COMBINING PV AND FOOD CROPS TO AGROPHOTOVOLTAIC – OPTIMIZATION OF ORIENTATION AND HARVEST

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ABSTRACT: Presently ground mounted PV plants and food production are perceived to conflict with each other. This conflict can be resolved by the concept of Agrophotovoltaics (APV), the combination of PV and agriculture at the same plot. This concept has received little attention although it was proposed long ago. We started by investigating plant growth under existing PV installations and found that many species of natural plants grow quite well under these conditions. From those studies conclusions can be drawn which crops can be cultivated together with PV. Three categories could be identified: Crops that benefit from some shading, crops that are not much influenced and crops that depend on maximum irradiation and are not suitable for APV. We also developed a simulation program that calculates global radiation at ground level inside rows of modules. A major result was that the conventional installation towards south leads to persistent shade and uneven ripening of crops. A solution is to orient the arrays towards south east or south west. A preliminary experiment with salad was carried out confirming these results. The realizable potential for Germany in a conservative estimate was found to be 53 GW which is equal to the official goal for 2020. Much more potential can be expected for arid and semiarid regions.

Keywords: Large grid-connected PV systems, Photovoltaics and agriculture, Optimal orientation of arrays, Categories of crops, Agrophotovoltaic

1 INTRODUCTION

During recent years many ground mounted, mainly grid connected photovoltaic (PV) plants were erected. Alone in Germany there are 5 GW_p installed in 2011 [1]. Due to economics of scale effects, these plants deliver electricity at significantly lower costs than smaller roof mounted systems. So far mainly unproductive spaces like former waste deposit sites or former military training grounds were utilized, but also agriculturally productive fields were employed. The present practice precludes further agricultural production other than pasture for sheep because the arrays are too close to each other and mounted too close to the ground.

Recent legislation in some countries like Germany and Italy specifically excludes agricultural lands for PV because of a perceived conflict between PV and food production.

It is the purpose of the present paper to demonstrate that agricultural cultivation of a large variety of plants and energy production with PV can occur simultaneously. In this manner the above conflict can be avoided and at the same time the potential of PV power generation is greatly increased. Another purpose is to identify plants that can optimally be grown in combination with PV and optimize both PV output and agricultural yield. We carried out extensive simulations of radiation availability for plants under different array configurations, studied plant growth under present PV plants and did also an intensive literature review concerning the shade tolerance of agricultural plants in the temperate latitudes [2].

The history of this concept is a long one. Already in 1982 we published a theoretical study [3] showing that there is enough radiation underneath PV arrays to permit cultivation of many different crops. Since the panels have to be installed at a certain distance to prevent shading particularly in winter, much solar radiation reaches the ground during the growing season. At the time of the first publication a larger inclination of the modules (about equal or somewhat less than geographic latitude) was customary than today. Other publications appeared during the years [4], [5]

Today, at least in moderate climates, practical evidence for the fundamental feasibility of this approach is the abundant growth of weeds under existing ground mounted PV installations and the fact that unwanted vegetation has to be controlled and is thus contributing to maintenance cost.

Only in recent years this concept that we now call Agrophotovoltaic (APV) has attracted more interest. In southern Bavaria M. Guggenmos has experimented with wheat and vegetables and obtained under his non optimized PV plant very good results [6].

A very comprehensive study including an actual experiment in the south of France appeared recently [7]. The authors developed a model for radiation intensity within a PV field including boundary effects. Two different values of ground cover by the panels were evaluated. They also estimated the influence of shade on crop yield using existing models from agroforestry (interspersing crop areas with trees). They applied the concept of LER (Land Equivalent Ratio) that originally had been developed to quantify yields of mixed agricultural systems, like the combination of different crops, or trees and crops, to the combination of PV with crops. LER is defined as:

$$LER = \frac{Yield\ of\ plants_{APV}}{Yield\ of\ plants_{no\ PV}} + \frac{Electricity\ yield_{APV}}{Electricity\ yield_{only\ PV}}$$

For different boundary conditions they obtained very attractive LER values between 1.35 and 1.73.

Interesting is also the combination of PV and energy plants because PV has a much higher conversion efficiency than photosynthesis but biomass is storable and therefore complements the weather and seasonal dependence of PV.

2 INVESTIGATION OF PLANT GROWTH UNDER EXISTING PV INSTALLATIONS

In an initial study plant growth under established PV installations was evaluated. Three PV plants with different geometries were investigated. The main findings were:

- There is abundant growth of natural vegetation under and between modules suggesting that also food crops could grow under suitable conditions
- Mainly plants tolerant of shade grow within PV plants
- Humidity is high throughout the area but in particular directly underneath modules indicating sufficient rain and low evaporation
- Light and humidity are more uniform if the modules are higher above ground

It was found that dependent on the elevation of the modules two or three different biological zones could be identified. Vegetation in Zone 1 indicated low irradiance but sufficient humidity levels - the latter due to low evapotranspiration conditions. Optimal growing conditions, which mean regular light exposure and simultaneously sufficient soil moisture, were available in Zone 2. Zone 3 showed highest irradiation and lowest humidity levels due to high evapotranspiration. As an example the installation with three zones is shown in Fig. 1.

