FPV, AVS, & Carbon Storage: An Academic Review

December 21, 2022

David Bongiorno, Dhruv Makwana, Patryk Zagula & Rushabh Pathak

Table of Contents

Executive Summary - FPV **4**
Technical Background & Introduction **5**
Effects of Submersion 5
Water Absorption 5
Water Reflection & Refraction 6
Temperature 6
Effects of Water Salinity – Exposure to salt spray & seawater 7
Floating PV Array Rig Design Considerations **7**
FPV Elements **7**
Housing 7
Mooring & Anchoring 8
Floats 8
Enhancement Systems **8**
Cooling & Cleaning Systems 8
Tracking Systems & Solar Alignment Systems 9
Case Studies & Applicability Discussion **9**
Feasibility In the United States 10
System Cost – NREL Benchmark Analysis 12
Effects On Water Quality & Aquatic Ecosystems 13
The Synergy of Hydroelectric and Floating Photovoltaic Plants 14
Case study of Longyangxia hydro-PV hybrid energy system conducted by Bo Ming, Pan Liu, and Lei Cheng (Ming et al., 2021) 15
Prospects for Hybridization 16
Conclusion **16**
Appendix: **17**
FPV Classifications **17**
Pontoon 17
Superficial 17
FPV Pros & Cons - Comparison With Land-based PV 17
Additional Figures **19**
Resources: **21**
Executive Summary - AVS & Carbon Storage 24
Agrivoltaic Systems (AVS): **25**
AVS Installation: 25
Crop Selection: 26
Power Generation: 27
Challenges & Constraints: 28
Benefits of AVS: 29
Economic Feasibility: 30
Carbon Storage: **33**
Case Study I: 33
Case Study II: 34
References: 36

FLOATING PHOTOVOLTAIC (FPV)

A brief exploration of Floating Photovoltaic System functions, benefits, and applicability

DECEMBER 19, 2022

DAVID BONGIORNO & RUSHABH PATHAK

Executive Summary - FPV

One of the more exciting burgeoning renewable energy technologies is that of the floating photovoltaic (FPV) module. The underlying mechanics of constituent photovoltaic (PV) cells is the same as it's on-land variant: incident photons from sunlight striking a light-sensitive PV cell will elevate create an electron-hole pair and elevate electrons to the conduction band; migratory minority charge carriers are swept to the electrical contacts of the cell and a usable direct current (DC) is available for supplied power. However, FPVs are beneficiaries of improved performances due to water-based optical and temperature effects that may boost their efficiencies. Furthermore, variants of FPV arrays and modules are of increasing interest because of the niche they can satisfy within the growing photovoltaic market as a dual-use technology with largely non-intrusive environmental impacts and a demonstrable synergy with stored hydropower reservoirs.

As previously mentioned, several categories of FPV systems have emerged since the initial patent of a FPV module was issued in 2008, as research into the various domains of improvement have been patiently researched over the past few decades. These categories are broken down by key design choices, namely: depth of operation (floating on or submerged beneath the surface of the body of water, choice of water body type – freshwater (lakes, reservoirs) or saltwater (brackish estuaries, bays, seas, etc.), and the type of PV array housing (typically classified as pontoon or superficial).

Additionally, the synergy of floating photovoltaics and currently existing hydroelectric power plants, is an avenue that is of great interest. The possibility of extracting more renewable energy per square unit area and impacting key environmental factors such as water evaporation, algae and the consumption of agricultural and industrial land is one to be carefully looked at.

Technical Background & Introduction

Effects of Submersion

Aside from the intrinsic benefit of keeping PV panels clean from contaminants there is an inherent efficiency benefit for sinking a PV array underwater or streaming a continuous veil of water over the surface of the panels. In their textbook ***Submerged and Floating Photovoltaic Systems: Modelling, Design and Case Studies*** researchers Marco Rosa-Clot and Giuseppe Marco Tina describe the overview of the optical and thermal considerations of utilizing submerged PV panels, which we will summarize for context with later comparative studies.

Water Absorption

The first consideration is that of the depth of operation of the panel and the relationship to irradiation absorbed. Marco Rosa-Clot and Giuseppe Marco Tina first note that the spectral irradiance is quickly curtailed as depth increases. Figure 1 below illustrates that a thin channel of water behaves as a filter blocking large wavelength light (λ > ~1100 nm at depth of 5 cm i.e. the green line in Figure 1), but short wavelength light is largely passed even significant depths (~300 nm <= λ <= ~750 at a depth of 1 m, i.e. the pink line in Figure 1).

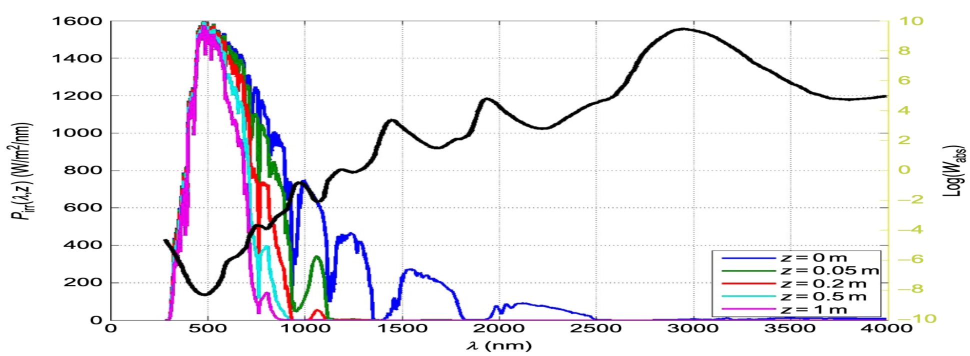

Figure 1: Spectral irradiance for a panel placed at various depths; the logarithm of water absorption is given by the black line.[2,Pg67]

M. Rosa-Clot and G. Tina go on to compare the photoelectric efficiency of various semiconductor materials at various depths, which they define as the total energy available to a given material at a given depth to the incident global irradiance:[2,Pg 69]

$$\eta_{ph}(z) = \frac{\frac{1}{\lambda_G}\int_0^{\lambda_g} E(\lambda,z)\lambda d\lambda}{\int_0^{\infty} E(\lambda,z)d\lambda}; \quad where\ z := \ depth, \lambda_G := \ cutoff\ wavelength$$

It should be noted that the numerator in this relationship includes the entire theoretical energy produced via the photo-electric effect (as given by the integral from 0 to λ_G i.e. the cutoff frequency) and does not consider the losses due to excess heat dissipation from high energy photon interaction, optical losses, and ohmic losses. Therefore, the plotted photoelectric efficiencies, $\eta_G(z)$ in Figure 2 will be much higher than practically feasible implementations. That being said the set of comparisons, as illustrated in Figure 2 demonstrates an interesting point that at very shallow depths (around 2 cm), materials with a low bandgap energy (such as silicon and copper indium diselenide) achieve a modest increase in efficiency then decrease with depth; whereas materials with relatively larger bandgap energies (such as amorphous silicon and cadmium telluride) perform better as depth increases up to about 0.4 - 0.5 m.

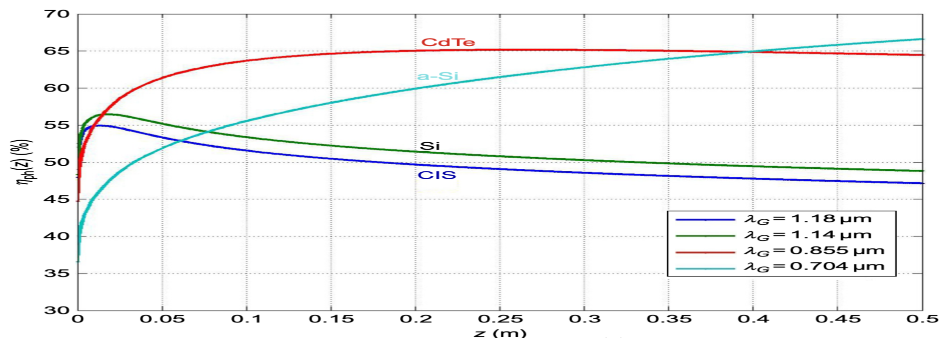

Figure 2: Comparative chart of the photoelectric efficiencies($\eta_G(z)$) of various semiconductor materials as a function of depth.[2, Pg 70]

Water Reflection & Refraction

Another point worthy of mentioning is the slight benefit submerged PV panels experience due to a reduction of reflected light. The addition of a layer of water with a refractive index closer to that of the top layer of glass which houses the PV (n_{Water} = 1.33, n_{Glass} = 1.53 respectively) allows for more light waves to pass through before hitting the PV layer; this successive stepping of refractive indices to minimize the entrance wave impedance (i.e. improve transmittance) is also known as index matching.[3]

M. Rosa-Clot and G. Tina explore this via Fresnel formulations to determine the amount of reflected, plane-polarized light on air-water and air-glass interfaces for comparison. As Figure 3 demonstrates for low angles of incidence the amount of light reflected drops from about 4.5% to 2.6%.[2, Pg 74]

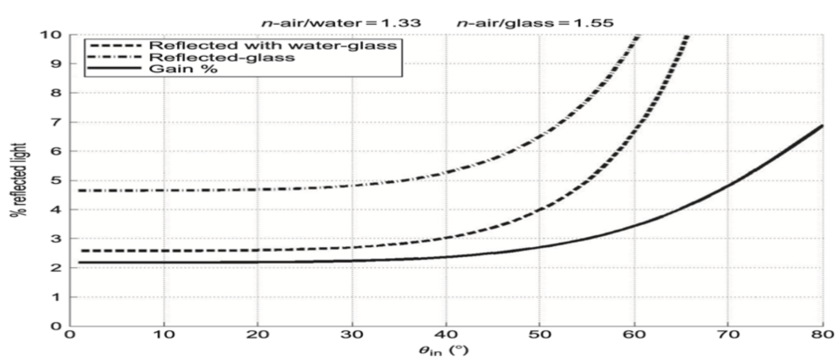

Figure 3: Comparative plot of light reflected off different interfaces as a function of angle of incidence.

