Rethinking PV generation capacities

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Abstract

Photovoltaic (PV) systems are key to energy sector decarbonization. However, the popular southward orientation poses challenges for low-voltage grids, leading to midday overproduction and stability issues due to increasing PV penetration. This study investigates alternative PV orientation strategies to mitigate midday peak generation. Using metadata from Germany's *Marktstammdatenregister* and simulated yield data retrieved via the Global Solar Atlas API, the expected hourly production profiles of reference PV systems with various azimuth and tilt angles are analyzed. The GSA-based estimates are validated against four years of high-resolution empirical PV generation data from Utrecht, The Netherlands. The comparison reveals systematic deviations consistent with eastward-oriented roof alignments and confirms the robustness of GSA estimations for comparative analyses. To revalidate the approach, we provide the underlying analysis framework as an open-source solution.

Keywords: renewable energy production, generation capacity, PV orientation, open-source, simulation

1. Introduction and State of the Art

In pursuit of the Paris Agreement and to reduce carbon emissions, a qualified majority of countries commit to expanding their renewable energy production to cover a substantial share of their electricity demand. Photovoltaic (PV) systems play a central role in the ongoing global energy transition due to their high scalability, ease of transportation, distribution, and installation. In contrast to large-scale hydropower plants or other centralized power plants, PV installations generally require minimal construction permits or environmental impact assessments and can be deployed across a wide range of available open spaces, including roofs and vertical building walls. Their rapid scalability and continuously declining costs – driven by sustained research efforts, public funding initiatives, and the expansion of large-scale manufacturing capacities – have accelerated their global adoption. According to [1], global solar PV capacity is expected to reach an installed accumulated rated capacity of approximately $7.1\ TW$ by 2030.

While these numbers are an important step towards supporting the Paris Agreement, the (slow) expansion of the electrical grid remains the bottleneck towards reaching these goals. It is the grid operators' responsibility to maintain the security of supply and power quality at all times. Currently, regulatory standards often mandate that grid connections must be upheld under worst-case scenarios (e.g., taking the maximum possible production at the lowest possible local demand), resulting in straightforward calculations in terms of handling. Therefore, the maximum peak power of the inverter is considered the worst-case scenario, where full-feed-in PV systems are assumed with the simultaneity factor of 1.0 in normal operation [2].

Recent research efforts, such as displayed in [3], have increasingly focused on optimization strategies aimed at maximizing the yearly energy yield of PV installations through improved system design, orientation, and spatial configuration and energy storage solutions to mitigate the PV surplus grid feed-in. The ideal PV orientation and tilt angle for maximizing daily energy yield, assuming negligible shading effects, can therefore be expressed analytically as a function depending solely on the geographical latitude of the installation site. According to established engineering practices, PV systems are usually oriented southward in the Northern Hemisphere and northward in the Southern Hemisphere. The optimal tilt angle β can be described as follows

$$\beta \approx 0.76 * \varphi + 3.1° \qquad \text{(eq. 1)}$$

with φ denoting the geographical latitude.

10.18086/swc.2025.04.39 Available at http://proceedings.ises.org

Note that the linear and constant correction term are applied to the theoretical tilt angle derived from latitude. Lower solar elevations during winter months result in increased atmospheric attenuation, leading to a relatively stronger reduction in irradiance at shallow angles. Moreover, the diffuse component of solar radiation is less sensitive to surface tilt, as a portion of the irradiance is isotropic. Both effects cause the annual optimum tilt angle to be slightly steeper than the latitude itself, allowing the PV modules to capture the low-lying winter sun more effectively.

To further increase daily and seasonal PV yield, PV systems can be mounted on mechanical tracking structures that adjust the panel orientation throughout the day to continuously face the sun, thereby increasing the overall energy yield. However, these systems are significantly larger, require more space, and incur higher costs and maintenance demands. In practice, the potential gains are often within a tolerable range even if tracking is not implemented.

The large-scale expansion of PV systems, driven by declining costs that are becoming increasingly attractive to private households and by government incentives, is creating growing challenges in many regions due to excess energy fed into low-voltage power grid, which can threaten grid stability to an extent that distribution system operators reserve the right to curtail the feed-in if necessary. While such measures are technically justified, they directly contradict the very purpose of installing PV systems for private households and small-scale stakeholders, resulting in unused or “wasted” potential.

