GROUND IRRADIANCE MODELLING: OF KEY IMPORTANCE FOR DESIGNING NATURE INCLUSIVE SOLAR PARKS AND AGRIVOLTAICS SYSTEMS

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Solar electricity from solar parks in rural areas are cost effective, can be deployed fast and can therefore play an important role in the energy transition. The optimal design of a solar park is, amongst others, affected by income scheme, electricity transport capacity and land lease costs. Important design parameters for utility-scale solar parks, that may affect landscape, biodiversity and soil quality, include ground coverage ratio, size and tilt of the PV tables. Particularly, low tilt PV at high coverage reduces the amount of sunlight on the ground strongly and leads to deterioration of the soil quality over the typical 25-year lifetime. In contrast, vertical PV or an agri-PV design fairly high above the ground leads to more and homogeneous ground irradiance; these designs are favoured for pastures and croplands. In general, the amount and distribution of ground irradiance and precipitation will strongly affect which crops can grow below and between the PV tables and whether this supports the associated food chain. As agrivoltaics is the direct competition between photosynthesis and photovoltaics. Understanding when, where and how much light reaches the ground is key to relate the agri-PV solar park design to the expected agricultural and electricity yields.

Keywords: see the list of keywords

1 INTRODUCTION

Solar electricity from solar parks in rural areas are cost effective, can be deployed fast and can therefore play an important role in the energy transition. The design of a solar park, particular in case of low tilt PV at high coverage ratios, could strongly reduce the amount of sunlight on the ground. At the same time, after the 20-30 years lifetime of a utility-scale solar parks, the land should be reusable for agriculture or nature. Therefore, landowners and public authorities demand that the soil quality remains equal during this period. As we will show below, ground irradiance modelling is paramount in the design phase of the solar park to ensure that soil quality conditions are met.

For agrivoltaics, the competition of photons for photosynthesis and photovoltaics is even more obvious. In particular, when the solar park operator varies the orientation of the PV tables over the days or seasons, for example the angle in horizontal single axis-trackers, and can actively control, within the physical limits, the share of ground irradiance for photosynthesis versus the irradiance for electricity yield.

We present methodology and modelling results on the ground irradiance between and below PV tables in utility-scale and agri-PV solar parks. Line profiles of ground irradiance are compared to the open field value. We link the ground irradiance simulations with ecological observations at existing solar parks of various designs. Using the Mitscherlich equations [1], the solar park design can be evaluated for the photosynthetic potential for shade- and sun-loving species. Based on our results, we can make recommendations for park design and future research.

2 METHODOLOGY

2.1 Solar park design and ecology

Schotman *et al*. have investigated the relation between solar park design and ecology [2]. They identified two groups of south-facing designs that are regarded as 1) a safe design for soil quality, see left side of Fig. 1, and biodiversity and 2) a more “risky” design. In contrast, they also encountered other south-facing designs that had low potential to maintain soil quality. Due to the high land lease costs in the Netherlands, alternating east- and west-facing low-tilt solar parks, with very high ground coverage ratio within the active area of the solar park, are a prominent choice nowadays (Fig. 1 right). Schotman *et al*. have included two solar parks with this design in their research. Also these have little to no ecological potential.

Figure 1: (left) south-facing solar park with ample vegetation below panels and (right) east- and west-facing solar park, with nearly bare soil below the panels. Photo by Alex Schotman via [2].

In the presence of not too much nutrients and water, species-rich grasslands are favoured in the Netherlands. Enough light for vegetation growth below the panels also is a basic condition for a healthy biodiverse soil. High-quality biodiversity in solar parks in general means flower rich grasslands with many insects above and in the ground. In this work, we will investigate the light distributions for these solar park designs and look for alternative designs, that have similar light distributions as ecologically safe designs, but with industry conform coverage ratio.

