A STANDARDIZED CLASSIFICATION AND PERFORMANCE INDICATORS OF AGRIVOLTAIC SYSTEMS

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ABSTRACT: The rapid decrease of photovoltaic system costs enables the potential of agrivoltaic systems. These dual-land use systems mitigate land-use conflicts for places with limited open space and show the potential for added value in crop and livestock cultivation. However, many different names and interacting possibilities between agriculture and PV can be found. This makes it difficult and confusing for stakeholders to compare and benchmark existing installations as well as propose and set new (EU) legislation schemes. This work proposes a standardized classification of agrivoltaic systems, which is usable worldwide. The classification is based on the application, system, farming type, PV structure and flexibility and is able to categorize each existing agrivoltaic installation properly. Seven key performance indicators for agrivoltaic systems are suggested and discussed.

Keywords: agrivoltaic, rangevoltaic, KPIs, classification

1 INTRODUCTION

Photovoltaic (PV) installations have become a key element in the renewable energy transition. However, large surface areas are needed to further increase the amount of photovoltaic energy, leading to land use conflicts with other sectors like agriculture. One solution for these conflicts are agrivoltaic (AV) systems, which combine conventional agriculture (cultivating crops and livestock on land) and the production of photovoltaic energy on a single site. These dual land use systems are getting more attention for countries with limited open space; nevertheless, the concept has also proven to potentially be a win-win solution for crop development [1] and livestock [2] in (semi-)arid and hot environments.

The term "agrivoltaics" was first mentioned in a publication in 2011 [3]. However, the concept is known under several names in the world: "agrophotovoltaics" in Germany [1], "agrovoltaics" in Belgium [4], "agrovoltaico" in Italy and "solar sharing" in Asia. Moreover, many different designs and applications can be linked to agrivoltaics: photovoltaic greenhouses, sheep grazing between solar arrays, the combination of PV with crops, etc. Both aspects (the several names for the same concept and the many different applications with PV) make it difficult for the different stakeholders (PV developers, researchers, policy makers, farmers) to clearly distinguish the different agrivoltaic possibilities without being confused.

The purpose of this work is to provide a general and standardized agrivoltaics classification, including correct names and portmanteaus, which is usable worldwide and independent from local climate conditions, local farming practices, economical crop market values…. This classification is based on multi-disciplinary components (farming type, PV structure,…), which are unique elements to describe each agrivoltaic system properly. Additionally, this work proposes key performance indicators that can be used to better benchmark and compare existing installations. This work offers the first step into a practical framework for the synthesis and analysis about existing agrivoltaic systems and the development of new and promising ones. Stakeholders can use this classification to better understand the different agrivoltaic options and opportunities, resulting in new generalized agrivoltaic legislation schemes.

2 CLASSIFICATION LEVELS

Several criteria can be used to classify agrivoltaic systems. In this work, the point of view is to make a standardized classification independent of local (weather-farming) conditions, but still able to describe each unique worldwide agrivoltaic system properly. Following criteria are selected: application, system, farming type, PV structure and flexibility (as shown in Figure 1). These criteria will be discussed in more detail in the following sections.

2.1 Application

A first logical step is to classify agrivoltaic systems based on their application, which can be crop + PV or livestock + PV.

In this work the portmanteau "***agrovoltaics***" for crop + PV is suggested, where the prefix "*agro*" refers to agronomy, the science and technology of producing and using crops in agriculture, and "*voltaics*" refers to photovoltaics. For the application of livestock + PV, the portmanteau "***rangevoltaics***" [5] is given, where the prefix "*range*" refers to rangelands, lands that are grazed by domestic livestock and, "*voltaics*" refers to photovoltaics.

Note that the use of PV as abbreviation for photovoltaics can be used, as long as the prefix is maintained (agrivoltaics = agri-PV, agrovoltaics = agro-PV and rangevoltaics = range-PV).

2.2 System

The second stage in the classification is based on the type of system, which can be open or closed.

Closed agrovoltaic systems are photovoltaic greenhouses, where PV modules are placed on the roof. Greenhouses have a fully controlled and closed microclimate (CO2, temperature, humidity, …) which differs completely with the uncontrolled meteorological conditions of an open (air) agrovoltaic system.

Closed rangevoltaic systems refer to the 'enclosed' area where livestock is placed, acting as a replacement for agricultural fences, for example by vertical bifacial systems [6]. By contrast, open rangevoltaic systems are placed in the open area between or above the livestock.

