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Evaluation method and module design for cost-effective compliance with irradiance guidelines to maintain soil quality in solar parks

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Abstract. Ground mounted solar parks lead to changes in the micro-climate under and between the PV tables. In particular, the vegetation on the soil is, in various degrees, shaded from direct sunlight and indirect, diffuse light. Also, the changes in precipitation distribution, air temperature and wind speed will affect the conditions. This leads to varying conditions for the vegetation affecting photosynthesis, which on the longer term influences the soil quality. To ensure sufficient light for photosynthesis, initial thresholds for irradiance have been drafted by TNO and Wageningen University and Research for the climate conditions in the Netherlands. Based on these rules, we present for the first time a method to evaluate the trade-off between soil irradiance and energy yield, related to table configuration and module choice, for utility-scale solar parks. Irradiance on the ground has either passed around the PV tables, passed through the gaps between panels or is transmitted between the solar cells in the panels. This leads to an optimisation of the module transparency and the size and relative position of the PV tables, when minimising the costs and at the same time complying with these irradiance criteria. To illustrate this optimisation, we have simulated the annual energy yield and ground irradiance and calculated the effect on the levelised cost of electricity. We present two solar park designs, that have the same ground irradiance distribution. One design is installed with partially transparent, bifacial modules, the other with gaps between the opaque, bifacial modules. Although the transparent bifacial modules have a somewhat lower module power, this system produces more kWh per hectare and has a lower levelised cost of electricity. The present paper shows that the partial transparency of bifacial modules is a key feature to maintain the soil ecology, and profitability, thus contributing to societal acceptance.

Keywords: Bifacial PV / module design / ecology / soil quality / transparency / nature-inclusive

1 Introduction

Photosynthesis is the basis for all ecosystems. Plants absorb light and convert the energy together with carbon dioxide and water to carbohydrates, a form of chemical energy and oxygen. Most life forms depend on these products. Photovoltaics, in the form of solar electricity, is a major contributor to the transition to a sustainable, renewable energy system. Solar panels absorb light and convert it to electrical energy. Both photovoltaics and photosynthesis depend on the absorption of photons. And both use photons with wavelengths in and near the visible spectrum.

In general, the rule is the more light is absorbed by the photovoltaic, PV, panels, the less light will reach the soil and plants. Thus, for a given module type, the PV system design and ground irradiance are directly linked. The higher the energy yield per hectare, the less light is available for photosynthesis. Table size, height, tilt angle and table-table distances play an important role in the amount and distribution of the irradiance on the ground. But also, the (lack of) transparency of the solar panels is a significant aspect. By nature, bifacial modules which are now dominant in the market, could play an important role since the rear panels of the modules have to be transparent. Depending on cell dimensions and manufacturing choices, the area not covered by the cells could contribute to a module transparency of up to 10%. Note: these bifacial modules have the same spacing between cells and cell strings as regular monofacial modules and should not be

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confused by so-called specials, like modules for agri-PV or covered walkways and car parks that have additional spacing between cells or cell strings.

However, in the last few years, an increasing number of module manufacturers fill the area between the cells with a light scattering layer, e.g., a white reflective foil. This reflector increases the front side efficiency of modules because some of the reflected light is coupled back into the adjacent solar cells, thus increasing the photocurrent. However, the foil also prevents that light is being transmitted through the module. Sometimes the white, reflective layer even extends for some distance behind the solar cell to maximise light scattering and thus the front-side power, at the cost of partially shading the rear side of the bifacial cells.

Ground-mounted solar parks change the microclimate under and between the tables with solar panels. This leads to relatively high variability, in location and in time, of light and water availability, in stark contrast to grasslands, where their distribution is rather homogeneous [1]. These changes and variations in light distribution, precipitation interception and soil humidity are likely to significantly affect terrestrial carbon cycling [2]. Soil microbial communities respond differently to changes in both precipitation and shading levels in ecosystems with low precipitation, but vegetation growth is reduced due to the lower precipitation below the solar panels [3]. Although the leaves of trees also shade the forest floor, the main difference with solar panels is that trees provide the forest floor with leaf litter [4]. The decomposing leaves become soil organic matter by the actions of animals and microbial communities in the soil [5]. In this way the energy of the intercepted light still reaches the soil in the form of chemical energy. In contrast, solar panels also intercept the light, but the converted energy is transported to be used elsewhere, depriving the soil of incoming energy.

The effect of uniform shading on plant growth has been studied in great detail. It is important that the results of (relative) shading studies depend strongly on location and that the tolerance for shading, direct sunlight, heat, wind and humidity varies widely between plant species. Above 90% shading, that is less than 10% of the annual irradiance reaches the vegetation, a strong reduction in plant growth is observed, thereby strongly reducing the carbon intake of the soil. Above 40% of the annual irradiance the growth is hardly affected. However, in the intermediate range of irradiances widely varying results are reported, ranking from studies that show no impact [6,7] to others that report a large reduction of vegetation growth [8]. These results are relevant for the Dutch context. Other groups studied the effect on biodiversity in operational solar parks [9]. Knegt et al. report that between the tables the biodiversity is comparable to the reference situation, but below the tables and just North of the tables, in a South-oriented set-up, biodiversity parameters like the Shannon index[1] were strongly reduced, particular when the original biodiversity was high [11].

Lambert et al. compared the soil properties in a solar park with that of an abandoned vineyard and with semi-natural land cover, like pinewood and shrubland. Although the former two have lower soil quality, both chemically and physically, the soil in the solar parks have lower temperatures and strongly reduced CO_2 outflows [12]. As the construction of the solar park could damage the topsoil and vegetation, it is also important that the vegetation and thereby the soil can recover during the operational phase. Whereas the restoration success and plant biodiversity were found to be reduced, some species showed no change in growth and appeared to be more shade-tolerant [13]. A study in the Czech Republic found clear differences between under the panels and between the rows. Under the panels, plant species that tolerate more extreme soil properties were more prevalent. Although this leads to diversity, there is also the risk that the extremer conditions under the panels supports invasive species [14]. This agrees with observations that species like Urtica dioica, common nettle, and Rubus fruticosus, blackberry, are relatively more prevalent under the PV tables [9].

