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3D View Factor Power Output Modelling of Bifacial Fixed, Single, and Dual-Axis Agrivoltaic Systems

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Abstract. This study investigates the performance of agrivoltaic systems employing bifacial photovoltaic modules. A comparison between yield in Sweden and Italy was carried out. Three agrivoltaic system designs were evaluated: vertical fixed, single-axis tracker, and dual-axis tracker. The results showed that the specific production varied between 1090 to 1440 kWh/kW$_p$/yr in Sweden and 1584 to 2112 kWh/kW$_p$/yr in Italy, where the lowest production was obtained with the vertical fixed agrivoltaic system while the highest production was obtained with the dual-axis tracking agrivoltaic system. The vertical fixed design had a higher electricity production during low solar elevation angles, while the single-axis and dual-axis tracking designs had significantly higher power production during mid-day. The electricity production gain using a dual-axis tracker design was mostly during mid-day, but the increase compared to the single-axis tracker was only 1-2%. The study concludes that low-height, fixed agrivoltaic systems without tracking are well-suited for high-latitude countries like Sweden, while elevated systems with tracker solutions are more suitable for locations like Italy. The findings suggest that the performance of agrivoltaic systems with bifacial photovoltaic modules is highly dependent on geographical location and the specific characteristics of the crops grown beneath them.

Keywords: Electricity Production, Bifacial, Agrivoltaics

1. Introduction

Agrivoltaic (AV) systems have emerged as a promising solution for sustainable agriculture and renewable energy conversion. By integrating solar panels into agricultural landscapes, AV systems increase land use efficiency through dual use of land. In addition, AV systems offer the benefits of reduced water consumption, lower soil erosion, and improved microclimates for crops [1]. However, designing an AV system requires careful consideration of specific dimensions such as height and pitch to optimise crop and electricity yields. As a result, specific designs have been developed for AV systems, such as fixed vertical, horizontal single-axis trackers, and dual-axis trackers on stilts, to mention some [2].

Bifacial photovoltaic (PV) modules have shown potential for increasing the power output of AV systems due to their ability to generate electricity from both sides of the panel. The increased height and ground clearance of bifacial AV systems enhance bifacial PV modules' performance by increasing the reflected irradiance on the modules' surface [3].

This study makes several novel contributions to the AV field. Initially, we employed a 3D-view factor approach developed by Sandia National Laboratories to create a power output model for bifacial PV systems that includes a detailed analysis of the shading and reflection effects of the ground on the PV modules that exclusively focused on fixed-tilted systems [4]. To expand on this, we further developed the approach to incorporate single-axis and dual-axis tracking AV systems. This enabled us to accurately simulate and compare the performance of all three types of systems. As a result, we can now analyze and assess the power output of bifacial AV systems in a more comprehensive and robust manner. In this study, we also compare the performance of different bifacial AV system designs. Taken together, these contributions provide new insights into the design and performance of bifacial AV systems, with potential implications for both the agriculture and renewable energy sectors.

2. Modelling approach

This study evaluates the power output of three different AV systems designs, namely, vertical fixed (VF), single-axis tracker (1T), and dual-axis tracker (2T), at two locations: Piacenza, Italy, (45.02° N, 9.72° E) and Västerås, Sweden, (59.55° N, 16.75° E). The designs are illustrated in Figure 1 below.

