AgriVoltaics World Conference 2023
PV System Technologies
https://doi.org/10.52825/agripv.v2i.986

Published: 23 May 2024

Key Advantages of Agrivoltaic Systems in Germany – A Comparison of the Electricity Yield of Different Systems

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Abstract. In addition to food production, energy can also be produced on agricultural land. This can lead to land use conflicts and often results in political discussions. As the energy transition progresses, the area required for renewable energies is increasing, leading to more land use conflicts. Agrivoltaics (APV) allows for continued farming alongside solar power production, providing a solution to this conflict. In this analysis, the land energy yields of different APV concepts were compared with those of other renewable energies. The results show that wind and PV can produce the most energy on land, regardless of whether the sectors are electricity, heat or transport. When considering different APV concepts on cropland, it is important to consider which area is being evaluated. A distinction can be made between the PV-system area (the visually influenced area in the landscape) and the loss of farmland. Depending on the perspective, the concepts have different advantages. The APV vertical concept enables 3 times more electricity production per loss of farmland compared to a conventional ground-mounted PV system. However, in relation to the PV-system area, the electricity yield is only 1/3 of this. The APV horizontal concept has the highest electricity yields per area of loss of farmland. The APV 3D tracing system has the highest electricity yield of all APV concepts per PV-system area. Initial economic analyses show that higher energy yields per loss of farmland are accompanied by higher costs for APV systems. These results can be used for political advice.

Keywords: Energy Yield, Advantages, Agrivoltaics, Germany, Renewable Energies

1. Introduction

One of the biggest global challenges are a) securing the world's food supply and b) restructuring energy systems to limit climate change [1]. One possible approach to addressing these conflicts is through the use of agrivoltaic (APV) systems, as demonstrated at recent agrivoltaics conferences. APV can reduce the loss of arable land for electricity generation with photovoltaics by allowing for dual land use. APV also provides the possibility of protecting cultivated plants. In Africa, the shading provided by solar modules is a key advantage and often enables the first agricultural use of land that would otherwise be unproductive due to heat and water limitations [1]. In temperate zones such as Germany, these benefits are less pronounced. Here, protection from extreme weather events such as hail is more important. However, plant protection is only one of the advantages of APV. In Germany, another aspect is of key relevance [2].

In Germany, land is scarce. For this reason, the political goal has been announced that the conversion of agricultural land should be greatly reduced in the future and even brought to net zero. The need for land for renewable energies, which will be necessary for the transformation of the energy system, is the subject of many debates in Germany. In this context, photovoltaic electricity generation on agricultural land is of particular relevance.

To demonstrate the decisive advantage of APV systems, energy yields per hectare farmland can be used as an indicator of land use efficiency. For targeted political advices, it is therefore of particular interest to know how much energy different renewable energies produce per hectare and year and what opportunities arise with the different APV concepts. For a comprehensive comparison, the levelized costs of electricity (LCOE) of the different systems should also be considered.

Against this background, this paper focuses on the research questions:

1. Can APV help to reduce land-use conflicts?
2. How do energy yields differ between the systems?
3. How high are energy yields of APV systems compared to other forms of renewable energy?

2. Material and Methods

The study compares the area energy yields of four different APV concepts (see figure 1) with existing renewable energies in Germany. The following APV-systems are considered (starting with upper right):

- APV vertical: The modules of this system are built vertically, agriculture is possible between the rows. Around the module structure, a distance of about 1 metre is no longer feasible for intensive agricultural crop production. See also [3].
- APV horizontal: This concept is elevated 5-6 meter above the ground to enable common agricultural machinery to farm below the modules. See project APV-Resola [2].
- APV 2D tracking: This system is tracked in two dimensions. Farming is possible between and below the modules.
- APV 3D tracking: This concept is tracked in three dimensions and thus enables the highest energy yield per installed capacity. The system uses cable wires for stabilisation. See also [4].

Figure 1. The different observed agrivoltaic concepts.