Chen et al. report a meta-study on 28 reports focussing on the response of the ecosystem. Arid, desert-like environments benefit from the presence of solar parks, whereas in more boreal, humid conditions, particular on cropland the effect was somewhat negative [15]. One could even consider changing the design or operation of a solar park in such a way that plants receive sunlight when growth conditions are ideal and give more shading to reduce thermal stresses and increase water retention, particular during periods of heat and drought [16].

Wageningen University and Research, WUR, and TNO have investigated the effect of reduced irradiance due to solar panel shading in existing solar parks on the amount and quality of the plant biodiversity [17–19]. To illustrate the importance of the ground irradiance, Figure 1 shows the vegetation/soil below two solar parks for two situations. One solar park with sufficient soil irradiance to allow vegetation growth and one with very low soil irradiance that is not enough to sustain vegetation below the tables. In the second case, only under the gap between the lower side of two neighbouring tables vegetation growth can be seen. We have shown that in solar parks with large tables, up to 6P, in alternating east- and west-facing installation with ground coverage ratios well above 90%, the annual ground irradiance in the darkest locations can be as low as 2–3% of the open field irradiance[2]. To emphasise, this is a reduction in annual irradiance by 97–98%. Installing partially transparent solar panels that are 4–6% transparent would increase the ground irradiance, in this situation, by a factor of three compared to the situation with fully non-transparent panels.

[1] The Shannon index H' is a biodiversity indicator, ranging from the lowest H'=1 for an environment with a single abundant species to the highest H'=ln(R), where all R number of species are equally common [10].

[2] The open field irradiance is the irradiance on a field without solar panels. By definition this is identical to the global horizontal irradiance, GHI.

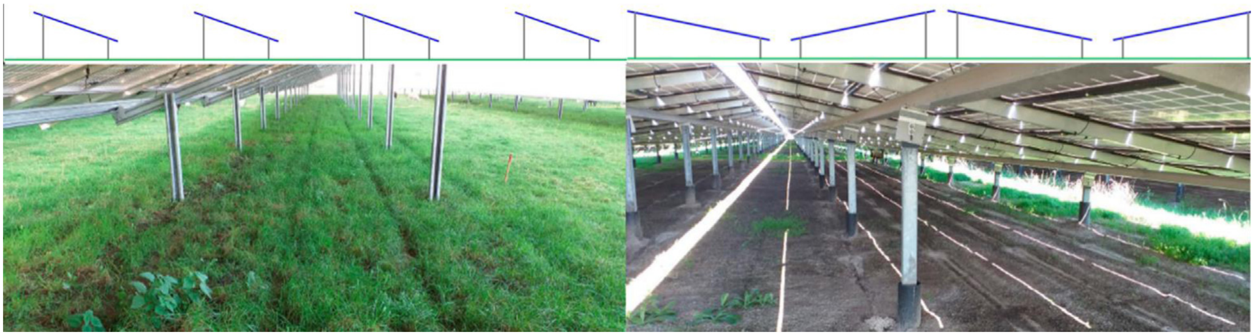

Fig. 1. Cross-section and photograph under the PV tables of two solar parks. (left) South-facing solar park with a relatively low ground coverage ratio of 55% and (right) east-west solar park with a very high ground coverage ratio of >95%.

> The shading and irradiance levels can be understood in gardening terms as published by the Royal Horticultural Society, United Kingdom. *Full sun* is often referred to as more than six hours of direct sun. In this document that would be more than 38% or more than 50% relative irradiance, respectively for 16 and 12 hours of daylight. *Partial sun/shade* stands for 4-6 hours of sun, corresponding to a minimum of 25% and 33% relative irradiance. *Moderate shade* is two or three hours, roughly between 12% to 25% irradiance. Less than two hours, 12-16% irradiance, is considered as *deep shade* and "it is likely that only a very limited selection of extremely shade tolerant plants will survive" [20].

This work has led to a first set of requirements for the ground irradiance to maintain soil quality via vegetation growth [17–19]. Relative ground irradiance <10% is not sufficient to maintain sufficient photosynthesis and should be absent. At the other hand of the scale over 40% of ground irradiance is sufficient for diverse plant growth. The requirement states that this zone should cover at least 25% of the land. Although there will be some photosynthesis, it's likely that irradiance in the 10-15% of the open field irradiance will lead to a poor biodiversity. Therefore, only 40% of the land or less should have irradiance levels in this range. In other words, 100% of the land should have irradiance level >10%; 60% of the soil area should have irradiance level >15%; and a quarter of the total soil area should have an irradiance >40%. Whereas the two lower irradiance criteria are required to ensure sufficient photosynthesis remains to maintain the soil quality, the high irradiance in at least 25% of the land will, in addition to maintaining soil quality, promote flowering plant species and subsequently offer a feeding habitat for pollinators [21].

Special conditions in the Netherlands, like subsidy support rules, high land-lease costs and grid congestion, lead to solar park designs characterised by high ground coverage ratios and tilt angles, ~12°, that are very low with respect to the latitude at 52°N. At the same time, the political and societal conditions are changing. Permit requirements are increasing, and it becomes harder to have a positive business case. The tendency is to install high-power solar panels at high density, distributing the project and land cost over a larger number of panels and generated kWh. This shifts the balance to more photovoltaics and less photosynthesis.

The present work does not investigate the relationship between light, water and vegetation growth or how changes in vegetation growth affect the soil quality parameters or biodiversity over a longer period. It accepts as starting point that there is a certain amount of irradiance needed to maintain soil quality. And to work from that point, the set of irradiance requirements as presented by WUR and TNO is applicable for Dutch soil and climate conditions. In the following work, it is shown how design choices on module or system level can pass or fail this set of requirements. It also shows that to achieve the same ecological results, different choices can be made and that these choices affect both the cost of electricity and the amount of generated solar electricity.

We present a case study to evaluate the trade-off between module bill of materials, ground irradiance and the annual energy yield for typical solar park designs in the Netherlands. Bifacial modules are considered with and without non-transparent reflector foils and compared to monofacial modules. We calculate the effect the change in module transparency has on the ground irradiance distribution. We also simulate the annual energy yield taking into account the increase in ground irradiance below the partially transparent panels and the resulting increase in rear irradiance due to the albedo of the underground. The bifacial modules with reflector foil exhibit a 2% higher front-side power. We will show that the increase in annual energy yield per module is only 1.0% to 1.4% higher than that of partially transparent bifacial modules. To fulfil the requirements for minimal ground irradiance, one can either change the park design, typically leading to fewer panels per hectare or ensure that the module is partially transparent. The present study allows to evaluate the consequences in terms of ground irradiance, energy yield and land usage. We appeal to module manufacturers to consider the value of the transparency of bifacial modules and keep them available for the application of utility-scale solar parks characterised by high ground coverage ratios and/or large PV tables. Furthermore, we urge to relevant authorities to supply adequate legislature or permitting guidelines to maintain sufficient irradiance and photosynthesis on the entire area of the solar park.

