódis et al. (2019)	354	n.a.	35.9	101.3
Croatia	Bódis et al. (2019)	85	n.a.	7.8	91.4
Switzerland	Walch et al. (2020)	267	n.a.	24.58	n.a.
Great Britain	McKenna et al. (2022)	1,190	n.a.	153.0	128.6
India	Sethi et al. (2025)		n.a.	n.a.	182.5–365
California	Gagnon et al. (2016)	526	77	114.0	216.9
EU-28	Bódis et al. (2019)	7,935	n.a.	680.3	85.7
United States	Gagnon et al. (2016)	4,922	731	926.4	188.2
Global	Gernaat et al. (2020)	36,000	n.a.	8,300.0	230.6
Global	Joshi et al. (2021)	200,000	n.a.	27,000.0	135

It is instructive to consider what Serbia's potential would look like if our usable roof area (205.6 km²) were combined with the yield intensities from other studies. Using European intensity of 85.7 GWh per km² (Bódis et al., 2019), Serbia's generation potential would drop to around 17.6 TWh, but it would still be higher than other Serbian studies. With the British value of 128.6 GWh per km², it would be about 26.4 TWh, and with the U.S. average national intensity of 188.2 GWh per km², its yield would about 38.7 TWh. If the Serbian values of Batić and Ivančić, (2023), who reported 151.9 GWh per km², were applied instead, our usable roof area would correspond to 31.2 TWh, while Doljak and Samardžija (2017) yield of 156.7 GWh per km² would imply 32.2 TWh. This exercise highlights that the higher numbers obtained in this study, compared to other Serbian studies, are also a consequence of the roof area.

5. Conclusion

This study provides the first building-level, municipal-scale assessment of the national rooftop PV potential in Serbia. Unlike previous studies, the assessment included all building types and parts of Serbia for which spatial data existed. The total area of rooftops suitable for PV installation in Serbia is estimated to be 205.6 km². This is sufficient space to accommodate PV systems, with total capacity of 41.11 GW and annual electricity production of 51.47 TWh, which exceeds current national electricity consumption by approximately 40%. Apart from outlining these important numbers, the analysis provides a solution to the main policy issues that Serbia is facing: the absence of geospatially explicit data, which is required to create the appropriate incentives, support programs for prosumers, and modernize the distribution grid. The reasons for that lie in unclear policy and technical framework for solar energy development, as well as complex permitting and grid connection processes by the utilities.

This study not only quantifies Serbia's rooftop PV technical ceiling but also converts geospatial data into useful recommendations for decision-makers. Rooftop PV potential at the level of government closest to citizens was mapped and related it to prosumer dynamics, energy poverty reduction, and cooperative models. With this groundwork, Serbia can push its shift to renewables in a way that matches both EU climate goals and what local communities actually need.

Before this study, PV potential in Serbia, and in each municipality, has been underestimated, with a clear consequence to energy policy. With more realistic spatially estimated potential (explained in the previous chapter), it is more obvious that renewable energy is abundant and affordable across Serbia. The advantages of potential being divided among municipalities leave room for a dedicated local energy policy to be independently created from the local toward the national level. This is a whole new paradigm shift from top-down declarative policy to the bottom-up development of regions that are more eager for energy transition. Current centralized energy policy is not reaching smaller investments and local energy authorities, but creates a long queue of projects waiting to get a connection permit from the national transmission and distribution system operators.

This study explicitly addresses technical potential of rooftop PV through a performance-ratio model that incorporates efficiency and system losses. However, aspects such as irradiance over tilted surfaces and spacing between modules to avoid self-shading could not be represented, as high-resolution 3D roof geometry and national digital surface models were not available. Incorporating a digital surface model into the methodology, could substantially reduce this uncertainty. For this reason, the estimates presented here should be interpreted as a technical ceiling, with actual yields likely lower once these geometric and shading factors are fully considered.

Additional sources of uncertainty include incomplete building-footprint coverage in some southern municipalities, which makes the national total conservative, and the reliance on present-day crystalline silicon technology assumptions. While bifacial panels or tilt optimization could increase output, sub-optimal mounting and degradation would reduce it. Finally, the analysis does not incorporate grid hosting capacity, regulatory frameworks, or economic feasibility, which will ultimately determine how much of the technical ceiling can be realized in practice. Future extensions should integrate 3D building data, shading-aware irradiance models, and grid-constrained scenarios to refine estimates toward deployable potential.

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