SOLAR ROOF POTENTIAL ANALYSIS CASE STUDY: TEST AREA IN SOUTH OF GERMANY

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ABSTRACT: As climate change progresses, enhancing the utilization of renewable energy sources has to become imperative, with photovoltaic (PV) systems representing one of the most cost-effective solutions. The solar rooftop potential is essential for grid operators to plan further grid improvements due to more decentralized feed in of electricity. The use of LiDAR data to generate 3D building models is already state of the art in commercial tools for solar potential analysis. The goal of this study is to develop an open source approach for identifying suitable roof areas for PV installation and quantifying their solar potential. The approach focuses only on solar irradiance on horizontal surfaces to avoid complex models for inclined, utilizing a horizontal step model to approximate roof geometries. The resulting map illustrate daily sunshine hours for each square meter of roof area with economic evaluations based on feed-in compensation rates of electricity. Roof sections receiving at least four hours of sunlight are classified suitable for PV deployment. Comparative analysis with satellite imagery shows strong correlation, indicating that the developed open source code effectively identifies viable areas for PV installation and provides a reliable estimate of actual solar rooftop potential.

Keywords: Photovoltaic, LiDAR, Building roof area, Solar potential, Economic assessment

1 INTRODUCTION

1.1 Background

In the context of climate change, the EU concluded the "Green Deal" in 2019, which stipulates that the EU should become climate-neutral by 2050 [1]. The energy sector accounts for a quarter of the greenhouse gas emissions in 2021 [2], so this sector must be consistently transformed from fossil energy sources to renewable ones such as solar, wind or water. In 2022 only 38 % of the electricity was generated from renewable sources [3]. PV systems are one of the cheapest options for generating electricity [4] and are therefore particularly interesting for politic, industry and research.

Modeling solar roof potential aids grid operators in planning the necessary infrastructure improvements or upgrades to accommodate distributed generation sources and maintain grid stability.

1.2 State of the art

The calculation of the solar potential can be based on several types of data. If a detailed analysis is needed a Digital Surface Model (DSM) is recommended which includes relevant information about the surfaces and the surroundings. The input data can be provided through different techniques: “simple aerial or satellite imagery, Light Detection and Ranging (LiDAR) that stores the geometrical information of a scanned surface as a 3D point cloud, stereo imagery which consists of pairs of geo-referenced photographic images covering the city and allowing to create a 3D model of the city by photogrammetry.” [6].

Huang et al. estimate the solar rooftop potential of Aichi, Japan by comparing different input data of LiDAR, AW3D (global 3D map) and Solargis. The results show that the calculation based on LiDAR data is the most precise technique [7]. Martínez-Rubio et al. determines the PV potential for solar facades by LiDAR data. The findings depend on the geographic location and on the influence of shading caused by neighboring buildings [8]. Omar et al. used AW3D, satellite imagery and spatial data, including sun azimuth and sun altitude to identify reasonable roof parts for PV of an office buildings in Kuala Lumpur, Malaysia including a shadow analysis [9]. Horváth et al. give a large-scale solar potential estimation of a region using typical structures and city pattern without considering shading [10]. AI-Quraan et al. studied two scenarios to determine the optimum solar rooftop potential using PV*SOL software for the performance evaluation [11].

LiDAR data are a common data base for calculating the solar rooftop potential, enabling a detailed model of the roof shapes. Due to this accuracy, this method is considered as time-consuming and is therefore not recommended for large areas. [7]

1.3 Objectives

In the field of solar energy assessment, processing input data typically requires expensive software solutions such as ArcGIS [7], [9]. This study introduces a Python-based script as a cost-effective alternative for processing and analyzing LiDAR data. The primary objective is to accurately identify suitable roof sections for photovoltaic (PV) systems while accounting for shading effects from partial roofs and neighboring structures and to calculate their solar potential.