2.2 Ground irradiance simulation tool

TNO has developed a software package, named BIGEYE, that simulates the electrical output of solar panels in the presence of ground reflection and nearby objects. In particular, to simulate the irradiance on the rear of the bifacial panels, it is necessary to determine the irradiance distribution on the ground below and around the solar panels. The calculation of the spatial irradiance distribution takes into account the patterns of hard shadows by the PV panels, but also the distribution of diffuse light, e.g. from clouds. The simulated output during a year, approximated in 1-hour "constant" time-steps, has been shown to be within 1% accurate compared to the actual full-year output. For more details of the BIGEYE software package and its experimental validation, including benchmarking with other simulation tools, we refer to previous ECN/TNO publications [3][4].

For the energy yield calculations, the ground irradiance, which varies point by point and with the time of the day and the seasons, is an intermediate result. However, these results can also be directly used to study the effect that objects like PV panels have on the irradiance on the ground. The amount of light that reaches the ground directly affects biodiversity, soil quality and the possibility to combine solar energy with agriculture.

The ground irradiance distribution map is calculated for each time step, e.g. 1 hour or 10 minutes, using BIGEYE's fully 3D view factor approach. For this work, the ground irradiance map for each time-step is extracted from BIGEYE and line profiles perpendicular to the PV tables are obtained. For reference purposes, the irradiance in an empty field is also calculated for the same time period. In the next step, the irradiance is used as input for the photosynthetic rate calculation, using the Mitscherlich equations [1].

3 RESULTS

3.1 Ground irradiance simulation for existing solar parks

We have generated three generalised designs based on the ecological observations and measurements of the PV table designs by Schotman [2]. Ground irradiance profiles were determined for these designs and plotted in Fig. 2.

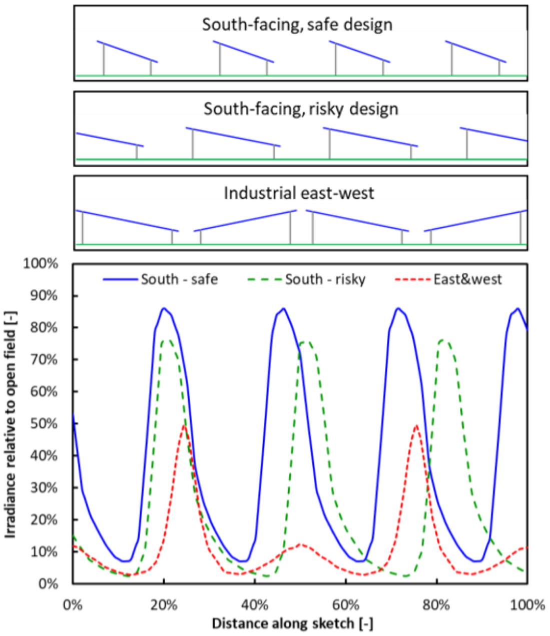

Figure 2: Cross-sections to scale and ground irradiance line profiles for three typical types of solar parks.

The industrial east- and west-facing design yields a ground irradiance profile, red dots, with two bright(er) regions. The higher bright region is quite narrow and is due to the bottom gap between two tables, where the midday sun reaches the ground through the north-south running opening. The much lower, but broader region is related to the top gap. Not only is this gap more narrow than the bottom gap, also it is much higher above the ground. This causes the direct light projection fallen through this gap to vary more from west to east due to the sun's movement during the day, see Fig. 1. The east & west profile indicates that a large fraction of the ground per pair of tables exhibits rather low ground irradiance in the range 3% to 12%.

3.2 Effect of minimum height of PV tables

Fig. 3 shows the effect of the minimum height of the PV tables on the ground irradiance distribution for the industrial east & west facing solar park design, while keeping all other parameters fixed. The profile with a ground clearance of 20 cm (red line) reveals a very sharp transition from the open field value of ~6.3 to nearly zero irradiance below the panels. In the top gap between two panels, there is a narrow region peaking at 16% of the open field irradiance level. The bottom gap, at 20 cm from the ground shows an even sharper peak with over 90% of the open field irradiance. Increasing the clearance changes the sharp step from high to near-zero irradiance to a more gradual transition but also with less high and less deep extrema.