Fig. 1 Three zones of vegetation, modules close to ground shown at an existing non-APV site.

3 SELECTION OF POSSIBLE CROPS FOR CENTRAL EUROPE

There is very little information about the shade tolerance of agricultural plants of temperate latitudes [7]. Nevertheless very general recommendations about the more suitable crops can be given. It is obvious that plants with very high radiation demand (C4 plants like corn) are not a good choice. Based on available information a large number of crops were divided into three categories in respect of their yield under shading conditions:

1. + positive effects are dominant: higher yield
2. 0 no significant change: equal yield
3. – negative effects dominate: diminished yield

A few examples of plants that were investigated and categorized are captured in the table below.

Table 1 Examples of plants within each growth category.

Category:		
–	**0**	**+**
Corn (Maize)	Rape	Potatoes
Wheat	Rye	Salad (all kinds)
Horticulture	Oats	Spinach

Our present evaluation has been carried out under existing, ground mounted PV plants. We suggest verifying these preliminary results by field experiments with optimized elevated PV systems. Nevertheless it can be stated that a significant number of crops grow better under some shade, an even larger one is not seriously affected in yield. This results in a large potential for PV area that will be quantified in a later part of this paper.

4 CALCULATION OF RADIATION UNDERNEATH DIFFERENT ORIENTATIONS AND HEIGHTS OF ARRAYS

In order to provide the theoretical foundation for future pilot projects a generally applicable program was developed that permits calculation of radiation at ground level with different parameters such as inclination, elevation, orientation and spacing of arrays.

For this calculation the ray tracing software Radiance [8] was used. A 100 x 100 m^2 module field was simulated. The arrays consisted of standard modules of 1m width. The spacing between the arrays was varied from 2.5 m to 7.5 m, the elevation referred to lower module edge was either 2 m or 4 m. Radiance reads values of horizontal direct and diffuse radiation from a satellite based data set in half hour steps for all daylight hours of the year 2000, altogether 8,900 time steps. For every step the radiation in kWh/m^2 at 10 cm above ground is calculated along a profile perpendicular to the arrays from the front edge of one module to the next module in the middle of the field. The results are therefore not subject to boundary effects. Location in all cases is Freiburg, Germany, module inclination is 25°. Fig. 2 and Fig. 3 present results for two configurations oriented directly towards south.

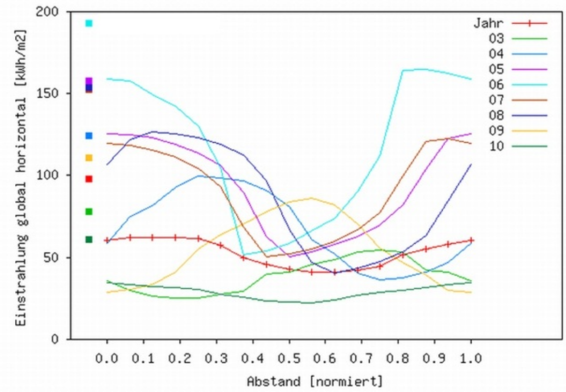

Fig. 2 Monthly sums of horizontal global radiation (kWh/m^2) vs. normalized distance between two rows, elevation 2m, spacing 2.5m, orientation south.

The x-axis is normalized from the beginning of one array to the same point of the next one, to the left is south. The y-axis shows the monthly sums of normal global radiation arriving at ground level. The curves depict all relevant months, including the full year (divided by 12 to fit in the graph). The squares on the left side represent the monthly sums of unobstructed global radiation.

In both Figures a significant dip in irradiation behind the module rows can be identified during the summer months. This shade is relatively insensitive to elevation and spacing of the rows. The explanation is very straightforward: During the summer months the solar orbits remain relatively close to solstice. Therefore the shade occurs always in approximately the same direction. Since the solar rays are parallel, the effect is also not very dependent on elevation of the arrays.

On the other hand the uneven radiation exposure is deleterious for plant harvest because the effect occurs during the main growing season. The plants are not ripening at the same time.

