AgriVoltaics World Conference 2024
Best Practices
https://doi.org/10.52825/agripv.v3i.1400

Published: 27 Mar. 2025

Integral Design of an Agrivoltaics Research System in Northern Minas Gerais, Brazil

Frederik Schönberger[1,*], Ana Valentina Puentes[1], David Jung[1], and Polyanna Mara de Oliveira[2]

[1]Fraunhofer Chile Research, Chile

[2]Agricultural Research Company of Minas Gerais (EPAMIG), Brazil

*Correspondence: Frederik Schönberger, frederik.schonberger@fraunhofer.cl

Abstract. This study aims to derive conceptual agrivoltaic (AV) designs for the first AV research pilot in Minas Gerais Brazil by applying a Key Performance Indicator (KPI) based evaluation method. A selected AV design is assessed regarding its shading characteristics in various scenarios using raytracing algorithms in Python based on the Solstice software. The proposed Elevated AV system demonstrates the best performance respecting the project specific objectives. For the respective design we vary row distances in three scenarios, enabling regression analysis to relate the annual average shading rate to the row pitch. The analysis reveals that for a 30% shading rate, a 3.2 m row distance is required, which is finally recommended to respect the rather sun-loving crop types. Through a border effect analysis, we conclude the necessity of implementing a total AV pilot area of approximately 700 m² to conduct agricultural experiments on 300 m² without edge effects. In general, we highlight the importance of precise AV system design for optimizing agricultural and photovoltaic (PV) performance.

Keywords: Agrivoltaics, Conceptual Design, Shading Simulation

1. Introduction

Minas Gerais, the fourth largest Brazilian state in terms of territorial extension, is experiencing rapid growth of utility-scale photovoltaics (PV) while inhabiting a miscellaneous and thriving agriculture characterized by a diverse mix of small to big-scale producers [1]. The semi-arid region of the state is characterized by climatical change with periods of long droughts and high temperatures, creating dependency on irrigation for agricultural [2].

Minas Gerais is distinguished as the Brazilian state with the highest solar capacity in centralized PV power generation with 4.29 GW and is ranked second in distributed generation, with a total capacity of 3.8 GW [3]. The northern region of Minas Gerais provides excellent conditions for PV generation due to its abundant solar irradiance levels most of the year and vast land resources. Furthermore, the region holds considerable importance in terms of agricultural production, particularly in the irrigated perimeters of Jaíba, Gorutuba, and Pirapora. However, the expansion of centralized PV may lead to conflicts over land utilization as respective systems occupy large areas traditionally designated for agriculture, potentially resulting in socio-economic implications.

Considering the projected challenges in Minas Gerais, agrivoltaics (AV) represents a concept capable to adapt agriculture to climate change by combining farming and PV electricity generation on the same land area within semi-arid climates [4]. Under respective concept, PV electricity generation might be further expanded with significantly lower surface area demand due to its double use character.

In this context, the Agricultural Research Company of Minas Gerais (EPAMIG), the Minas Gerais Energy Company (CEMIG) and the Minas Gerais State Agency for Research and Development (FAPEMIG) finance and implement a research project with the scientific support of Fraunhofer Chile Research and the Fraunhofer institute of Solar Energy Technologies (ISE) that seeks to investigate the feasibility of AV for the local agriculture of Northern and Central Minas Gerais. In the project three pilot systems at two locations are installed [5]. As one of the project's partial results, we present in this study the results of an integral design process for the first AV research facility in Minas Gerais, Brazil for a diverse mixture of tropical and temperate crops.

2. Methods and data

The present work develops AV system designs tailored to the project specific context and objectives. First, we derive three conceptual AV designs. Second, we select one conceptual design through quantitative Key Performance Indicators (KPI) relating their characteristics to the underlying research project objectives. Third, we simulate the light interception of the PV panels to derive the average annual shading rate with a raytracing simulation tool for different pitch distance scenarios. Finally, we perform a cubic 3rd degree polynomial regression for the row pitch as a function of the shading rate to determine the appropriate pitch for the predefined shading rate. Additionally, we simulate different receiver surfaces to understand how border effects influence the annual average shading rate.