Fig. 2. Illustration of reflective mesh between solar cells in bifacial module. (left) Experimental bifacial module from ECN in 2016 [24] and (right) partially transparent, bifacial solar panel outdoors in the sun. Whereas in the white bifacial case, there is no light transmitted to the wall behind the panel, we can clearly see the ground irradiance distribution and shading pattern of the partially transparent bifacial module.

Table 1. Properties of the three module types. The "Monofacial" module has a white back sheet. The "Transparent bifacial" module is laminated without a reflecting foil between the cells, the "White bifacial" module has such a foil.

	Pmpp [W]	I_{sc} [A]	V_{oc} [V]	Transparency	Bifaciality factor
Monofacial	540	13.6	49.7	0	0
Transparent bifacial	529	13.4	49.7	6.6%	75%
White bifacial	540	13.6	49.7	0	75%

2 Materials and methods

2.1 Transparency of (bifacial) modules

After the emergence of the first commercial production of modules with bifacial solar cells, by companies like Yingli [22] and PVGS [23], it was noted that bifacial modules exhibited a lower front-side power compared to monofacial modules despite having the same quality bifacial solar cells. Whereas a white back sheet would reflect the partially transmitted (infra)red light back to the rear of the solar cells and thus improve the conversion efficiency, a transparent back sheet or rear glass would transmit most of that light. This leads to a lower performance of the bifacial module, under front side illumination, compared to the monofacial version with the white back sheet. In addition, also the areas around the solar cells could either scatter (full spectrum, light back towards the solar cells and front glass, in case of a white back sheet or, in case of a transparent back panel transmit that, full spectrum, light. Obviously, in solar parks the open rear side would more than compensate this loss by converting the rear irradiance from albedo and diffuse light.

The concept of white, bifacial modules was investigated by R&D institutes like ECN [24] and SERIS [25]. These applied a light scattering material on the "transparent area", either by adding a material between the cells or by making the rear glass opaque at those areas. We can see an example of such a white bifacial module in Figure 2 on the left. The mirror behind the module shows the bifacial solar cells through the transparent back sheet. This white bifacial module gives a uniform shadow pattern on the wall. In contrast, the pattern of light and shadow by a partially transparent module, Figure 2 right, clearly shows the light passing between the individual cells and between cells and mounting frame. This light will be incident on the soil and is available for photosynthesis.

A partially transparent bifacial module has a simpler module bill of materials containing rear glass (or transparent back sheet), encapsulant, cell matrix, encapsulant and front glass. In contrast, the bill of materials for a white bifacial module needs an additional layer to ensure the scattering of the light that is incident next to the solar cells.

2.2 Simulation cases

Three cases are considered: (1) a non-transparent monofacial panel with a white back sheet, (2) a partial transparent bifacial panel without a reflector between the cells and (3) a non-transparent bifacial panel with a reflector foil. The cell and total module area in all modules are identical and the area between the cells and the frame amount to 6.6% which equals to the effective transparency of the bifacial module without the reflector.

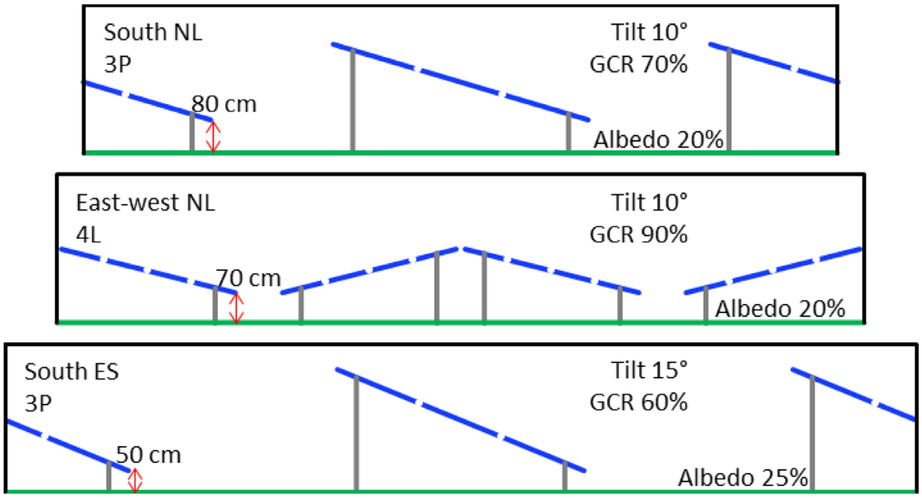

Fig. 3. Schematic view of the three solar park configurations. The text in each box states the orientation of the solar park: south-oriented or east-west facing; the table configuration: 3 panels in portrait or 4 in landscape; the tilt angle of the tables; the ground coverage ratio GCR and the ground clearance. For each solar park design two repeating units of tables and gaps are depicted. All figures are on the same scale, except that the height is 1.3x exaggerated for clarity.

The modules consist of 24×6 cells divided over 2×3 bypass diode blocks. The solar cells have an efficiency of 22%, leading to a maximum power point of 540 Wp for the monofacial module design. The dimensions are $2281 \times 1158\,mm^2$. Module parameters are summarised in Table 1. The transparency fraction is the area of the module that is not covered by the opaque frames, cells and, when present, the reflecting foil or white back sheet.

Relative changes in IV-characteristics were scaled accordingly to previously published results [24]. The monofacial and the non-transparent bifacial module have identical power ratings, while the transparent bifacial module suffers a 2% lower short-circuit current as the light between the cells pass through the module. The bifaciality factor of the two bifacial module types is the same. Only the partially transparent bifacial module has a non-zero transparency.

2.3 Simulation of energy yield and ground irradiance

To evaluate the trade-off between energy yield and ground irradiance of commercial modules, we calculated the annual yield and the ground irradiance of typical solar parks designs in the Netherlands and Spain. The effect on soil quality is evaluated based on the ground irradiance criteria developed by TNO and WUR. Note: the criteria are developed for the Dutch context and we recommend developing standards for other regions than the Netherlands.

