Agri Solar Thermal Systems: A Brief Study on the Energetic Potential of Bifacial Solar Thermal Systems

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Abstract

The limited availability of land for large-scale solar technologies has led to the idea of combining agricultural and energetic land use. Especially bifacial Agri photovoltaics has shown to be attractive regarding low installation costs. Bifacial Agri solar thermal systems have been neither analyzed nor tested in this context, which results in a lack of research in this field. Therefore, the objective of this paper is to outline the energetic potential of a bifacial solar thermal system. An analytic modelling approach based on solar irradiance analysis was chosen to obtain the specific thermal energy yield for a whole reference year. This included considerations of incidence angle and collector efficiency along with operation temperature and model assumptions. In comparison to a conventional collector facing south and inclined at 45°, the provided annual thermal energy per m^2 collector area of the bifacial module (90° east-west oriented) was calculated to be 0.9 % less (451 $\mathrm{kWh/m}^2$). The results suggest that a bifacial Agri-ST system is capable to deliver a comparable amount of thermal energy per m^2 of collector area. Furthermore, the calculations indicate an increased seasonality of the bifacial over the conventional system. By neglecting shading effects and assuming isotropic diffuse irradiance this potential was presumably overestimated in this study. System simulations should be carried out in the future to consider these effects as well as transient operation states.

Keywords: Agri solar thermal, bifacial system, incidence angle, efficiency, specific annual energy yield, solar thermal system, flat-plate collector, insulating glass flat-plate collector

1. Introduction

1.1 Background and Motivation

The use of land for the provision of renewable energies has become a topic of discussion in politics and society in recent years. While in urban areas the roof surfaces of buildings are used for renewables, rural areas offer open spaces for the use of wind energy, photovoltaics (PV), solar thermal energy (ST), and biomass. The expansion of these technologies is essential to reduce greenhouse gas emissions, but both suitable and affordable land is limited. The different utilization options are increasingly competing with each other (Epp, 2021b, 2021a; Röpcke, 2021). This problem will intensify in the upcoming years due to the required growth of renewables. Furthermore, there will be an increase in demand for solar district heating (SDH) in European countries (Epp, 2021c). However, to cover the heat demand of a community which is connected to the district heating network, several hundreds to thousands of square meters of installed collector area is required. In rural areas, this land is often used for agriculture and are therefore not available for renewable energies.

Against the background of this competition for space, two-sided irradiated (bifacial) PV modules were recently investigated for the integration of solar cells in agriculturally used areas (Gerhards et al., 2022; cf. Katsikogiannis et al., 2022). By vertical installation (90° tilt angle) and orientation to east-west, each side is exposed one half of the day to supply electrical energy. This approach promises to take up only a fraction of agricultural land by placing the modules vertically while providing renewable electricity to the nearby community. This concept is called Agri-PV and can provide combined agricultural and electricity production, making an important contribution to climate action and other Sustainable Development Goals of the UN (Huck, 2022). Agri-PV systems have become a mature technology in the last years and are considered to be state-of-the-art.

1.2 Agri-PV and Agri-ST Systems

The concept of Agri-PV has its roots in 1981 when Goetzberger and Tastrow introduced the idea of growing potatoes underneath a collector field. However, this concept did not become established until 2013 (Scharf et al., 2021). For

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this type of installation, the agricultural use is still in the foreground and may not be influenced by the electricity generation, or only insignificantly. This has also been stated in the first standard DIN SPEC 91434 (Deutsches Institut für Normung e. V., 2021). For this purpose and in order to maximize both agricultural yields and electricity production, the right system design must be selected.