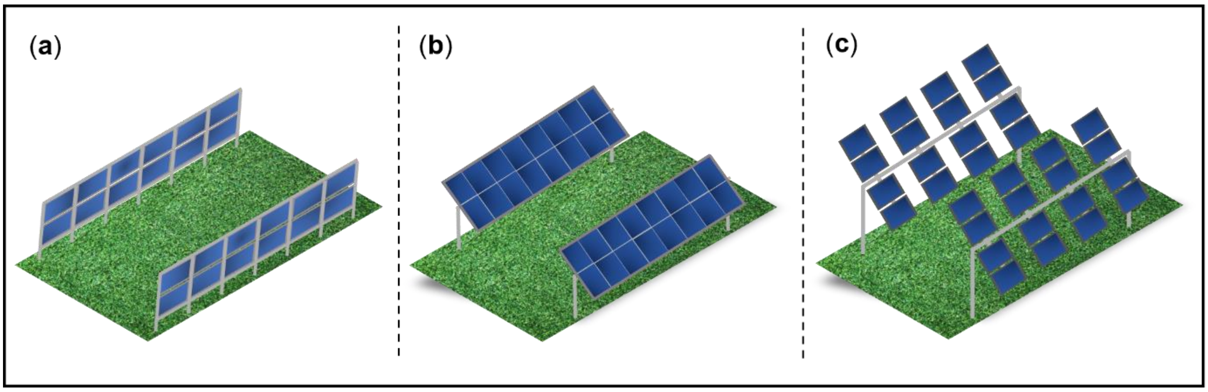

Figure 1. (a) The vertical fixed (VF) AV system, (b) single-axis tracker (1T) AV system, and (c) dual-axis tracker (2T) AV system.

The dimensions of the investigated AV systems are presented in Table 1. The VF PV modules face east and west, while the 1T AV system has a north-south orientation that corresponds to east-west tracking. The 2T system has a primary axis oriented south to north and a secondary axis oriented east-west to track the sun towards south. Hourly global horizontal irradiance (GHI), wind speed, and ambient temperature data were collected from PVGIS-SARAH2 using a typical meteorological year (TMY) [5]. The albedo data was assumed to be fixed at 0.2.

The simulations were carried out using the modelling framework illustrated in Figure 2. We calculated the direct and diffuse shading factors for each AV design using input data such as the geographic location, orientation, and dimension of the PV modules, as well as the height, and row spacing. To perform these calculations, we assumed an isotropic sky and used a 5-degree dome discretization. To further improve the accuracy of the shading factor calculations, we used a 1-degree bi-linear interpolation method to interpolate the shading factors. By using this method, we were able to accurately capture the diffuse shading effects on the PV modules. However, we first calculated the tracking and back-tracking angles for the 1T and 2T designs by using the model as described in Zainali et al. [6]. This model was necessary to accurately simulate the movement of the PV modules in response to changes in the Sun's position throughout the day, which is particularly important for tracking systems. The solar radiation model and PV model is based on the modelling and optimisation framework of the open-source package Agri-OptiCE [7,8]. The global horizontal irradiance for each timestep was decomposed by using Engerer2 separation model [9] to obtain the amount of direct and diffuse irradiance that reached the surface. The decomposed components were transposed to obtain the incident radiation on a tilted plane from the horizontal radiation data using the Perez model [10].

Table 1. AV system dimensions

Dimensions\Systems	VF	1T	2T
Installed Capacity [kW]	22.8	22.8	22.8
Height [m]	1	3	4.5
Row spacing [m]	10	10	10
Pitch [m]	-	-	3.5
Row length [m]	20	20	14
Panel width [m]	1	1	1
Panel length [m]	2	2	2
Primary axis Max/min tilt [°]	-	55/-55	55/-55
Secondary axis Max/min tilt [°]	-	-	55/0