Temperature

Additionally, the flow of water on the panels allows for ambient cooling and mollification of the thermal drift effect, in which an increase temperature decreases the open circuit voltage of the panel and effectively lowers the max power point (MPP) at which the PV panel can yield productive power (about 0.45% reduction in power per ℃ for low end commercial PV modules).[4, Pg 86]

Moreover, at very shallow depths (less than 5 cm), the addition of a thin layer of water can improve the efficiency of the panel, by keeping its temperature low and consistent. This is demonstrated In Figure 4 below in which M. Rosa-Clot and G. Tina compare the relative efficiencies of different types of PV materials both “dry” and at 65℃ and submerged at a water temperature of 20 ℃. In summary, across technologies, a gain in efficiency of roughly 5% - 20% can be achieved when the panel is deep enough to benefit from the ambient cooling, but not so deep to reduce the irradiation being absorbed by the panel.[2, Pg 77]

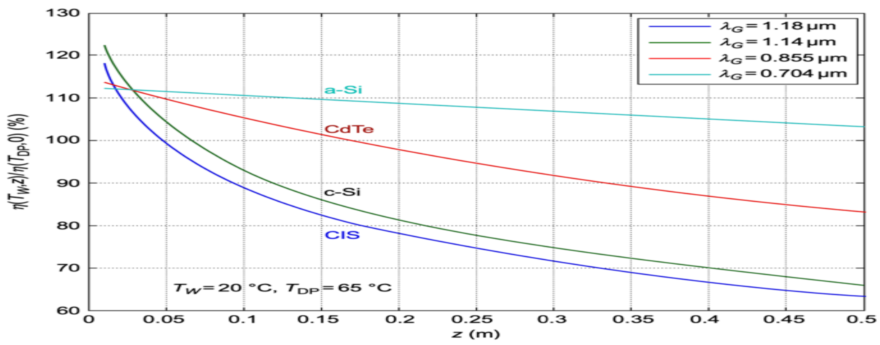

Figure 4: Comparative plot of relative efficiency in % versus water depth.[2, Pg 78]

Effects of Water Salinity – Exposure to salt spray & seawater

The next design consideration concerns the type of aquatic environment in which the panel will float (or be submerged). The physical damage due to corrosion from the presence of salt water or salt spray, while of concern for many exposed electronics, is not of concern for the PV cells themselves. Their construction within sealed glass housings lends a resilience to corrosion and the cells are regularly tested against a codified standard (IEC 61701 Salt Mist Corrosion Test) to ensure consistent durability. [5]

However, actual PV electrical generation performance is another matter. Scientists from the Wuhan University of Technology and China's National Engineering Research Center for Water Transport Safety (WTS Center) detail this in their analysis of the effects of salt spray and seawater (3.5% salt concentration and pH value of 8.2) on PV performance (10 W panels exposed to 800 W/m^2 from an artificial solar irradiance source). The demonstrable effects of a saline environment yielded reduced performance (6% loss in output power in salt spray case, and 10% loss in output power in sea water case). This is attributed to a combination of light scattering in the case of salt spray application and in the case of seawater application, the gradual deposition of salt crystals blocking incident light on the panels (causing a decrease in light absorption and heat dissipation); the cooling effect of the running seawater initially attributes a short-lived efficiency gain of 20%, and without scouring ultimately, overall performance drops by 10% once a sufficient layer of precipitate covers the panels. The researchers also note that similar results to the sea spray experiment should be applicable to freshwater environments in which there is heavy mist or easily condensable water. [6]

Floating PV Array Rig Design Considerations

FPV Elements

The physical mounting of the FPV array is where many of the design considerations take place. At a minimum the system will require the PV panels and associated housings and electrical equipment, moorings to keep it steady in the water and maintain orientation, and a floatation system to provide buoyancy. The next logical constraining input is the location site and the bidirectional effects between the local environment and the FPV system. Beyond this, considerations for active cooling (water veils, pumps, or sprinklers) and tracking systems can be added for improved FPV performance and lifespan. The following sections include a brief description of these considerations as outlined by R. Claus and M. López and further description of FPV classifications are provided in the Appendix.[7, Pg 3]

Housing

As previously discussed, the PV cells themselves are resistant to corrosion within marine environments, but considerations should be taken for chosen structural supports in defense against saltwater corrosion and biofouling and to prevent the spread of marine microplastics. It is for this reason that composite materials such as fiber-reinforced polymers are chosen over corrosion-susceptible materials such as steel and aluminum in the panel housing design. [7, pg3]

Mooring & Anchoring

There are many options for mooring/anchoring systems, but their overall function is to mitigate the undesired movement of the array within the water via a chosen system of weights, fasteners, and cabling (typically steel chain or wire ropes within seawater and synthetic fiber rope or rubber hawsers in freshwater). The researchers makes the point that mooring & anchoring systems (along with seabed stability analysis around the point of anchoring) should be of concern as they represent a sizable portion of capital cost for analogue marine renewable energy technologies such as offshore wind turbines (about 10%).[7, Pg 4]

Floats

The primary objective of the floatation structures and devices (or pontoon) is to obviously provide buoyancy to the overall FPV system; they should be able to withstand consistent UV-radiation and be made of non-hazardous materials. Since the floats make direct contact with the water the bilateral environmental concerns are applicable here as well. There exists the possibility to utilize the pontoon cavities as reservoirs for Compressed Air Energy Storage (CAES) systems.[8] Thanks to the advent of thin-film PV technologies (such as amorphous silicon, cadmium telluride, copper indium gallium selenide, et al), lightweight modules can be arranged into buoyant structures capable of floating on the water without additional pontoons. Such FPV variants are denoted as "Superficial". For these FPVs, the thin-film PV panels are mounted on lightweight that can rest on the water's surface or submerge to a modest depth for cleaning, thermal dissipation. If placed in intense marine environments the ability to submerge could provide the benefit of avoiding wind battering but could expose the structure to greater wave loads. Basic descriptions of these two classes of FPVs and their subvariants, along with the technology's inherent benefits are presented in the Appendix.

Enhancement Systems

Cooling & Cleaning Systems

As previously discussed, the efficiency of FPVs can be improved by submerging the panels within a very shallow depth via heat dissipation and leveraging the optical benefits of an interceding layer of water. The alternative to submersion is to periodically or continuously pump a thin film of water or spray of water upon the panels. The former is accomplished via a low-pressure (~ 1 bar) water veil and the latter via a high-pressure (2-3 bar) sprinkler system. Extrapolating the needs of a single module, the researchers suggest a pumping rate of 1–2 l/min so 100 m^3 can create a water veil for ~1000 PV modules for one hour.[1, Pg 1734] In both systems the designer has the choice of applying the cooling system to either side of the panel, but in the case of experimental sprinkler systems, spraying both sides resulted in improved performance.[1, Pg 1735] These systems are depicted in Figure 5a and Figure 5b below:

Figure 5a: Picture of the experimental water veiled cooling system installed on a FPV plant in Pisa (Italy).

Figure 5b: Sprinkler cooling system

Tracking Systems & Solar Alignment Systems

Given the FPV system buoyantly sits upon its site, there exists the possibility for low-effort rotation and tracking of the system to receive the maximum amount of solar radiation. The basic operation is that the tracking system rotates the system about the vertical axis like a carousel. While a variety of tracking systems have been explored such as rotation driven by motors, ropes & winches, pressure driven rollers, or bow thrusters, R. Cazzaniga et al. recommend fixing the FPV system with sufficient central mooring and using bow thrusters to adjust its orientation. This type of tracking system has been undertaken with low power (two 600 W electric engines in one FPV system in Pisa and one 8 kW bow thruster for a FPV system studied in Suvereto). [1, Pg 1735-1736]

The tracking system must be used in conjunction with a solar alignment system. This is necessary for tracking as the FPV's platform orientation is subject to drift in the water and makes consistent orientation relative to a reference difficult. The solar alignment system can be governed by light-intensity sensors or even commercial cameras to track the movement of the sun (or the brightest spot in the sky). The researchers note even with a low-cost camera (with a resolution less than 0.5 °) a bow thruster tracking system can track the sun within 2° of its actual position.[1, Pg 1736] These systems are depicted in Figure 6a and Figure 6b below:

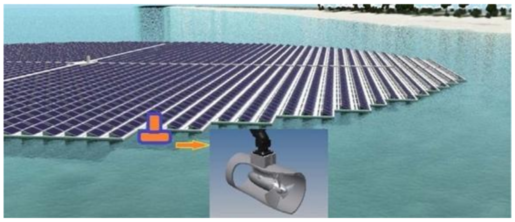

Figure 6a: Tracking with bow thrusters.

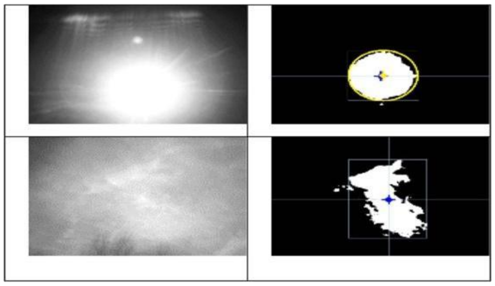

Figure 6b: Camera acquisition of sun image: on the left two images of clear (upper) and cloudy (lower) sky; on the right the relative reconstruction in software.

Case Studies & Applicability Discussion

Now we shift our focus to discuss the observed benefits of applying this photovoltaic modality across several categories – lending credence to their advocated adoption in a wide variety of scenarios, along with relevant qualifiers and limitations as of this writing. Perhaps the most apparent benefit of FPVs lies in the ability to free up physical land and place them on otherwise nonutilized bodies of water such as wastewater treatment plants and irrigation ponds. This point is especially significant in countries in which population density is high and in places where land availability (and thus pricing) is a concern.[9]

Feasibility In the United States

An analysis done examining the feasibility of FPVs within the continental United States determined that there are 24,419 different bodies of water that are applicable sites for FPVs. Moreover, they demonstrated that utilizing FPVs on just 27% of the available man-made bodies of water could yield 9.6% of the country's 2016 electricity generation capacity of 2116 GW (resulting in 786 TWh annually). These results were achieved by utilizing the National Renewables Energy Laboratory's (NREL) open-source System Advisor Model (SAM) for PV based electric generation on a filtered subset of recorded bodies of water recorded within National Hydrography Dataset (NHD) of the United States Geological Survey. The permissible sites were ones not designated for recreational use, navigation, tailings, or as protected fish and wildlife ponds by the National Inventory of Dams (NID) of the United States Army Corps of Engineers. The researchers utilized an average capacity density of 10000 m^2/MW capacity density (as derived from a linear regression-based estimate of the performance of 51 different global FPV systems. Their model fills 27% of each available body of water with panels and sets their tilt to a fixed ~11° so that the pontoons holding the FPV arrays can be arranged closely together, which the author concedes as suboptimal for tracking the sun, but beneficial to mitigate wind loads and shading. [10, Pg 1682 – 1683]

Indeed, within the United States (and many other countries) a great potential lies largely untapped. The authors went on to conclude that several states (Idaho, Maine, New Mexico, and Oklahoma) have the potential to generate more than their 2016 electric generation capacity. The addition of FPV is particularly logical within states with large land values such as New Jersey, California, and Florida. For example, Florida as of 2016, claimed a land value of $18,323/hectare and crucially the greatest amount of water surface area available - 309,000 hectares (only ~1.8% of its total area within the state). [10, Pg 1684] This is further illustrated in Figure 7 below:

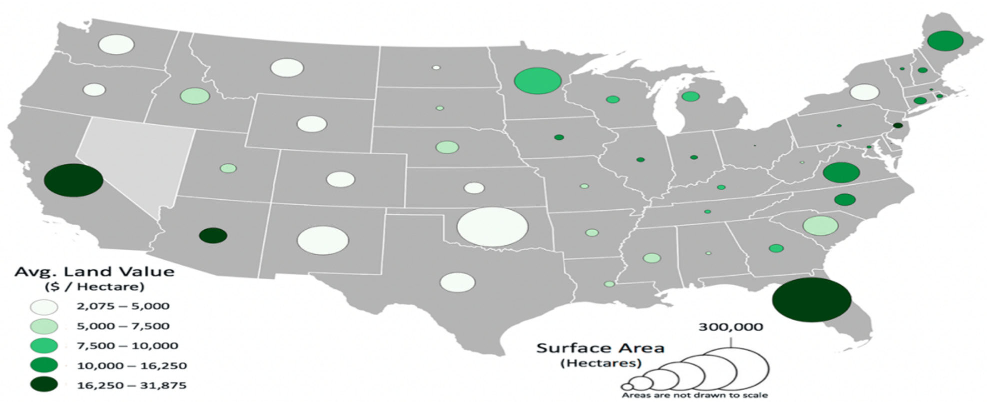

Figure 7: Cumulative surface area (dot size) of feasible U.S. water bodies for FPV installation by state and the associated average land values for the state (dot color). Circles are not drawn to scale of states. [10, Pg 1684]

A similar monetary benefit is possible within regions experiencing high utility costs as introduced FPV provide an alternative source of energy. As R Spencer et al. espouse, states that have positive PV generation potential such as California (with 15.5 ¢/kWh retail utility costs) stand to benefit as illustrated in Figure 8 below:

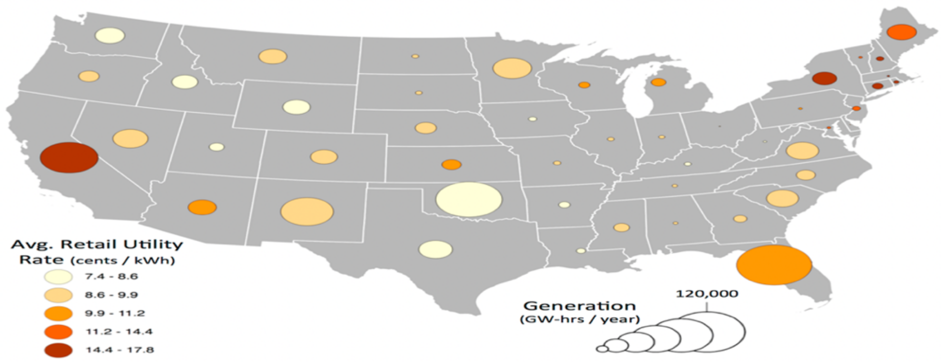

Figure 8: Potential generation (dot size) of FPV installations on feasible U.S. water bodies by state and the associated average retail utility rates for the state (dot color). [10, Pg 1684]

Lastly this study emphasizes the often cited benefit of reduction in water evaporation[1,3,7] as an additional environmental benefit further lending to the recommendation of an FPV plant for a given site. Within the United States evaporation rates range from below 90 cm/year in the Northeast to more than 245 cm/year in the dry and arid Southwest. This significant potential for evaporation mitigation is illustrated in Figure 9 below:

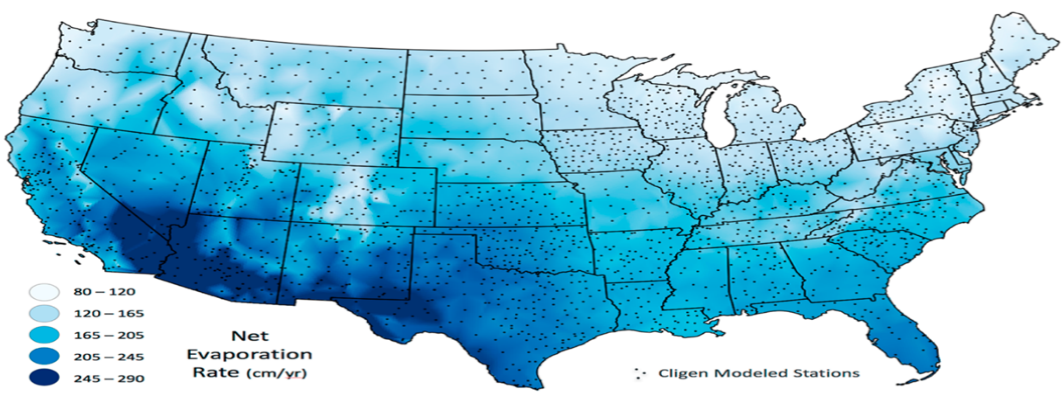

Figure 9: Estimated net evaporation rates of open surface water bodies in the United States. Each dot represents a feasible FPV water body. [10, Pg 1685]

Domestically FPV integration into undesired locales is already underway. Some examples include the Healdsburg Floating Solar Farm in California which occupies two ponds on the town's wastewater treatment plant. The farm employs 11,600 panels within a Class II system; it is the largest floating solar farm in the United States, providing a generation capacity of 4.8 MW to the town and supplying 8% of Healdsburg's annual electricity consumption. [11] The plant can be seen below in Figure 10.

California is not alone, FPV projects continue to be commissioned such as the second largest American FPV project located on a retention pond at a water treatment plant in Sayreville, NJ. The Sayreville solar farm (another Class II system seen in Figure 11) is the 2nd largest plant yielding 4.4 MW and provides 100% of the power for the plant. [11] An interesting note is that the FPV was constructed under a Power Purchase Agreement (PPA) in which the solar construction firm covers the cost of installation, and the consumer pays for the utilization of the plant's resources.[12] In this way Sayreville entered into a 15 year agreement with the solar construction firm (RETTEW in this case) and saved an estimated $1 million in energy costs for the borough according to a NJ municipal engineer. [13]

An additional monetary driver comes in the form of offered provisions to further incentivize FPV production. Such policies include New Jersey's Successor Solar Incentive Program (SuSi)[14] and Massachusetts' Solar Massachusetts Renewable Target (SMART) which pays PV system owners a base rate between 9¢/kWh - 39¢/kWh, and an additional 3¢/kWh if the PV system is a FPV system on a man-made body of water.[15]

Figure 10: Healdsburg Floating Solar Farm - California - 4.8 MW capacity

Figure 11: Sayreville Floating Solar Farm – New Jersey – 4.4 MW capacity

System Cost – NREL Benchmark Analysis

A 2021 report from NREL provides a benchmark cost analysis of a "typical" FPV system on artificial bodies of water for future system modeling and comparison with similar generation technologies. The data, assumptions and associated costs related to FPV components used to model their 10 MW_{DC} fixed tilt FPV system are inferred from averages of additional studies and interviews with a variety of different FPV developers and installers.[16, Pg 6] This system is subject to "average site conditions" consisting of wind load of about 40 m/s, snow load of 20 psf, water depth of 50 m, water level variation of 10 m, and swell height of 1 m.[16, Pg 7]

The NREL study emphasizes the importance of the structural supports in their system cost analysis. Within this the cost of floats constitute 75% - 85% the structural balance of the system (SBOS); within the U.S. the average cost of floats ranges between \$0.20 - \$0.40 /W_{DC} (\$0.22/W_{DC} - \$0.90/W_{DC} in Europe). However, the economies of scale can contribute to the reduction of cost for this subcomponent with \$0.40/ W_{DC} for a 2 MW FPV system, \$0.36/W_{DC} for a 5 MW FPV system, \$0.30/W_{DC} for a 10 MW FPV system, and \$0.20/ W_{DC} for a 50 MW FPV system.[16, Pg 9] A comparison of various FPV system costs based on capacity is depicted below within Figure 12:

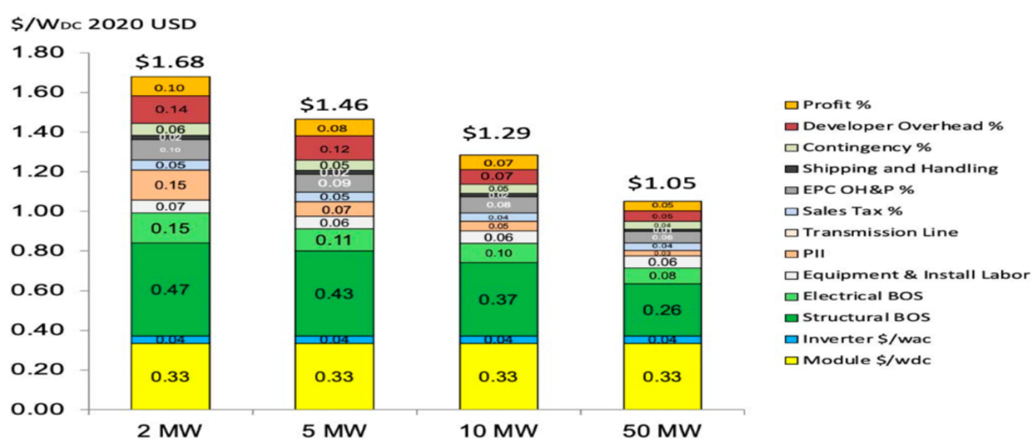

Figure 12: Benchmark cost of base-scenario FPV system with varying system sizes

In their comparison with an equivalent 10 MW traditional ground-mounted PV systems, NREL notes a system cost premium of about \$0.25/W_{DC} for the FPV site. This cost is largely attributed to the structural and floatation systems and mooring/anchor systems (which are in turn sensitive to additional wind and environmental loads).[6, Pg 10] The assorted sensitivity vectors of inputs to FPV system cost are depicted below within Figure 13:

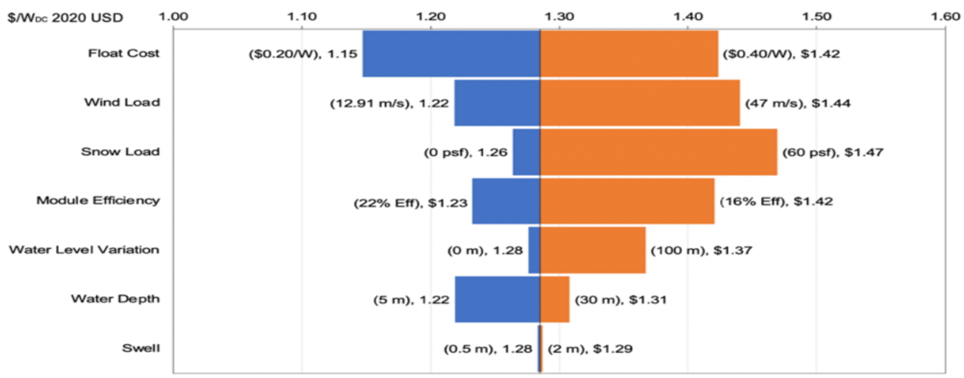

Figure 13: Sensitivity of FPV installed system cost to varying input assumptions

One last point of monetary comparison is that of the levelized cost of energy (LCOE): traditional ground-mounted PV claims \$47.1/MWh (\$32.4/MWh with a 26% investment tax credit) whereas FPV systems are about 20% more expensive with an LCOE of 56.6/MWh (\$37.8/MWh with a 26% investment tax credit).[16, Pg 12] A comparison of ground-mounted PV system costs and FPV system costs is depicted below within Figure 14:

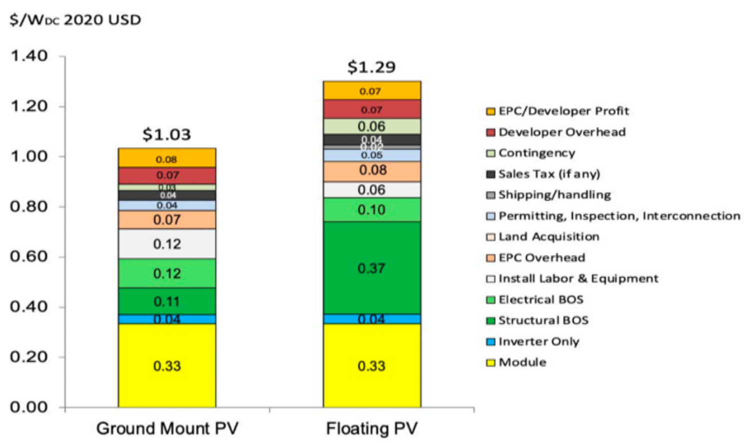

Figure 14: U.S. installed costs of 10-MWDC base-scenario FPV system and ground-mounted PV system

Effects On Water Quality & Aquatic Ecosystems

This is admittedly the one subtopic with the largest gap in knowledge as research into FPV technologies predominantly focuses on system design, performance, and cost. The common refrain that when applied to natural bodies of water FPVs mitigate water evaporation and reduce algae blooms is an oversimplification. Some effects of FPVs include the reduction of ambient water temperature and the altering of water chemistry (nitrification and deoxygenation) and composition (salinity concentration and sedimentation mixing and distribution) and microbial ecology via prolonged shading and evaporation reduction.[17, Pg 4-9]

It should be underscored that the biosphere under the surface is a highly dynamic environment and the significance of the effects rendered by an FPV plant are specific to the purposes of the water body and the particular construction of the FPV plant (largely in terms of surface area and structural materials). For example, one study using historical data simulated the application of 4 – 39 km^2 (10% – 100% of total surface area) of FPV panels covering reservoir on lake Rapel in Chile reduce the amount of chlorophyll-a (a proxy for freshwater algae - chlorophytes, diatoms, and cyanobacteria). The researchers note only panels covering more than 16 km^2 (40% of total surface area) kept the chlorophyll-a concentration below 10 µg/l (the upper threshold cited from World Health Organization's guidelines for safe recreational water environments). However, an FPV plant covering 27-39 km^2 (70% – 100%) resulted in critically low concentrations of chlorophyll-a (less than 0.4 µg/l) that would hamper microalgae levels to the point of affecting the lake's greater food chain. Depending on the intended purpose this effect may be harmful or beneficial (e.g. the water is to be used for drinking purposes), so one must prudently consider the ecological context in which the FPV plant is placed.[18, Pg 4-6] Tabular summaries of FPV effects on water quality[19, Pg 758] and site criteria[20, Pg 2] are provided in the Appendix.

The Synergy of Hydroelectric and Floating Photovoltaic Plants

Hydroelectric Power Plants (HPP) and Floating Photovoltaic Plants are two sources of renewable and clean energy sources. HPPs use the potential energy of 'falling' water to generate electricity, typically from a dam, a reservoir, and a turbine. On the other hand, the FPVs convert solar radiation into electricity (as facilitated by semiconductors), and are typically installed on water bodies such as lakes or reservoirs. (*Hybridizing Floating Solar with Hydropower – Pv Magazine International*, n.d.)

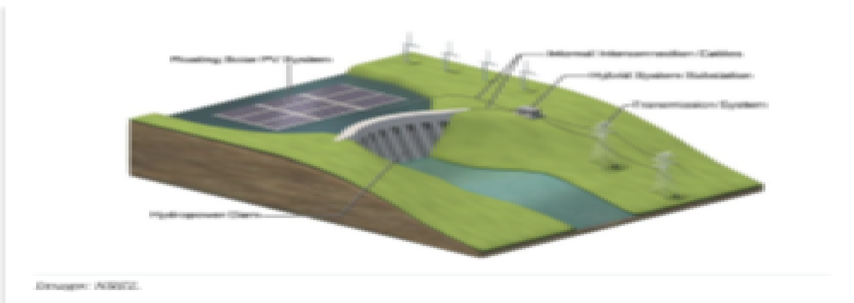

Figure 15: Hybridizing FPV with Hydro Power Plant

There exists a dual use of water bodies where a Hydroelectric Power Plant (HPP) is operated in tandem with a Floating Photovoltaic plant (FPV). Several studies have synergy between HPP and FPV. Another motivating argument for combining both technologies is that both of these are renewable energy sources and need to be developed as much as possible to achieve the goals of the Paris Agreement. The general idea is that the HPP will cover the energy demand throughout the day and the FPVs would near the peak load during the sun hours. Of course, there are a lot of considerations here. For example, how should the HPP and FPV be integrated and what should ideally be the size of the FPV

One inherent benefit of combining both technologies is that, since the HPPs are already connected to the electrical grid, joining the FPV to them would ensure using the existing infrastructure and reduce the cost of installation of FPVs. In temperate regions, PVs work best during the hot summer days with long solar hours. Coincidentally, this is the same time when HPPs are affected due to the excess heat due to the seasonal alteration in the water cycle. So, the FPVs can help reduce the fluctuation caused by power generated. To explore this aspect, we can look at a case study of the existing hybrid energy system of Land-based PV and Hydroelectric Power Plants.

Case study of Longyangxia hydro-PV hybrid energy system conducted by Bo Ming, Pan Liu, and Lei Cheng (Ming et al., 2021)

The hydro-PV hybrid energy system of Longyangxia, China is a massive Hybrid-Energy System (HES) composed of a land-based PV plant of 850 MW coupled with a 1280 MW capacity Hydroelectric Power Plant. The working model for such a system is that the fluctuating PV output is transmitted via a 330 kV line to the HPP and its nameplate component values are illustrated in Figure 16 below:

Technical parameters for the Longyangxia hydro–PV hybrid energy system.

Component	Parameter	Value	Unit
Hydropower reservoir	Normal pool level	2600	m
	Flood limited water level	2594	m
	Active storage	19.3	billion m^3
	Installed capacity	1280	MW
	Average annual energy production	5.94×10^6	MWh
PV plant	Installed capacity	850	MW
	Average annual energy production	1494	GWh
	Occupied area	20.4	km^2

Figure 16: Technical parameters for the Longyangxia hydro-PV hybrid energy system

The next step toward the hybridization of both the technologies is facilitated by the HPP adjusting its own power output in order to compensate for the PV fluctuations and ensuring that the net demand is always satisfied. In real-time, the power generated from the PVs is fluctuating. Due to this the Hydro plant is constantly adjusted so that the fluctuations from the PVs are covered by the output of the HPP. Below are the tables for the hybrid energy system power output for the flood season and non-flood season.

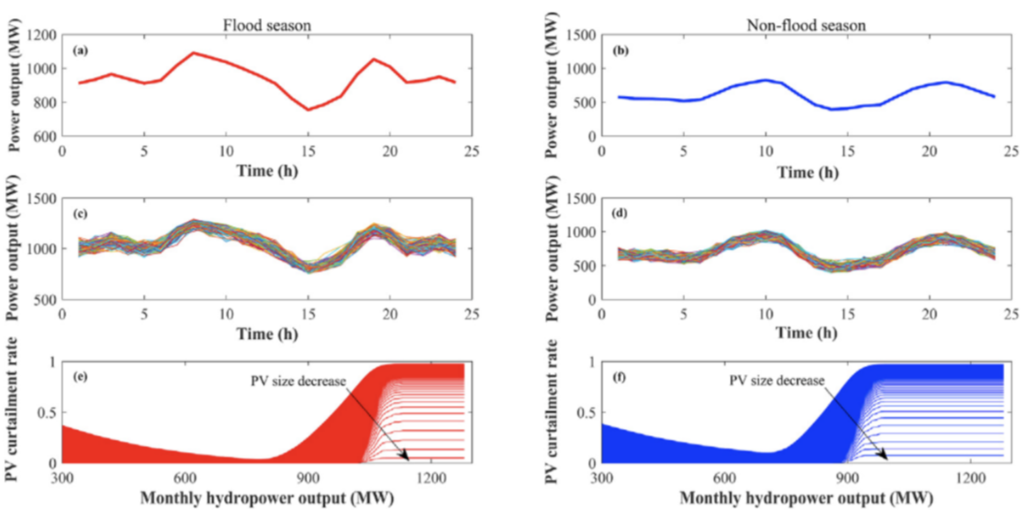

Figure 17: Comparison of load scenarios with hybridization of FPVs and HPPs

The load curves ‘a’ and ‘b’ depict the typical load scenarios. ‘c’ and ‘d’ are generated scenarios and ‘e’ and ‘f’ are PV loss functions. From this case study, it can be understood that the hybrid generation of energy with renewable sources, offers a great solution to overcome the challenges faced by both the mentioned technologies and produce more renewable energy per square unit of "land".

Prospects for Hybridization

Additionally, according to the U.S.-based studies (Gadzanku et al., 2022), combining solar and hydropower in a full hybrid system configuration may, at most, lead to the deployment of 7,593 GW, which would generate an estimated 10,616 TWh of electricity annually and cover 20% of the nation's reservoirs. Moreover, this method of integrating solar and hydro yields advantages, such as enhanced system performance at various time scales, more storage options due to pumped hydro, higher transmission line utilization rates, decreased PV curtailment, lower interconnection costs, and reduced water evaporation.

Based on a study conducted by the NREL (Gadzanku et al., 2022), there are a lot of reasons to go for the hybridization of FPVs and hydroelectric power plants. Because solar and hydropower complement each other, FPV and hydropower hybridization have advantages on a daily and seasonal level. At the diurnal scale, the results indicate that full hybridization, by utilizing more hydropower flexibility, might minimize generator operations and maintenance costs and reduce cycling for gas-fired production. Results indicate that hybridizing FPV leads to more efficient use of water resources on a seasonal basis, with hydropower output being lowered in the rainy season to preserve water for use in the dry season. In nations or regions that heavily rely on hydropower generation yet are susceptible to droughts and overall reductions in hydropower output, this might be a crucial resilience tool.