The data were collected by a literature review. As only limited literature is available the main source for the data were expert interviews with various plant designers and planners of the four APV concepts. The focus where on the installed capacity per hectare, the percentage of loss of farmland, and the costs of installed capacity. We calculate the area-related energy yields, considering the range of solar radiation in Germany and different facility sizes. We compare the energy yield with focus on electricity, heat and mobility. To compare the results regarding the energy yields with other common renewable energies the data of Böhm [5] is used.

The results depend on the different land perspectives. We consider the following two dimensions:

1. PV-system area: this area describes how much area is visually affected in the landscape. In addition, it is the area that must be politically approved and is usually fenced off for insurance reasons in Germany.
2. Loss of farmland: In the case of APV most of this area can still be used for agricultural production in between or below the modules. The area only includes this actual loss of farmland.

The difference between ground-mounted PV and APV and both area perspectives is explained in figures 2 and 3. For ground-mounted PV, the PV system area is equal to the loss of farmland. With APV, the PV system area is generally larger than with ground-mounted PV for the same electricity yield. However, the loss of farmland only corresponds to the strip that can actually no longer be used for agriculture (see also fig. 3).

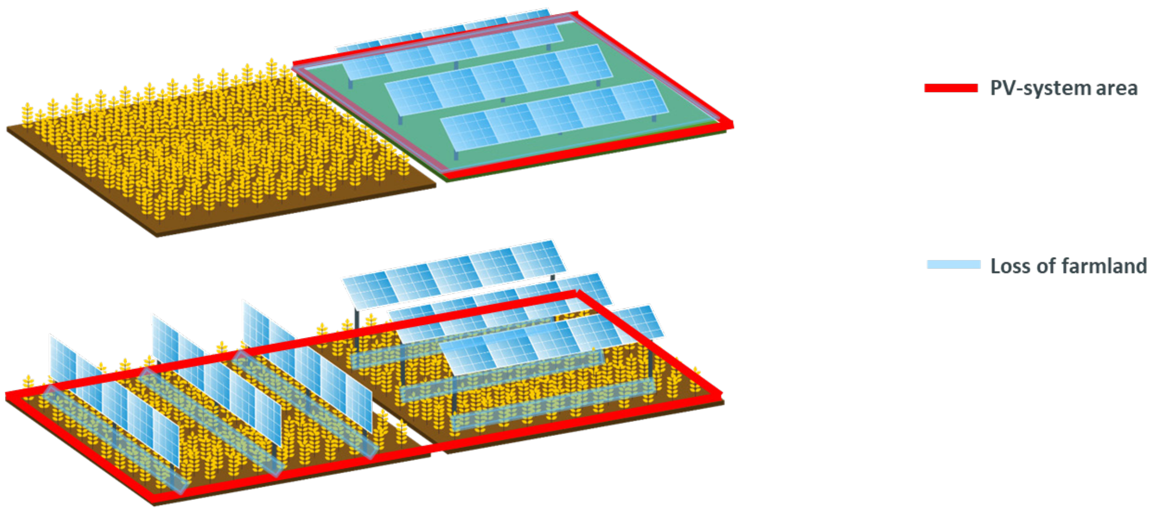

Figure 2. Different area perspectives for ground-mounted PV and APV.

Figure 3. Image to highlight the loss of arable land through a vertical APV concept.

3. Results

When comparing different APV concepts with ground-mounted PV systems on arable land, it illustrates how important the correct area reference is. It becomes clear that when comparing the installation area, conventional ground-mounted PV systems can generate significantly more electricity per hectare than the APV concepts (see figure 4). If, on the other hand, it is considered that a large part of the area is still available for intensive agricultural production and is not required for the system, then the APV concepts have a clear advantage (see figure 5). If the perspective is on the area that can no longer be used for agriculture due to the module mounting, which is 8-15% depending on the concept, significantly more electricity can be produced than with a standard ground-mounted PV system. The horizontal APV concept does not have the highest electricity yields per installation area, but in relation to the actual loss of farmland, the electricity yield is the highest. The APV vertical concept enables 3 times more electricity production per loss of farmland compared the ground-mounted PV system. If you look at the PV-system area, the electricity yield is only 1/3 of the yield from the ground-mounted PV. The APV 3D tracing system has the highest electricity yield of the APV concepts if looking at the PV-system area.