2.3 Farming type

Agrovoltaic systems can further be classified according to the farming practices. A distinction between two groups of farming is assumed: field crop farming and orchard farming, which differ from each other in several respects. Field crop farming refers to production of the typical field crops including, wheat, potatoes [4], rice, … These crops are grown annually as part of a crop rotation system. Field crops have typically a lower economical value and are in most countries highly mechanised.

Orchard farming refers to fruit-(apples, pears, berries, grapes, …) or nut-producing trees/shrubs which are planted in a specific geometric row-based layout. These crops are typical perennial, with a higher economical value and require already some protection against extreme weather conditions by hail/shade nets, plastic covers…

2.4 PV structure

There are two different structural options for agrivoltaic systems [7]. One method is to place the solar array on stilts (2-5m high), where crops can grow, or livestock can roam underneath. The other option is to place the solar array close to the ground, with larger spacing between rows, ensuring that crops can be grown, or cattle can walk in the space between them. Important is that the spacing of the structure elements for both options are in line with the dimensions of the available agricultural machinery, ensuring the agricultural activities.

Stilted structures are typically used in less mechanised situations, for example in orchard farming or places with limited agricultural mechanization (for example in Asia). Stilted structures offer the advantage of higher PV array densities (until a certain value to ensure adequate crop yields) and consequently the possibility to protect all crops or livestock against heat stress and other extreme weather events. The higher elevation will also ensure that damage by livestock is limited. The main disadvantages are the increased visual pollution (due to the higher elevation of the PV modules) and the higher investment costs due to the stilts and additional wind reinforcements/foundations.

By contrast, spaced systems close to the ground are more suitable in situations where the dimensions of the agricultural machinery are too large to span the PV array on stilts (typically for field crop farming). Spaced systems will result in lower PV array densities, the impact on crop and livestock will be localised and there is an increased chance of damage by livestock. Nevertheless, the initial investment will be more in line with typical ground mounted systems and the impact on the landscape will be lower. The vertical bifacial structure of Next2Sun [8] is an example of a spaced agrivoltaic system.

2.5 Flexibility

The last stage of classification is based on the flexibility of the PV structure.

Large scale agrivoltaic systems acting as local energy generators will probably be fixed (i.e. not movable from one field to another), while small scale agrivoltaic systems (e.g. solar pump systems or drink spots for cattle) may be mobile and could be temporarily used in function of the farming- practices and needs (not mentioned in the classification).

Fixed large-scale agrivoltaic systems can be subdivided in dynamic and static systems. Static systems offer the lowest Operational Expenditures (OPEX) and are suitable for rangevoltaics, however, dynamic systems (tracking systems) can provide better control of the microclimate below the PV modules. The controlled microclimate is especially beneficial for agrovoltaics systems, resulting in better (control of) crop- yields and quality [6].