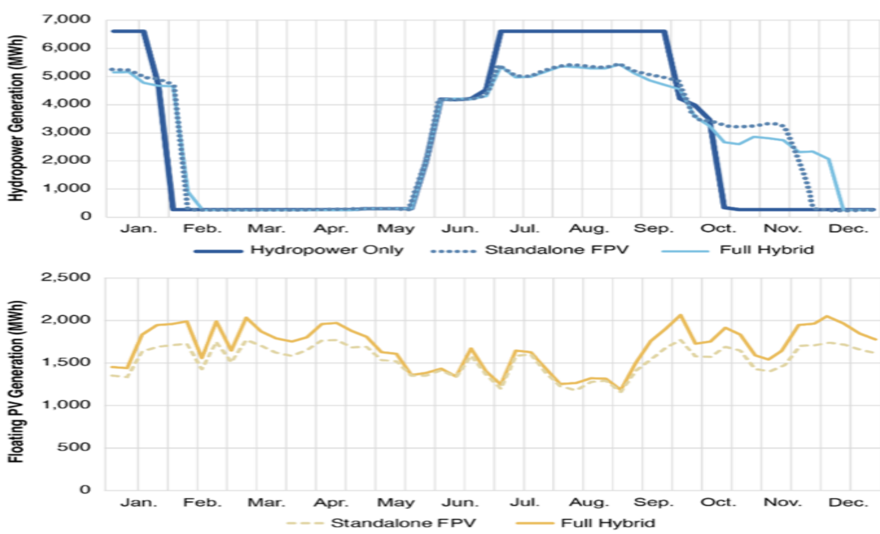

Figure 17: Comparison of power generated by stand-alone systems vs Full Hybrid systems

Conclusion

In summary the present field of advanced generation sources is greatly enhanced by the prospect of floating photovoltaic systems. As a platform, their flexibility in design, observed performance capabilities, synergies with stored hydropower, and potential environmental effects warrant further extensive research. Indeed, the applicability of this photovoltaic variant is vast as it can free up valuable land, penetrate high-cost utility markets, reduce water evaporation, and provide renewable power within a wide variety of locales domestically and abroad. Of course, deeper examinations and research on the full scope of bidirectional environmental impacts and system design improvements to overcome system costs, system scaling, and deployment in marine environments are paramount to fully realize the latent potential of this nascent solar platform and approach the targets of the Paris Agreement.

Appendix:

FPV Classifications [7, Pg 7]

Pontoon

Class I: PV panels are arranged on parallel pontoons which are connected by trusses. These variants can withstand wave heights up to 2m. Their elevated height above the water helps to minimize the exposure to saltwater spray. Lastly, their simple construction and supporting structure can accommodate the addition of a single-axis tracking system and a CAES system. E.g. The Swimsol SolarSea®

Class II: PV panels are each supported by an individual pontoon with included railing. The array of PV panels are pinned together in a modular fashion without supporting structures which lowers the cost of necessary supporting structures, but reduces the flexibility to integrate enhancement systems (like water veils, or tracking systems). E.g. The Hydrelio®

Class III: PV modules and electrical components are installed into monolithic floating islands. The rigidity of these variants eliminates the need to construct a catwalk, improves safety, and makes maintenance easier albeit at a higher cost. E.g. The "Zon op Zee" (Solar-at-Sea) plant located in the Dutch North Sea.

Superficial

Rigid: Thin-film PV modules are mounted on submergible structures with pumpable floats that allow the unit to sink up to 2 m beneath the surface; more studies are needed to improve resiliency against significant mechanical loads under high waves.

Flexible: Thin-film PV sheets are spread across a neoprene sheet within a lightweight enclosure. These variants sit directly on the waves eliminating the need for pontoons, and thus experience beneficial self-cooling and self-cleaning. Their simplified and flexible construction allows for enhanced reliance against incoming waves and a reduction on the mooring needed. However, since these variants sit on the water, their orientation and position are at the mercy of ambient waves around them making the introduction of tracking systems impractical at sea.

FPV Pros & Cons - Comparison With Land-based PV

At the end of 2018, the installations of FPVs reached 1.3 GWp (Cazzaniga et al., 2019) and it will only further increase as the technology matures with time. When planning to install a large solar farm on the land, there have to be considered multiple environmental impacts attached to it. These types of large-scale Solar projects need plenty of land area, potentially varying from 2.2 acres/MW to 12.2 acres/MW (Silva & Branco, 2018), in order to be functional. Even after consuming a drastic amount of land, these solar farms do not have the capacity yet to be able to match the energy output of conventional energy as produced from fossil fuels (land requirement per MW output). Not just this, the consumption of such large amounts of land can affect native wildlife. It is because of such reasons, the need to explore FPVs seems all the more logical. Here it can be seen how the installation of large-scale solar farms can impact the environment.

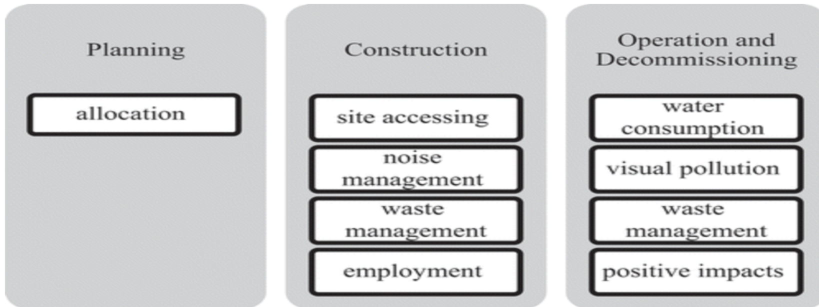

Figure 18: Environmental characteristics analyzed at all phases of a PV project

To have a more detailed look at how the FPVs fare versus the conventional PVs, let us consider all the key stages of the operation for an FPV plant as opposed to a similar Land-based PV plant. This can help understand the important benefits and shortcomings of Floating Photovoltaics and give a general idea of what direction this new technology should head towards. (*Where Sun Meets Water FLOATING SOLAR HANDBOOK FOR PRACTITIONERS*, 2019)

1. Site Identification

Clearly, the FPV does not hamper agricultural land or industrial areas. This is in contrast to the PVs where you need to allocate a fairly large section of land that can be used for something else. One more benefit of FPVs here is that usually, there can be a water body near the area where the FPVs are supposed to supply the load. Hence, this reduces the losses in transmission compared to the land PVs as they need to be situated on the far outskirts of cities.

2. Power System Benefits

As discussed earlier in the report, there is a possibility to couple the FPV with currently existing hydro power plants, giving us a hybrid operation. This opens up a whole new dimension for the generation of more renewable energy per unit area and reduces the cost of operation of FPVs.

3. Energy Yield

In the case of FPVs, there is almost zero shading. Hence, the FPVs get more solar irradiance as compared to the land PVs. However, there may be losses due to misalignment of module orientations.

4. Performance

It has been observed that the initial performance of FPVs is higher by 5-10% overall, depending on the climate of the site. Even so, the long-term degradation and performance of FPVs are still not certain as the technology is fairly immature. A concrete point cannot be made for the FPVs in this aspect as of now.

5. Engineering and Design

A key advantage here for the FPVs is that there is a relatively flatter surface for installation, whereas for the land PVs the installation must take place in accordance with the terrain constraints. However, there is only a limited amount of ‘tilt’ available for FPVs to provide safety from wind loads. This limited tilt might affect lower efficiencies when installed at higher altitudes.

6. Mounting and Support Structure

The support structure designed for an FPV has to make sure that it withstands not only wind and snow, which is usually the only impedance on land-based PVs, but also strong waves and water currents as previously discussed. Moreover, it is a much more difficult process as compared to say a rooftop PV installation.

7. Safety

Due to the high humidity levels, there may be lower insulation resistance, which could lead to more risk of electrical leakage. Additionally, there persists a danger because of the constant movement that the cables may get damaged and cause fires.

8. Investment Costs

Seemingly, due to the elaborate mounting and support structure, the initial investments are higher compared to land-based PVs.

Additional Figures

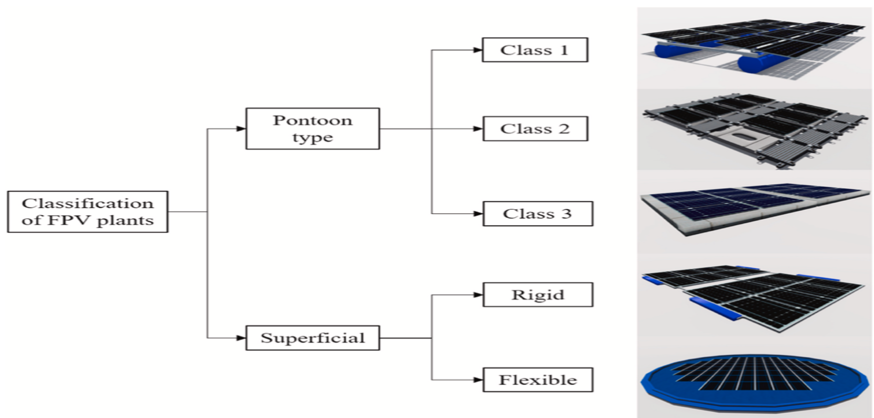

Figure 19: Floating Photovoltaic Plant categorizations based on high-level system construction

System	Opportunities	Threats
Physical	Reduced Evaporation Reduced Water Temperature Reduced Sedimentation Continued Horizontal Mixing	
Chemical	Reduced Salinity	Anoxia Nitrification Release of Methane Release of Hydrogen Sulfide Release of Ammonia Release of Heavy Metals from Bed Sediments
Biological	Reduced Algae Growth Reduced Faecal Coliforms E. Coli Concentrations Reduced Predator Vigilance for Fish Increased Zooplankton	Algal Biomass Peaks Delayed Algal Composition Modified Large Algal Blooms Success of Blue-Green Algae Improved Reduced Mixing and Turbidity Fish Die Shading Affects Fish Feeding

Figure 20: Potential opportunities and threats of FPV on water quality [19, Pg 758]

Factor	High preference	Low preference
Location	• Near load centers and populated regions • Easily accessible by road • Secured/fenced • Close to manufacturing facilities or ports for simplified logistics	• Remote places with high transportation cost[a]
Weather and climate	• High solar irradiation • Little wind or storms • Calm water • Dry region where water conservation is important	• Cold regions with freezing water • High winds and risk of natural disasters such as typhoons and tsunamis • Seasonal flooding • Drought events that lead to exposure of water bed
Type of water body	• Manmade reservoirs • Hydropower dams • Industrial water bodies, such as cooling ponds and wastewater treatment facilities[b] • Mine subsidence areas • Irrigation ponds	• Natural lakes • Tourist or recreational sites
Water body characteristics	• Regular shape • Wide opening toward south (for northern hemisphere) or north (for southern hemisphere)	• Narrow strip between mountains (gorges) • Presence of islands/obstacles in the middle
Water body ownership	• Single owner • Legal-entity owner	• Multiple owners • Individual private owners
Underwater terrain and soil conditions	• Shallow depth • Even terrain • Hard ground for anchoring • Water bottom clear of any cables, pipelines, or other obstructions	• Soft mud ground for anchoring
Water conditions	• Freshwater with low hardness and salinity	• Salty water • Dirty/corrosive water • Water prone to biofouling
Other site conditions	• Existing electrical infrastructure, transmission lines • Easy water access • Sufficient land area for deploying and placing electrical equipment • Self-consumption loads, such as wastewater treatment and irrigation pump facilities	• No existing electrical infrastructurec • Complicated banks, presence of bund walls • Extensive horizon shading from nearby mountains • Nearby pollution sources (for example, chimneys, burning crops, quarries)
Ecology	• Simple and robust ecology	• Natural habitat of preserved species • Frequent bird activity • Water species that are sensitive to water temperature, dissolved oxygen, and sunlight

Source: Authors' compilation.
a. In some cases, FPV can be highly valuable to remote regions.
b. This is relevant only if water quality remains suitable for FPV.
c. This may not be a concern, depending on the circumstances of the FPV project.