2 DATA INPUT

2.1 Study area

Senden-Hittistetten is a model village for Smart Grids research of the Ulm University of Applied Science (THU) in cooperation with the local DSO. It is located in the south of Germany and consists of about 180 residential buildings with 89 installed PV systems.

2.2 Data sources

The LiDAR data from 2019 were provided by the Bavarian geodetic administration [12]. The building model is built up by standardized roof shapes with a spatial resolution of 1 m x 1 m. Deviations can be in the range of up to 1 m, the height accuracy is typically 20 - 30 cm. Not included in the analysis is tree shading due to the lack of data about the tree coverage.

In many studies [8], [13], [14] the LiDAR input data is in form of point clouds, there first of all a 3D model has to be created. In this case (like in [7]), the geometries of the buildings were already described with 3D-Polygons. The azimuth (0° is north), inclination (90° is horizontal) and the size for each partial roof are given.

OpenStreetMap (OSM) data of buildings and roads [15] were used to validate the LiDAR data set.

A German residential PV systems registry [16] was used to validate the results of this study.

3 APPROACH

The first step involves validating the LiDAR data to ensure its accuracy and completeness. This is achieved by cross-referencing the LiDAR data with OpenStreetMap data. OSM provides a complementary dataset that helps identify and correct discrepancies in the LiDAR data. Afterwards the preparation for the sunshine simulation is done, therefore inclined roofs have to be approached by a vectorized step-model. The geometry information of the roofs is then fed into the simulation tool, that determines the hours of sunshine per square meter. The results are economically assessed, and the final solar rooftop potential is calculated.

3.1 Validation of LiDAR data

Figure 1 presents a comparison between LiDAR-derived building outlines and OSM data for buildings and roads. The comparison reveals discrepancies, such as inaccuracies in the LiDAR outlines, exemplified by the highway intersection shown red in the figure. A cross-check with satellite imagery confirmed these errors, and the LiDAR dataset was subsequently corrected. After the correction the matching rate of building outlines between LiDAR and OSM is 95 %. The deviation primarily arises because OSM includes additional buildings that are not captured in the LiDAR dataset.

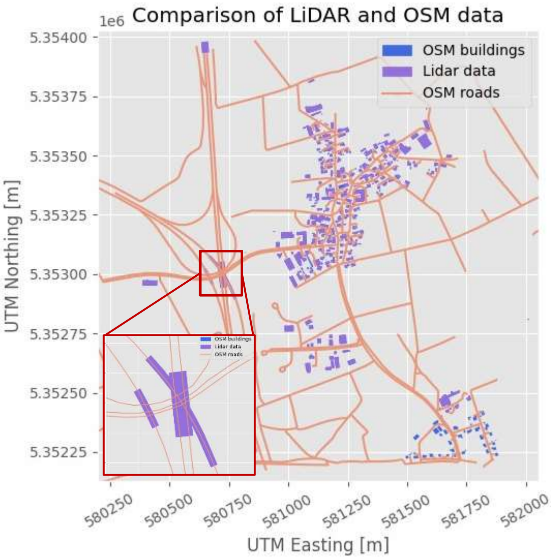


Figure 1: Comparison of LiDAR Data Accuracy and OpenStreetMap (OSM) Alignments

3.2 Data preparation for sunshine simulation

The model is designed to be as straightforward as possible, thus avoiding complex irradiance models for inclined surfaces such as Perez's [8] model. Instead, the analysis employs horizontal solar irradiation power, necessitating the conversion of the input 3D geometries into a block structure through the use of a vectorized step-model (Figure 2).

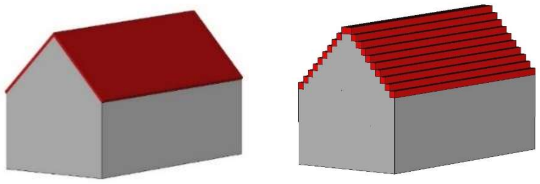


Figure 2: Approaching a sloped roof through horizontal partial roofs

3.3 Sunshine simulation

The simulation calculates sunshine hours in a 1m x 1m grid within 15-minute time intervals based on shading effects of neighboring buildings, as well as the sun's azimuth and altitude throughout the day. The simulation day is a day where day and night are equally long. A further explanation for this choice is given in the next chapter. The number of steps determines the accuracy of approaching inclined roofs. The simulation assumes that the modules are installed roof-parallel.