For modelling of the energy yield and the ground irradiance, we use the proprietary TNO tool BIGEYE [26,27]. This is a software package originally designed to calculate the energy yield of solar parks with bifacial solar panels. One major contribution to irradiance on the back of these panels and thereby on the bifacial gain is the light that is reflected by the underground, which is partially shaded by the panels and partially in full sunshine. This pattern of shade and light depends on the weather and on the position of the sun in the sky. This so-called ground-reflected light is often ignored for monofacial panels that face towards the sky at small tilt angles but cannot be neglected for bifacial panels. The need to incorporate the ground reflected light was the driving force to develop BIGEYE and led to the development of the ground irradiance simulation within BIGEYE.

BIGEYE is an advanced modelling tool based on fully 3D view-factor calculations incorporating direct and diffuse light components as well as reflections from nearby objects and the ground (albedo). BIGEYE achieves high accuracy for PV system performance based on monofacial as well as bifacial modules [28] and has been benchmarked in the past to other PV energy tools [29]. The simulations use weather data for a typical meteorological year with hourly resolution. The ground irradiance is calculated with an initial resolution of four grid points per meter, but the triangular grid pattern is refined to take the distance to the PV tables into account. The irradiance model considers a planar underground with any slope angle and does not correct for shading from growing vegetation.

3 Results

3.1 Annual energy yield

The annual energy yield and the ground irradiance of each module is calculated for two common solar park configurations in the Netherlands based on a typical meteorological year; (a) an east-west solar park with GCR of 90% and four panels in landscape and (b) a south oriented solar park with GCR of 70%. A third configuration, typical for Spain, is evaluated with a south orientation and a GCR of 60%. Both south-oriented solar parks are simulated with

Table 2. Relative annual energy yields of bifacial modules with and without a reflecting foil between the cells compared to the monofacial reference module for three park configurations. The annual open field irradiance is given in column GHI, the diffuse percentage is given in column DHI.

Park design	Country	GCR	GHI [kWh/m^2]	DHI	Transparent BF	BF with reflective mesh	Gain foil
East-west	NL	90%	1040	55%	+0.9%	+1.9%	+1.0%
South	NL	70%	1040	55%	+2.0%	+3.4%	+1.4%
South	ES	60%	1886	31%	+2.2%	+3.5%	+1.3%

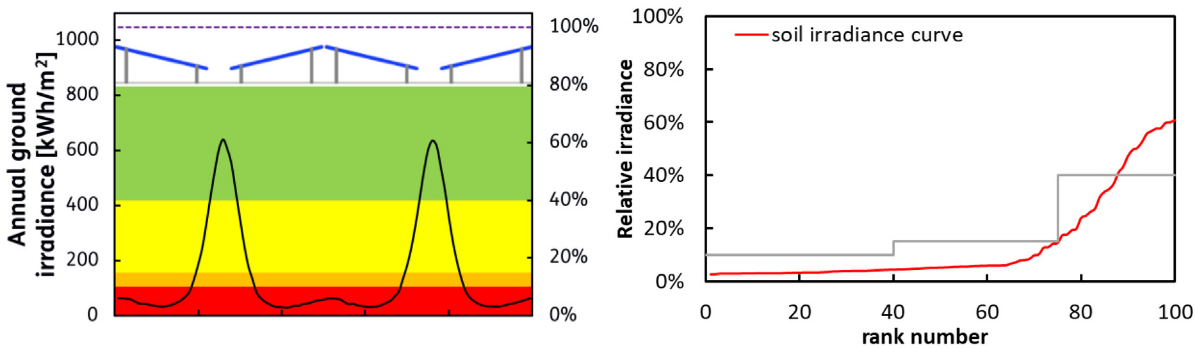

Fig. 4. (left) Cross-section of the soil irradiance using the monofacial module for two repetitive units of the east-west solar park. The dashed line indicates 100% of the annual GHI. The coloured zones represent ranges of the open field irradiance as explained in the main text. Red is <10%, orange is 10-15%, yellow is 15-40% and green is >40%. (right) Rank ordered curve for 100 points, corresponding to one repeated unit of the cross-section (see text for clarification of Rank). The corresponding curve to assess the soil irradiance test criteria is given by the grey line.

three panels in portrait orientation. The albedo value is taken as constant over the year, fixed at 20% for the Netherlands and 25% for Spain. Cross-sections of the three different configurations are shown in Figure 3.

We present the annual energy gain relative to the monofacial module to illustrate the bifacial gains in Table 2. At first glance, the bifacial gains for the bifacial modules with reflective mesh seem rather small, only 2–3% higher than the annual energy yield for the monofacial module. We'd like to stress here that the solar park designs with high GCR, relatively low ground clearance and large tables lead to rather small contributions from ground reflected, "albedo", light due to low ground irradiance levels. Similarly, the low tilt angles lead to low view factors and high angles of irradiance for diffuse light from the sky contributions. The presented bifacial gains are in the same range as the values reported for bifacial gain for fixed tilt and single-axis tracked PV [28]. From Table 2, it becomes clear that the annual energy yield of a bifacial module with the reflecting foil is 1.0–1.4% higher compared to the partially transparent bifacial module, only partially banking on the 2% higher power rating under standard measuring conditions.

The monofacial module and the bifacial module with reflective mesh (white bifacial) have the same conversion efficiency under front side irradiance. Due to the bifaciality, however, the energy yield is 2% higher for the east-west solar park and 3.5% higher for the south-oriented solar park. The partially transparent bifacial module has a 2% lower conversion efficiency than the bifacial module with reflective mesh but also benefits from the rear irradiance. The bifacial gain outweighs the front side efficiency, leading to a 1% higher energy yield for the east-west solar park, compared to the monofacial module and 2% higher for the south-facing solar parks. Despite the gain in power under standard test conditions of 2% due to the reflective mesh, compared to the partially transparent bifacial module, the gain in annual energy yield is only between 1.0% and 1.4%.