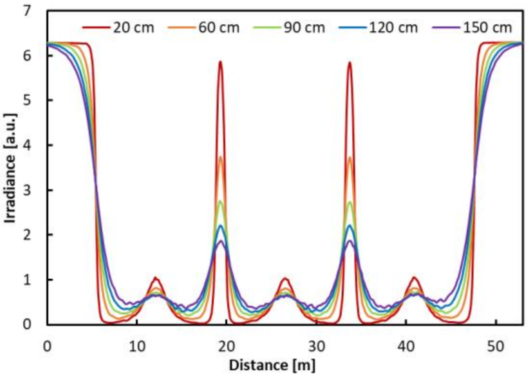

Figure 3: Variation in ground irradiance distribution as function of the minimum height for the industrial east & west design.

Increasing the minimum height of the PV tables makes the irradiance distribution more homogeneous. Although, exact boundaries between poor and good ecology cannot be drawn, it is very likely that increasing the minimum irradiance will be an important step towards nature-inclusive designs. Comparing low height (red) with high height (purple), we see that the minimum irradiance increases from near zero to about 8% of the open field irradiance. Also, the ecological observations on south-facing solar parks confirm that larger installation height leads to improved growth conditions [2].

3.3 Irradiance and photosynthesis

Fig. 4 shows the relation between the (photo-active) irradiance and the CO_2 fixation rate for several crop species [5]–[7]. These curves are generated by the Mitscherlich equations [1]. In these equations, the difference between species and their growth rate is governed by: a) the respiration rate, i.e. the metabolism of the plant without any growth; b) how fast the synthetic rate increases at low irradiance levels and c) the maximum rate of photosynthesis. For instance, clover has a high respiration rate and thus needs over 70 mmol m^{-2} s^{-1} PAR irradiance for a net-zero photosynthetic rate, in contrast with potato net-zero growth is reached at only 5 mmol m^{-2} s^{-1}. On the other hand, the rather low maximum growth rate of potato is already reached at 400 mmol m^{-2} s^{-1}, while e.g. spinach only reaches its saturation point (defined as 95% of the maximum rate) at irradiance levels above 1200 mmol m^{-2} s^{-1}. These growth rates not only determine the conditions under which crops grow better, but also what kind of plants can survive (let alone grow) in the darker regions below solar panels.

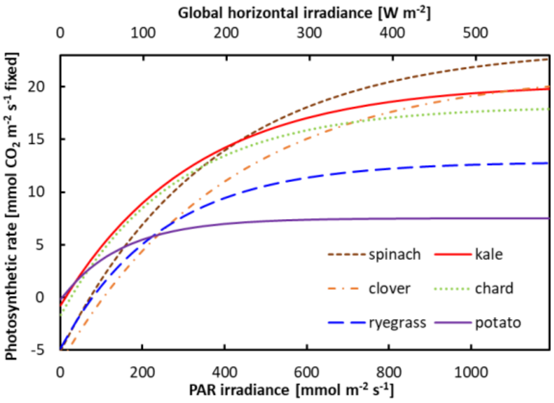

Figure 4: Photosynthetic rate, expressed in terms of CO_2 fixation per unit area and time, as function of the PAR (bottom axis) and GHI (top axis) irradiance for a selection of crops.

3.4 Increased ground irradiance designs

For ease of comparison we have made irradiance distribution diagrams that show which fraction of the land gets what amount of irradiance in Fig. 5. On the one hand, typical east- and west-facing, low tilt solar parks in the Netherlands exhibit poor potential for soil quality and biodiversity [2]. This is corroborated by the distribution diagram that shows over 80% of the active area with <20% irradiance compared to an open field and even 60% with <10%. On the other hand, south-facing systems that show good ecological potential have 40% of the active area with <20% irradiance and just under 20% at less than 10%.