The first possibility of combining agricultural use and PV on the same area is to install the PV modules above the agricultural area as a kind of roof construction (see Fig. 1). In this case, rows of stable (steel) supports are erected at a freely selectable distance. The distances between the rows are chosen in such a way that the system is integrated into the respective agricultural management and has a minimal impact on it. The system is erected with the aid of a wide variety of foundations, such as screw foundations or pile-driven foundations, which are anchored in the ground so that they provide the overall structure with sufficient stability even under varying wind loads. Concrete foundations are not used in this case, as they can disturb the ecology and workability of the soil in the long term. (Trommsdorff et al., 2020)

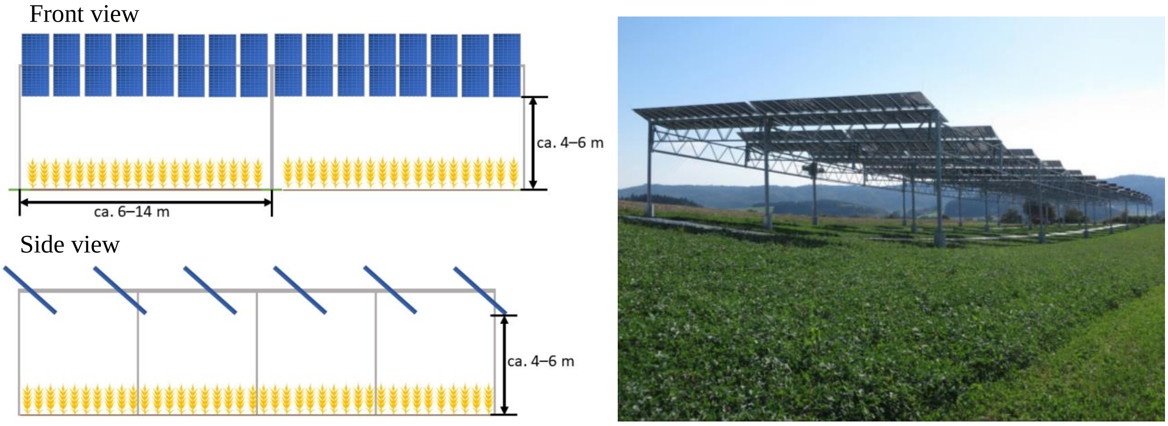

Fig. 1: Schematic illustration (left) and test plant (right) from Scharf et al. (2021) of an elevated Agri-PV system on a arable field.

This type of installation is more expensive as compared to conventional ground-mounted types (Scharf et al., 2021) which is why another type of Agri-PV has been introduced by the company Next2Sun GmbH. This so-called bifacial Agri-PV system does not require elevated mounting supports but instead the PV modules are installed vertically as seen in Fig. 2. The distance between the module rows is chosen in such a way that the agricultural machine has enough space to mow the field and thus cultivate the area. However, this vertical installation requires the collectors to be orientated toward east and west, rather than south. Therefore, the system has its peak power before and after solar noon.

So far, a solar thermal variant of this concept does not exist and thus, the problem of limited land-availability remains unsolved for solar thermal systems. Therefore, this paper focuses on Agri-ST technology. The usage of concentrators to increase the efficiency of the modules is difficult because the rear side of the module must not be covered. Generally, for a solar thermal realization, evacuated tube collectors could be considered even if compound parabolic concentrators cannot be used. However, in this study, a first potential estimation of that novel concept is done for which the investigation of flat-plate collectors (FPC) is considered to be sufficient.

Common FPCs have a non-transparent rear side which contains the solid materials to insulate the absorber and increase the efficiency. It needs to be removed in order to allow for bifacial operation. In addition, the casing of the module which is typically made of aluminum, needs to be replaced by a transparent material. The resulting design is similar to an insulating glass unit with an absorber between front and rear cover.

In the last years insulating glass flat-plate collectors have been developed and investigated thoroughly (Giovannetti et al., 2014; Giovannetti and Kirchner, 2015; Summ et al., 2020; Summ et al., 2021). The design concept is well-suited for a bifacial Agri-ST application and numerous investigations have shown that the performance is in a similar order of magnitude as compared to conventional FPCs. Additionally, Nikolić and Lukić (2015) investigated double-exposure flat-plate collectors and showed that a bifacial operation can perform significantly better with the usage of reflecting surfaces. In this study, no reflecting mirrors are considered and insulating glass FPCs are investigated in order to have a comparable bifacial setup as shown in Fig. 2.