The potential calculation performed here is intended as a basis for future applications in planning or research. As the development of more and more powerful modules continues, modules with 430 Wp were selected for this simulation [17].

Given that most of the evaluated rooftops are on residential buildings, it can be assumed that investors are particularly focused on consuming the electricity directly in the building. Consequently, the system's sizing specifically, the installed PV power must align with the economic viability of the available space. Therefore, the calculated solar potential does not necessarily correspond to the maximum that can be technically achieved, but rather an economically feasible expectation.

The analysis aims to determine the minimum sunshine hours required for the economic operation of a PV system. The calculation is considering data such as investment costs and compensation rates as well as local irradiance power.

3.3 Calculation of solar rooftop potential

The simulated sunshine hours per square are base to determine the minimum sunshine hours which are needed to operate a PV system economically. The calculation is considering German data of investment costs and compensation rates as well as PV module data and irradiance power. It is assumed that the whole generated electricity is fed into the grid. The analysis does not include the actual electricity demand or electricity price.

The specific investment costs for 1 m² PV are calculated based on specific investment costs as well as PV module power and size. The annual electricity yield is determined by average solar irradiance power, efficiency of PV modules and sunshine hours per year. The amortization time is calculated with specific investment costs, compensation rate and electrical output.

Table 1 illustrates the results of the calculation for different investment costs and sunshine hours. The higher the investment costs, the more sunshine hours are needed to achieve an amortization time below 20 years. The analysis showed that four sunshine hours are set as the absolute minimum for the PV suitability of a roof area in Senden-Hittistetten. Areas receiving fewer than four sunshine hours are classified as shaded.

Table I: Economic assessment based on investment costs and sunshine hours

Investment costs			1500	1800	2100	2400	$\frac{€}{kWp}$
Specific investment costs			322.81	387.37	451.93	516.49	$\frac{€}{m^2}$
Sunshine hours	**Electrical profit**	**Financial profit**	**Static amortization time**				
$\frac{h}{d}$	$\frac{kWh}{m^2 * a}$	$\frac{€}{m^2 * a}$	years	years	years	years	
1	55.77	4.57 €	70.0	84.7	98.8	112.9	
2	111.54	9.15 €	35.3	42.4	49.4	56.5	
3	167.31	13.72 €	23.5	28.2	32.9	37.6	
4	223.08	18.29 €	17.6	21.2	24.7	28.2	
5	278.85	22.87 €	14.1	16.9	19.8	22.6	
6	334.61	27.44 €	11.8	14.1	16.5	18.8	
7	390.38	32.01 €	10.1	12.1	14.1	16.1	
8	446.15	36.58 €	8.8	10.6	12.4	14.1	

The simulation calculates the shading rate based on the sunshine hours for each roof which is then used to determine the roof-parallel solar rooftop potential, taking into account the available area as well as the dimensions and power of individual PV modules.

Bayod-Rújula, Ortego-Bielsa et al. [23] have demonstrated that the horizontal roof-parallel installation of modules is not the optimum for flat roofs. Therefore, a correction factor of 50 % is applied to calculate the PV potential with tilted modules considering the necessary row spacing to minimize mutual shading.

4 RESULTS AND VALIDATION

4.1 Results

The simulation results are presented in the form of graphs illustrating the sunshine hours per day and for PV suitable roof areas. Figure 3 provide an exemplary case for a specific address that has existing PV installations. The simulation incorporates height values above sea level, therefore the elevation profile is taken into consideration, so shading effects of higher or lower standing buildings are respected.