3.2 Ground irradiance

The ground irradiance is calculated for all combinations of module type, transparency, and solar park configuration. Figure 4 shows the cross-section of the ground irradiance for an east-west configuration in the Netherlands through two sets of tables relative to the criteria needed to maintain soil quality in solar parks in the Netherlands. The result shows a high irradiance peak on the aisles between the tables. It also shows a much wider and shallower peak underneath the top opening between a west-facing table and its neighbour to the east. The coloured bars indicate the irradiance zones according to the TNO-WUR soil irradiance criteria. Red corresponds with relative ground irradiance <10% and should be absent. Green, >40%, is sufficient for a diverse plant growth and should cover at least 25% of the land. The orange range, 10–15%, should cover less than 40% of the land. The rest of the land falls in the yellow zone with 15–40% relative irradiance.

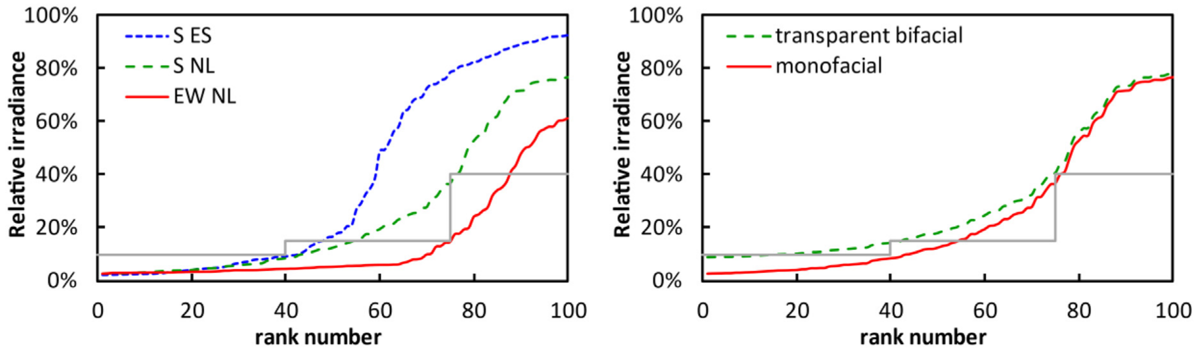

Fig. 5. Soil irradiance test curves. (left) The effect of three solar park designs on the ground irradiance using the white bifacial module. The east-west solar park is labelled "EW NL" and shown with a solid red line; the "S NL" stands for the south-oriented solar park in NL, plotted with long, green dashes; and the south-facing solar park in Spain "S ES" is represented by the short, blue dashes. (right) The effect of partially transparent, green dashes, and fully opaque, solid red line, on the ground irradiance for the south-oriented solar park in the Netherlands. In both graphs, the grey solid line represents the ground irradiance guidelines as proposed for the Netherlands.

Table 3. Irradiance extrema and area fractions in the different irradiance zones for the three park designs times the two transparencies. Min G and Max G are, respectively, the minimum and maximum relative irradiance under or between the solar panels.

Park design	Module	Min G	Area <10%	Area 10–15%	Area 15–40%	Area >40%	Max G
East-West	Opaque	2.6%	71%	5%	12%	12%	61%
	T = 6.6%	8.9%	18%	51%	17%	14%	63%
South – NL	Opaque	2.6%	45%	10%	22%	23%	77%
	T = 6.6%	8.9%	11%	30%	32%	27%	78%
South – ES	Opaque	2.0%	43%	6%	11%	40%	92%
	T = 6.6%	8.3%	16%	21%	21%	42%	93%

One critical criterium to maintain soil quality is that ground irradiance anywhere in the park should be above 10% of the open field irradiance depicted by the red bar in the graph. In Figure 4, it can be easily checked that the monofacial panel would fail the test as the lowest irradiance falls well within the red zone. To assess whether sufficient area of the solar parks receives more than 15% or more than 40% is much harder. We therefore take a representative and repetitive cross-section through the solar park, e.g., two double tables as depicted in Figure 4. We divided 100 points uniformly over this cross-section and plot the corresponding relative irradiances in order of increasing values. Thus, each position gets a rank number, with the position with lowest irradiance the rank number 1, the position with the next lowest irradiance rank number 2, up to the position with the highest irradiance rank number 100. Not only is it then fairly easy to evaluate the ground irradiance profile, one can also directly compare the ground irradiance profiles for different solar park designs. Figure 4, right panel, shows the resulting relative irradiance curve as function of the rank number for the east-west configuration with monofacial modules. Clearly, this densely packed solar park design does not fulfil the ground irradiance criteria.

To show the applicability of the soil irradiance test method, we plot in Figure 5 the comparison for the three solar park design using the white bifacial module and in the right panel a comparison of the partially transparent and the opaque module applied in the south-orientated solar park in the Netherlands.

Figure 5 (left) shows that despite the differences in GCR, in orientation and in location, the relative ground irradiance under the tables, in particular in the darkest regions, is the same for the same module transparency. In contrast, the different module transparencies have little influence on the ground irradiance in the brightest zones as can be seen in Figure 5 (right).

The lowest and highest ground irradiance values, indicated by labels "Min G" and "Max G" and the distribution over the area are summarised in Table 3. The park design – location combination has the largest influence on the highest irradiance and the fraction of the land with high, >40%, irradiance. The transparency, or lack of, determines the minimum irradiance values. We note that despite the present combination of park design and module type does not pass the soil irradiance criteria, the change from monofacial to transparent bifacial module

