RAINWATER MANAGEMENT IN AGRIVOLTAIC SYSTEMS - RESEARCH & DEVELOPMENT POTENTIAL

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Agrivoltaics is a concept in which a piece of land is simultaneously used for both energy and food production by mounting photovoltaic modules at a certain height above (or in between strips of) agricultural land. A local and system-level incorporation of water management is imperative to the sustainable implementation of agrivoltaics. Water raining on the modules can be gathered and used for distinct purposes: groundwater recharge, crop irrigation, and cleaning and cooling of the PV modules. This research provides an initial overview of positive and negative impacts for each water use concept and outlines issues that should be taken into consideration and the potential for research and development. Various Managed Aquifer Recharge (MAR) technologies are a way to clean and store the water periodically in an underlying aquifer. Irrigation increases yield within the plant level and therefore increases the system's output. Thanks to the power supply generated by the PV modules, high-tech irrigation systems can be implemented in agrivoltaic systems; the special adaption of irrigation systems to agrivoltaics poses significant potential for research and development. Meanwhile, the necessity, i.e., profitability of cleaning and/ or cooling PV modules depends on local environmental and economic factors. Several cleaning techniques have been developed to mitigate soiling, ranging from manual cleaning to fully automatic cleaning systems. In agrivoltaic systems, the soiling risk can increase. Semi-automatic systems seem to have the greatest potential for agrivoltaics, because they can be used with farming equipment. Multiple cooling techniques have been developed to decrease cell temperature to increase power output, with some of them involving water. Water flowing over the module surface is a promising cooling technique for agrivoltaic applications. Attaching a perforated tube to the upper edge, the entire module can be covered in a thin film of water which cools very effectively (while also cleaning the surface). A closed-circuit system could be created involving the technical components used for rainwater harvesting. The economic feasibility of cooling panels in agrivoltaic systems needs to be investigated. In certain locations, rainwater-harvesting could also be relevant for ground-mounted PV systems.

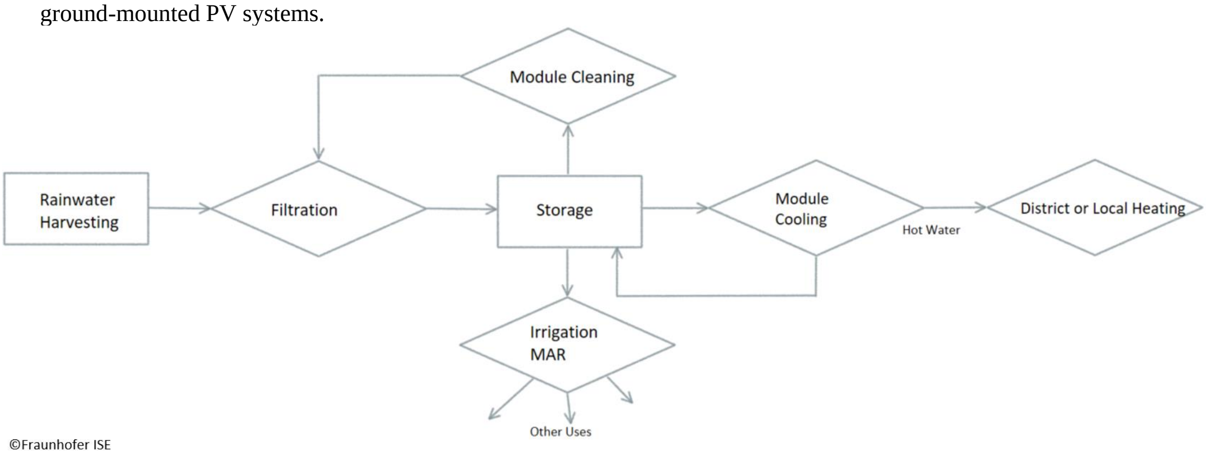

Figure 1: Flowchart of an integrated water management approach for agrivoltaic systems

1 SCIENTIFIC INNOVATION AND RELEVANCE

With elevated modules in agrivoltaic systems, rainwater collecting at the lower edge of the module ("dripping edge") and hitting the soil with a high speed can cause severe problems not just within the system: The force with which the water drips from the module is enough to damage plants and deform the soil (splash erosion) [1]. Also, surface runoff is increased, which can sweep seedlings away and on a larger scale, can aggravate flooding while also disturbing the local hydrologic balance and ecosystem. One Solution to this problem, which is currently in development, is attaching a disperser to the dripping edge to facilitate a more homogenous distribution of rainwater beneath the modules. Another approach is attaching a gutter to the lower edge of the module and "harvesting" the rainwater, which can then be used for several purposes. It is important to consider water management on a local and regional level as to implement the agrivoltaic system successfully. Under unfavorable circumstances, the agrivoltaic system could aggravate or create problems for local water management that need additional technical workarounds.