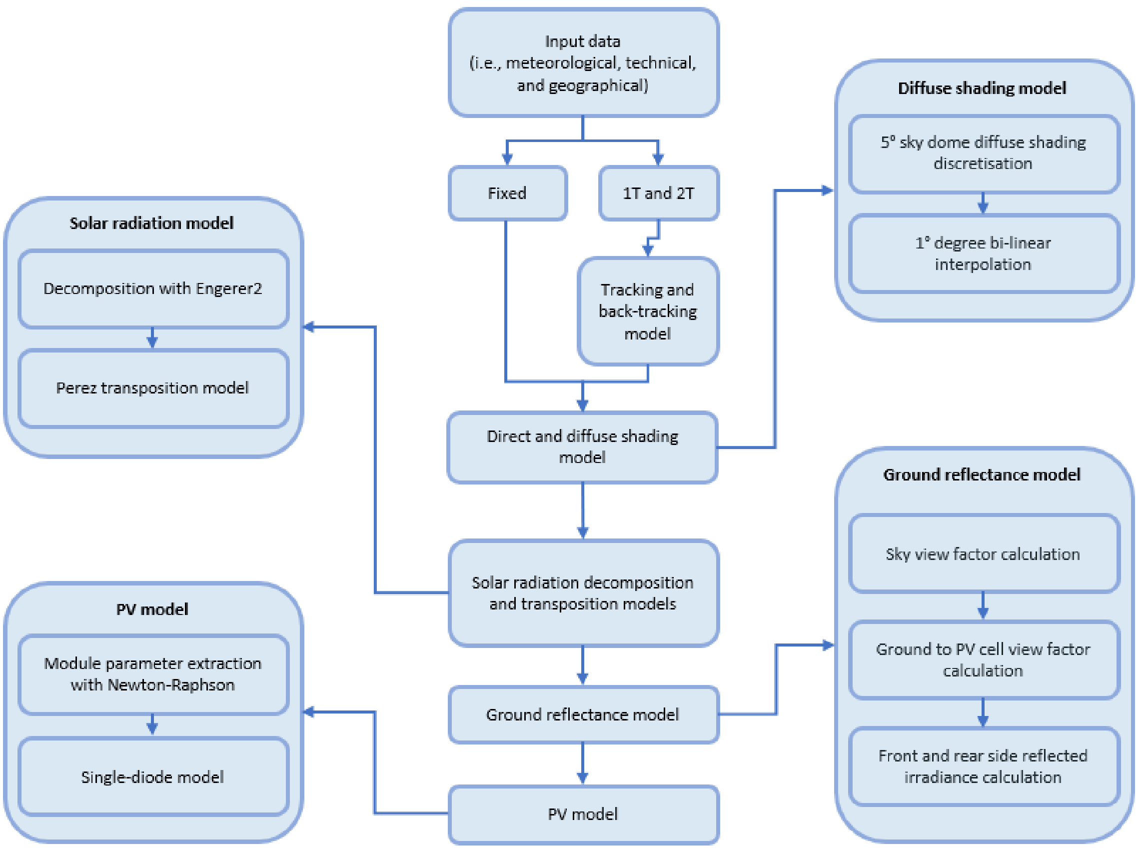

Figure 2. Modelling framework

Accurate calculation of the ground reflected component reaching the rear side of a PV module requires determination of the view factor between the module and the ground. This view factor quantifies the fraction of radiation leaving the ground that directly strikes the module's rear surface, and it is an essential factor in understanding the PV modules' performance. Figure 3 below illustrates the view factors between planar differential areas and serves as a helpful reference for calculating these factors.

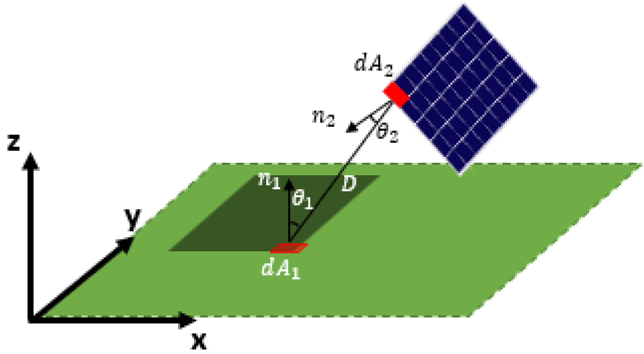

Figure 3. View factors between planar differential areas.

The view factor is determined using the following equation [11]:

$$F_{1\rightarrow 2}=\frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos(\theta_1)\cos(\theta_2)}{\pi D^2}dA_2 dA_1 \quad (1)$$

where A_1 is the area of the emitting surface, A_2 is the area of the receiving surface, D is the distance between the centers of two surfaces, and θ_1 and θ_2 are the angles between the surface normal and a ray between the two differential areas. To approximate the integral equation, the ground is discretized into gridded cells and the distance between the emitting cell and each receiving cell is calculated to estimate the view factor. Using the decomposed GHI into direct and diffuse radiation, the reflected irradiance reaching the rear side can be calculated with the following equation [12]:

$$E_{ground\text{-}reflected}=\left((1\text{-}f_b)DNI\cos(90\text{-}\theta_s)+DHI(1\text{-}f_d)\right)\alpha F \quad (2)$$

where, $\boldsymbol{f_b}$ is the direct shading factor on each ground gridded cell, DNI is the direct normal irradiance (W/m^2), $\boldsymbol{\theta_s}$ is the solar elevation angle, DHI is the diffuse horizontal radiation (W/m^2), $\boldsymbol{f_d}$ is the diffuse shading factor, $\boldsymbol{\alpha}$ is the albedo, and F is the view factor. Finally, the power output of the bifacial PV modules is modelled using a single-diode model with a Jolywood Sunwatt JW-D72N-380 module and SG20RT Sungrow inverter for all designs.