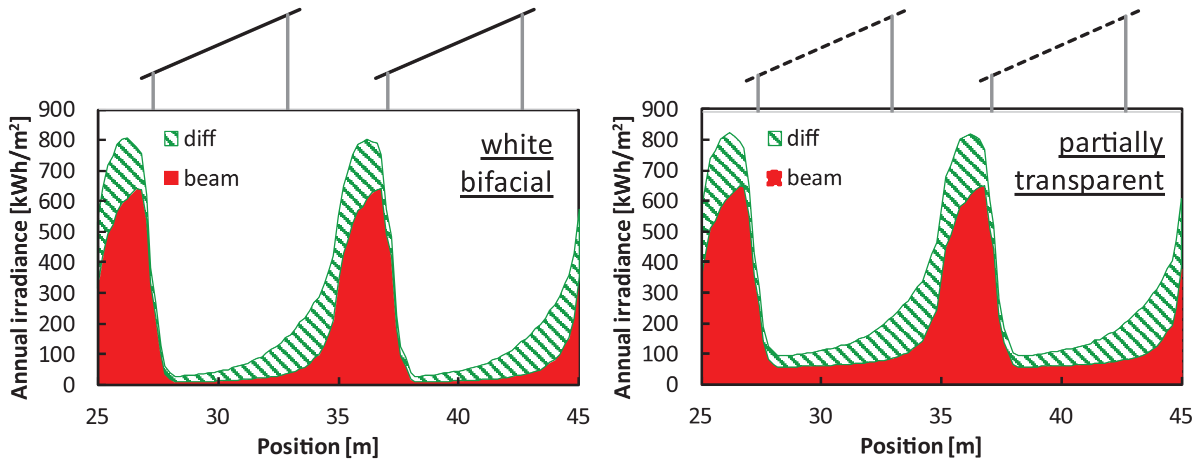

Fig. 6. Calculated ground irradiance using the direct or diffuse fraction for the south-facing solar park in the Netherlands. The solid red area represents the simulation with only the direct "beam" and circumsolar contributions; the simulation with only the indirect "diffuse" fraction of the GHI is given by the striped, green area, stacked above each other. The left hand figure shows the simulation for the white bifacial module, the right hand for the transparent bifacial module. The position of the PV tables is given by the cross-sections above the graphs.

Table 4. Overview of minimum irradiance "Min G", module and system power, specific yield and levelised cost of electricity for a 22-hectare solar park in the Netherlands for different module and table designs. Module sizes are identical.

Module type	Module spacing [cm]	Min G	Module power [W]	Installed power [MW]	Specific yield [kWh/kWp]	LCoE [€/MWh]
Monofacial	0	2.6%	540	31.4	985	58.9
White bifacial	0	2.6%	540	31.4	1019	56.9
Transparent bifacial	0	8.9%	529	30.8	1026	57.0
White bifacial	6.0	8.9%	540	29.5	1025	57.6

design greatly increases the ground irradiance below the PV tables. It clearly allows to consider the effects on both energy yield and soil irradiance.

In Figure 6 we have plotted part of the ground irradiance cross-section for the south-facing solar park in the Netherlands. In addition to the standard meteorological file, we separated the GHI into the two components, viz. beam (and circumsolar) and diffuse. The Erbs method is used to extract the diffuse horizontal irradiance, DHI, from the GHI for each timestep [30]. The global horizontal component, considering only beam and circumsolar, is then given by GHI − DHI, the diffuse component is 0. When considering only diffuse contributions, both global and diffuse components are given by DHI. We note that the sum of the "beam" and "diffuse" ground irradiance for each grid point is identical to the ground irradiance for the original GHI.

We clearly see that the beam irradiance on the soil is mostly concentrated on the aisles. Note that because the beam literally shines underneath the lower (South) edge of the PV tables, the irradiance under the lowest part of the PV tables is almost fully direct. Beyond that first region, the soil irradiance decreases very quickly, to values as low as 2-3% of the GHI. When moving towards the high (North) end under the tables, the gradual increase of "direct" soil irradiance is rather subdued. Therefore, most of the light that reaches the soil under the tables is diffuse.

In the case that the bifacial module is partially transparent, see Figure 6 righthand side, the shape of the curves does not change a lot, but it appears as if all curves are shifted upwards with 5–6%. Looking in detail, the increase in annual ground irradiance is somewhat larger below the tables compared to the aisles.

3.3 Land-use and levelised cost of electricity

Instead of transmitting light through parts of each module, one can also increase the light on the soil below the PV tables by changing the space between the tables, the height of the tables or change the table size itself. However, spacing the modules slightly further apart is closest to current practice. To make a 3P south-facing table with 2281×1152 mm^2 modules as transparent as with a 6.6% transparent module, the spacing between all modules should be 6.0 cm. Consequently, the pitch will increase by 11.7 cm, for this example with a tilt of 15°, and the table becomes 6.0 cm per panel wider. This leads to 6.6% increase in the area required and therefore also in a 6.6% increase in land lease costs. The most common way to determine the value of the generated electricity by a solar park is the levelised cost of electricity, LCoE. It is the sum of the up-front costs to build the solar park plus the annual operating and maintenance costs divided by the sum of the generated energy over the project lifetime. The annual

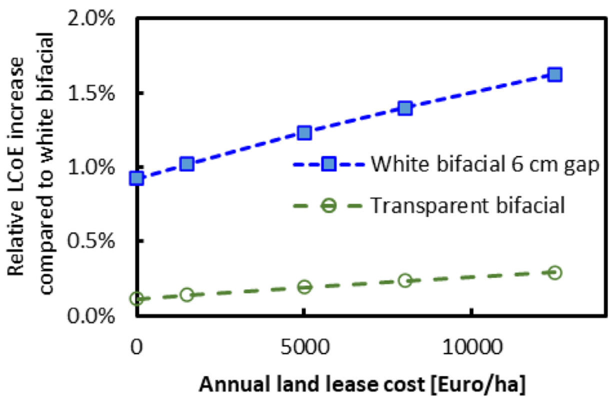

Fig. 7. Effect of annual land lease cost on the LCoE for the two nature-inclusive options. The value given is the relative increase in LCoE compared to that of the white bifacial module solar park design without sufficient ground irradiance. The solar park with transparent bifacial modules has a 0.01 to 0.02 Eurocent/kWh higher LCoE compared to the 5 to 6 Eurocent/kWh for the reference. The solar park with the same white bifacial modules as the reference but including the additional spacing of 6 cm between the modules is 0.05 to 0.10 Eurocent/kWh more expensive.

energy yield is corrected for degradation and the amount of generated electricity and the annual costs are less valuable for each consecutive year, a prevalent financial practice referred to as discounting. The LCoE allows to directly compare energy projects with different time profiles of costs and electricity production like solar, wind, fossil and nuclear.

We have built a cost model based on the work by Vartiainen et al. [31] and determined the LCoE of various design options. One important aspect of that study is that the various cost components are more or less area-related. We updated the values to be in agreement with the 2024 annual advice to the government for solar energy subsidy scheme [32]. We assumed a capital investment of 535 €/kWp, annual operational and maintenance costs of 15.4 €/kWp/year excluding land lease costs, weighted average cost of capital of 6% and land lease costs of 5000 €/hectare/year. The size of the different solar parks was fixed at 22 ha, with a ground coverage ratio of 70%. The results are summarised in Table 4. The module cost in terms of €/Wp are kept equal for all investigated module types.