Figure 21: Floating Photovoltaic site suitability [20, Pg 2]

Resources:

1. Cazzaniga, R., Cicu, M., Rosa-Clot, M., Rosa-Clot, P., Tina, G. M., & Ventura, C. (2018). Floating photovoltaic plants: Performance Analysis and Design Solutions. *Renewable and Sustainable Energy Reviews*, *81*, 1730–1741. https://doi.org/10.1016/j.rser.2017.05.269
2. Rosa-Clot, M., & Tina, G. M. (2018). Chapter 4 - Submerged PV Systems. In *Submerged and floating photovoltaic systems: Modelling, Design and case studies* (pp. 65–87). essay, Academic Press.
3. Krauter, S. (2004). Increased electrical yield via water flow over the front of photovoltaic panels. *Solar Energy Materials and Solar Cells*, *82*(1-2), 131–137. https://doi.org/10.1016/j.solmat.2004.01.011
4. Fthenakis, V., & Lynn, P. (2018). Chapter 3 - PV Modules And Arrays. In *Electricity From Sunlight: Photovoltaic-Systems Integration and Sustainability* (pp. 86–86). essay, Wiley.
5. Marsh, J. (2022, November 29). *Are solar panels resistant to salt and corrosion?* EnergySage. Retrieved December 20, 2022, from https://news.energysage.com/solar-panels-resistant-salt-corrosion/
6. Zhang, Y., & Yuan, C. (2021). Effects of marine environment on electrical output characteristics of PV module. *Journal of Renewable and Sustainable Energy*, *13*(5), 053701–053701-9. https://doi.org/10.1063/5.0060201
7. Claus, R., & López, M. (2022). Key issues in the design of floating photovoltaic structures for the Marine Environment. *Renewable and Sustainable Energy Reviews*, *164*, 1–17. https://doi.org/10.1016/j.rser.2022.112502
8. Cazzaniga, R., Cicu, M., Rosa-Clot, M., Rosa-Clot, P., Tina, G. M., & Ventura, C. (2017). Compressed air energy storage integrated with Floating Photovoltaic Plant. *Journal of Energy Storage*, *13*, 48–57. https://doi.org/10.1016/j.est.2017.06.006
9. Slater, N. J. (2021, March 31). *DNV publishes world's first recommended practice for floating solar power plants*. DNV. Retrieved December 20, 2022, from https://www.dnv.com/news/dnv-publishes-world-s-first-recommended-practice-for-floating-solar-power-plants-199138
10. Spencer, R. S., Macknick, J., Aznar, A., Warren, A., & Reese, M. O. (2018). Floating photovoltaic systems: Assessing the technical potential of photovoltaic systems on man-made water bodies in the continental United States. *Environmental Science & Technology*, *53*(3), 1680–1689. https://doi.org/10.1021/acs.est.8b04735
11. YSG Solar. (2022, January 21). *3 Largest Floating Solar Farms in the United States in 2022 | YSG Solar*. YSG Solar. Retrieved December 20, 2022, from https://www.ysgsolar.com/blog/3-largest-floating-solar-farms-united-states-2022-ysg-solar
12. YSG Solar. (2021, March 4). *Power Purchase Agreements: State by State | YSG Solar*. YSG Solar. Retrieved December 20, 2022, from http://ysgsolar.com/blog/power-purchase-agreements-state-state-ysg-solar
13. Jaffe, J. (2021, March 30). *Sayreville: Home to Largest Floating Solar Array in U.S.* TAPinto. Retrieved December 20, 2022, from https://www.tapinto.net/towns/raritan-bay/sections/green/articles/sayreville-home-to-largest-floating-solar-array-in-u-s
14. State of New Jersey Board of Public Utilities. (2021, July 28). *NJBPU approves 3,750 MW successor Solar Incentive Program*. State of New Jersey Board of Public Utilities | Newsroom & Public Notices. Retrieved December 20, 2022, from https://www.nj.gov/bpu/newsroom/2021/approved/20210728.html
15. Shemkus, S. (2021, September 7). *Ponds, reservoirs could host floating solar in space-constrained Massachusetts*. Energy News Network. Retrieved December 20, 2022, from https://energynews.us/2021/09/07/ponds-reservoirs-could-host-floating-solar-in-space-constrained-massachusetts/
16. Ramasamy, Vignesh, & Margolis, Robert. (2021, October 1*) Floating Photovoltaic System Cost Benchmark: Q1 2021 Installations on Artificial Water Bodies*. United States. https://doi.org/10.2172/1828287

17. Exley, G., Hernandez, R. R., Page, T., Chipps, M., Gambro, S., Hersey, M., Lake, R., Zoannou, K.-S., & Armstrong, A. (2021). Scientific and stakeholder evidence-based assessment: Ecosystem response to floating solar photovoltaics and implications for Sustainability. *Renewable and Sustainable Energy Reviews*, *152*, 1–14. https://doi.org/10.1016/j.rser.2021.111639
18. Haas, J., Khalighi, J., de la Fuente, A., Gerbersdorf, S. U., Nowak, W., & Chen, P.-J. (2020). Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility. *Energy Conversion and Management*, *206*, 1–8. https://doi.org/10.1016/j.enconman.2019.112414
19. Essak, L., & Ghosh, A. (2022). Floating Photovoltaics: A Review. *Clean Technologies*, *4*(3), 752–769. https://doi.org/10.3390/cleantechnol4030046
20. Energy Sector Management Assistance Program; Solar Energy Research Institute of Singapore. 2019. *Where Sun Meets Water: Floating Solar Handbook for Practitioners*. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/32804 License: CC BY 3.0 IGO
21. Cazzaniga, R., Rosa-Clot, M., Rosa-Clot, P., & Tina, G. M. (2019). Integration of PV floating with hydroelectric power plants. *Heliyon*, *5*(6), e01918. https://doi.org/10.1016/J.HELIYON.2019.E01918
22.Gadzanku, S., Lee, N., & Dyreson, A. (2022). *A product of the USAID-NREL Partnership ENABLING FLOATING SOLAR PHOTOVOLTAIC (FPV) DEPLOYMENT Exploring the Operational Benefits of Floating Solar-Hydropower Hybrids*. www.nrel.gov/publications.
Hybridizing floating solar with hydropower – pv magazine International. (n.d.).
23. Ming, B., Liu, P., & Cheng, L. (2021). An integrated framework for optimizing large hydro–photovoltaic hybrid energy systems: Capacity planning and operations management. *Journal of Cleaner Production*, *306*, 127253. https://doi.org/10.1016/J.JCLEPRO.2021.127253
24. Silva, G. D. P. da, & Branco, D. A. C. (2018). Is floating photovoltaic better than conventional photovoltaic? Assessing environmental impacts. *Impact Assessment and Project Appraisal*, *36*(5), 390–400. https://doi.org/10.1080/14615517.2018.1477498

AGRI PHOTOVOLTAICS/CARBON STORAGE

A brief exploration of Agri Photovoltaic and potential of Carbon Sequestration In PV sites

DECEMBER 19, 2022

PATRYK ZAGULA & DHRUV MAKWANA

Executive Summary - AVS & Carbon Storage

AVS technology is the cultivation of crops beneath solar panels. Because of its dependability, sustainability in land usage for clean energy generation, sustainable techno-economic system, and fulfillment of the human race's social demands, it is gaining favor in variable-scale applications. As a result, governments throughout the world, including Germany in 1982, Japan in 2004, the United States in 2008, China in 2016, India in 2018, and South Korea in 2019, have already authorized guidelines allowing the use of AVS on agricultural land. This study briefly addresses the many types of agri-photovoltaic systems, the microclimate variables that impact crop growth and power production from the systems, and their economic feasibility. It also addresses the benefits and drawbacks of agrivoltaic systems, as well as their environmental and social consequences.

Carbon sequestration potential in existing and new PV site is an area worth exploring to better understand the effects of infrastructure having on soil. In recent years, scientists observed the alteration of soil when infrastructure was built, seven years later they compared the soil to a nearby grassland to better understand the carbon potential. The results clearly indicate a better need for farming techniques as well as carbon management. To that, another area worth exploring is the effects of cattle grazing with plants installed underneath plants. Obviously the results are tremendous, in fact, grazing treamtent can increase the soil productivity and promote carbon sequestration growth. The case studies further examine the ideas and theory behind the relationship between carbon sequestration and PV sites.

Agrivoltaic Systems (AVS):

Two German scientists suggested the concept of merging agricultural and solar energy development into an agrivoltaic system in 1982 (Goetzberger & Zastrow, 1982). Agrivoltaic farming is the process of cultivating crops beneath solar panels. It grows vegetables in the shadow of solar panels. This approach will increase the land equivalent ratio (LER) and farmer income in areas with good irradiation, big flat expanses, and low land production capacity (Agostini et al., 2021). This improves land-use efficiency by allowing solar farms and agriculture to coexist rather than compete. Additionally, this type of land area will lower expenses associated with construction, upkeep, and cultivation while enhancing land-use effectiveness and AVS's real estate value (Barron-Gafford et al., 2019; Choi et al., 2021). The AVS technology is gaining popularity in variable-scale applications due to its reliability, and sustainability in land use for clean energy generation, viable techno-economic system, and fulfillment of the social need of the human race (Mamun et al., 2022a; Neupane Bhandari et al., 2021). The average amount of energy produced daily by solar systems in almost 100 countries is 4.5 kWh/kW/day (Nordberg et al., 2021). As a result, the governments of various nations, including Germany in 1982, Japan in 2004, the United States in 2008, China in 2016, India in 2018, and South Korea in 2019, have already approved rules for the application of AVS and shown the technology's potential on agricultural land (Gorjian et al., 2022; Honsberg et al., 2021).

AVS Installation:

According to numerous recent research, many crops tend to flourish when planted in such conditions. Solar panels must occasionally be lifted or hung to allow plants to grow beneath them. Another possibility is to install them on greenhouse roofs. This permits light and rainwater to reach the crops while allowing agricultural machines access. The panels are 2-3 meters from the ground and sit at an angle from the ground, creating shade and protecting crops from the elements (Majumdar & Pasqualetti, 2018).

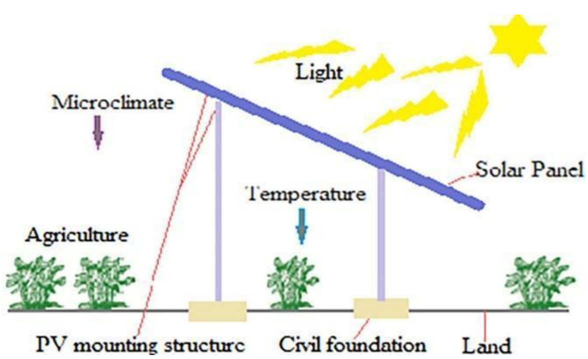

Fig. 1. AVS Installation (Giri & Mohanty, 2022)

Any flat-plate collector should be pointed south (within the northern hemisphere) and inclined at an angle equal to or slightly higher than the geographic latitude. To avoid excessive shadowing, collector rows should be set some distance apart, with a usual rule of thumb of around three times the collector's height. Because of this configuration, a significant quantity of solar energy will reach the ground between the collecting plates. The amount that reaches the ground will be especially high during the summer months, which coincide with the growing season. If the collectors are positioned directly on the ground, the radiation intensity between them will be exceedingly inhomogeneous, with practically complete shadowing beneath the collectors. The dispersion of radiation can be evened out by raising the collectors on a suitable support structure. Solar collectors are designed to operate well in the winter and transition seasons. For improved energy and food production, a good AVS design would effectively control air circulation, air temperature, radiation, photosynthesis, and wind speed below the structure. Since plants only need around 5-10% of the total incident light, PVs can use the remaining light to produce energy (Giri & Mohanty, 2022). During the other seasons, they do not intercept the majority of the light. As a result, they almost perfectly complement the plant growing season (Chae et al., 2022; Goetzberger & Zastrow, 1982).