To address these shortcomings, and also because feed-in tariffs are increasingly declining due to oversupply, politics have begun integrating regulatory incentives that promote alternative installation geometries. As one mitigation strategy, Switzerland offers single-payment incentives for new PV installations with tilt angles of 75° or greater [4], which consequently led to an increase of façade-integrated systems. These systems provide more balanced energy production throughout the day, with a less pronounced peak amplitude and a smoother generation profile, which helps mitigate the issue of midday peak generation.

The conventionally applied guideline – that maximum profit is achieved through optimal panel orientation – is increasingly being replaced by the consideration that a central aspect of the energy transition is that profit can only be realized when energy is consumed or stored in local proximity to avoid grid fees. In this context, aligning the orientation and tilt angle of PV systems with the power load profiles of buildings becomes particularly meaningful, especially since PV installations are often located on or near buildings.

This work, therefore, examines the potential of alternative PV panel orientations to enable power grid-conducive operation and proposes a set of recommendations to align PV system production profiles as closely as possible to actual energy demand.

2. Simulation Approach

In Germany, the Market Master Data Register (*Marktstammdatenregister*, MaStR) [5] provides a nationwide database of all installed PV systems and their metadata including geographical location, site category, size, number of modules, total DC power (kWp), inverter power (in kW), nominal net power (automatically calculated), inverter power limitation, type of building use (residential or commercial), as well as the orientation, azimuth and tilt angle. Even though, for privacy reasons, installations below $30\ kWp$ do not include location information beyond the postal code in the publicly accessible dataset, MaStR provides a highly informative dataset for assessing PV performance in Germany.

However, the MaStR does not provide historical production or consumption data; therefore, simulated values from external sources, such as the Global Solar Atlas (GSA) [6], must be used instead. GSA is a map-based platform that provides high-resolution simulated solar resource data, as expected PV yield, and analytical tools for assessing solar power potential on a global scale. GSA provides an API to retrieve expected hourly PV yield per day for a definable PV system configuration, parameterized by system type, rated capacity (in kWp), orientation (azimuth and tilt), and the geographic coordinates of the chosen location.

As a database for Europe, the GSA utilizes historical weather data covering the period from 1994 to 2024 from Solargis [7]. While the Solargis database maintains solar radiation and temperature records at sub-hourly resolution, data retrieved through the Global Solar Atlas (GSA) API are available only as hourly mean values. To accurately simulate photovoltaic system performance across different regions, the underlying modeling framework is structured as follows:

The Solar radiation model is based on data from geostationary meteorological satellites and global meteorological models. It computes clear-sky irradiance to accurately determine the sun's position in an hourly resolution. Cloud cover effects are incorporated using a cloud index that attenuates radiation values according to satellite-derived cloud information. In a post-processing step, the model corrects global horizontal irradiance (GHI) by separating it into direct and diffuse components and adjusting for terrain-induced shading. GSA accounts for atmospheric parameters, such as wind speed, humidity, and ambient temperature, which influence the PV module temperature and, consequently, the PV power yield. The PV power simulation incorporates effects of module tilt, orientation, terrain shading, and DC-AC conversion losses using the Sandia Inverter Model.

For this study, the *"small residential rooftop PV"* configuration available within the GSA API is selected[1]. This configuration accounts for reduced natural ventilation, resulting in higher module operating temperatures, as well as increased soiling losses due to limited accessibility for cleaning and non-optimal mounting geometries. The dataset retrieved from the GSA API includes detailed system configuration parameters and multiple generation information, monthly averaged hourly PV output values (in Wh), which were used as the simulated benchmark dataset.

The combination of the MaStR dataset and the GSA enables the estimation of expected hourly PV generation potential across all German-registered PV systems. The GSA implements several simplifications, such as representing cloud cover with a basic cloud index and relying on historical data from selected meteorological stations, which may not perfectly reflect actual consumption or generation patterns. In the subsequent section, the simulated production data are therefore compared with real-world generation data to assess accuracy.

3. PV production curves

The GSA provides a solid basis for comparing expected hourly PV production for each calendar month and for assessing the impact of panel orientation. Figure 1 shows the simulated year-round generation curves profiles of a 1 kWp-PV system for various combinations of azimuth and tilt angles for a PV installation in Bielefeld-Sennestadt, with all references to time and time of day given in Coordinated Universal Time (UTC).