The LCoE of the solar park based on the incumbent white bifacial module with totally non-transparent tables (i.e., no-module spacing) is only marginally lower than that for the design based on the 6.6% transparent bifacial module. Both bifacial table designs are significantly better than for a monofacial design that has the same ground coverage ratio. Adding 6.0 cm spacing between the modules to give a 6.6% transparent table, increases the specific yield to values comparable to the transparent bifacial design. But the additional space required decreases the installed number of modules by 6.0%, the nameplate capacity by 4.1% and the annual energy yield by 4.2%. Consequently, the LCoE of the 6.6% transparent tables with the white bifacial module and the increased module-module spacing is 1% higher than for the tables with 6.6% transparent bifacial modules. In both cases the minimum ground irradiance is equal and very close to the threshold.

The chosen land lease costs of 5000 €/hectare/year are fairly low for the Netherlands. Higher and more realistic land lease costs up to 8000 €/hectare/year would slowly increase the difference in LCoE. In Figure 7, the LCoE is plotted as function of the land lease cost using either the transparent bifacial module without module spacing or the white bifacial module with 6 cm module-module spacing. These data assume the specific yield and cost components as used for Table 4. For the east-west solar park design the same results are found that the transparent bifacial module yields a lower LCoE than the white bifacial module in combination with the 6 cm module-module spacings.

Two aspects contribute to the increase in LCoE for the solar park with white bifacial modules and 6 cm additional gap. This solar park has 6% fewer panels per unit area. Therefore, the land lease costs per panel are about 6% higher and increases in land lease costs will increase the difference in LCoE. The second contribution comes from all fixed costs and land area related costs in the LCoE calculation, like green management or project management. These costs are also distributed over fewer panels and lower kWh generation. That means that even if land itself is for free, the cost of maintaining that land will lead to an offset in LCoE. In Figure 7, we see that this leads to almost 1% higher LCoE for the white bifacial module solar park with 6 cm gap compared to the transparent bifacial module solar park.

To increase the soil irradiance under the tables, also more distance between the PV tables or higher clearances can be applied. However, these measures are less effective in increasing the irradiance below the PV tables and require therefore even more land. In addition, height increases might be limited by permit restrictions while higher clearances will increase the costs for the mounting structure and require more building materials. Elevating the PV tables does not allow more light to reach the soil but redistributes light from the aisle regions to under the tables.

A more effective option is to decrease the table size and table-table distances. This also redistributes the light and will increase the amount of light in the darkest regions. Smaller tables also mean more tables and therefore increases the costs of mounting poles and foundation.

4 Discussion

To our knowledge this is the first time that the transparency of bifacial panels has been evaluated in terms of soil ecology and profitability for the application of utility scale solar parks. Because the ecological value was not quantifiable, there was no reason for module manufacturers to keep producing partial transparent modules for this type of solar parks. For agri-PV this is different as it sometimes requires panels with much higher transparencies. In the Netherlands the ground irradiance rules have been used; some major parks (200 MWp) that are developed on land owned by the government will only be built if they adhere to these rules. For project developers it is easier to adhere to these rules if partial transparent modules are commercially available.

Alternative solutions are to increase the spacing between modules, lower ground coverage ratios, smaller tables or higher installation heights. These design choices reduce the energy yield per unit area, which is particularly costly for regions with high land lease costs like the Netherlands. For module suppliers this is disadvantages as sales reduces because less modules fit on the same project plot area.

Module spacings should be technically possible with one or two clamps. However, it increases the table size and therewith the park size. In addition, labour costs for mounting will increase when each clamp only holds one module. Although the daily light patterns are different the effect on the annual ground irradiance is very similar to having partial transparent modules. Also, the energy yield per module will not change drastically. Non-transparent modules need to be spaced 60 mm apart to match the effective transparency and ground irradiance of the PV table based on partially transparent modules. This module-module spacing will increase the land usage by 6.6%.

Lower ground coverage ratio will allow more (diffuse) light to pass under the higher and lower end of the table. This can be rather effective for east-west configurations, but the GCR typically will need to be decreased to close to 75% or even lower to pass all soil irradiance criteria. Land usage will increase by about 20% for the same installed capacity. On the plus side, the higher ground irradiance and larger aisles between the modules will have a small positive effect on the annual energy yield and bifacial gain. However, GCR alone does not account for the full impact of the shading by the PV tables and, consequently, the amount of light available for photosynthesis. For example, with the same GCR, the soil between vertical panels receives more light than those under a fixed tilt system. This difference becomes even more pronounced if the panels are mounted on single-axis trackers. This one of the main reasons to propose norms based on ground irradiance conditions rather than using GCR as a norm.

Smaller tables and accordingly scaling all distances and heights, will effectively distribute the available ground irradiance more evenly. This is easiest understood by the two extremes in a Gedankenexperiment: putting all modules in a single large table will give one big area with very little ground irradiance and another area without any panels with open field irradiance. The other extreme we can think of is to make the tables and spacings very small. This creates a shadow net with a light interception comparable to the GCR and the remaining light is distributed homogeneously over the full area. For realistic table sizes, the trend at constant GCR is maintained: larger tables and spacings lead to darker shaded regions and brighter illuminated regions; smaller tables and spacing will increase the irradiance in the shaded regions and reduce the irradiance in the illuminated regions. Therefore, ground irradiance rules based on GCR limits or that prescribe a minimum distance between the tables are not sufficient. One can comply with the rule but the resulting ground irradiance distribution could still have negative effects on part of the soil.

Higher installation heights will redistribute the light. It will intercept the same amount of diffuse and direct light. But the combined illumination pattern of direct and diffuse light will change. The indirect shading will become larger and more diffuse the higher the table is above the soil. But it will remain centred around the object. The direct shading will be cast further and further from the PV table with increasing height. One cannot say, without knowing the details and running the simulations whether a height increase (or decrease) will be beneficial or detrimental in terms of passing or failing the soil irradiance criteria.

In absence of transparent bifacial modules, it is clear that adapting the solar park design to improve the conditions for photosynthesis by the vegetation will increase the investment costs and/or land lease. There is little to no incentive for a solar park developer to do so. The relevant authorities should supply sufficient legislature or permitting guidelines to drive designs that maintain sufficient irradiance and photosynthesis on the entire area of the solar park. Solar parks that apply partially transparent modules have the direct benefit of sufficient ground irradiance with no or smaller adaptations to the solar park design.