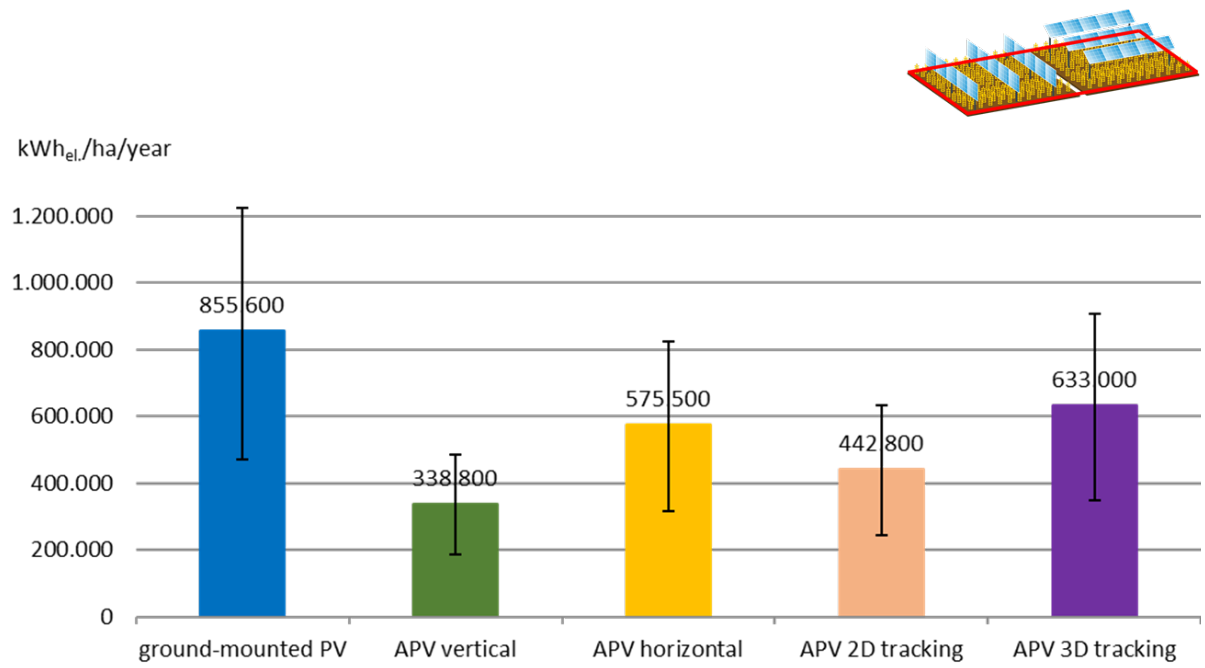

Figure 4. Comparison of the electricity yield per hectare of PV-System area between different APV concepts.