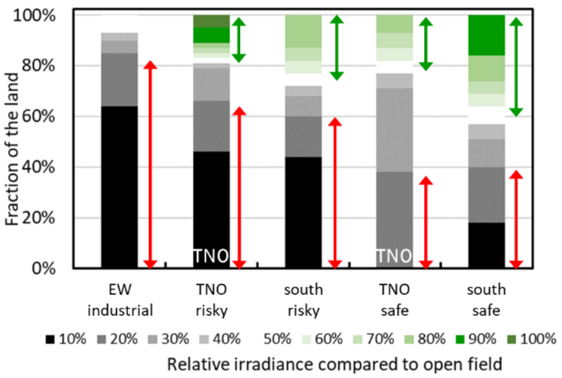

Figure 5: Ground irradiance distribution for the designs of Fig. 2 and Fig. 6. Red and green arrows indicate the area with respectively <20% and >50% irradiance.

Our results indicates that there is no sharp boundary, not even a gradual transition region. There are probably interactions between high and low irradiance regions. We deduce that as long as the darker regions are not too dark and too large and interspersed with large(r) regions with higher irradiance levels, the conditions are sufficient to ensure soil quality. In contrast, when the brighter regions are relatively small and dark and separated by larger regions with very low irradiance, the conditions are not suitable for plant growth. The first case corresponds for instance with the east- and west-facing industrial design, the latter case with the south-facing safe design. Exact conditions where the solar park design allows sufficient light on the ground to safeguard soil quality will be investigated in a four-year follow-up project EcoCertified Solar Parks, supported by the Dutch government and with participation of many project developers.

Because there is not a single value that describes the potential for soil quality, we will regard the distribution bar diagram as a fingerprint to steer the design of nature-inclusive solar parks. In particular, we will look for east- and west-facing variants that have similar or better ecological potential than the two south-facing designs. And at the same time have a ground coverage ratio that is more in line with the present industry standard.

We have varied some design parameters to increase the ground irradiance to levels comparable to the south-facing designs, see Fig. 2. The first improvement step, labelled TNO risky, is to open the gaps between the tables, both at the top and at the bottom, see Fig. 6. As a result, we obtain a bright region of about 20% of the land with over 50% of the open field irradiance. This is comparable to the irradiance distribution of the south – risky design.

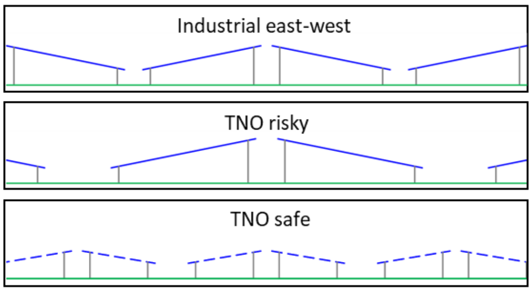

Figure 6: Cross-section to scale, comparing the industrial east-west design, Fig. 2 with two designs that lead to better ground irradiance levels and distribution.

In the next step, we also reduce the table size from 8 m to 4 m wide, decreasing all gaps correspondingly, and replace the back sheet modules with partially transparent bifacial modules. This design, labelled TNO safe, has similar bright regions as the TNO risky and south risky designs. More importantly, the fraction of dark area is strongly reduced and the minimum irradiance level is increased from around 5% to over 15% of that of the open field.

Table I: Ground coverage ratio, GCR, and area fractions with less than 10%, G < 10%, or more than 50% irradiance, G > 50%, for the five solar parks designs.

	EW industrial	TNO risky	South risky	TNO safe	South safe
GCR	89%	77%	69%	77%	53%
G < 10%	60%	45%	40%	0%	20%
G > 50%	0%	20%	25%	25%	40%

3.5 Orientation of design

One final example on the relevance of a clear understanding of the ground irradiance distribution is agrivoltaics. We have modelled a typical “high” PV design that allows tractors to drive below the structure. PV tables are 4 m across, on a 19-m pitch, and 5 m above the ground. The tables are oriented along the east-west or the north-south direction. Line profiles of the ground irradiance, taken perpendicular to the long direction of the PV tables are shown in Fig. 7. Note that the open field irradiance is approached by the irradiance at 0 m for the east-west oriented tables.