The plots of Figure 1 illustrate the significant effect of the azimuth angle on the estimated PV generation profile. Systems oriented toward the east or west exhibit generation patterns that deviate from the typical single midday peak observed in south-facing systems. East-facing systems reach their peak yield in the morning (around 9 to 10 a.m.), whereas west-facing systems peak in the afternoon (around 2 to 3 p.m.). This difference naturally arises from solar irradiance, which varies throughout the day and impacts PV panels differently depending on the time and orientation.

Increasing the tilt angle amplifies this effect: on more steeply inclined panels (greater than 40°), the generation curves become narrower and more pronounced, further highlighting the time-shifted peaks for east- and west-facing orientations. In contrast, north-facing systems exhibit much flatter generation curves. In the Northern Hemisphere, north-facing modules receive primarily diffuse rather than direct sunlight, resulting in substantially lower total energy yields compared to south-facing configurations. While this orientation produces a more uniform distribution of generation throughout the day, it certainly leads to a significant reduction in annual energy yield. It should be noted that no positive effect can be expected for orientations steeper than optimal. With a suboptimal tilt angle, the energy yield is always reduced, and therefore, it cannot produce a more consistent or more favorably shaped generation profile with regard to its conduciveness to the power grid.

[1] Note that, due to the large size of the dataset, direct client-size querying of the MaStR is impractical. Therefore, data access is implemented via a backend interface using FastAPI. In this configuration, the client application sends a raw SQL query string that is URL-encoded and embedded within a request URL. The backend processes the request and returns the query results as a JSON object containing the column header and corresponding data rows from the database.

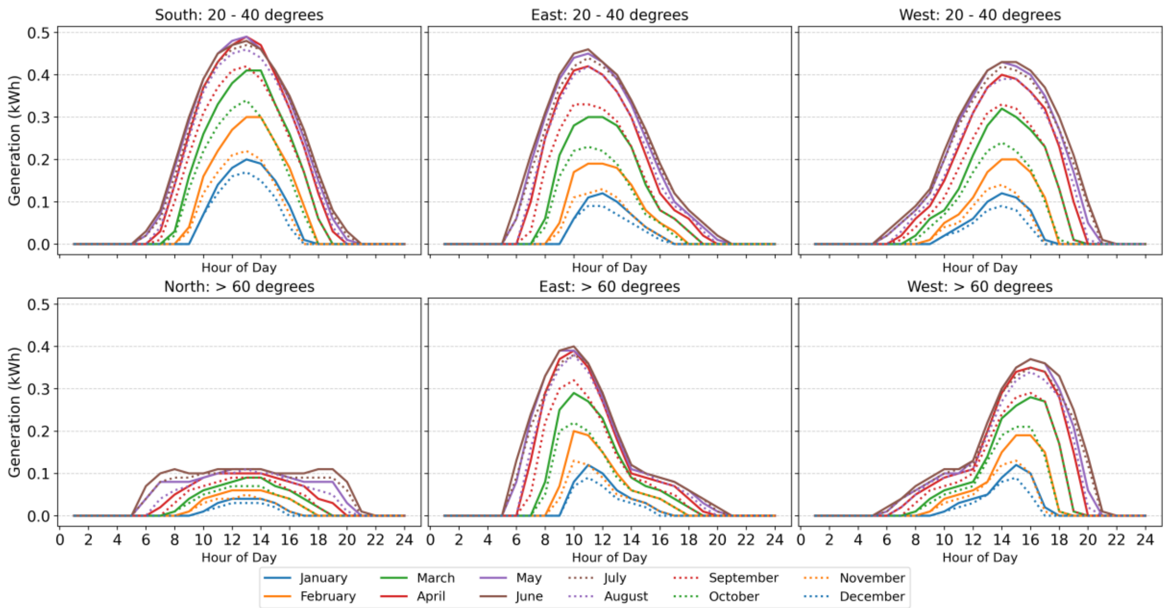

Figure 1: Comparison of average yield depending on selected angles and tilts for a 1 kWp-PV installation at Bielefeld-Sennestadt

To date, there are no widespread open data repositories that provide access to historical generation data of sufficient quality and variability for German PV installations. Instead, historical generation records from Utrecht, The Netherlands, available under [8], are used in the following analysis. Utrecht is located at nearly the same latitude as Bielefeld-Sennestadt, thus experiencing similar solar irradiance, and has a very similar composition of installed PV systems, as shown in Table 1. The values for the optimal tilt β for south-facing PV systems, according to Formula 1, are also displayed in the table, making the similarity between the examples evident. For both cities, systems are predominantly oriented southward, with a minor share of systems facing east and west, supporting the justification as a representative proxy for the study area Bielefeld. The Utrecht dataset contains four years of 1-minute resolution power generation measurements from 175 rooftop-mounted residential PV systems. Neglecting the influence of local weather conditions, PV systems with identical technical characteristics at both locations would be expected to exhibit similar generation profiles.