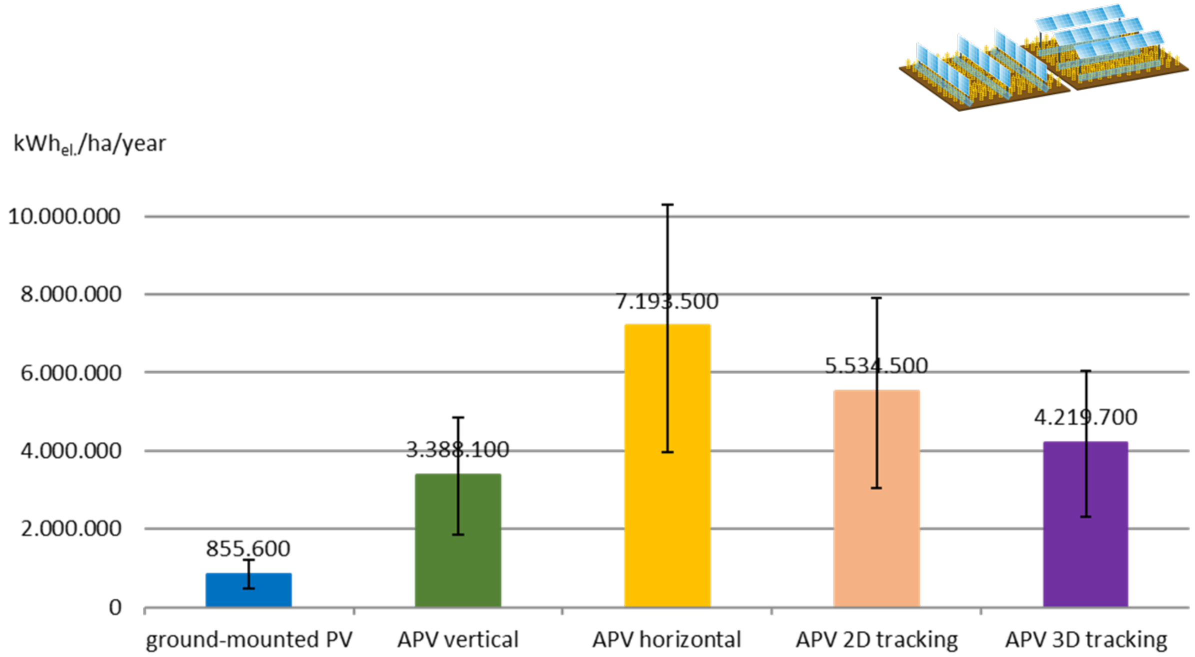

Figure 5. Comparison of the electricity yield per hectare of loss of farmland between different APV concepts.

According to the results of Böhm [5] we can compare the different energy yields for the sectors of electricity, heat and mobility with other common renewable energies. In addition to PV, electricity can also be produced with biogas from maize silage and with wind turbines. If the loss of land for food production is taken into account, the possible electricity yield (Fig. 6) differs greatly. Ground-mounted PV can produce over 20 times more electricity than biogas from maize silage, even if the waste heat is converted into electricity using an OCR (Organic Rankine Cycle) process. With APV, significantly more electricity yield is possible. By far the most electricity per loss of farmland can be produced with wind turbines, even if storage losses are taken into account.