2 AIM AND APPROACH

The research presented here aims to provide an initial overview of positive and negative impacts for each water use concept, as well as agrivoltaics-specific issues that have to be taken into consideration. These act as a basis for pointing out research and development potential. For each application, literature was reviewed to get a general overview over different technologies and possible impacts. After that, the implementation into an agrivoltaic system was theorized. With regards to synergetic and adverse effects, the arising questions and ideas where then classified as research and (in some cases) development potential.

3 RESULTS

3.1 Managed Aquifer Recharge (MAR)

MAR involves infiltrating water through the vadose zone or directly into the aquifer whereby its quality is improved [2]. MAR can eliminate the need for storage devices and can be used to mitigate seasonal change in water availability. Several techniques are distinguished, depending on means of infiltration and extraction. The simplest method of infiltration involves filling infiltration trenches or basins with water, which then infiltrates through the vadose zone by means of gravitational force. This is an increasingly common way to ensure drainage in urban areas while reducing rainwater discharge to water treatment plants. The water is filtered while passing through the vadose zone; it's quality can improve immensely.

Other applications focus on a controllable storage of the water. Wells can be used to infiltrate water into an aquifer and extract it at a later point in time. In "Aquifer Storage and Recovery" (ASR), only one well is used for both infiltration and extraction. Depending on flow velocity in the aquifer, the water forms a bubble around the infiltration site. Only the outer layer of this bubble interacts with the aquifer medium and the native groundwater and therefore experiences a change in water quality. Therefore, ASR is only suitable if a change in water quality is not desired.

"Aquifer Storage, Transfer and Recovery" (ASTR) uses two wells: one for infiltration, another one for extraction. This causes a flux toward the extraction well, which pulls the entire infiltrated volume of water through the porous medium that makes up the aquifer. While traveling through the aquifer, the water interacts with the medium on a small-scale level, resulting in an improved water quality.

"Soil Aquifer Treatment" (SAT) was originally developed as a wastewater treatment technique. Water is infiltrated via infiltration basins and filtered while passing the vadose zone. An extraction well is placed somewhere in the vicinity of the infiltration site to regain the water. The extracted water is of suitable quality for irrigation. [2]

The suitability of a location for infiltration / MAR depends on an array of hydrogeological, hydrochemical and geo-chemical factors, such as the coefficient of permeability, hydraulic conductivity, the chemical makeup of the involved waters and that of the aquifer, presence and makeup of suspended solids, etc. [2]. Thus, MAR requires large scale considerations and technical effort, which is why it makes the most sense in conjunction with large AV systems, where a significant amount of water can be gathered and infiltrated. Coupling the two systems could eliminate the need for technical components for storage or intense cleaning of the water. To really be considered a part of the agrivoltaic system, the extracted water should at least partially be used to increase the output of the system (either through irrigation or cooling/cleaning the panels). As the infiltrated water can be used multi-purposely, MAR can be coupled with any other use of water described here, which would otherwise require storing water in tanks/ ponds or increase consumption of potable water. The infiltration and extraction wells should be somewhat close to the agrivoltaic system, otherwise long pipelines would be necessary to transport the water back and forth. This seems inefficient and would further separate the two systems. Finding a location that is suitable for both technologies might prove difficult, especially because some MAR-techniques require significant amounts of space. A main goal of agrivoltaics however, is mitigating land use conflicts by increasing land use efficiency, making it more likely to be implemented in regions suffering from land scarcity. Research needs to be conducted to define criteria for the suitability of locations for an integrated agrivoltaics-MAR-approach. The possibility of the water picking up contaminants while running over the modules' surface is also cause for consideration. Besides that, the precise technical execution and the economical feasibility should be investigated.

Outside of agrivoltaics, covering infiltration sites with overhead solar energy collectors to reduce evaporation and achieve dual land use seems promising. One more issue that persists (at least in Germany) is the legality of infiltrating gathered rainwater directly into aquifers. Current rainwater management practices need to be reconsidered to combat climate crisis impacts.

3.2 Irrigation

Irrigation increases yield within the plant level and therefore increases the system's output. This effect is especially interesting in conjunction with high value crops. In arid regions, the danger of salinization must be considered. The applied irrigation water is partially used by the plant, while the rest evaporates or seeps into the soil. Both the plants' uptake and the evaporation leave behind dissolved salts, causing the salts to accumulate in the soil and therefore in the seepage water. This can cause the permanent degradation of land. Salinated water seeping downward can lead to the salinization of the underlying aquifer. Measures taken to combat this include applying additional water to wash out the salts or using desalinated water for irrigation [6]. Reduced evapotranspiration in agrivoltaic systems may alleviate the risk of salinization. Thanks to the power supply generated by the modules, high-tech irrigation systems like overhead or drip irrigation can be implemented in agrivoltaic systems even in remote or undeveloped locations. The creation of a self-sufficient system that doesn't need additional water or power input seems within reach and could revolutionize agriculture.