Table 1: Azimuth distribution of PV systems in Bielefeld-Sennestadt and the open-source data from Utrecht

City & data	**Bielefeld Sennestadt (MaStR)**		**Utrecht (open-source dataset)**	
Optimal tilt β	**42.62°**		**42.696°**	
Azimuth	# of installations	percentual share	# of installations	percentual share
South	186	76%	137	78%
East	22	9%	16	9%
West	37	15%	22	13%
North	-	0%	-	0%
Total	245	100%	175	100%

4. Results

To assess the reliability and informative value of the GSA estimates, they are compared with the Utrecht dataset. For this purpose, the system configuration metadata provided with the Utrecht dataset serves as input parameters for the GSA API (as implemented in the corresponding Python script available in the repository).

Since the GSA provides data in the form of monthly mean daily generation profiles with an hourly resolution, the high-resolution measurement data from Utrecht is transformed into the same format. Thus, monthly averages are computed for each hour of the day, resulting in mean daily generation curves with hourly granularity equivalent to those retrievable from the GSA. Although the Utrecht dataset covers a four-year time period, not all PV systems recorded data continuously throughout this timespan. Consequently, the monthly averages are based on varying time intervals and the number of data points. The interested reader is referred to the associated GitHub repository for details.

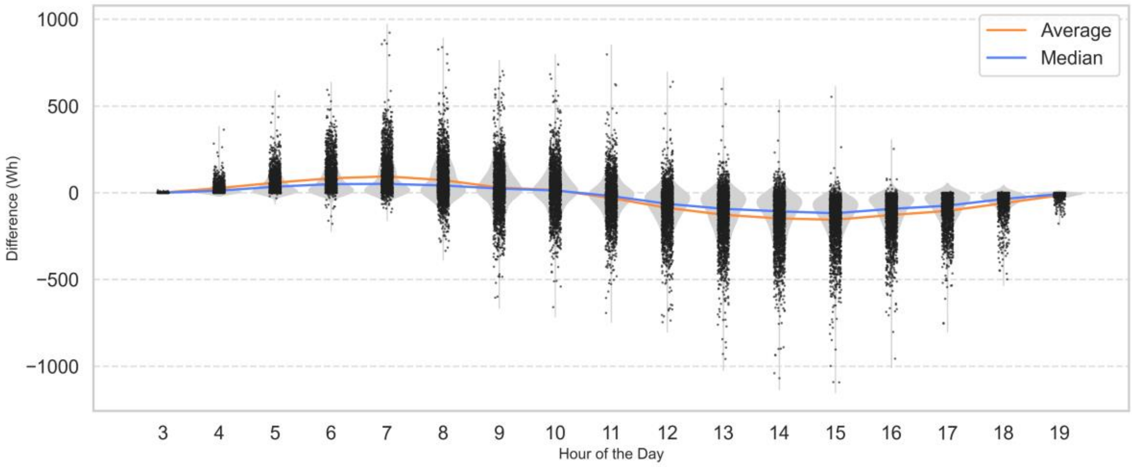

Figure 2: Hourly deviation between historical production data and GSA estimation data

To provide a comparison that considers all 175 PV systems included in the Utrecht dataset, Figure 2 illustrates the aggregated monthly generation profiles of both datasets over a daily timespan. The comparison reveals a systematic deviation when analyzing the deviation between the curves: When computing the difference for each of the 175 installed PV systems as

$$\mathbf{\Delta} = \frac{\sum_{k=1}^{60} \text{Utrecht}}{60} - \text{GSA} \qquad \text{(eq. 2)}$$

and focusing on the median and average generation curves, the resulting deviation appears approximately symmetrical around midday, showing a positive deviation in the morning hours and a negative deviation in the afternoon. The causes of the observed deviations cannot be clearly determined based on the available data. Within the existing Utrecht dataset, the accuracy and granularity of the orientation and tilt angle information cannot be verified. Likewise, there is no information available on the installed inverters, their efficiency curves, or potential temporal shading effects.