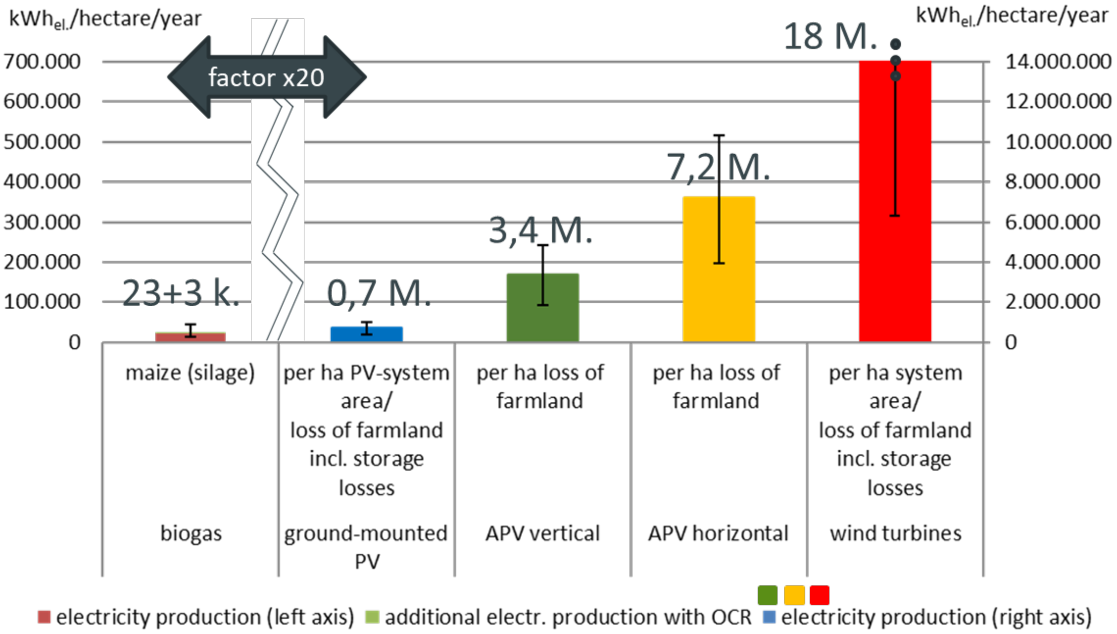

Figure 6. Comparison of the electricity yield per hectare between common renewable energies in Germany.

If the heat yield of the area is compared (Fig. 7), a similar picture emerges. If the waste heat of a biogas plant and the electricity that is converted into heat with heat pumps is considered, over 100 times more heat can be produced if an APV vertical plant is built and the electricity is used in heat pumps. The APV horizontal concept shows about twice as high heat yields per loss of land for food production.

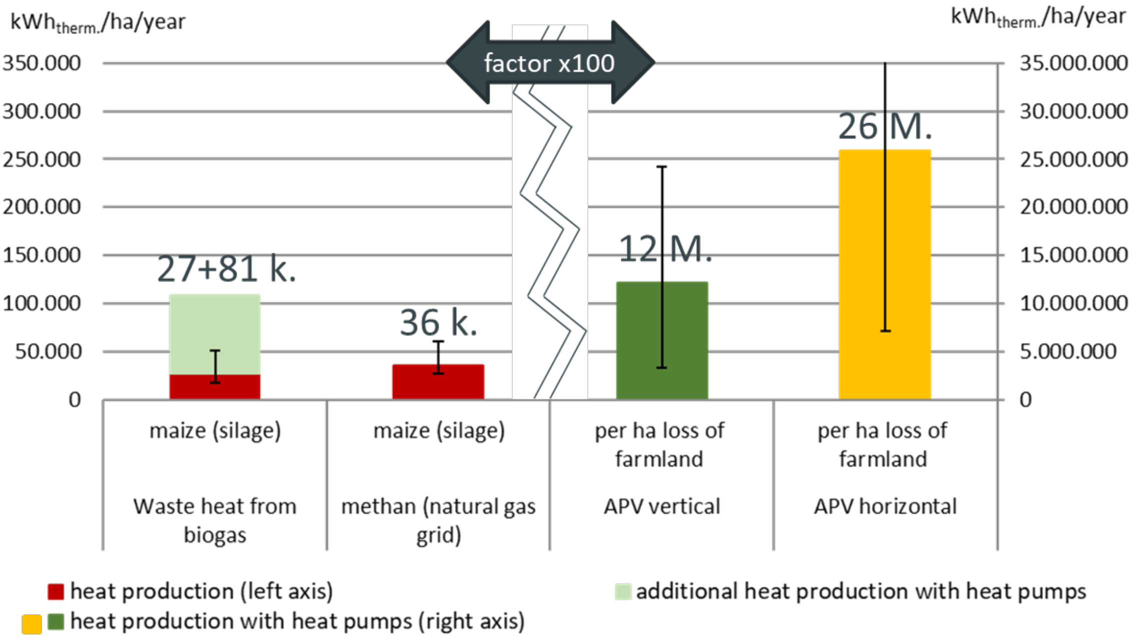

Figure 7. Comparison of the heat yield per hectare between common renewable energies in Germany.