There is a high potential for the development of agrivoltaics-adapted irrigation systems, e.g., using the modules' mounting structure for installation. Moreover, the power supply enables the operation of monitoring equipment and data processing units on site. Linking sensor data from within the field with plant models and weather data/forecasts could be used to create a highly efficient irrigation control system. Additionally, this data can be used to develop a custom PV-tracking algorithm to increase total system efficiency.

One more aspect to look into is water storage: irrigating with rainwater necessitates water storage. As storage tanks and ponds use up space and involve the risk of algae growth and other contamination, more elegant storage solutions should be developed.

3.3 Cleaning

Dirt on the surface of the modules reduces effective irradiance which in turn reduces power output [3]. Several techniques have been developed to mitigate this. They can all be placed on a spectrum ranging from manual cleaning in low-labor-cost regions to fully automatic cleaning systems in extremely exposed or isolated locations [3].

In agrivoltaic systems, the agricultural activity beneath the panels might increase the risk of soiling, while the elevated position of the modules and the plants underneath make it hard to reach them. Recently, the possibility of residuals from pesticides and fungicides depositing on the backside of the modules has been cause for concern. It is not yet clear whether this will require counter measures to maintain the bifacial gain.

Automatic cleaning systems are costly and thus only profitable in locations with very high exposure. Considering that in most locations, the exposure might only be intensified during certain seasons (e.g. harvesting season), semi-automatic systems seem to be a fitting, more economical alternative. This indicates significant potential for the development of semi-automatic systems that can be used with the farming equipment, e.g. brushes that can be attached to tractors. For systems with low clearance heights in areas with low labor costs, manual cleaning could also be an option.

3.4 Cooling

As power output decreases with rising cell temperature, cooling the modules is beneficial in some locations. Again, a range of techniques for mitigation has been developed; with respect to the topic at hand pertaining to rainwater, only the ones using water for cooling were investigated: photovoltaic/thermal (PV/T), water spraying and flowing water. From an energy efficiency point of view, PV/T systems would be the preferred option, because they increase the efficiency of solar energy conversion. But with the backside covered with tubes and insulation, PV/T modules are opaque. As the crops under the panels need light and the light distribution should be as even as possible, using PV/T modules in agrivoltaic systems would require special consideration. System parameters like elevation and row-to-row distance would have to be adjusted. An opaque backside would also eliminate the possibility of utilizing the amount of radiation that is reflected by the ground with bifacial modules. Due to the elevated position of the modules and greater row distances, this portion is more significant in agrivoltaic systems compared to ground-mounted PV systems. Further analysis might uncover agrivoltaic applications where PV/T can be implemented successfully.

A different possibility is attaching sprinklers to the modules to spray them with water. But as the module isn‘t fully covered with water, only a few spots are actually cooled while the rest of the modules surface isn’t covered by water or isn‘t covered long enough to create a lasting effect. Additional efficiency losses are caused by wind or inexact orientation of sprinklers.

Out of the cooling techniques involving water, free flowing water seems to be the most promising for agrivoltaic applications. It involves attaching a perforated tube to the upper edge of the module. Depending on the flow rate, water covers the entire front of the module and cools it very effectively: Luboń et al. managed to increase power output by 20% [4]. With the gutter for rainwater harvesting already attached to the lower edge, the technical effort to create a closed circuit should be within reasonable limits. Including a heat exchanger could increase the energy output of the system. However, pumping the water through the system and compensating losses also requires energy. Whether the increase in power output can cover this energy expenditure is unclear and depends on module technology, irradiance, configuration of the water circuit and other factors. Rough calculations of different system configurations might be able to give an indication. Moreover, installing a water circuit would put additional load on the mounting structure, which is already one of the main economic concerns in agrivoltaics [5]. Additional technical components may also influence the light distribution beneath the panels.

The necessity, i.e., profitability of cleaning and/ or cooling PV modules is inherently dependent upon local environmental and economic factors, which is why these should be explored with special regard to agrivoltaics.

4 CONCLUSION

The above stated aspects need to be investigated to achieve a successful and sustainable implementation of not just water-utilizing applications but agrivoltaics in general. Agrivoltaics can be powerful tool in the Water-Energy-Food Nexus. Current research is largely focused on understanding the interplay of crop and PV-system. It is of great importance to consider water as an equally implicated sector, not only in research, but in the conceptualization and technical design of future agrivoltaic projects. There is great potential for agrivolatic systems to be an asset to water management and to address challenges even beyond the agricultural and energy sector. To achieve this goal, research projects and experiments must be conducted to examine each of the applications from a technical, agricultural and economical point of view.

5 REFERENCES

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