The sinusoidal pattern of deviation over the course of the day indicates that the production expectations are exceeded before noon and underachieved afterwards. This suggests that several systems are likely oriented more eastward than reported by the dataset. This assumption is further supported by the fact that the spread of measured values is larger in the upper range during the morning and in the lower range during the afternoon. An aerial view of Utrecht also reveals that the city's building layout is rotated several degrees east of south, implying that many roof surfaces and rooftop PV systems are not perfectly south-facing but instead oriented a few degrees toward the east.

Furthermore, the analysis of seasonal differences is conducted using the mean system capacity of $2.28\ kWp$ from the Utrecht dataset as a reference for comparison with the GSA estimates. This reference system is again used as input for the GSA API to retrieve the corresponding estimation curve. Subfigure 3a displays the resulting mean system generation retrieved from the GSA API, whereas Subfigure 3b depicts the mean transformed generation curves derived from the Utrecht dataset.

To address the fundamental issue of excess PV feed-in, the Utrecht dataset is adjusted by assuming a PV orientation that primarily avoids short periods of high generation and better aligns with typical building consumption profiles. For this purpose, it is assumed that half of the installed modules in Utrecht are oriented toward the east and the other half toward the west, each tilted at 45°. The potential of this hypothetical configuration is then evaluated again via a corresponding request to the GSA API. The difference in hourly generation per month between a purely south-facing orientation and a mixed east-west orientation is illustrated in the first row of Figure 4.

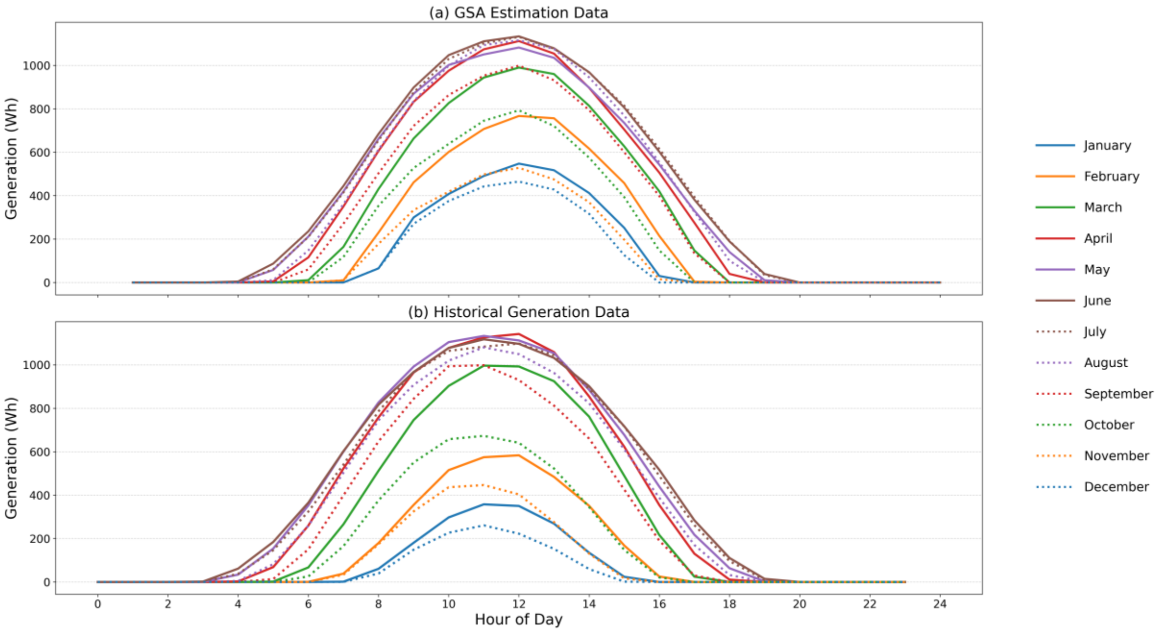

Figure 3: Monthly average generation profiles of the reference PV system in GSA estimation and historical generation data over the course of a year

A particularly notable feature of this configuration is that, especially during the winter months, the PV yield exhibits a very consistent daily pattern when averaged over the days of the month. Moreover, the fraction of the day during where more than 50% of the expected daily peak power per month is achieved is significantly higher. Consequently, this configuration also shortens the periods of the day during which the production output changes rapidly, thus supporting grid operators, who are increasingly challenged by steep rising or falling load gradients at the distribution substation level. The main drawback of this orientation, however, is that the yield peak during midday hours is approximately 63% lower than that of a pure south-facing configuration in winter months, and about 30% lower during summer months. Table 2 illustrates that the east-west alignment results in annual energy losses of slightly more than 25% compared to the optimal south-facing configuration.