To validate the model, we used 5-minute data collected from 7th July to August 27th, 2022, at an experimental facility located at Kärrbo Prästgård, Sweden (59.55° N, 16.75° E), which is a VF AV system. The facility measured GHI, DHI, ambient temperature, wind speed, and albedo. We used these measurements as input parameters for the model, which was then run to simulate electricity production from the VF system over the same period. The model's output was compared the actual electricity production measured at the experimental facility during the validation period.

3. Results

The validation results from 7th July to August 27th, 2022 at Kärrbo Prästgård, Sweden, showed that the model was able to accurately predict the VF AV system's electricity production with a mean absolute error (MAE) of 0.76 kW, R^2 of 93%, and a root mean square error (RMSE) of 1.53 kW as seen in Figure 4.

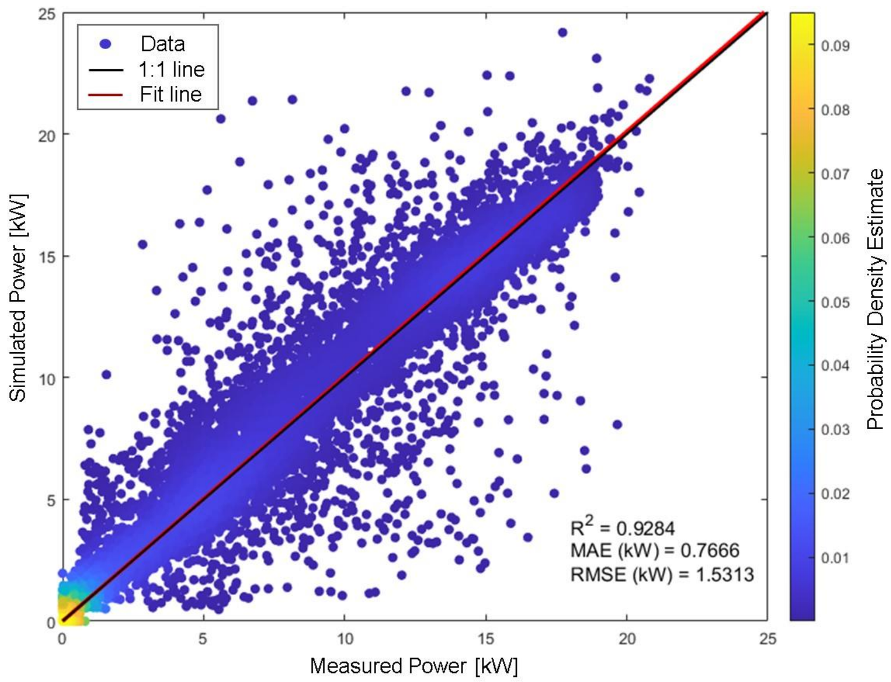

Figure 4. Comparison of actual and predicted 5-minute electricity production from a VF AV system at Kärrbo Prästgård, Sweden from 7th July to August 27th, 2022.

The power output results for both Sweden and Italy using the VF, 1T, and 2T AV systems are presented in Table 2. The specific production, which represents the production per installed kW_p, was also calculated. In Sweden, the specific production varied from 1090 to 1440 $kWh/kW_p/yr$ across all AV systems, with the VF and 2T systems yielding the lowest and highest power outputs, respectively. The 2T system provided a 32% increase in specific production compared to the VF system, while the 1T system only improved the specific production by 21% compared to the VF system in Sweden.

In Italy, the specific production varied more between the AV systems, ranging from 1584 to 2112 $kWh/kW_p/yr$ when comparing the VF and 2T systems. The 2T system provided a 33% increase in specific production compared to the VF system, which is similar to the power production gain seen in Sweden. Interestingly, the specific production increase going from the VF to the 1T AV system was significantly higher in Italy, with an increase of 24% compared to 21% in Sweden.

Table 2. Comparison of power output results and specific production for Sweden and Italy using different AV systems.