The simulation covers the roofs with a 1 m x 1 m grid indicating how many hours per day the sun shines on each square. As expected, there is plenty of sun on south-facing roofs, eastern and western surfaces receive less irradiation while the ones to the north are shaded most of the day. The suitability plot assesses the results of the sunshine simulation based on the economic analysis. Squares with more than four hours of sun are set as suitable for PV (green), areas with less are set as not suitable for PV (red).

A comparison of the suitability results with the PV covered area on the satellite images shows a good match between simulation and reality, but in detail some areas stand out. The satellite image shows an even inclined north-east roof without shading elements, the simulation on the other hand returns shaded squares on the same surface (white marker). This effect occurs on roofs with a complex geometry where a simple approach by horizontal steps is inaccurate. Approx. 10 – 15 % of the roofs are affected with more or less extreme dimensions, therefore the results always have to be rechecked with satellite images to evaluate the accuracy.

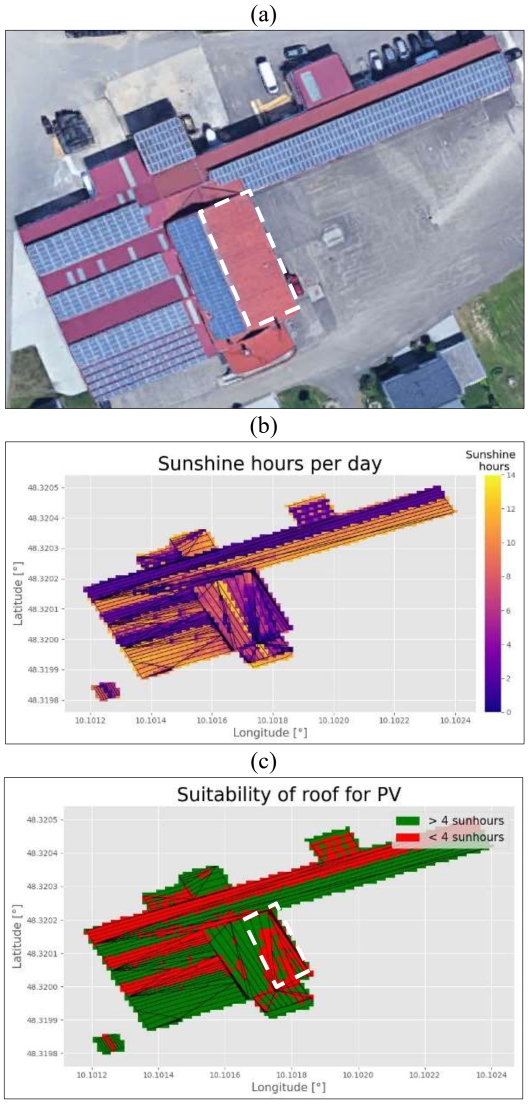
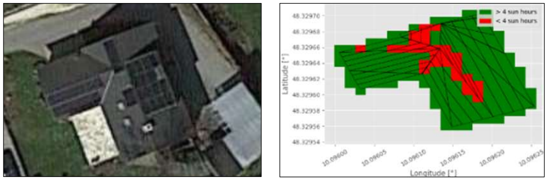
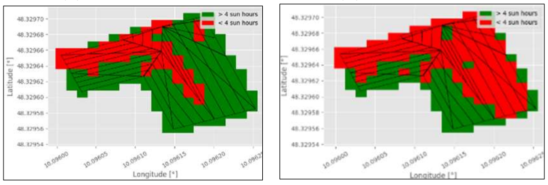


Figure 3: Simulation results: (a) satellite image for the selected address, (b) sunshine hours per day, (c) suitability of roof areas for PV

Figure 4 illustrates why an autumn day is chosen for the potential simulation. It shows the evolution of the sunshine duration during the year based on the equinoxe, as well as the longest (2023-06-21) and shortest (2023-12-22) day of the year. The 2023 satellite image shows a dormer to the east which is not included in the 2019 LiDAR data and therefore has no shading effect in the simulation. A comparison of the results indicates that north-facing roofs are ¾ of the year considered as shaded (except summer), while roofs to the east and west receive enough sun for ¾ of the year (except winter) to enable an economic PV operation. Roofs to the south, southwest and southeast even get the whole year enough sun to work economically. The autumn day covers all areas suitable for PV most of the year, so it is set as the base for the simulation.