Fig. 2: Example of an bifacial Agri-PV system. (Next2Sun GmbH, 2022). The distance between the module rows is chosen in such a way that the agricultural machine has enough space to mow the field and thus cultivate the area.

1.3 Research Gaps and Scope

A bifacial solar thermal implementation in the context of Agri-ST does not yet exist and thus, no investigations on the energetic potential of this technology have been conducted. Therefore, the objective of this paper is to outline the energetic potential and compare bifacial collectors which can be used for Agri-ST plants with a conventional collector.

2. Methodology

The objective of this paper is to provide a first estimation of the bifacial Agri-ST concept by means of specific collector yield analysis and comparison with a conventional solar thermal setup. In order to compare the south-oriented, tilted collector field with a vertical Agri-ST collector field, analyses on the solar irradiance were conducted. A conventional collector field with an inclination of 45° facing south was compared to a bifacial 90° east-west oriented collector field.

The methodological approach for the presented research work is shown in Fig. 3. The key output is the collector yield calculation and comparison which is displayed in dark green. Three sets of technical data were included consisting of collector data, weather data, and operational data. Another set of model assumptions completed the input for the modelling approach.

An analytical modelling approach was considered to be sufficient for the first specific energy yield estimation of bifacial collectors. A system simulation approach was not selected in this study, instead a linear function was used for modelling the thermal yield. In that function, the beam irradiance, diffuse irradiance, average collector efficiency, and incidence angle modifier (IAM) were considered.

Weather data from PVGIS-SARAH (European Commission, Joint Research Centre, 2022) referring to the year 2016 was used to obtain the solar irradiance on the inclined surfaces. The selected dataset refers to a location in the center of Germany near the city of Kassel. The solar angles were also extracted from the data to compute the incidence Θ between the sun rays and the collector aperture surface using the geometrical relation (Quaschning, 2013):

$$\Theta = \arccos(-\cos(\alpha)\sin(\beta)\cos(\gamma_s - \gamma_c) + \sin(\alpha)\cos(\beta)) \qquad \text{(eq. 1)}$$

α : solar elevation β : collector tilt angle γ_s : solar azimuth angle γ_c : collector azimuth angle

In that manner, the IAM can be taken into account for the computation of the thermal energy output. For both systems, the IAM values according to Tab. 1 were considered. A linear interpolation was applied to account for intermediate values of Θ. To calculate the thermal energy output q, the solar beam irradiance G_b, diffuse solar irradiance G_d, and average collector efficiency η were taken into account. q was computed and compared for both the conventional and bifacial solar thermal system. The following relation represents the modelling approach to obtain the specific thermal energy output, where IAM is a function of Θ and η is a function of β:

$$q(t) = \int_0^t (G_b + G_d)\,\eta\ \mathrm{IAM}\ \mathrm{dt} \qquad \text{(eq. 2)}$$