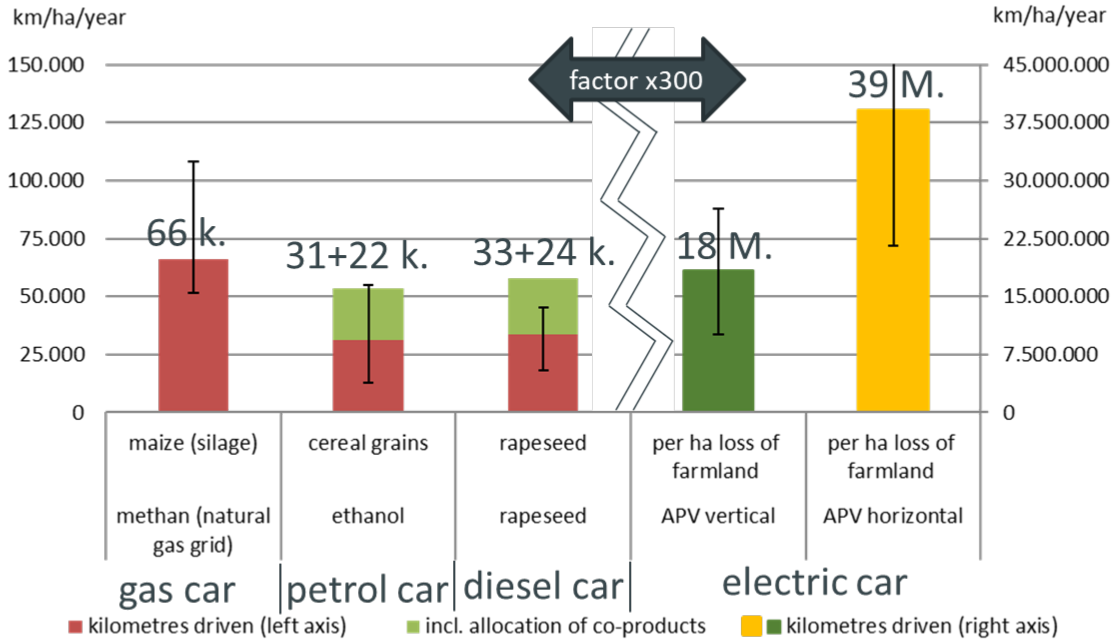

Figure 8. Comparison of the heat yield per hectare between common renewable energies in Germany.

Different renewable energies can be used to move a medium-sized car (see fig.8). If a gas car is powered by methane from silo maize, it is possible to drive 66 thousand kilometres per hectare and year. If a petrol car is powered by ethanol from cereal grains, it is possible to drive 31 thousand km/ha/a. If a credit for the co-products, such as animal feed, is taken into account via an allocation, an additional 22 thousand km/ha/a are possible. If rapeseed is used for biodiesel production and a diesel car is driven with it, 33k. km/ha/a plus 22k. km/ha/a are possible through the allocation. With APV, significantly more kilometres are possible in relation to the loss of agricultural land for food production. It is possible to drive more than 300 times further if the electricity is used in an electric car.

But it is not only the different energy amounts that can be compared, but also the different electricity production costs (LCOE) associated with the different systems. By optimising the APV systems for synergistic use with agriculture and not for economic optimisation as with ground-mounted PV, higher costs result, which are shown in Fig.9. First economic results show also that the APV vertical concept has almost the same LCOE as ground-mounted PV. The APV horizontal concept has the highest LCOE.