2.1 Study context

The study area is in the experimental field of EPAMIG in Mocambinho, Brazil (Lat: -15.087836, Long: -44.015762) which is characterized by the highest Global Horizontal Irradiation (GHI) in the state, with an annual average of 2,143 kWh/m^2. The climate is classified as Hot semi-arid climate (BSh) according to Köppen-Geiger, with temperatures ranging from 17°C to 32°C and annual precipitation between 600 to 800 mm [6]. Agricultural activities are exclusively dependent on irrigation. From an agronomic side, a shadow rate of 40% is proposed to research crop response to shading. Four different crops are planned to be investigated in the AV system: strawberry, melon, pineapple, and beans. On the project site, a tractor is used with a height of 2.60 m and a harrow with a width of 2.90 m.

2.2 Key performance indicators

To compare the proposed conceptual designs, we develop the subsequently presented KPI.

2.2.1 Power density

The power density (PD) [kWp/ha] describes the PV power installed per surface area. Respective indicator we derive as indicated in Equation 1:

$$PD = \frac{P_{np} * GCR * 10}{A_m} \quad (1)$$

where P_{np} is the PV module nameplate power [Wp], A_m is the module surface [m^2] and GCR is the Ground Cover Ratio [%].

2.2.2 Ratio of usable agricultural area

The ratio of usable agricultural area (R_A) [%] is computed in line with the German DIN SPEC 91434 AV norm as [7]:

$$R_A = \frac{A_L}{A_N + A_L} \tag{2}$$

where A_L is the usable surface and A_N is the not usable surface area. We assume for Elevated AV and Vertical AV a security distance of 0.3 m from each pile that mounts the system in the ground and for Interrow AV with tracking 1 m from each pile to avoid PV module collisions.

2.2.3 Electricity generation simulation

We simulate hourly PV performance with functions provided by pvlib python [8]: We use Typical Meteorological Year (TMY) data to calculate total plane-of-array irradiance (POA) [W m^{-2}] and its direct, sky diffuse and reflected components [W m^{-2}], using the isotropic sky diffuse irradiance model for the defined location, azimuth, panel tilt and albedo of 23%. Further, we obtain effective irradiance by calculating the angle of incidence and incidence angle modifier using the ASHRAE transmission model [9]. We calculate cell temperature T_c [°C] using an empirical heat loss factor model as implemented in pvlib based on the Faiman equation [10]:

$$T_c = T_a + \frac{POA}{U_c + U_v * u_2} \tag{3}$$

where POA is the plane-of-array irradiance [W m^{-2}], U_c is the constant heat transfer component [W m^{-2} K^{-1}], U_v is the convective heat transfer component [W m^{-2} K^{-1} (m s^{-1})$^{-1}$] and u_2 is the wind speed [m s^{-1}]. Direct Current (DC) output is modeled with NREL's PVWatts DC power model. We consider a temperature coefficient of -0.0037 °C^{-1} [11]. Finally, we add the DC outputs of the system and use the PVWatts inverter model for a 1 kW inverter with a nominal inverter efficiency of 96.1% to obtain alternating current (AC) energy output and apply a loss factor of 16.7%, including standard soiling losses of 5%. Hourly values are summed up to yearly values equaling the potential specific generation of the AV system.

2.2.3 Rainwater harvest potential

The rainwater harvest potential (RWH) [m^3/ha/a] describes the amount of rainwater that may be collected over the PV panel surface. RWH is calculated as:

$$RWH = P\ (cos\ \alpha + l) * w * n \tag{4}$$

with precipitation P [mm/a], module inclination α [°], the module length l [m], the module width w [m] and n as the number of modules per ha.

2.3 Shadow simulation

For one selected conceptual design we execute shadow simulations based on a raytracing method to model incident irradiance on the surface beneath the PV panels. Initially, irradiance is modelled for the open surface without AV, then compared to the irradiance with the AV system in place generating shadow. The internally developed algorithm utilizes the Solstice software through the Solsticepy and pvlib Python libraries to determine solar positions based on latitude, longitude, time and perform the simulations [8][12].

We use as an input the previously selected 3D model of the AV system, and GHI [W/m²] as measured on the project site by the National Institute of Meteorology (INMET) [6]. We derive from GHI the Direct Normal Irradiance (DNI) [W/m²] and Diffuse Horizontal Irradiance (DHI) [W/m²] based on the Perez atmospheric model by applying INMET data for dew temperature and atmospheric pressure [13]. To accelerate computational time, we chose for each month a representative day as proposed by Duffie et. al (2013) [14]. The shadow rate (SR) [%] is calculated from the total irradiation under the PV panels GHI_{APV} and the reference GHI_{ref} as:

$$SR = 100 - \left(\frac{GHI_{APV}}{GHI_{ref}}\right) * 100 \tag{5}$$

The GHI under the AV system GHI_{APV} is derived as:

$$GHI_{APV} = DNI_{APV} + DHI_{APV} \tag{6}$$

with DNI_{APV} as modelled through raytracing and DHI_{APV} as the diffuse component which is estimated as a fraction of the Ground Cover Ratio (GCR) with:

$$DHI_{APV} = DHI * (1 - GCR) \tag{7}$$

To quantify the edge effect of the AV system, four simulations are conducted with different receiver dimensions. For this, a 3D model with a row pitch of 3.5 m and three columns is used (Figure 1). For each of these receivers the annual average shading is modelled.