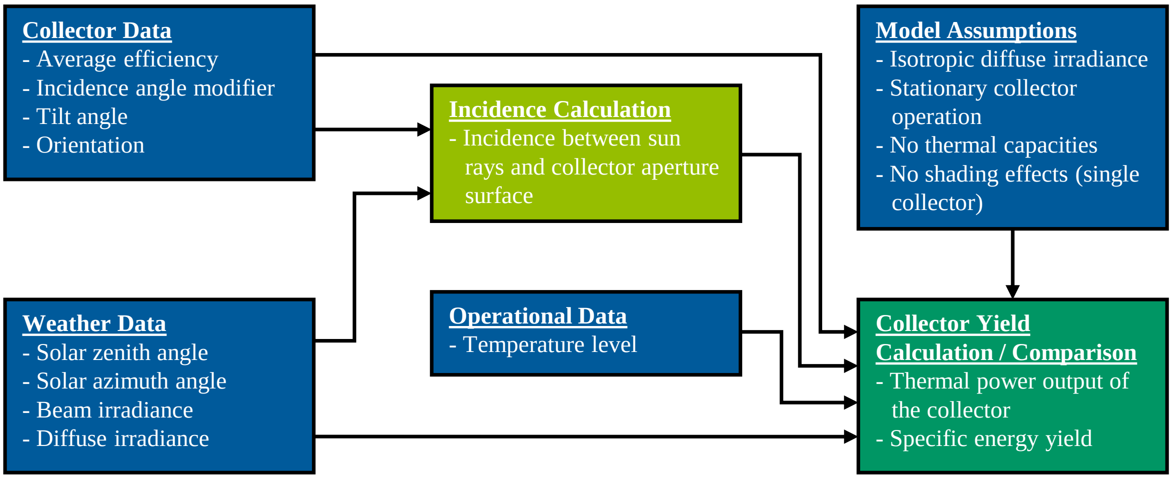

Fig. 3: Schematic illustration of the methodological approach for the presented study. Inputs are displayed in blue, intermediate computations in light green and outputs in dark green.

The thermal efficiency for the analysis was set according to the investigations of Giovannetti and Kirchner (2015) for a collector temperature level of 60 K above ambient ($\eta_{conventional} = 0.425$, $\eta_{bifacial} = 0.5$). The authors have shown, that a vertically installed collector performs better as compared to a 45° installed one. Convective losses of the module are affected by the collector tilt angle and with larger tilt, the performance will increase (Montoya-Marquez and Flores-Prieto, 2017). Hence, the vertically installed bifacial module shows a higher efficiency than the 45° tilted conventional collector. For the analysis, full-year data was used with an hourly resolution.

Tab. 1: Incidence angle modifier for both the conventional and bifacial flat-plate collectors. For intermediate values, a linear interpolation scheme was implemented.

Θ	0°	50°	70°	90°
IAM	1.00	0.98	0.80	0.00

3. Results and Discussion

The objective of this study was to provide a first estimation of the bifacial Agri-ST concept by means of specific collector yield analysis and comparison with a conventional solar thermal setup. The annual energetic comparison of the conventional and the bifacial collector is shown in Fig. 4. Both blue curves represent the cumulative specific irradiation on the aperture surface of the conventional (solid lines) and bifacial (dashed lines) collector. With a total specific irradiation of 1,185 $\mathrm{kWh/m^2}$ the south-oriented collector receives about 6.5 % more energy as compared to the bifacial system (1,108 $\mathrm{kWh/m^2}$). Between October and April, the south-oriented collector gains more energy compared to the east-west-oriented one. Yet, during the other parts of the year the bifacial collector appears to have more favorable conditions. In that time period, the slope of the dashed curve is slightly larger which suggests that more energy can be converted by the bifacial collector. Prior to the analysis, the east-west-oriented surface was expected to receive more energy during the winter period as compared to the south oriented one. The assumption was that the smaller solar elevation will be beneficial for the vertical installation and therefore the bifacial collector was expected to be preferably used during fall and winter.

However, the green curves reveal that the opposite seems to be true. Both show the cumulative specific energy yield of the collectors. The difference in total specific energy yield is smaller as for the irradiation. For the conventional collector it is 455 $\mathrm{kWh/m^2}$ and for the bifacial collector it results in 451 $\mathrm{kWh/m^2}$ which is a relative difference of only 0.9 %. This comparatively small difference is partially caused by the higher efficiency of the vertical collector (cf. section 2). As described above, the bifacial collector receives less solar energy during the wintertime but more energy during summertime. As a result, the slope of the curves deviates for these periods.