From a grid operation standpoint, these findings motivate the idea of expanding the east-west configuration to a level where its peak feed-in capacity approximately matches that of the exclusively south-facing installation. As illustrated in the lower left subfigure, this strategy enables a roughly 50% increase in the installed PV surface area. This also results in an increase of about 11% in the total annual energy yield, yet coming with an increased installation cost for the additional modules necessary.

Figure 4 (lower right) shows the resulting subplot derived from the analysis comparing the exclusively south-facing setup and the scaled east-west configuration. As expected, it is particularly evident for the summer months that the yield increases during the morning and evening hours, and that the expected daily production period is significantly extended depending on the month. Noticeable reductions in production are confined to the winter months, during which the east-west configuration fails to provide any advantage over the purely south-facing orientation.

In summary, it can be concluded that, on an annual average, the east-west configuration produces a more favorable generation profile, albeit at the expense of increased material requirements and investment costs. Nonetheless, the more decisive aspect lies in the expected daily profile per month, which clearly shows that, particularly in December and January, and even with 1.5 times the installed PV area, the hourly production values consistently remain below those of the south-facing configuration. A general recommendation regarding the PV orientation and assessment of the practical potential of the east-west configuration, therefore, requires consideration of both the seasonal and daily load profile of connected consumers.

The influence of the alternative east-west orientation depends on latitude in two major aspects. Assuming the optimal tilt angle, east-west configurations capture more solar radiation during the summer months in the northern hemisphere, resulting in higher energy production. As the optimal tilt angles for east- and west-facing modules diverge significantly at higher latitudes, the typically single-peaked daily production curve evolves into one featuring two distinct maxima. For installations located closer to the equator, the absolute difference between the optimal tilt angles of the two orientations becomes smaller. Consequently, the expected daily generation profile resembles a broader version of that of a purely south-facing configuration.

Table 2: System configuration with annual comparison

System Configuration	Annual PV yield (in kWh)	Relative Difference
GSA Mean System	78414.2	-
East-West System	58030.7	-25.99%
East-West System Scaled	87045.94	$+11\%$