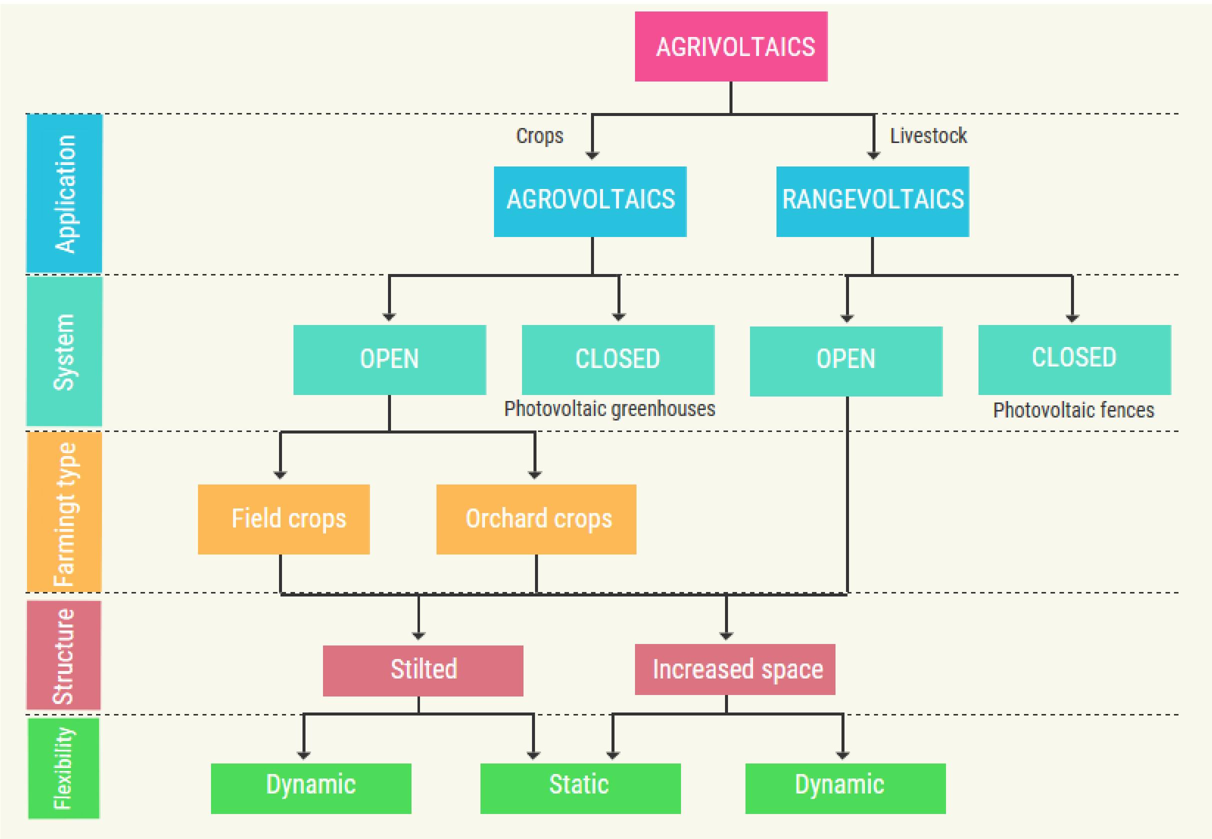

Figure 1: Classification of agrivoltaic systems

2.6 Further classification options

This work assumes economically viable and mature PV technologies resulting in no further classification based on the PV technology/materials. This will probably change in the future when the reliability and financial attractiveness of more advanced technologies increases. Research [9] shows already promising results of spectrum splitting foils, perovskite materials, CPV, … which could further increase the compatibility between PV and agriculture.

Additionally, the farming type with a distinction between field and orchard crops could be further subdivided in more detailed crop types and cultivars according to their shade tolerance, quality impacts and their compatibility with the PV microclimate. However, this compatibility and microclimate highly depends on the local climatic conditions (solar insolation, drought, air temperature, likelihood of hail, …) and farming practices, which makes it difficult to integrate this in the proposed general, worldwide classification.

3 PERFORMANCE INDICATORS

This work proposes seven key performance indicators (KPIs) that can be used to better compare and benchmark installed agrivoltaic installations.

3.1 Ground Coverage Ratio

The Ground Coverage Ratio (GCR) is one of the most impacting variables in an agrivoltaic design. The GCR is defined as the ratio between the surface area of the PV modules and the cultivated ground surface, as given in Eq (1).

$$GCR = \frac{A_{PV}}{A_{ground}} \qquad (1)$$

For agrovoltaics, high GCR values provide a high energy yield whereas the crop yield will be low due to reduced amount of solar radiation and subsequent photosynthesis rate. For rangevoltaics, a high GCR can be beneficial for milk production [2] due to reduced heat stress to the livestock.

3.2 Energy and agricultural yield

The energy yield $Y_{el,AV}$ [MWh/ha] is the annual produced electrical energy, expressed per unit of land in ha. Note that the energy yield depends on many specific and local variables: solar insolation, module efficiency, temperatures and effect of the microclimate, cable losses,… leading to the need to also mention the (normalized) performance indicator. Compared to standard ground-mounted PV systems, agri-PV systems will have longer cable lengths and therefore cable losses due to increased module spacing.

The agricultural yield $Y_{agri,AV}$ is the total amount of agricultural products with respect to the land area. This can be either specific weight in [kg/ha] (for example the dry matter of the crops in agrovoltaics) or specific volume in liter [l/ha] (for example the milk from cattle in rangevoltaics).

3.3 Agricultural quality

PV modules could possible protect crops against hail, heavy rain and sunburn which benefits the quality of the crops. Additionally, positive effects have been found on other quality characteristics [10]. For example, in vineyards, an improved aromatic profile of the grape (more anthocyanins and more acidity) can be measured in comparison to the reference field without PV modules.

Quality effects are difficult to express with one general indicator, and therefore must taken into account in the economic market value of the crop.