Country	**Sweden**	**Sweden**	**Sweden**	**Italy**	**Italy**	**Italy**
AV system	**VF**	**1T**	**2T**	**VF**	**1T**	**2T**
Power output [MWh/yr]	25	30	33	36	45	48
Specific production [$kWh/kW_p/yr$]	1090	1320	1440	1584	1961	2112

The power production throughout the day varies among the different systems, with the VF design having a higher electricity production during hours with low solar elevation angles. However, during mid-day, the 1T and 2T AV designs exhibit a significantly larger power production compared to the VF design. Figure 5 shows the power production gain achieved by the 1T and 2T designs, relative to the VF design, for both Sweden and Italy on June 21st, 2018. The graph illustrates the improvement in power output resulting from the alternative designs for this specific date and location.

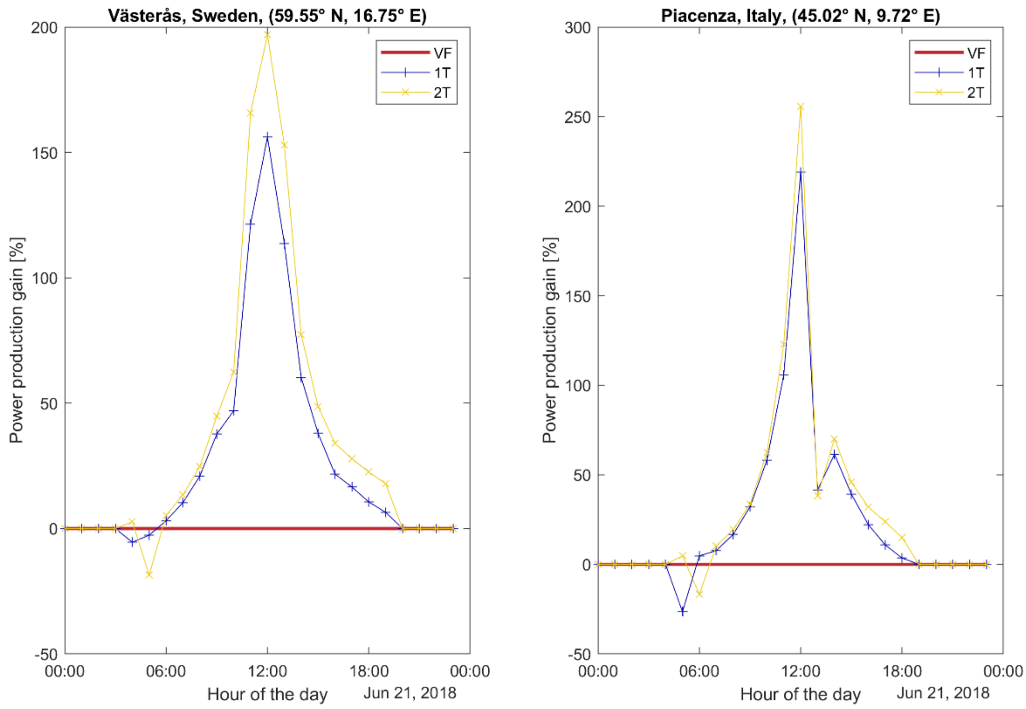

Figure 5. Power production gain of 1T and 2T designs compared to VF design for Sweden and Italy on June 21st, 2018.

The power production gain from a 2T design is achieved primarily during mid-day when the system can optimize its solar panel's exposure to the Sun. However, the yearly gain is only 1-2% compared to the 1T design. Moreover, the 2T design is more complex and usually leads to an increase in investment costs [13].

There is also significant seasonal variability of electricity production between different AV systems designs (Figure 6). Between September to March, the VF design produces roughly the same as the 1T and 2T designs. In Sweden, the average electricity production for the VF design was 1.56 kWh/kW$_p$, compared to 1.71 kWh/kW$_p$ for the 1T design and 1.99 kWh/kW$_p$ for the 2T design. A similar trend can be observed in Italy during these months, except for March and September. In September, the VF design had an electricity production of 5.3 kWh/kW$_p$ in Italy, compared to 6.5 kWh/kW$_p$ for the 1T design and 7.2 kWh/kW$_p$ for the 2T design. The 2T design showed a 32% increase in production compared to the VF design, which is significantly higher than the 19% increase observed in Sweden for the same designs during September. However, between May and August, the electricity production for both the 1T and 2T designs is significantly larger than that of the VF design in both Sweden and Italy.