(a) (b) 2023-06-21



(c) 2023-09-23 (d) 2023-12-22

Figure 4: Comparison of sunshine hours per day during the seasons: (a) satellite image for the selected address, suitability of roof areas for PV for (b) summer, (c) autumn, (d) winter

4.2 Error quote of the simulation

The step-model fails at 0.5 % of the roof parts. Due to the small share, this error quote is not further considered in the overall simulation. If the simulation is done only for a few buildings, this problem has to be respected.

The simulation calculates the sunshine appearance for each square 45 times per day (15 min time interval). Considering all squares of a building, up to 2.5 % of the values cause an error. The effect on the results is not noticeable as an analysis has shown.

4.3 Validation

The reference data of the residential PV system registry include installed power, number of modules, main and secondary orientation as well as inclination and year of installation. The validation is difficult since the mapping of existing PV systems to partial roofs is problematic. When no latest satellite images are available, the positioning of the newest PV systems are unknown. The mapping based on the reference orientation and inclination can be done, but when an address has more roofs with similar orientation, inclination and size a clear allocation is not possible. Another point is that PV systems with one inverter covering different orientations hold no information about the share of power per roof part. Further problems are that the LiDAR data does not contain information about interfering elements such as windows or chimneys that reduce the suitable area and therefore the installable PV power. The already mentioned inaccuracy of the step-model can minimize the expected results. For these reasons, no generally conclusive validation is possible.

For three PV systems, the exact allocation plans with installed power, orientation, inclination and number of modules are available. This enables precise allocation to the corresponding partial roofs. Figure 5 shows the allocation plan matching the building of the satellite image shown in Figure 4. For the validation the left partial roof oriented to the south is chosen, since there are no interfering elements and it is totally covered with PV.

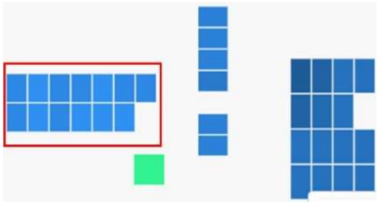


Figure 5: Allocation plan of address described on the left red: validated roof part

The deviation in the area ratio between the already installed PV area and the simulated area is 15 % to 25 %. This discrepancy is mainly due to the resolution of LiDAR data. Another reason are uncertainties in the 3D building model. An output comparison is not possible as the installed modules have a significantly lower power than the 430 Wp used in the simulation.

It is shown that if precise information is available, validation is possible.

5 CONCLUSION

This study aims to calculate the solar rooftop potential based on identified suitable areas using a sunshine simulation model. The model incorporates building geometries, sun azimuth, and altitude to estimate daily average sunlight hours, which are then economically evaluated using compensation rates for solar electricity fed into the grid. The analysis was conducted within a static economic framework, without consideration of the buildings electricity consumption.

Commercial tools such as [24], [25] can handle LiDAR data stored in an industry-standard binary format ("LAS") [26]. The LiDAR data used in this study were publicly available and therefore in a less detailed format, which comes with limitations in coordinate precision and resolution [27]. Due to the quality of the provided data and uncertainties in the 3D building model, the results should be considered indicative rather than definitive. The strength of this approach lies in its use of publicly available data for a preliminary potential estimation, in further steps commercial tools could be used for more precise results.

Despite these limitations, the study successfully identifies areas suitable for PV installations, as validated by comparisons with satellite imagery. The simulation estimates a solar rooftop potential of 6.1 MWp for the model village.