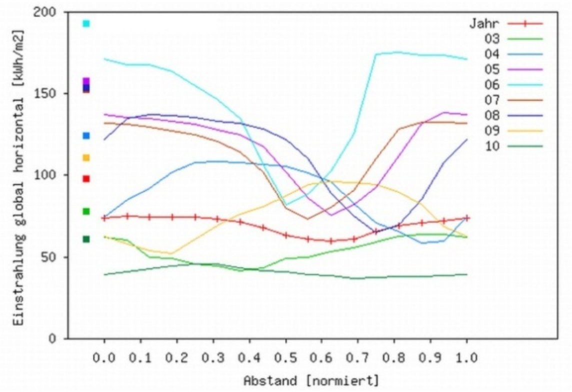

Fig. 3 Monthly sums of horizontal global radiation (kWh/m^2) vs. normalized distance between two rows, elevation 4 m, spacing 4 m, orientation south.

A solution for this problem is demonstrated in Fig. 4 and Fig. 5: If the arrays are not oriented directly south but rotated towards southeast or southwest, the radiation on ground level becomes very uniform. The reason follows from the explanation given above.

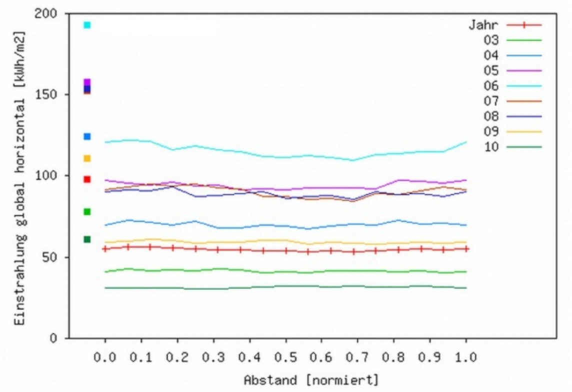

Fig. 4 Monthly sums of horizontal global radiation (kWh/m^2) vs. normalized distance between two rows, elevation 2 m, spacing 2.5 m, orientation southeast.

So we conclude that for best results the orientation of arrays in an Agrophotovoltaic system should not be directly south but towards southwest or southeast. Electricity yield will decrease by less than 5% due to this suboptimal orientation.

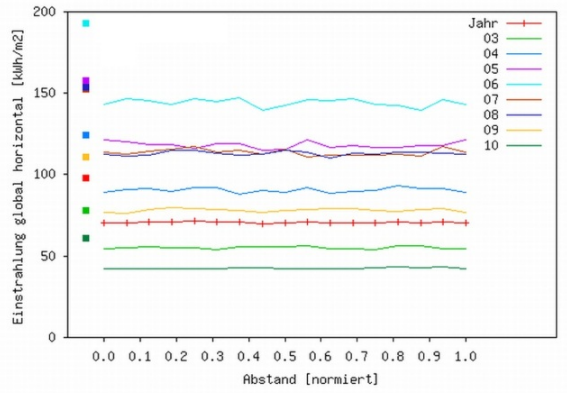

Fig. 5 Monthly sums of horizontal global radiation (kWh/m^2) vs. normalized distance between two rows, elevation 4 m, spacing 4 m, orientation southeast.

5 INFLUENCE OF SHADE ON CROP YIELD AND PRELIMINARY EXPERIMENT

Using radiation data obtained from the simulations together with agricultural data the crop yield in dependence of PV spacing can be obtained. Fig. 6 shows relative biomass yield vs. photosynthetic active radiation (PAR), which corresponds approximately to the spectral range of global radiation visible to the human eye, for the three categories defined above.

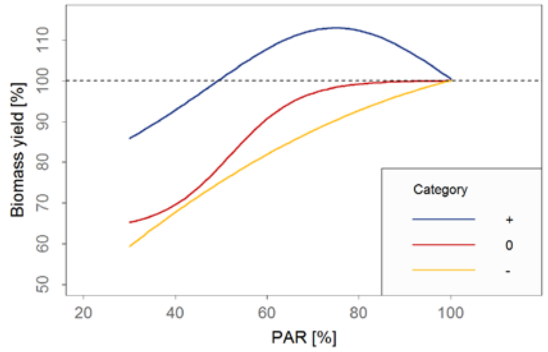

Fig. 6 Relative biomass yield of three categories of shade tolerance of crops vs. photosynthetic active radiation (PAR) which is proportional to global radiation.

The following conclusions can be drawn from Fig. 6: Plants of category “+” show at first a gain in yield with increasing shade and only with about 50% shading drop below the reference level. Plants of category “0” remain relatively flat until 70% shade and then drop significantly, whereas plants of category “–“ drop nearly linearly even at low shading.

A preliminary experiment was carried out in Weihenstephan near Munich. With salad plants a good result was obtained under a mock-up module row (Fig. 7).

Fig. 7 Salad plants growing under mock-up module row.

4 SYSTEMS AND ECONOMIC CONSIDERATIONS

Only fixed mounted systems are considered in this paper although the principle can also be applied to tracking systems.