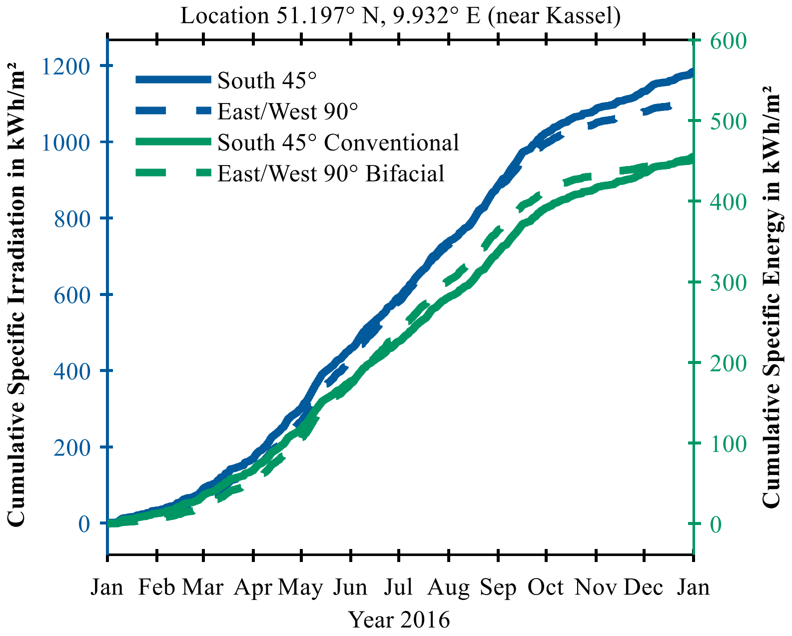

Fig. 4: Comparison of the annual cumulative specific irradiation for a 45° south-oriented (–) and a 90° east-west-oriented (- -) surface (left axis). On the right axis, the annual cumulative specific energy of a conventional (–) and a bifacial (- -) solar thermal collector is shown.

The effect of the annual solar movement on the incidence angle modifier is shown in Fig. 5. In the two plots, the IAM for the 45° south-oriented, 90° east oriented, and 90° west oriented collector aperture surface are compared. On the left, the time period during summer solstice is displayed. It can be seen that the blue area represents the east side of the bifacial collector, which is irradiated early in the morning with low incidence. Similarly, the west side is irradiated on the second half of the day, which is represented by the green area. Also as expected, the southern surface is most irradiated in the middle of the day. It is noteworthy that due to the early sunrise and late sunset, the time integral of IAM for east and west is larger than the gray area representing the conventional collector. This explains why the bifacial collector achieves a greater specific yield in summer than the conventional one. On the other hand, shading effects have been neglected in this study. Though, they could have a significant impact on the advantage which the bifacial concept offers over the conventional one. It is expected that shading in summer will partially offset the benefit of early sunrise and late sunset, and thus the bifacial system may provide less specific yield than shown here.

On the right, the same dataset is shown during winter solstice. Here, a different result emerges. The shorter days affect the bifacial collector in particular. The solar angles are less favorable in this case although the low elevations were initially assumed to be advantageous. Overall, the wintertime indicates a significantly lower energy yield compared to the conventional module.

This effect can be seen even clearer in Fig. 6, where the data from Fig. 3 is shown in the form of a bar chart for the individual months of the year. It can be seen that the months of April to August are those in which the bifacial concept delivers more thermal energy. During this period, the bifacial collector outperforms the conventional one by 15.1 %. On the other hand, the months of September to March benefits the conventional concept. Here, the collector is clearly more effective which is demonstrated by the specific energy yield which is 32.6 % higher compared to the bifacial collector in that time period.

Also noteworthy are the months of June and September, because the radiation values are significantly different from those of the other months (cf. Fig. 6). In September, the radiant energy for the bifacial collector is 12.2 % less as compared to the conventional one, whereas in June it is the other way round. The reason for the unexpected turnaround is the share of diffuse radiation, as described below.

Fig. 7 shows the time histories of the radiation values during June and September for the south-facing system. The beam radiation is shown in blue, the diffuse part of the radiation in green. It is noted that the fraction of diffuse radiation is greater in June than in September. This indicates, that the sky was cloudier in June than in September. Due to the fact that the bifacial collector can use the diffuse radiation on both sides, it can be assumed that this collector performs better on cloudy days than the conventional collector. This in turn explains why the energy values for the conventional and bifacial collectors in Fig. 6 differ so much. However, it was assumed that the diffuse radiation is isotropic, and the collector converts the radiant energy on both sides to the same extent. In combination with the shading effects, these simplifications are likely to affect the total specific energy yield and could make the comparison work in favor of the conventional system.