These results offer valuable insights for optimizing PV module placement, wiring plans, and facilitating grid development or further research. Moreover, the study illustrates that LiDAR data, combined with an open source Python program, can provide indicative yield potential estimates for solar rooftop installations.

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REFERENCES

[1] Europäischer Rat, Rat der Europäischen Union, “Ein europäischer Grüner Deal.” Accessed: Apr. 08, 2024. [Online]. Available: https://www.consilium.europa.eu/de/policies/green-deal/

[2] “EU-27: GHG emissions breakdown by sector,” Statista. Accessed: Sep. 12, 2024. [Online]. Available: https://www.statista.com/statistics/1325132/ghg-emissions-shares-sector-european-union-eu/

[3] Statistisches Bundesamt, “Europäischer Green Deal: Klimaneutralität bis 2050.” [Online]. Available: https://www.destatis.de/Europa/DE/Thema/GreenDeal/GreenDeal.html

[4] “Fraunhofer ISE: Stromgestehungskosten für große Photovoltaik-Anlagen auf bis zu 3,12 Cent pro Kilowattstunde gesunken,” pv magazine Deutschland. Accessed: Apr. 08, 2024. [Online]. Available: https://www.pv-magazine.de/2021/06/22/fraunhofer-ise-stromgestehungskosten-fuer-grosse-photovoltaik-anlagen-auf-bis-zu-312-cent-pro-kilowattstunde-gesunken/

[5] Ministerium für Umwelt and Klima und Energiewirtschaft Baden-Württemberg, “Praxisleitfaden zur Photovoltaik-Pflicht,” 2023, Accessed: Apr. 29, 2024. [Online]. Available: https://www.baden-wuerttemberg.de/de/service/presse/pressemitteilung/pid/praxisleitfaden-zu-photovoltaik-pflicht-veroeffentlicht-1

[6] M. Brito, S. Freitas, C. Catita, and P. Redweik, “Modelling solar potential in the urban environment: State-of-the-art review,” *Renew. Sustain. Energy Rev.*, vol. 41, Jan. 2015, doi: 10.1016/j.rser.2014.08.060.

[7] X. Huang, K. Hayashi, T. Matsumoto, L. Tao, Y. Huang, and Y. Tomino, “Estimation of Rooftop Solar Power Potential by Comparing Solar Radiation Data and Remote Sensing Data—A Case Study in Aichi, Japan,” *Remote Sens.*, vol. 14, no. 7, Art. no. 7, Jan. 2022, doi: 10.3390/rs14071742.

[8] A. Martínez-Rubio, F. Sanz-Adan, J. Santamaría-Peña, and A. Martínez, “Evaluating solar irradiance over facades in high building cities, based on LiDAR technology,” *Appl. Energy*, vol. 183, pp. 133–147, Dec. 2016, doi: 10.1016/j.apenergy.2016.08.163.

[9] R. C. Omar, W. A. Wahab, R. F. Putri, R. Roslan, and I. N. Z. Baharuddin, “Solar suitability map for office buildings using integration of remote sensing and Geographical Information System (GIS),” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 451, no. 1, p. 012032, Mar. 2020, doi: 10.1088/1755-1315/451/1/012032.

[10] M. Horváth, D. Kassai-Szoó, and T. Csoknyai, “Solar energy potential of roofs on urban level based on building typology,” *Energy Build.*, vol. 111, pp. 278–289, Jan. 2016, doi: 10.1016/j.enbuild.2015.11.031.

[11] A. Al-Quraan *et al.*, “A New Configuration of Roof Photovoltaic System for Limited Area Applications—A Case Study in KSA,” *Buildings*, vol. 12, no. 2, Art. no. 2, Feb. 2022, doi: 10.3390/buildings12020092.