The basic requirements for an APV system are:

- Sufficient space and elevation to enable cultivation with mechanical equipment
- Selection of suitable crops from categories + and 0
- Orientation and spacing of rows adapted to the crops to be grown, including crop sequences
- Appropriate boundary conditions for PV such as grid connection and demand in the neighborhood

The output of APV plants may be optimized in different ways. The Land Equivalent Ratio (LER) evaluates separately electricity and biomass. We find LER of 1.9 for optimal conditions such as summer crops of category "+" plants and 1.8 for winter crops. Also for plants of category "0" values of 1.6 to 1.75 are found. When looking at the economic side, however, it turns out that LER is not a suitable gauge because it compares quantities of different value. In other words, under present conditions electricity provides much higher returns than agricultural products.

Among other, the economic calculation has to take the following items into account:

- Feed-in tariff for electricity or value of other incentives provided
- Wholesale electricity price
- Value of directly on-site consumed electricity or retail electricity price
- Value of crops produced simultaneously
- Additional cost of support structure mandated by soil cultivation
- Cost of capital

In Germany, with current PV market conditions (even if APV was applicable to ground mounted PV) Feed-in Tariff first estimates result that only under optimistic conditions APV might be economical. One reason is that in an example calculation agriculture provides only 14% of the entire economic return. But circumstances are likely to change in the future: Food prices are increasing, so farm income per area should rise, and at the same time the cost of PV continues to go down. This is expected to lead to a more equivalent value of the two outputs.

6 POTENTIAL OF APV

Finally, APV potential was estimated for Germany. Germany is a densely populated country with a relatively small agricultural land area. So it can be considered a conservative example compared to less populated countries.Three types of potential were estimated, the theoretical, the technical and the realizable potential. The theoretical potential is the maximum potential without any constraints. In our case it is based on the total agricultural area of Germany. The technical potential is limited to crops of category + and 0 (of the latter only summer cultures) and the realizable potential considers further practical restrictions. In a very approximate manner it is estimated to be 10% of technical potential.

For the installed power a spacing of 3.5 times module width was assumed. This yields an installed PV power of 430 kW_p/ha. The three potentials are summarized in Table 2.

Table 2 Estimated PV power potentials for Germany.

Potential type	Boundaries	Power per area [kW_p/ha]	Area [Mio ha]	Potential [GW_p]
theoretical	entire agricultural area	430	13.45	5784
technical	crops of category + and 0	430	1.24	533
realizable	10% of technical	430	0.24	53

The realizable potential is still very large if considered in the following context: The German Government has decided that the final installed PV power should be 52 GW_p by 2020. So APV could double this power. Quite likely 52 GW_p will not be the limit. Other estimates [9] find that 200 GW_p will be required.

The main objective of this paper was to investigate the application of APV in Germany, but the importance of APV in other parts of the world may be much larger. Worldwide 30% of all energy is consumed for agricultural purposes [10]. Nevertheless in many developing countries large parts of the population do not have access to affordable energy. Furthermore, much fresh water is often used for irrigation purposes in these areas though its availability is already limited. APV can contribute to solve the conflicts mentioned above.

In many arid and semiarid regions a large number of food crops suffer from radiation, heat and evaporation stress and would benefit from partial shading. Even plants that would normally not grow in these regions could be cultivated under PV modules. PV generates much more energy per area than is needed for desalination and irrigation. This energy is available for other purposes, for instance to replace diesel generators. In many cases APV is economical today if electricity is sold at its real price and not subsidized as it is unfortunately in many countries.

APV also has good chances in tropical and semitropical regions because many plants like bananas, coffee, tea and many others are cultivated under trees since they do not tolerate too much radiation.

8 SUMMARY

The concept of APV is the production of agricultural commodities under PV modules. The paper at hand analysed simultaneous production of biomass, e.g. food crops and electricity. Biomass and electricity are generated at the same time. In this manner the conflict between energy and food production can be alleviated. We studied the application of APV in Germany and assume its global potential to be very large, in particular within arid climate zones. We determined optimal conditions for combined harvest. A simulation program for radiation at ground level with shading by modules was developed. The most interesting result was that the conventional orientation of rows towards south leads to uneven ripening of crops. A possible solution is to orient the modules towards southeast or southwest.

Boundary conditions for APV in Germany were investigated. Possible crops to be grown under PV must be shade tolerant. A considerable number of such crops could be identified. The crops could be divided into three categories: + benefits from shade, 0 shows no influence at some shade, and – is shade intolerant. An optimal geometry of the installation was determined and the potential for Germany was evaluated. The major result is that a very conservative realizable potential is 53 GW_p which is equal to the official goal for installed total power in 2020. Even more potential exists for arid, semiarid and tropical regions.

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