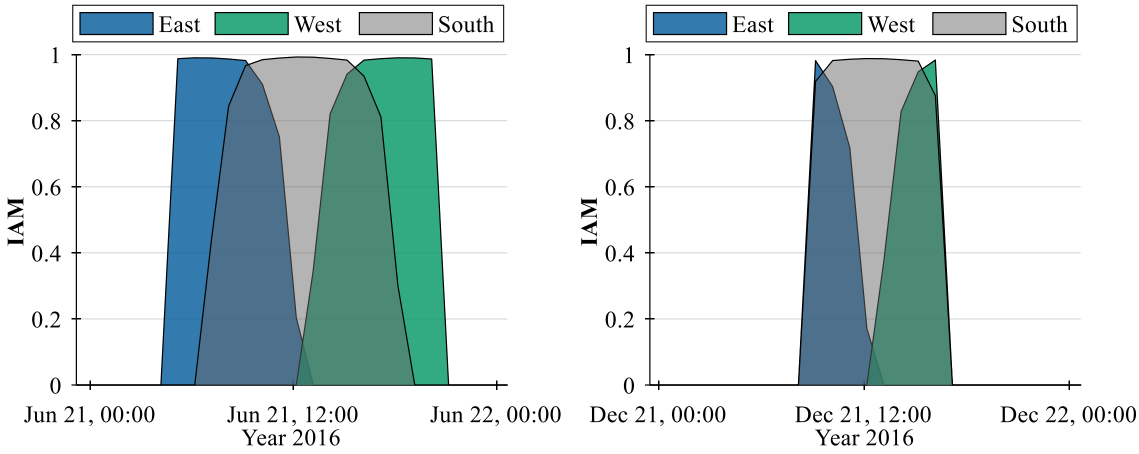

Fig. 5: Incidence angle modifier for the 45° south-oriented, 90° east-oriented, and 90° west-oriented collector aperture surfaces at the summer solstice (left) and winter solstice (right). Early sunrise and late sunset during summertime is beneficial for the bifacial system, whereas the shorter days are more favorable for the conventional installation.

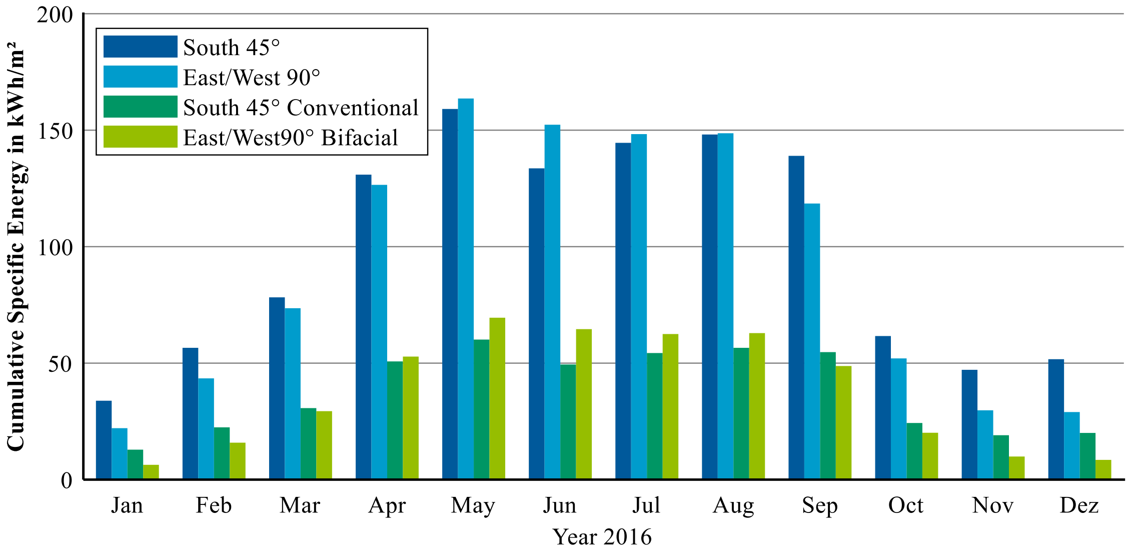

Fig. 6: Bar plot comparison of the monthly cumulative specific irradiation for a 45° south-oriented and a 90° east-west-oriented surface. The green bars represent the monthly cumulative specific thermal energy of a conventional and a bifacial solar thermal collector.