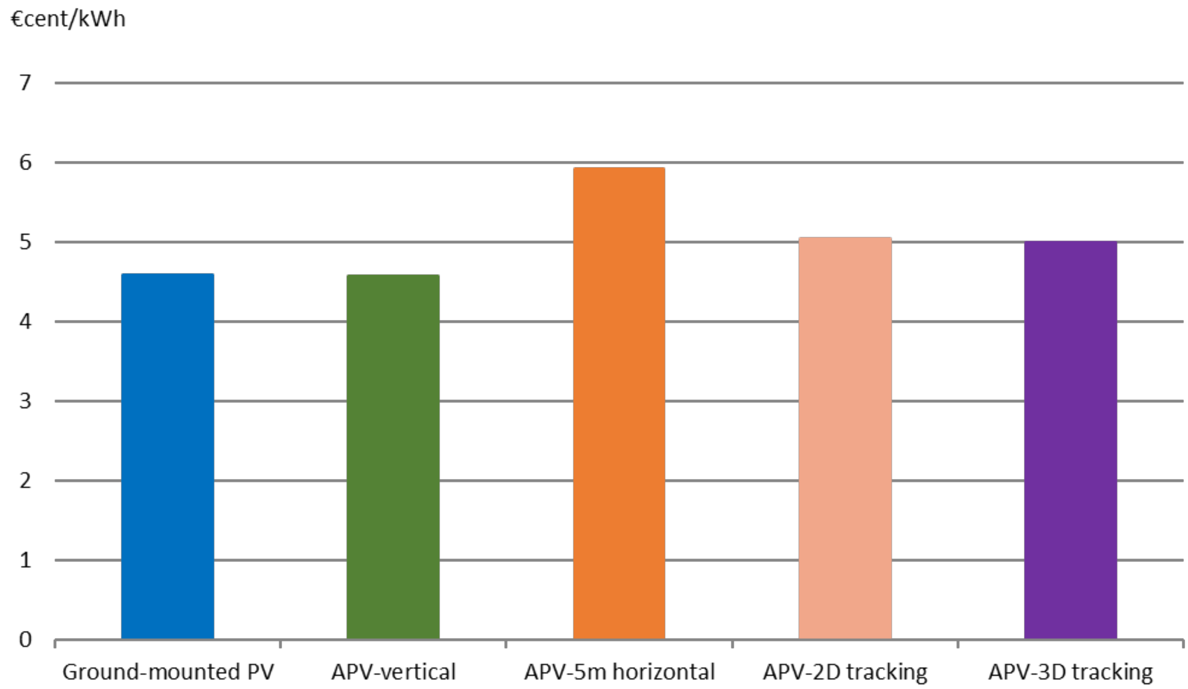

Figure 9. Comparison of the electricity production costs (LCOE) of ground-mounted PV and different APV concepts.

With the differences of the return to land we can estimate the costs per hectare the differences in LCOE and energy production per PV system area leads to differences in the return to land of up to 12.000 €/hectare/year for the horizontal concept and around 5.000€/hectare/year for the APV vertical concept. This differences in return to land compared to ground-mounted PV can be seen as yearly costs to save one hectare of agricultural land. This costs are very high, especial if comparing to the return to land of normal crop production systems in Germany of 250-500 €/hectare/year (own results from agri benchmark network). This shows the huge differences between costs of the APV system and possible agricultural revenue on crop land.

3. Discussion and Conclusion

In the political approval process, reference is often made only to the PV-system area, which is therefore of central importance for planners. However, this reference is difficult with APV, as agricultural land can still be used within this area. The advantages of APV become clear when looking at the area in detail. Much more electricity can be generated on land that is no longer available for intensive agricultural production.

By comparing APV with various common renewable energies, we were able to show that, after wind turbines, APV can provide the most energy per area lost for food production. It is the same for electricity as well as for heat and for the mobility section. APV only shows disadvantages in comparison to the energy yields of PV-system area with ground-mounted PV.

This study does not consider that there are yield effects of agricultural production between or among modules in APV systems. The yield effect can be positive or negative depending on the crop, the region and the weather conditions as shown by several presentations on the agrivoltaics conferences and other studies [6–9]. For this reason, the yield effects are not taken into account. From an energy perspective, agricultural production is also not considered. Theoretically, it is possible to produce energy plants, as rapeseed for example, on the area of the PV system and also use it for energy production. We have assumed food production within the APV plant. Given the results, the possible energy production with plants will not significantly change the results of the APV systems.