While the ground irradiance norms could potentially change because of progressing scientific understanding of the slowly changing soil quality, the principles are robust to these changes. The trade-off between gaps and transparency will chance the absolute cost of the system but does not change the most economic choice. In the case with the gaps between the modules, the gaps replace highly efficient module area. In the other case, the white mesh area, that has a factors lower efficiency compared to the module efficiency, is removed. This means that it is always more efficient to remove the mesh than to increase the gaps.

Irradiance can reach the ground below the PV tables either by passing between the tables and under the edges of the PV tables or via the transparency of the PV table itself. Typically, the soil in the aisles between the PV tables receives enough irradiance to maintain a lot of plant growth. However, this plant growth can partially "close" the opening between the table edges and the ground. This way, the ground irradiance below the PV table will be further reduced. Basically, because of the plant growth, the effective height of the PV system will be lowered, thereby concentrating the light even more in the aisles and the shading even more under the tables. Transparent panels have the advantage that the ground irradiance below the panels becomes less dependent on vegetation growth and maintenance surrounding the tables.

The arguments are not only valid for countries like the Netherlands. In Figure 6 we showed the division of the ground irradiance in diffuse and direct (beam plus circumsolar) parts. It showed that the regions with the lowest irradiance were receiving mostly diffuse light, about 70%. The meteorological data that we used for the Netherlands had a beam:diffuse division of 45:55%. In sunbelt regions, the GHI will be much higher, but the diffuse fraction much lower. For example, the weather file we applied for the simulation of the solar park in Spain has a 69:31% beam:diffuse distribution. That means that even in countries where the open field irradiance is too high for optimal photosynthetic conditions, the soil irradiance under PV tables might end up being (too) low. So also, in regions with high annual irradiance levels and many clear sky days, but low amounts of diffuse light, the advantages of partially transparent panels that transmit both direct and diffuse light for soil irradiance are obvious.

We note that another element to consider is the cost of the additional foil, both in terms of the costs of manufacturing, but also the lifecycle impact of manufacturing, productive lifetime and recycling, which requires further research. If this leads to a 1% lower module price, the LCoE of the transparent bifacial module will be on par to that of the incumbent white bifacial module. A poorly designed or manufactured reflector foil can even reduce the rear side efficiency and bifacial gain when the reflective mesh partially overlaps with the rear side of the solar cells.

Increasing the gaps between non-transparent bifacial modules to adhere to the irradiance rules, defies the very purpose of inserting the reflective mesh in the first place as the higher front side efficiency does not result in a higher energy output per land area and requires longer interconnection cables. It is counterintuitive that a higher module efficiency under standard test conditions leads to a lower energy yield per hectare and a higher LCoE. We have shown that the LCoE of the transparent bifacial table design is 1% lower than for the incumbent non-transparent bifacial table with additional gaps between the modules. Moreover, the project developer will purchase 6% fewer non-transparent modules per project owed to the larger footprint of the table design. Given the fact that the LCoE of a transparent module is only 0.2% higher than the incumbent white bifacial one, the transparent option will be business-wise preferred when priced at least 1% lower, even in absence of ecological constraints. These arguments amount to good reasons for module manufacturers to keep the partial transparent bifacial module in their product portfolio for utility scale solar parks.

5 Conclusion

We present for the first time a method to evaluate the trade-off between soil irradiance and energy yield, related to table configuration and module choice, for utility-scale solar parks. The definition of ground irradiance thresholds to maintain soil quality is essential for this approach. To ensure sufficient light for photosynthesis, initial thresholds for irradiance have been drafted by TNO and Wageningen University and Research for the climate conditions in the Netherlands. Based on these rules, we present an approach to investigate solar park designs that meet these requirements. This commands an optimisation of the module transparency and the size and relative position of the PV tables, to minimise the costs.

To illustrate this optimisation, we have simulated the annual energy yield and ground irradiance and calculated the effect of design options on the levelised cost of electricity. We considered the module transparency and gaps between the modules. Compared to partially transparent bifacial modules, the implementation of the reflective mesh in these bifacial panels gives an 1% to 1.4% increase in annual energy yield but reduces the soil irradiance. Surprisingly, in absence of ecological constraints, the LCoE of the transparent module is only 0.2% higher than the incumbent white bifacial one. A 1% lower price for the transparent module will bring it on par with the white bifacial. The remaining irradiance is mostly composed of diffuse irradiance. However, a 6.6% partial transparency increases the irradiance in the darkest regions by 65% of the threshold light intensity required to maintain soil quality. To achieve the same below non-transparent panels, the footprint of the solar parks needs to be increased, mainly adding land lease costs. This corresponds to an increase in LCoE of 1%. In addition, the manufacturing with a reflective mesh requires more effort while its impact on recycling needs further research.

Intuitively, one would think it is more profitable to apply white, bifacial modules with higher standard test condition, STC, efficiency to generate additional power as compared to more transparent, bifacial modules with lower STC efficiency. But when ground irradiance criteria have to be met, the non-transparent bifacial modules have to be positioned some distance apart to maintain soil quality. So, despite the actual higher front power of bifacial modules with a reflective mesh, the energy yield per hectare is lower. This leads to a higher LCoE than for a system with the transparent, bifacial modules when ground irradiance thresholds are maintained.

In summary, this work shows the importance of partial transparency of bifacial modules to maintain the soil ecology and profitability of utility-scale solar parks in the Netherlands and likely elsewhere, thus contributing to societal acceptance of renewable energy projects. Therefore, we appeal to relevant authorities to supply adequate legislature or permitting guidelines to maintain sufficient irradiance and photosynthesis on the entire area of the solar park. Furthermore, we urge module manufacturers to consider the value of the transparency of bifacial modules and keep them available for the application of solar parks characterised by high ground coverage ratios and/or large PV tables to lower the cost of nature-inclusive solar park designs.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

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

Author contribution statement

Conceptualization, KC and BBVA; Methodology, KC and BBVA; Software, BBVA; Validation, KC and BBVA; Formal Analysis, BBVA; Investigation, BBVA; Resources, KC and BBVA; Data Curation, BBVA; Writing – Original Draft Preparation, BBVA; Writing – Review & Editing, KC; Visualization, KC and BBVA; Supervision, KC; Project Administration, KC; Funding Acquisition, KC.

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