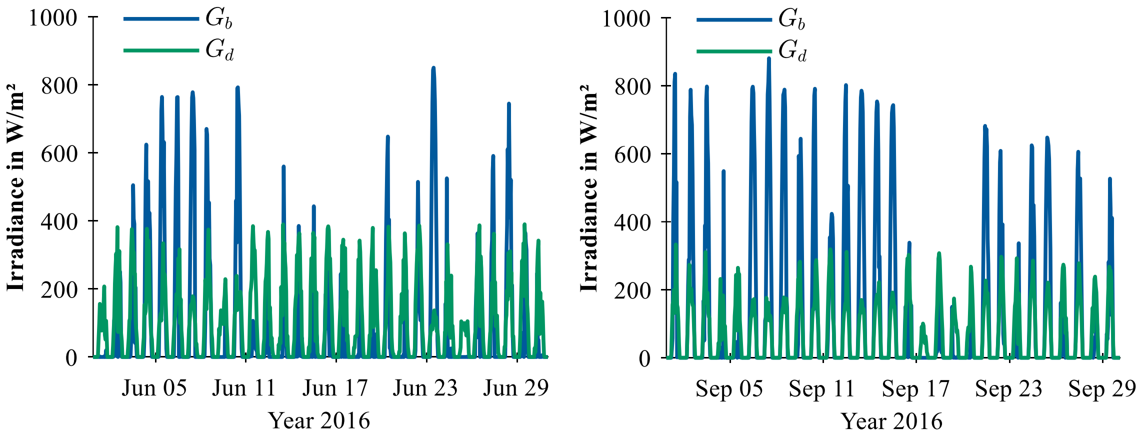

Fig. 7: Line Plot of the direct (blue) and diffuse (green) radiation fraction for the months of June (left) and September (right). It can be seen that the diffuse component is slightly larger in June than in September.

4. Conclusions

The analytical modelling approach has shown that a 45° south-oriented flat-plate collector delivers 0.9 % more thermal energy than a 90° east-west oriented bifacial flat-plate collector. Three main reasons were identified which explain this unexpected small difference. First, the efficiency of the bifacial collector is greater as compared to the conventional one because the vertical installation will positively affect the convective losses (cf. Giovannetti and Kirchner, 2015; Montoya-Marquez and Flores-Prieto, 2017). Second, the incidence and IAM during summertime are more favorable for the bifacial collector leading to a 15 % advantage regarding specific thermal energy yield. Third, the bifacial system is capable to convert the diffuse components of the radiation at the side facing away from the sun.

These results suggest that a bifacial Agri-ST system is capable of delivering a comparable amount of thermal energy per m² of collector area. Furthermore, an increased seasonality of an Agri-ST system can be assumed. This shift of the energy yield into the summer months can be either advantageous or disadvantageous for the thermal consumer, depending on the system design and control strategy. The energetic disadvantage of bifacial collectors appears moderate and acceptable. Additionally, under consideration that new areas for solar thermal can be opened up by using that novel system, the potential of Agri-ST is considered remarkable. However, this potential was presumably overestimated in this study by neglecting shading effects.

Shading is expected to be the most important unconsidered aspect as on the one hand it has an influence on the collector row spacing and thus the utilization rate on the fields. On the other hand, shading will reduce the solar yield and may reduce or even eliminate the advantageous summer yields for the bifacial collector. How big this influence is should be further investigated in future studies. At the same time, changing the parameters which were selected for this study, may have an impact on the results. Therefore, it is reasonable to continue these studies with an extended range of input parameters. System simulations could help to consider these aspects in future studies and also account for transient effects.

Apart from of the theoretical analysis, practical questions are still unanswered, such as the hydraulic connection of the modules or the mounting system under consideration of agricultural boundary conditions. In this respect, the results of this study are to be seen as a first assessment of the potential, which is to be verified and extended in further analyses in order to be able to demonstrate the full potential of this technology.

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