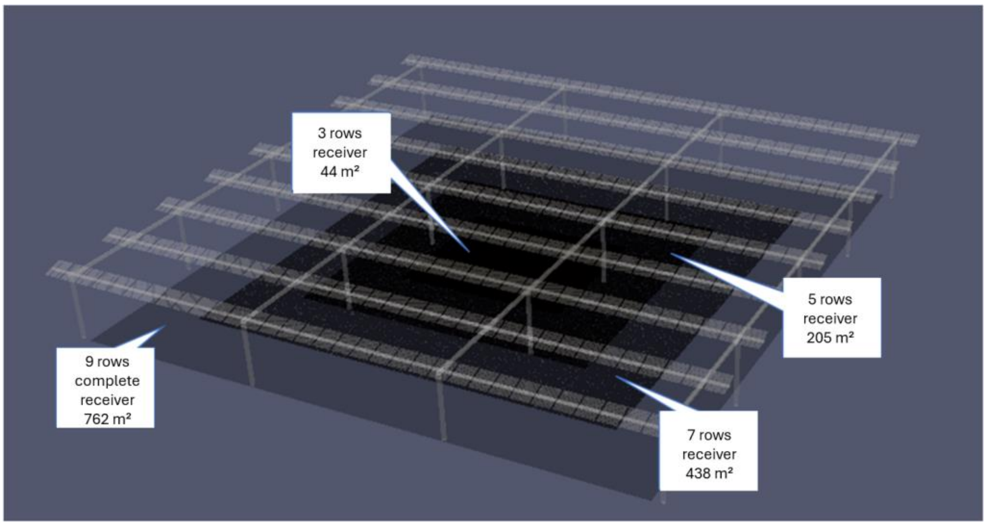

Figure 1. *Different surfaces of receivers underneath the AV system*

To obtain finally the project specific shading rate of 40%, we execute a cubic 3rd degree polynomic regression with the row distance as the variable parameter. Respective regression type is selected by iterative trials comparing simulated scenarios with the fit of the regression.

3. Results and discussion

3.1 Conceptual designs

Table 1 describes the technical specification of the three derived AV system types. All systems use bifacial glass-glass panels (415 Wp, 1.72 m x 1.13 m). The Elevated AV system is oriented at 330° NW which aligns to the terrain orientation and agricultural work direction. It installs one panel in landscape with a row pitch of 3.5 m, a post distance of 9.3 m aligned to pass three times with the used machinery, and a panel angle of 15° aligned to the latitude of the project location. The Vertical AV system likewise uses bifacial glass-glass panels, oriented at terrain orientation of 60° NE. It installs two panels above each other in landscape to reduce piling, with a row pitch of 9.3 m and a panel angle of 90°. The Interrow Tracking system represents a rather standard PV system with increased row distance featuring panels oriented at 60° NE and 240° SW. It installs one panel in portrait with a row pitch of 11.3 m and a panel tracking range of +/- 60° for sun tracking.

Table 1. *Technical data on conceptual AV designs.*

System type	Elevated AV	Vertical AV	Interrow Tracking
PV panel	Bifacial glass-glass – 415 Wp (1,72 m x 1,13 m)		
Azimuth [°]	330° NW	60° NE	60° NE,240° SW
Panel installation	1 panel in landscape	2 panels in landscape	1 panel in portrait
Row pitch [m]	3.5	9.3	11.3
Post distance [m]	9.3	-	-
Panel angle [°]	15°	90°	+/- 60°

3.2 Key performance indicator evaluation

Derived KPIs are compared in Table 2, revealing that the AV Elevated system achieves the most balanced performance among the three designs. We observe that the AV Elevated system has the highest power density at 697 kWp/ha, compared to 519 kWp/ha for AV Vertical and 324 kWp/ha for Interrow Tracked stressing its superior land use efficiency in terms of electricity generation. In terms of agriculturally usable area, the AV Elevated and AV Vertical maintain a high ratio of 94%, while Interrow Tracked drops to 82% due to the considered 1 m security distance from each pile, highlighting a compromise in land usability.