AVS mainly has two types of designs: portable and adjustable as shown in Fig. 2. As the name suggests the portable structure can be entirely shifted easily to any location that has better solar radiation, whereas the adjustable structure can be titled to produce energy throughout the year. The optimum tilt angle depends on a geographic location's latitude, longitude, and season change. Experimentally the following equation is determined for calculating the optimum tilt angle:

$$Optimum\ tilt\ angle\ = 90^{0} - (\text{Earth's axis tilt angle} + \text{Latitude of location})$$

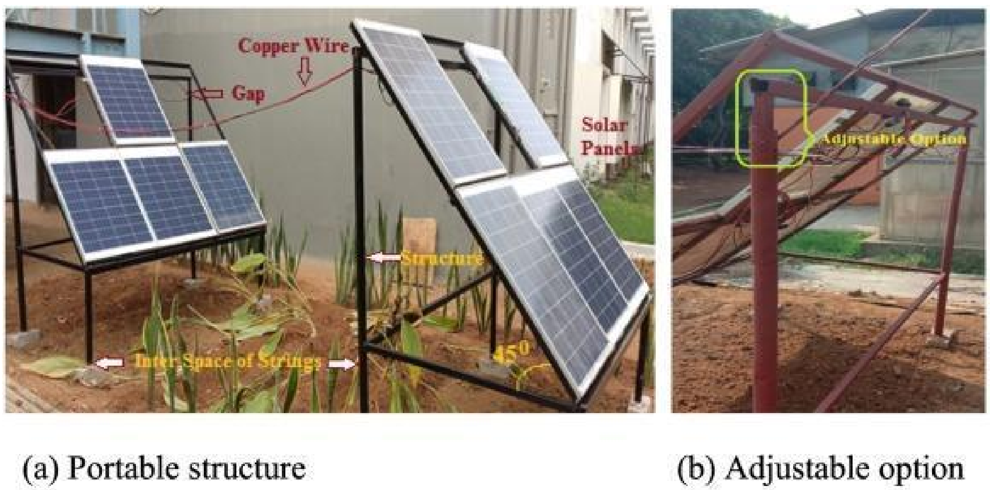

Fig. 2. Designs of AVS (Giri & Mohanty, 2022)

Crop Selection:

Crop selection depends on the microclimate aspects under the PV structure that are suitable for the crop. The following conditions are the main microclimate aspects that are considered for the selection of the right crop:

(1) Air temperature:
The AVS causes significant differences in air temperature. The air temperature around AVS is drastically lower as compared to stand-alone PV systems due to the presence of crops (Armstrong et al., 2016; Hassanpour Adeh et al., 2018; Marrou et al., 2013).

(2) Humidity:
Growing crops beneath PV systems causes significant changes in relative humidity, independent of the ground clearance height (Armstrong et al., 2016; Marrou et al., 2013).

(3) Wind speed:
Regardless of ground clearance height, wind speed greatly influences crop growth. Significantly different wind speed profiles result in larger AVS (Brown, 2019; Marrou et al., 2013).

(4) Wind direction:
AVS causes significant changes in wind direction regardless of the ground clearance height (Brown, 2019; Hassanpour Adeh et al., 2018).

(5) Soil temperature:

Different crops showed a notable discrepancy in the rate of leaf emission due to changes in soil temperature (Armstrong et al., 2016; Marrou et al., 2013).

(6) Soil moisture:
Due to an unequal shadowing from agrivoltaic systems, sharp discrepancies were observed in localized gradients in soil moisture (Brown, 2019).

(7) Crop temperature:
Crop temperature does not significantly vary under shadowing, and the growth rate under PV installations is shown to be comparable to traditional agricultural practices (Marrou et al., 2013).

(8) Vapor pressure deficit (VPD):
During growing seasons VPD is always lower in AVS compared to conventional (Marrou et al., 2013).

(9) Photosynthetically active radiation (PAR):
PAR in the shaded region is drastically lower than in the unshaded region (Santra et al., 2018a).

The shading caused by APVs reduces water evaporation from soil which is beneficial for water-scarce regions but it harms the photosynthesis process. Fig. 3 shows different crops that are suitable for AVS under the "+" category, while crops that don't perform well under shade are kept in the "-" category. The "0" category shows crops that don't have any shading preferences when overall crop yield is considered.

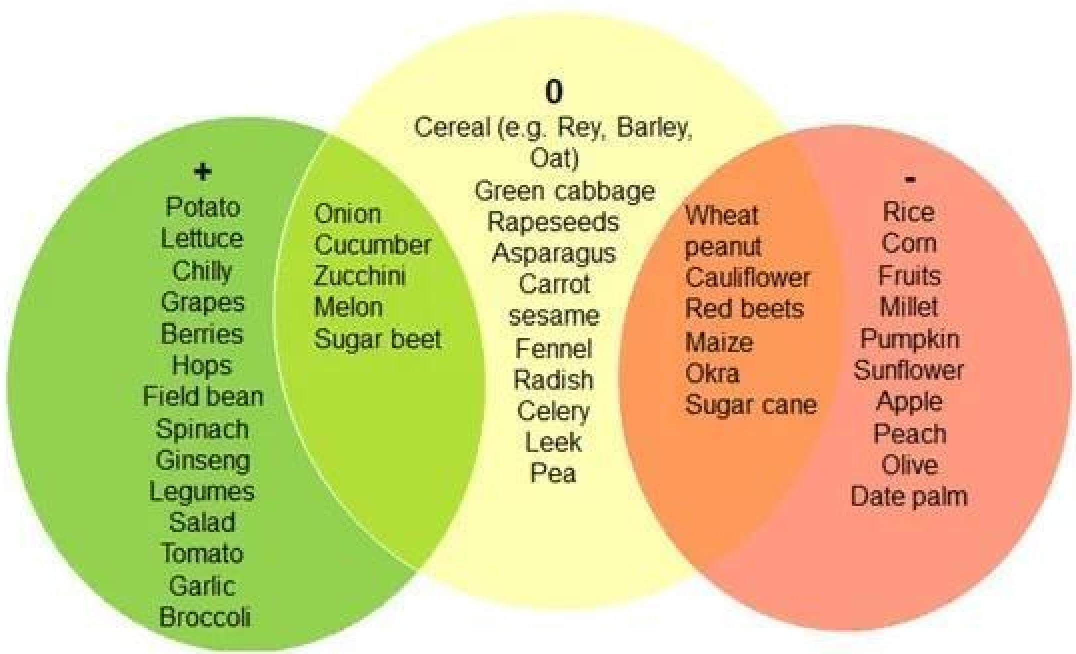

Fig. 3. Effect of APVs on various crops (Mamun et al., 2022)

Power Generation:

As previously mentioned, solar radiation, tilt, array azimuth angle, and dust deposition all have an impact on power generation. Although some PV cells employ dispersed radiation, direct radiation is typically regarded as the most efficient for energy production. According to the findings of several research, amorphous silicon (a-Si) and cadmium telluride (CdTe) solar panels have a higher agricultural output than mc-Si (crystalline silicon) solar panels.

Factors that affect power generation in AVS are as follows:

(1) Radiation:
    Direct radiation is generally considered more energy production (Adeh et al., 2019).
(2) Tilt and Azimuth:
    PV modules with the least angle of incidence from sunlight receive maximum solar radiation (Malu et al., 2017).
(3) Ambient temperature:
    AVS have lower temperatures compared to conventional PV farms that help in obtaining optimum temperature for energy production (Dinesh & Pearce, 2016).
(4) Dust accumulation:
    Energy production declines as dust build-up increases. The relationship between deposited dust density and particle size in terms of dust accumulation (Guerin, 2017).

The orientation of PV is dependent on the location, for the Northern hemisphere the panels should be facing towards the south to receive maximum direct radiation. Orientation also depends on the solar azimuth angle, which is zero during solar noon, negative in the morning, and positive in the afternoon. Ambient temperature is affected by wind speed as PV panels function efficiently at a lower temperature, which can be achieved through proper cooling systems. So, the high wind speed acts as a coolant for AVS, increasing its production by nearly 27%. Agricultural activities hurt the power generation of PVs as it causes dust accumulation on the PV surface, reducing its capacity by nearly 50% due to dust accumulation over six months (Rahman et al., 2015; Roy & Ghosh, 2017).

Challenges & Constraints:

Suitability of Plants:

It is a continuing concern for researchers in Agrivoltaic, as crops with high net photosynthetic levels and high tolerance to shading are best suited for this practice. However, the result from previous studies shows that this effect is crop-specific. So, for some crops, the annual yield decreases as the AVS influences the evaporation rate but for some crops like cabbage and lettuce, the annual yields can be maintained or even increased. Studies show that appropriately selected crops can help improve water use efficiency and also help check water losses in dry climates (Valle et al., 2017; Weselek et al., 2019). Apart from these, Livestock grazing is another major problem for AVS as it could cause harm to both AVS and animals (Ketzer et al., 2020).

Land use efficiency:

Although, researchers suggest that AVS offers benefits by providing Dual-use and better real estate value. But AVS should also offer help in countries with dense populations, hilly regions, and small islands with land scarcity. The other challenges offered by AVS are harmful to crops if not installed properly, and increased humidity due to shading which can become a breeding ground for diseases and parasites. The installation cost of AVS also serves as a roadblock for the wider application of AVS (Scognamiglio, 2016).

Shading:

Shading is the most critical issue for implementing AVS. As AVS reduces the available radiation for crops by up to 40-50%. The seasonal changes also alter the shading and microclimate conditions under the PVs which then affects the annual yield of a crop. But to overcome this problem researchers have classified crops that can be cultivated under AVS, depending on the availability of light i.e., full shade, low light, and moderate light (Sekiyama & Nagashima, 2019). Table 1, shows the various crops that can be under the above-mentioned conditions.

Major commercial shade-intolerant crops	**Shade-tolerant-crops**		
	Full shade	**Moderate light**	**Low light**
Cabbage, corn, cucumber, pumpkin, rice, tomato, turnip, and watermelon	Alfalfa, arugula, Asian greens, broccoli, cassava, chard, collard greens, hog peanuts, kale, kohlrabi, lettuce, mustard greens, parsley, scallions, sorrel, spinach, sweet potatoes, taro, and yam	Beans, carrots, cauliflower, coriander, green peppers, and onions	Mushroom

Table 1. Crops that be grown under Agrivoltaic Systems (Mamun et al., 2022)

Benefits of AVS:

Water Use Efficiency (WUE):

Studies show that water use efficiency is not seriously affected by Agrivoltaic systems. Especially in water-scarce regions, the shading provided by AVS helps retain the water present in the soil, this helps in the usage of water for irrigation by up to 20%. The water used for cleaning PVs can again be used for irrigation purposes, further increasing the efficiency and reducing the water used for irrigation. Lastly, AVS also helps harvest rainwater, which benefits the water-scarce region. One example is in Rajasthan, India where with the help of 105 Kw AVS rainwater was harvested, improving the WUE and land equivalent ratio (LER). Since access to water is predicted to be receding for many regions around the world, it becomes really important to implement AVS (Santra et al., 2018).