3.4 Spatial efficiency

The combination of PV and agriculture on the same land leads to an increased spatial efficiency. A performance indicator to highlight this efficiency is the Land Equivalent Ratio (LER) [3]. This work extends the LER from [3] to also integrate the impact of the crop quality in Eq (2):

$$LER = \frac{E(Y_{agri,AV})}{E(Y_{agri}, N)} + \frac{Y_{el,AV}}{Y_{el}, N} \qquad (2)$$

Here Y_{agri} stands for the agricultural yield (kg/ha or l/ha) in “normal” (N) or agrivoltaic (AV) circumstances. The new defined LER integrates the economic market value E of the agricultural yield to take account of the possible improved quality aspects (e.g. 10 undamaged apples may be economically worth more than 100 damaged apples by a hail storm).

The same methodology is applied for the energy yield Y_{el} (MWh/ha) in normal (N) or agrivoltaic (AV) conditions, where the comparison must be applied for the same location, orientation and flexibility (e.g. tracking or fixed). A LER value greater than 1 increases the productivity of the land in agrivoltaic circumstances relative to separate PV and agriculture installations.

3.5 Water savings

An important indicator for agrivoltaics (especially in (semi-)arid areas) is the influence of the PV modules on the water balance. First of all, the sheltering effect of the PV modules can ‘catch’ the precipitation that would otherwise flow away. This collected water can then later be used for irrigation or used as drinking water for the cattle. The reduced solar radiation also decreases the evapotranspiration rate (mm/hour) leading to an improved water use efficiency (WUE), reduced drought stress and irrigation needs [1].

3.6 Human comfort

On days with high solar intensities, it is recommended to the farmers and land workers to take breaks in the shade to avoid too much sunlight with health issues as a consequence. The shade provided by the modules ensures less radiation and the availability of shade. This results in less heat stress for the farmer during cultivation of the field. The farmers’ comfort during cultivation can be expressed with the Wet Bulb Globe Temperature (WBGT) in Kelvin [11].

3.7 Economic indicators

Agrivoltaics have different advantages as listed above. To really break through, agrivoltaics should be financially attractive. A measure to define if the agrivoltaic project is financially interesting is the price-performance ratio (ppr) given in Eq (3):

$$ppr = \frac{p}{pb} \qquad (3)$$

The p is the annual extra cost for an agrivoltaic implementation compared to the cost of a ground mounted

PV installation. This extra cost mainly depends on the levelized cost of electricity (LCOE) of agrivoltaics and the LCOE of ground-mounted PV.

The *pb* stands for performed benefits which are created by the annual revenues of the preservation of the agriculture land and the revenues of its products [12]. As already discussed earlier, this *pb* should also consists the quality aspects [12].

A *ppr* value greater than 1 is seen as not reasonable for agrivoltaics implementation, as the costs of the agrivoltaic PV plant are higher than the revenues of the preservation and agricultural products. A value equal to 1 is seen as economically reasonable because the income of the farmer has been diversified. A *ppr* value smaller than 1 means the performance benefits of agrivoltaics are greater than normal revenues of the agricultural land. The smaller the *ppr*, the more interesting the project [12].

Note that besides the price performance ratio, the traditional cost-effectiveness of the agrivoltaic project must be attractive for investors. This again depends on the LCOE, electricity selling price and avoided electricity costs. The financial attractiveness can be given by the Net Present Value (NPV) and the Internal Rate of Return (IRR).

4 SUMMARY

The rapid increase of photovoltaic installations highlights the potential of agrivoltaic systems. These dual-land use systems mitigate land use conflicts for places with limited open space and moreover, show the potential as an added value in crop- and livestock cultivation.

The many different names and interacting possibilities between agriculture and PV make it difficult and confusing for stakeholders to compare and benchmark existing installations as well as propose and set new (EU) legislation schemes.

This work proposes a standardized classification (including names) of agrivoltaic systems, which is usable worldwide. The classification is based on the application, system, the farming type, PV structure and flexibility. These elements makes it possible to describe and categorize each existing agrivoltaic installation properly.

This work suggests to mention each sub-category (for example: static stilted orchard agrovoltaic system) in future research papers or documents to order to better compare (rangevoltaic <=> agrovoltaic) and benchmark new installed installations.

When comparing agrivoltaics, the use of the proposed seven KPIs will help to make meaningful comparisons and grounded decisions in case of possible new installations.

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