Table 2. *KPI comparison for the conceptual AV designs.*

System type	AV Elevated	AV Vertical	Interrow Tracked
PD Power density [kWp/ha]	697	519	324
R_A Ratio usable agricultural area [%]	94%	94%	82%
Specific PV yield [kWh/kWp/a]	1,785	1,421	2,174
RWH Rainwater harvest [m³/ha/a]	2,846	-	1,370

Specific PV yield shows the Interrow Tracked system with the highest yield at 2,174 kWh/kWp/a, followed by AV Elevated at 1,785 kWh/kWp/a, and AV Vertical at 1,421 kWh/kWp/a. The AV Elevated system reveals a RWH potential of 2,846 m³/ha/a, compared to 1,370 m³/ha/a for Interrow Tracked, while AV Vertical contributes none. However, the Interrow Tracked and AV Vertical systems allow direct precipitation on the cropped surface while the AV Elevated system causes altered rainfall distribution which must be considered in the final design selection. Overall, the AV Elevated system demonstrates for the present use case the best-balanced performance, combining high power density, significant agricultural usability, competitive PV yield, and substantial RWH capacity aligning to the formulated project objectives. However, for other use cases another system type may be more adequate, depending in each instance of the climatic and agricultural context as of the project specific objectives.

3.3 Shading simulation-based design verification

Figure 2 shows the daily average and annual average shading rates for the three simulated AV row pitch scenarios (3 m, 3.5 m, 4 m). All scenarios follow a similar trajectory throughout the day, which is expected given that the only variable is the pitch distance. For all scenarios, after a gradual increase in the daily average shading rate starting at 7:00 am, the maximum rate is observed during the high irradiance period between 13:00-14:00 hours. Following this peak, as the sun approaches the zenith at noon, shading decreases moderately until 16:00. After 16:00, shading decreases significantly due to the low position of the sun and the influence of the sunset edge on the west side. The average annual shading rates result between 24.1% for the 4 m row pitch scenario and 31.5% for the 3 m row pitch. Respective values differ herewith significantly from the project-specific target value of 40%.

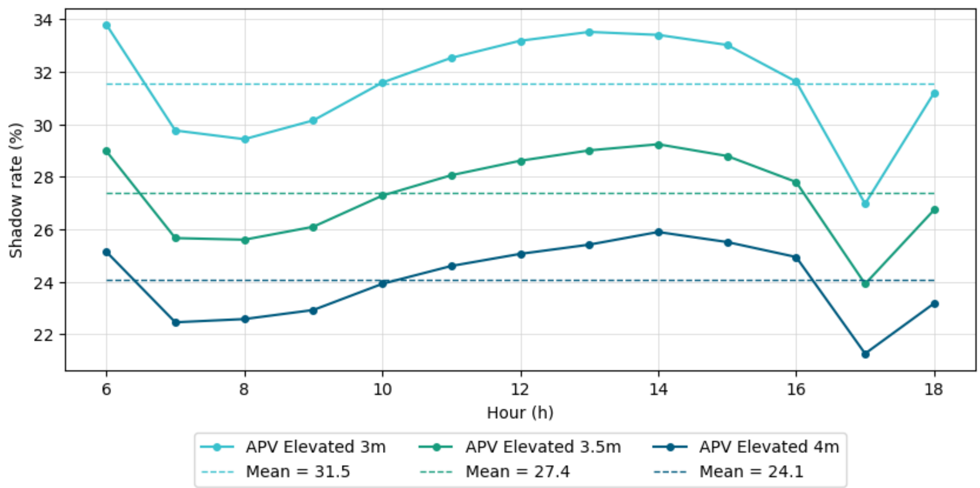

Figure 2. *Daily average and annual average shadow rates for the simulated row pitch scenarios.*

Subsequently, we regress the row pitch as a function of the average annual shading rate to interpolate the pitch necessary to achieve an annual average shading rate of 40%. Figure 3 illustrates the result of the cubic 3rd degree polynomial regression indicating that for a 40% shading rate, a pitch of 2.3 m is required, while for a more conservative scenario with a 30% shading rate, a row pitch of 3.2 m is adequate.