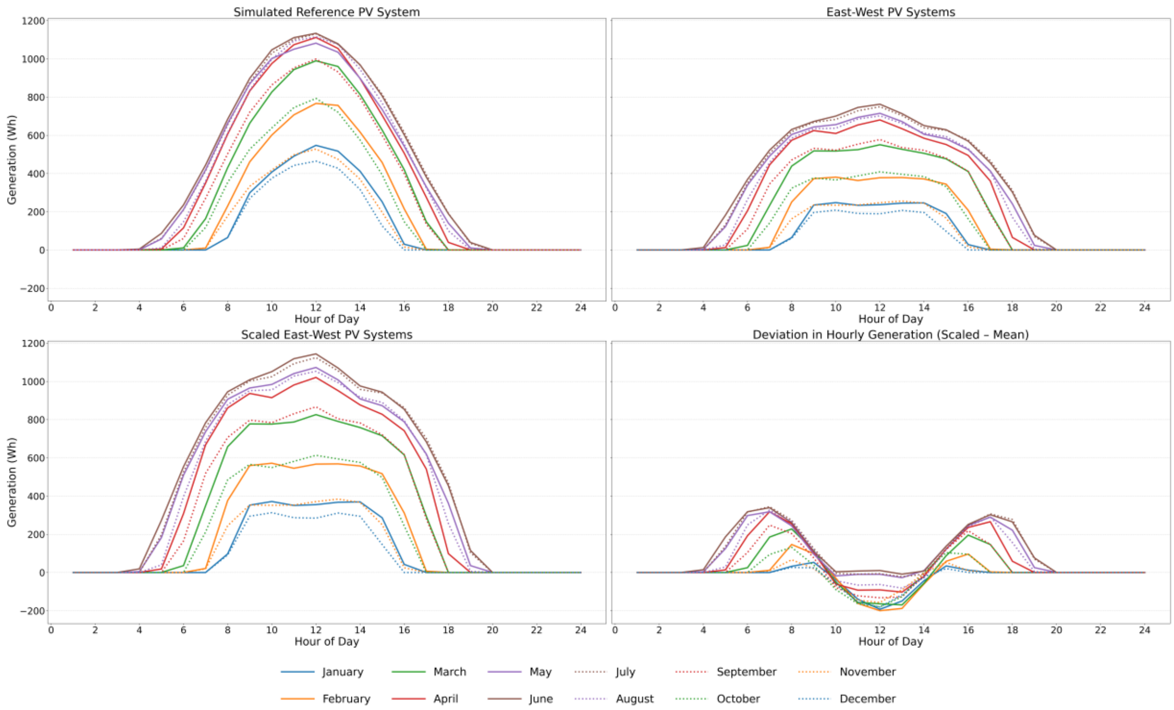

Figure 4: Monthly comparison of PV generation of reference vs. east-west systems

The advantage of the east-west orientation becomes particularly evident when considering the expected production above a given power threshold relative to the peak power production of a uniquely south-oriented system. As illustrated in Figure 5, the east-west configuration achieves one to three hours more per day above 80% of the daily peak production of the respective month, especially during the summer months. This effect is primarily due to the 1.5-times larger effective installation area associated with the east-west setup. Furthermore, across all months of the year, the expected number of hours during which at least 50% or 65% of the peak power is reached is consistently higher for the east-west orientation compared to the uniquely south-facing configuration. Figure 5 illustrates that the temporal broadening of the production profile is not limited to periods of negligible PV generation but instead results in a longer daily duration of significant power output throughout the entire year.

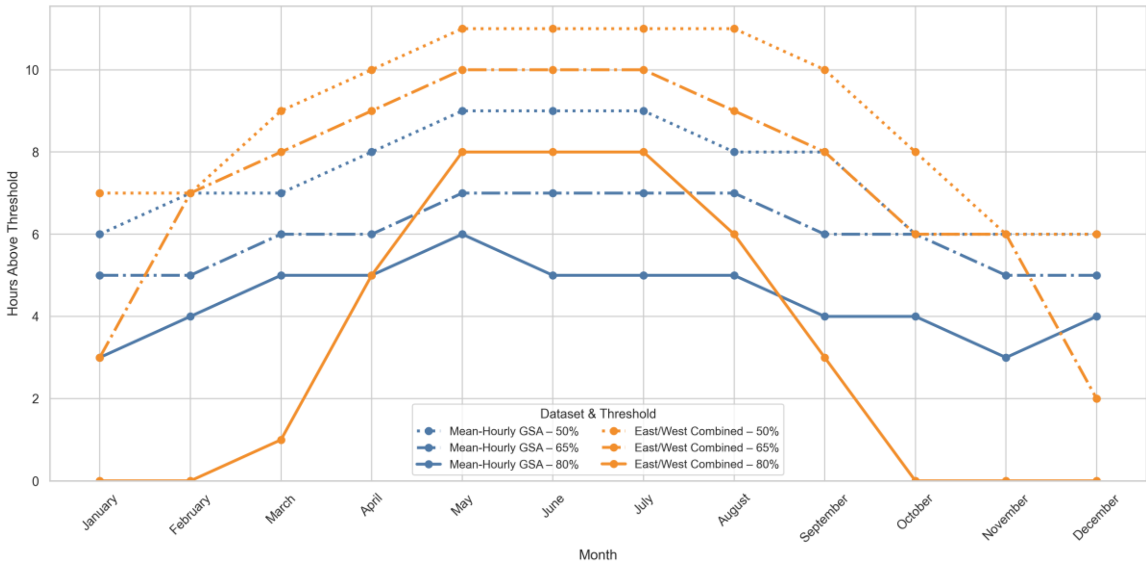

Figure 5: Duration of PV generation above monthly peak production (50-80%)

5. Conclusion

The orientation and tilt angle of the installed PV systems in Bielefeld-Sennestadt and Utrecht provide no indication that the installation configurations were selected with regard to grid support or production curve optimization. It is more plausible to assume that deviations from the optimal orientation angle are due to structural or architectural constraints, such as the slope of rooftops or garages. Similarly, for the azimuth orientation, it can be assumed that factors such as the availability of unshaded surfaces, land-use restrictions, or building and rooftop alignment were the decisive reasons for these installation configurations.

In fact, the growing issue of PV overproduction and the resulting overload of local distribution transformers is gaining the focus of responsible parties affected. Countermeasures towards that are also relatively recent and have been promoted primarily through political incentives, as exemplified by recent initiatives in Switzerland [4]. Nevertheless, the high level of PV expansion has begun to constrain further approvals for PV system installations due to local overproduction issues. Current regulatory frameworks often consider only the peak feed-in power when granting approval, while neglecting parameters such as orientation and tilt angle – which, as demonstrated in this study, could contribute to more grid-friendly generation profiles.