The simulations in this study used a fixed albedo. However, in high-latitude countries such as Sweden, there will be a higher albedo during the winter due to snow, which could lead to improved performance. Similarly, the designs could have increased performance when specific crops with higher albedo are used.

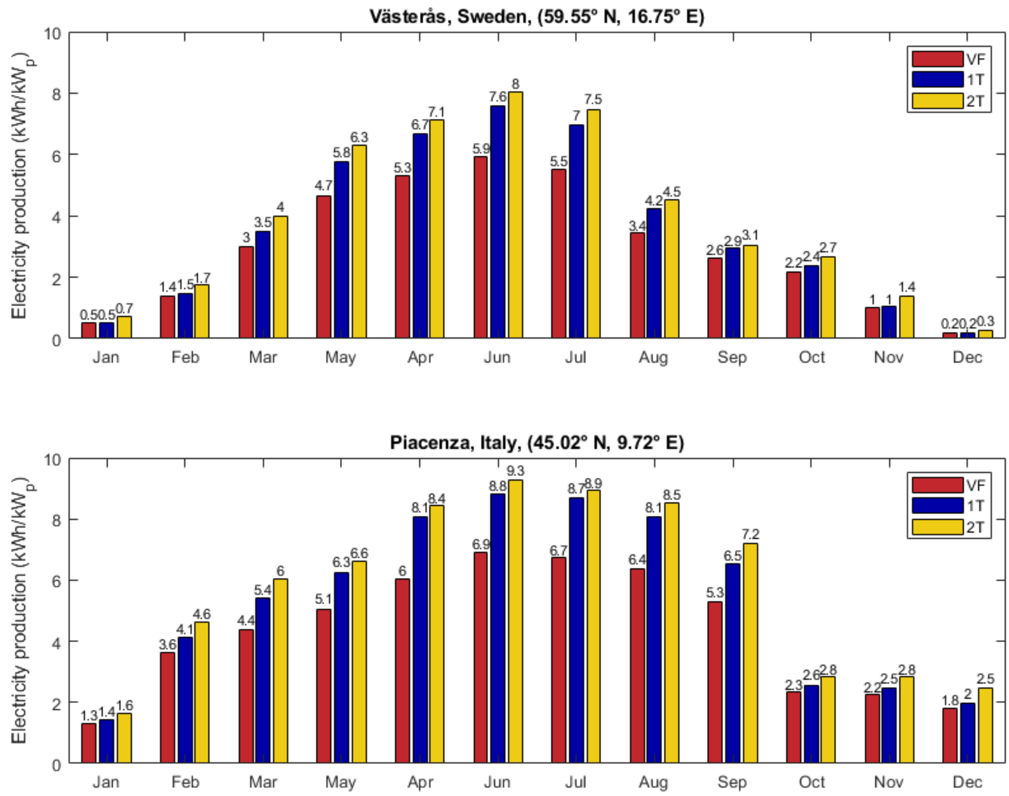

Figure 6. Monthly electricity production for VF, 1T and 2T designs in Sweden and Italy.

4. Conclusion

This study demonstrates that the power output of agrivoltaic systems using bifacial photovoltaic modules is strongly influenced by both geographic location and the system layout. In high-latitude countries such as Sweden, the vertically mounted AV system is a promising solution as it can achieve a high electricity production. Conversely, in countries like Italy, AV systems with tracker solutions can significantly increase the electricity production. Therefore, the choice of AV system design should consider the specific geographical location and the availability of solar irradiance throughout the year. Further research is needed to explore the economic feasibility of implementing these different AV system designs.

Data availability statement

The data that support the findings of this study are available from the corresponding author, Sebastian Zainali, upon reasonable request.

Authors contributions

Sebastian Zainali: Conceptualization, Methodology, Data curation, Validation, Formal analysis, Writing – Original Draft, Writing – Review & Editing; **Silvia Ma Lu**: Writing- Original Draft, Writing – Review & Editing; **Eleonora Potenza**: Writing – Review & Editing; **Bengt Stridh**: Writing – Review & Editing, Funding acquisition; **Anders Avelin**: Writing – Review & Editing;

Pietro E. Campana: Conceptualization, Writing – Original draft preparation, Writing – Review & Editing, Funding acquisition

Competing interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. The company European Energy is financing half of Sebastian Zainali's Ph.D. salary.

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