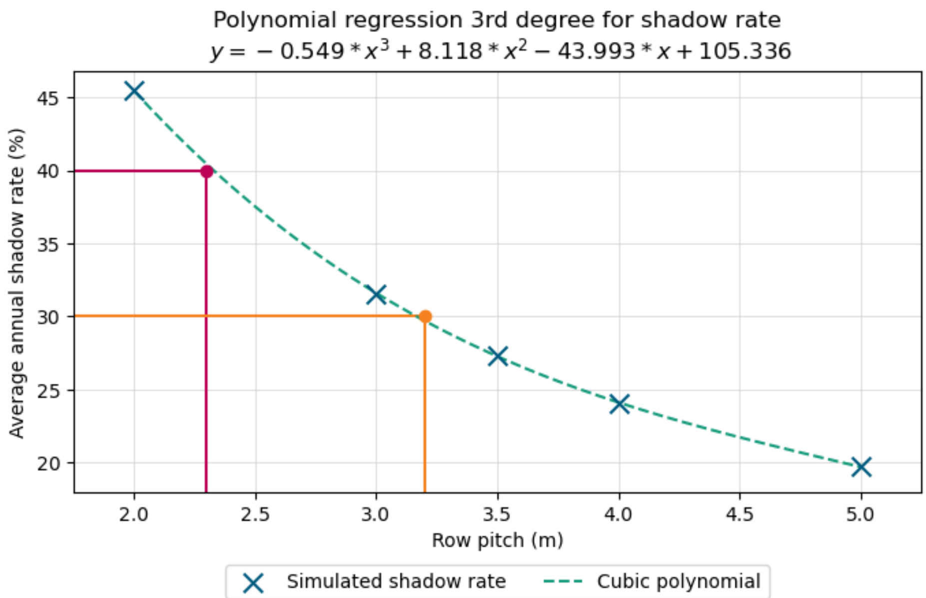

Figure 3. *Cubic polynomial regression of 3rd degree on the row pitch variable as a function of average annual shading.*

3.4 Sizing of agrivoltaic system

Observing the correlation between the receiver surface area and the annual average shading rate of the different scenarios, as shown in Figure 4, we detect an increase in the shading rate with decreasing surface area. The shading rate rises from 28.03% for the full receiver to

29.15% for the receiver covering only the area under the three central PV rows, which is attributed to a decrease in the edge effect. A stabilization of the annual average shading rate is detected with minimal changes (0.03%) between the two smallest surfaces from which we conclude that the edge effect is negligible from the 3rd row inward and 6 m inward from the lateral sides.

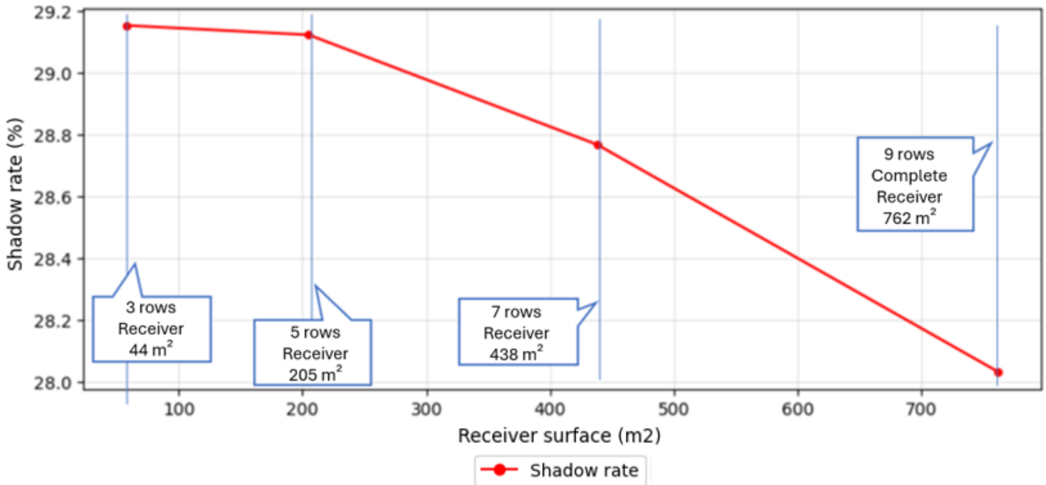

Figure 4. *Shadow rate as a function of the receiver surface area.*

Concluding, to implement a 300 m² surface for scientific agronomic experiments without edge effect impacts (considering shading), this project requires an AV system with an additional coverage of 6-7 meters on the north side due to the low zenith in winter months, and on the east and west sides because of the sun's position in the morning and afternoon hours, respectively. This results in a total surface area of approximately 700 m². However, within commercial scale applications the farmer would work the full surface area under the system having to cope with the effect of inhomogeneous shade that may cause altered yield quantities and ripening times.