This work analyzes the simulated power output for various orientations (East, South, West) and tilt angles of a $1\ kWp$-PV system over a one-year time horizon using hourly average monthly production estimations (Figure 1). These simulations are based on data retrieved from the GSA API and the configuration set of the open-source PV installation data of Utrecht.

The results confirm that a south-oriented system exhibits a single pronounced midday peak, which leads to excess production. This surplus often exceeds local demand and grid capacity, causing curtailment imposed by grid operators. The production distribution displayed in Figure 1 suggests that East-West configurations help reduce midday peak generation and contribute to a more balanced daily generation profile, aligning better with typical energy consumption profiles.

After comparison of the modeled PV configuration archetypes with the actual installation data from MaStR for Bielefeld-Sennestadt, it is evident that the potential of alternative orientations is not yet fully exploited. Most installations remain strongly biased toward south-facing alignments with standard tilts around 35° (due to rooftop tilts and similar), limiting the potential of optimization of daily power distribution.

6. Outlook

The findings of this study underline the importance of integrating PV orientation and tilt angle optimization into future regulatory and planning frameworks for distributed renewable generation. While conventional design guidelines still prioritize the maximization of annual yield, upcoming research and policy efforts should increasingly emphasize grid-conducive PV configurations that harmonize production with local demand profiles. Several directions for future research emerge from the findings of this study:

The transition toward a demand-oriented PV-based power system dimensioning requires rethinking the conventional “maximize yield” paradigm. The alignment of simulated PV generation profiles, and thus both orientation and tilt, with real-world household and commercial load curves would enable grid-relief effects and facilitate the on-site consumption of locally generated PV power. However, the optimal PV orientation is not determined solely by local load profiles, but also by the distribution grid's structure, the location of the grid connection, and the interaction with other generation assets. Accordingly, system design and sizing should be carried out based on simulations that incorporate local grid conditions.

This study did not explore the integration or use of battery energy storage, detailed economic feasibility analyses, complementary grid-supportive measures such as intelligent curtailment and load flexibility management, which are reserved for future investigations. However, the inclusion of relatively easily accessible basic information shall come into focus to adapt existing grid-connection procedures or even provide incentives for alternative azimuth and tilt usage, which could further promote grid-conducive PV generation and, in turn, the advancement of PV expansion in the grid, without requiring additional technical solutions or requirements.

7. Data and Code Availability

The code repository is available under the Apache 2.0 license in [9].

8. Acknowledgement

The presented "Sunny4Urban" project results are funded by the Federal Ministry Innovation, Mobility and Infrastructure Republic of Austria, carried out under the program “Digitale Technologien 2023”.

9. References

[1] SolarPower Europe. Global Market Outlook for Solar Power 2025-2029, 2025. Belgium.

[2] A. Sillaber. Leitfaden zur Verteilnetzplanung und Systemgestaltung [Guide to distribution network planning and system design]. 2016. Germany. doi: 10.1007/978-3-658-14713-6

[3] M. Arskan, M. Cunkas. 2024. An experimental study on determination of optimal tilt and orientation angles in photovoltaic systems. Journal of Engineering Research. doi: 10.1016/j.jer.2024.07.015.

[4] Swiss Federal Office of Energy SFOE, Legal Fact sheet for subsidies of PV installations (in German), Version from 07.02.2025 with ID: 7238 | 216. Last accessed: 2025-10-21. www.bfe.admin.ch/bfe/en/home/promotion/renewable-energy/promotion-photovoltaic-systems.html

[5] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen. Marktstammdatenregister. 2019. Accessed: 2025-10-21. www.marktstammdatenregister.de/MaStR

[6] Data obtained from the “Global Solar Atlas 2.0”, a web-based application developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). Last accessed: 2025-10-21. www.globalsolaratlas.info

[7] Solar resource map ©, Solargis. 2021. Last accessed: 2025-10-21. www.solargis.com

[8] L. Visser, B. Elsinga, T. AlSkaif, and W. van Sark. “Open-source quality control routine and multi-year power generation data of 175 PV systems”. Journal of Renewable and Sustainable Energy, vol. 14, no. 4. Zenodo. 2022. doi: 10.5281/zenodo.10953360

[9] Energy&IT Group, Rethinking PV Generation Capacities, Github. 2025. Last accessed: 2025-10-29 https://github.com/energyitgroup/rethinking-pv-generation-capacities