[12] Bayerische Vermessungsverwaltung, “3D-Gebäudemodelle (LoD2).” Accessed: Sep. 12, 2024. [Online]. Available: https://geodaten.bayern.de/opengeodata/OpenDataDetail.html?pn=lod2

[13] J. A. Jakubiec and C. F. Reinhart, “A method for predicting city-wide electricity gains from photovoltaic panels based on LiDAR and GIS data combined with hourly Daysim simulations,” *Sol. Energy*, vol. 93, pp. 127–143, Jul. 2013, doi: 10.1016/j.solener.2013.03.022.

[14] C. Catita, P. Redweik, J. Pereira, and M. C. Brito, “Extending solar potential analysis in buildings to vertical facades,” *Comput. Geosci.*, vol. 66, pp. 1–12, May 2014, doi: 10.1016/j.cageo.2014.01.002.

[15] “Geofabrik Download Server.” Accessed: Sep. 12, 2024. [Online]. Available: https://download.geofabrik.de/

[16] “Startseite | MaStR.” Accessed: Sep. 12, 2024. [Online]. Available: https://www.marktstammdatenregister.de/MaStR

[17] SunPower GmbH, “Hocheffiziente Solarmodule | Maxeon | SunPower Germany.” Accessed: Sep. 12, 2024. [Online]. Available: https://sunpower.maxeon.com/de/solarmodul-produkte/maxeon-solarmodule

[18] “Was kostet eine PV-Anlage? Wie arbeitet sie wirtschaftlich?,” Photovoltaik-Anbieter für Module und Speicher | Solarwatt. Accessed: Apr. 29, 2024. [Online]. Available: https://www.solarwatt.de/ratgeber/photovoltaik-kosten

[19] P. Lewicki, “Photovoltaik,” Umweltbundesamt. Accessed: Apr. 29, 2024. [Online]. Available: https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/photovoltaik

[20] Deutsche Wetterdienst (DWD),“Sonnenscheindauer: vieljährige Mittelwerte 1981 - 2010.” Accessed: Sep. 12, 2024. [Online]. Available: https://www.dwd.de/DE/leistungen/klimadatendeutschland/mittelwerte/sonne_8110_fest_html.html?view=nasPublication&nn=16102

[21] “Wetter und Klima - Deutscher Wetterdienst - Leistungen - Die Entwicklung der Globalstrahlung (1983 - 2020).” Accessed: Sep. 12, 2024. [Online]. Available: https://www.dwd.de/DE/leistungen/solarenergie/download_dekadenbericht.html

[22] “Wetter und Klima - Deutscher Wetterdienst - Leistungen - Download.” Accessed: Sep. 12, 2024. [Online]. Available: https://www.dwd.de/DE/leistungen/klimadatendeutschland/mittelwerte/sonne_8110_fest_html.html

[23] A. A. Bayod-Rújula, A. Ortego-Bielsa, and A. Martínez-Gracia, “Photovoltaics on flat roofs: Energy considerations,” *Energy*, vol. 36, no. 4, pp. 1996–2010, Apr. 2011, doi: 10.1016/j.energy.2010.04.024.

[24] “Use lidar in ArcGIS Pro,” ArcGIS Pro | Documentation. Accessed: Sep. 23, 2024. [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/help/data/las-dataset/use-lidar-in-arcgis-pro.htm

[25] “Lidar in GRASS GIS – Brendan Harmon.” Accessed: Sep. 23, 2024. [Online]. Available: https://baharmon.github.io/lidar-in-grass

[26] “What is a LAS dataset?,” ArcMap | Documentation. Accessed: Sep. 23, 2024. [Online]. Available: https://desktop.arcgis.com/en/arcmap/latest/manage-data/las-dataset/what-is-a-las-dataset-.htm

[27] “Geoprocessing considerations for shapefile output,” ArcGIS Pro | Documentation. Accessed: Sep. 23, 2024. [Online]. Available: https://pro.arcgis.com/en/pro-app/latest/tool-reference/appendices/geoprocessing-considerations-for-shapefile-output.htm