4. Conclusion

We reveal the Elevated AV design as the best match for the research project's KPIs, emphasizing the importance of clearly delineating objectives for AV system design. Cubic 3rd degree polynomial regression identifies a 2.3 m row distance to achieve a 40% annual average shading rate. However, a lower shading rate of 30% with a corresponding pitch distance of 3.2 m is recommended for sun-loving crops related to the project. Furthermore, we disclose the necessity of implementing a total AV pilot area of approximately 700 m² to conduct 300 m² of experiments without edge effects, highlighting the crucial role of edge effect mitigation in achieving representative agronomic experiments.

Conducted integral system design, in collaboration with local agronomists demonstrates the versatility of AV and its match with the local characteristics of agriculture in Minas Gerais. The results give a hint of the agrotechnical potential of AV in the state’s northern semi-arid climate, which will be pioneered and experimentally confirmed through the installation of the chosen pilot design presented in this study with its commissioning date at end of 2024.

Data availability statement

Additional data related to the KPI evaluation and simulation results in this study can be made available by the corresponding author upon reasonable request.

Author contributions

F. Schönberger: Project administration, Conceptualization, Methodology, Writing – Original Draft; V. Puentes: Conceptualization, Methodology, Software, Data Curation, Writing – Original Draft; J. David: Conceptualization, Methodology, Software, Data Curation, Writing - Review & Editing; P. Mara de Oliviera: Writing – Original Draft

Competing interests

The authors declare that they have no competing interests.

Funding

The authors acknowledge the financial support provided by the National Agency of Electric Energy (ANEEL) and The Minas Gerais State Research Support Foundation (FAPEMIG)

References

[1] Instituto Brasileiro de Geografia e Estatística. (2022). Demographic Census.

[2] Montenegro, S., Ragab, R., Gaiser, T., de Araújo, J. C., & Pappenberger, F. (2012). Impact of possible climate and land use changes in the semi-arid regions. Journal of Hydrology, 434-435, 55-68. https://doi.org/10.1016/j.jhydrol.2012.02.036

[3] ABSOLAR. (2024, May 21). Infográfico - ABSOLAR. Retrieved from https://www.absolar.org.br/mercado/infografico/

[4] Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nature Sustainability, 2(9), 848-855. https://doi.org/10.1038/s41893-019-0364-5

[5] Fraunhofer Chile Research. (2023, September 4). Proyecto Agro PV en Minas Gerais, Brasil. Retrieved from https://www.fraunhofer.cl/es/Prensa/news/cset-notices/Proyecto_Agro_PV_en_Minas_Gerais_Brasil.html

[6] Instituto Nacional de Meteorologia (INMET). (n.d.). BDMEP. Retrieved from https://bdmep.inmet.gov.br/

[7] Beuth Verlag. (2024). DIN SPEC 91434 - 2021-05. Retrieved from https://www.dinmedia.de/en/technical-rule/din-spec-91434/337886742

[8] Holmgren, W. F., Hansen, C. W., & Mikofski, M. A. (2018). pvlib python: a python package for modeling solar energy systems. Journal of Open Source Software, 3(29), 884. https://doi.org/10.21105/joss.00884

[9] Souka, A. F., & Safwat, H. H. (1966). Determination of the optimum orientations for the double exposure flat-plate collector and its reflections. Solar Energy, 10, 170-174.

[10] Faiman, D. (2008). Assessing the outdoor operating temperature of photovoltaic modules. Progress in Photovoltaics: Research and Applications, 16(4), 307-315. https://doi.org/10.1002/pip.813

[11] Dobos, A. P. (2014). PVWatts Version 5 Manual.

[12] Méso-Star. (2020). Solstice. Retrieved from https://www.meso-star.com/projects/solstice/solstice.html

[13] Perez, R., Ineichen, P., Maxwell, E. L., Seals, R. D., & Zelenka, A. (1992). Dynamic global-to-direct irradiance conversion models. ASHRAE Transactions, 98, 354-369.

[14] Duffie, J. A., & Beckman, W. A. (2013). Solar Engineering of Thermal Processes (2nd ed.). Madison, New York; John Wiley & Sons, Hoboken. https://doi.org/10.1002/9781118671603