The study results demonstrate that the respective area reference is important for APV and that each concept have different advantages and disadvantages, such as LCOE costs. Since the tracking mechanisms, bifacial modules, elevation concepts and foundations have an effect on the actual area requirement per amount of electricity generated, the concepts differ greatly from each other in some cases. The results help identifying good APV concepts for Germany and promote APV in future discussions.

The costs showing that the advantages of APV in relation of electricity yields per loss of farmland are related to disadvantages in terms of costs. For the same economic output per hectare, the government needs to either promote APV or intervene in a regulatory manner to encourage investment in APV systems as also shown by other studies [10]. In the further development of new concepts, in addition to technical optimisation, a stronger focus should be placed on possible reduction potentials of additional costs. In addition, the systems must be used where additional benefits/synergies e.g. hail protection, arise in order to reduce costs.

Data availability statement

The data are available on request from the author.

Underlying and related material

No underlying and related material.

Competing interests

No competing interests.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

References

1. R. J. Randle-Boggis, E. Lara, J. Onyango, E. J. Temu, and S. E. Hartley, “Agrivoltaics in East Africa: Opportunities and challenges,” *AGRIVOLTAICS2020 CONFERENCE: Launching Agrivoltaics World-wide*, 2021, doi: 10.1063/5.0055470.
2. S. Schindele *et al.,* “Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications,” *Applied Energy*, vol. 265, 2020, doi: 10.1016/j.apenergy.2020.114737.
3. C. Gerhards *et al.,* “The Agri4Power concept: A win-win situation for renewable energy generation and sustainable agriculture,” *AGRIVOLTAICS2021 CONFERENCE: Connecting Agrivoltaics Worldwide*, 2022, doi: 10.1063/5.0123509.
4. L. Svanera, G. Ghidesi, and R. Knoche, “Agrovoltaico®: 10 years design and operation experience,” *AGRIVOLTAICS2020 CONFERENCE: Launching Agrivoltaics World-wide*, 2021, doi: 10.1063/5.0055869.
5. J. Böhm, “Vergleich der Flächenenergieerträge verschiedener erneuerbarer Energien auf landwirtschaftlichen Flächen – für Strom, Wärme und Verkehr,” (in de), *Berichte über*

Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft, Aktuelle Beiträge, 2023, doi: 10.12767/BUEL.V101I1.462.

6. M. Laub, L. Pataczek, A. Feuerbacher, S. Zikeli, and P. Högy, “Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis,” *Agron. Sustain. Dev.*, vol. 42, no. 3, 2022, doi: 10.1007/s13593-022-00783-7.
7. P.-E. Noirot-Cosson, T. Riou, and Y. Bugny, “Toward assessing photovoltaic trackers effects on annual crops growth and building optimized agrivoltaics systems based on annual crops,” *AGRIVOLTAICS2021 CONFERENCE: Connecting Agrivoltaics Worldwide*, 2022, doi: 10.1063/5.0103326.
8. X. Zhang, X. Zhu, and W. Liu, “Agrivoltaics help to realize BLUE plan,” *AGRIVOLTAICS2021 CONFERENCE: Connecting Agrivoltaics Worldwide*, 2022, doi: 10.1063/5.0103215.
9. N. Savalle-Gloire *et al.,* “Transient shading effect on tomato yield in plastic greenhouse,” *AGRIVOLTAICS2021 CONFERENCE: Connecting Agrivoltaics Worldwide*, 2022, doi: 10.1063/5.0106050.
10. A. Feuerbacher, T. Herrmann, S. Neuenfeldt, M. Laub, and A. Gocht, “Estimating the economics and adoption potential of agrivoltaics in Germany using a farm-level bottom-up approach,” *Renewable and Sustainable Energy Reviews*, vol. 168, p. 112784, 2022, doi: 10.1016/j.rser.2022.112784.