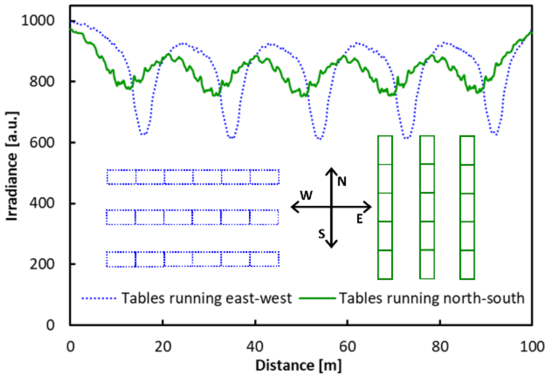

Figure 7: Ground irradiance line profiles for a simulated agri-PV system, see text, at 5 m height. The long edges of the PV tables are either running east-west (blue dots) or north-south (full green).

In the first case, the shading by the tables results in narrow east-to-west stripes with reduced irradiance, at about 60% of the open field, separated by wider stripes with irradiance up to 92%, the variation between minimum and maximum is ±19%. In the second case, the shadow and bright stripes run north-south with less pronounced minima and maxima, variation is ±8%. With this knowledge, the farmer can better decide which PV orientation she prefers, for instance how to space the rows of crops and where to plan gaps in the farming area for irrigation pipes or to drive on. Note that the average ground irradiance is, obviously, the same for both orientations.

4 DISCUSSION

Typical east- and west-facing designs of utility-scale solar parks, with a coverage ratio of 90% in the active part of the solar park, result in hardly any light on the ground underneath the PV panels, with the minimum lower than 5% of the open field irradiance. It is noted that the Dutch branch organisation Holland Solar issued a code of conduct that states a 75% maximum ground coverage. However that may be achieved by adding a green zone at the perimeter of the solar park, whilst the active part of the solar park has an effective coverage ratio often of over 90%. This green perimeter does not mitigate the soil degrading effect of low irradiance under the active areas. Note, that compared to agricultural land, green perimeters or corridors can support biodiversity development.

We have shown that distributing this additional “green” area over the active part of the solar park creates more areas with high ground irradiance. At the same time, it also decreases the land fraction with extremely low irradiance. Note that the active part coverage at 77% is still higher than both south-facing designs.

We also show the ground irradiance for a dilute PV installation, high above croplands allowing agricultural access. This contributes to a more homogeneous distribution of irradiance, compared to the utility PV park, preventing it to fall below 60% of the open field irradiance at any location. Still the orientation of the table influences the irradiation variation by over a factor two.

5 CONCLUSION

There are reasons for concern about the soil quality in utility-scale solar parks, when these have a very high coverage ratio as is often observed in east- and west-facing solar parks in the Netherlands. We have shown that over 80% of the ground receives less than 20% of the open field irradiance. In contrast, simulations of the ground irradiance of existing solar parks with sufficient potential for soil quality have only 40% of the ground receive less than 20%. Also, whereas the former has nowhere over 50% of the open field irradiance, the latter has 40% with at least 50% of the open field irradiance.

We have shown that by increasing the minimum height of the system, decreasing the size of the PV tables and decreasing the coverage ratio, the ground irradiance increases, in particular around the gaps between the tables.

The most direct way of increasing the lowest irradiance in a solar park design is to use semi-transparent PV panels, such as the commercially available bifacial glass-glass modules.

In conclusion: we have shown that we can achieve similar ground irradiance levels in an east- and west-facing design with 77% ground coverage ratio as is achieved by a south-facing design at 53% coverage.

ACKNOWLEDGEMENTS

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