Income Diversification:

AVS offers great employment opportunities in rural areas, as it provides more income streams from a single land. Income can be generated from crops and energy produced from the land, increasing its productivity by 70%. This would also allow the farmers to offset greenhouse gas emissions and also attract agri-tourism, providing another possible income stream (Weselek et al., 2019).

Environmental Outcomes:

Conventional solar farms leave barren land which is not the case for AVS as the land is continued for farming. AVS also helps decrease CO_2 emissions as opposed to conventional solar farms. AVS also helps improve crops' resilience to climate change and it also has the potential to become a driving factor for transferring to climate-smart agriculture (Leon & Ishihara, 2018).

Social Benefits:

A case study from Gujarat, India shows that implementing AVS has helped to increase micro-entrepreneurship, especially among women by encouraging employment in the processed food industry. This also helps in reducing the migration of the population from rural to urban areas. The government could also benefit from AVS by introducing taxation to these enterprises, while also promoting social welfare (Patel et al., 2018).

Economic Feasibility:

Studies indicate that although there isn't much difference in the OPEX of AVS and conventional PV systems, CAPEX of AVS is nearly 30% higher due to increased labor and designing expenses. Results of LCA analysis of AVS and conventional PV systems show that a conventional system even under low solar radiation conditions has a payback time of around five years, while AVS for suitable crops still has a payback time of four to eight years. However, some researchers argue that almost 50% of the initial investment can be earned back within two years of deploying AVS. To determine the economic feasibility of AVS, high CAPEX costs need to be justified. To overcome these risks, policies like FiT (Feed-in-tariff) (in Japan) can be introduced to help secure electricity sales for the long term (Mamun et al., 2022).

Dinesh & Pearce, 2016, conducted a study on two different types of AVS (half-density and full-density) to determine their revenue generation. Results showed that revenue from AVS far exceeded that of single-use agricultural land. Hence, justifying the trade-off between crop yield and power generation.

Another study from India by Patel et al., 2018, conducted in the state of Gujarat indicated that 98% of revenue generated from AVS was from selling electricity at USD 0.23 per kWh. This was achieved with help of Gujarat state's beneficial solar energy policies. The financial data generated from previous studies are presented in Table 2.

References	Revenue from Electricity (US$/ha/year)	Revenue from Agricultural products (US$/ha/year)	% of electricity revenue
Patel et al. 2019	1,55,473	3,505	98
Malu et al. 2017	51,341	3,507	93.6
Dinesh and Pearce et al. 2016	80,000	17,000	82.5
Schindele et al. 2020	70,981	12,809	85

Table 2. Financial data from previous experiments (Mamun et al., 2022; Schindele et al., 2020).

References:

Adeh, E. H., Good, S. P., Calaf, M., & Higgins, C. W. (2019). Solar PV Power Potential is Greatest Over Croplands. *Scientific Reports*, *9*(1), 11442. https://doi.org/10.1038/s41598-019-47803-3

Agostini, A., Colauzzi, M., & Amaducci, S. (2021). Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment. *Applied Energy*, *281*, 116102. https://doi.org/10.1016/J.APENERGY.2020.116102

Armstrong, A., Ostle, N. J., & Whitaker, J. (2016). Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environmental Research Letters*, *11*(7), 074016. https://doi.org/10.1088/1748-9326/11/7/074016

Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, *2*(9), 848–855. https://doi.org/10.1038/s41893-019-0364-5

Brown, A. (2019). Photovoltaic win–win. *Nature Climate Change*, *9*(1), 7. https://doi.org/10.1038/s41558-018-0381-9

Chae, S. H., Kim, H. J., Moon, H. W., Kim, Y. H., & Ku, K. M. (2022). Agrivoltaic Systems Enhance Farmers' Profits through Broccoli Visual Quality and Electricity Production without Dramatic Changes in Yield, Antioxidant Capacity, and Glucosinolates. *Agronomy*, *12*(6). https://doi.org/10.3390/agronomy12061415

Choi, C. S., Ravi, S., Siregar, I. Z., Dwiyanti, F. G., Macknick, J., Elchinger, M., & Davatzes, N. C. (2021). Combined land use of solar infrastructure and agriculture for socioeconomic and environmental co-benefits in the tropics. *Renewable and Sustainable Energy Reviews*, *151*, 111610. https://doi.org/10.1016/J.RSER.2021.111610

Dinesh, H., & Pearce, J. M. (2016). The potential of agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, *54*, 299–308. https://doi.org/10.1016/J.RSER.2015.10.024

Giri, N. C., & Mohanty, R. C. (2022). Agrivoltaic system: Experimental analysis for enhancing land productivity and revenue of farmers. *Energy for Sustainable Development*, *70*, 54–61. https://doi.org/https://doi.org/10.1016/j.esd.2022.07.003

Goetzberger, A., & Zastrow, A. (1982). On the Coexistence of Solar-Energy Conversion and Plant Cultivation. *International Journal of Solar Energy*, *1*(1), 55–69. https://doi.org/10.1080/01425918208909875

Gorjian, S., Bousi, E., Özdemir, Ö. E., Trommsdorff, M., Kumar, N. M., Anand, A., Kant, K., & Chopra, S. S. (2022). Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology. *Renewable and Sustainable Energy Reviews*, *158*, 112126. https://doi.org/10.1016/J.RSER.2022.112126

Guerin, T. (2017). Using agricultural land for utility-scale photovoltaic solar electricity generation. *Agricultural Science*, *29*(1), 40–49.

Hassanpour Adeh, E., Selker, J. S., & Higgins, C. W. (2018). Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLOS ONE*, *13*(11), e0203256. https://doi.org/10.1371/journal.pone.0203256

Honsberg, C. B., Sampson, R., Kostuk, R., Barron-Gafford, G., Bowden, S., & Goodnick, S. (2021). Agrivoltaic Modules Co-Designed for Electrical and Crop Productivity. *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, 2163–2166. https://doi.org/10.1109/PVSC43889.2021.9519011

Ketzer, D., Weinberger, N., Rösch, C., & Seitz, S. B. (2020). Land use conflicts between biomass and power production – citizens' participation in the technology development of Agrophotovoltaics. *Journal of Responsible Innovation*, *7*(2), 193–216. https://doi.org/10.1080/23299460.2019.1647085

Leon, A., & Ishihara, K. N. (2018). Influence of allocation methods on the LC-CO2 emission of an agrivoltaic system. *Resources, Conservation and Recycling*, *138*, 110–117. https://doi.org/10.1016/J.RESCONREC.2018.06.017

Majumdar, D., & Pasqualetti, M. J. (2018). Dual use of agricultural land: Introducing 'agrivoltaics' in Phoenix Metropolitan Statistical Area, USA. *Landscape and Urban Planning*, *170*, 150–168. https://doi.org/10.1016/J.LANDURBPLAN.2017.10.011

Malu, P. R., Sharma, U. S., & Pearce, J. M. (2017). Agrivoltaic potential on grape farms in India. *Sustainable Energy Technologies and Assessments*, *23*, 104–110. https://doi.org/10.1016/J.SETA.2017.08.004

Mamun, M. A. al, Dargusch, P., Wadley, D., Zulkarnain, N. A., & Aziz, A. A. (2022). A review of research on agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, *161*, 112351. https://doi.org/10.1016/J.RSER.2022.112351

Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., & Wery, J. (2013). Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? *Agricultural and Forest Meteorology*, *177*, 117–132. https://doi.org/10.1016/J.AGRFORMET.2013.04.012

Neupane Bhandari, S., Schlüter, S., Kuckshinrichs, W., Schlör, H., Adamou, R., & Bhandari, R. (2021). Economic Feasibility of Agrivoltaic Systems in Food-Energy Nexus Context: Modelling and a Case Study in Niger. *Agronomy*, *11*(10). https://doi.org/10.3390/agronomy11101906

Nordberg, E. J., Julian Caley, M., & Schwarzkopf, L. (2021). Designing solar farms for synergistic commercial and conservation outcomes. *Solar Energy*, *228*, 586–593. https://doi.org/10.1016/J.SOLENER.2021.09.090

Patel, B., Gami, B., Baria, V., Patel, A., & Patel, P. (2018). Co-Generation of Solar Electricity and Agriculture Produce by Photovoltaic and Photosynthesis—Dual Model by Abellon, India. *Journal of Solar Energy Engineering*, *141*(3). https://doi.org/10.1115/1.4041899

Rahman, M. M., Hasanuzzaman, M., & Rahim, N. A. (2015). Effects of various parameters on PV-module power and efficiency. *Energy Conversion and Management*, *103*, 348–358. https://doi.org/10.1016/J.ENCONMAN.2015.06.067

Roy, S., & Ghosh, B. (2017). Land utilization performance of ground mounted photovoltaic power plants: A case study. *Renewable Energy*, *114*, 1238–1246. https://doi.org/10.1016/J.RENENE.2017.07.116

Santra, P., Singh, R. K., Meena, H. M., Kumawat, R. N., Mishra, D., Jain, D., & Yadav, O. P. (2018). *Agri-voltaic system: Crop production and photovoltaic-based electricity generation from a single land unit. Indian Farming 68 (01), 20-23.*

Schindele, S., Trommsdorff, M., Schlaak, A., Obergfell, T., Bopp, G., Reise, C., Braun, C., Weselek, A., Bauerle, A., Högy, P., Goetzberger, A., & Weber, E. (2020). Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications. *Applied Energy*, *265*, 114737. https://doi.org/10.1016/J.APENERGY.2020.114737

Scognamiglio, A. (2016). 'Photovoltaic landscapes': Design and assessment. A critical review for a new transdisciplinary design vision. *Renewable and Sustainable Energy Reviews*, *55*, 629–661. https://doi.org/10.1016/J.RSER.2015.10.072

Sekiyama, T., & Nagashima, A. (2019). Solar Sharing for Both Food and Clean Energy Production: Performance of Agrivoltaic Systems for Corn, A Typical Shade-Intolerant Crop. *Environments*, *6*(6). https://doi.org/10.3390/environments6060065

Valle, B., Simonneau, T., Sourd, F., Pechier, P., Hamard, P., Frisson, T., Ryckewaert, M., & Christophe, A. (2017). Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Applied Energy*, *206*, 1495–1507. https://doi.org/10.1016/J.APENERGY.2017.09.113

Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., & Högy, P. (2019). Agrophotovoltaic systems: applications, challenges, and opportunities. A review. *Agronomy for Sustainable Development*, *39*(4), 35. https://doi.org/10.1007/s13593-019-0581-3

Carbon Storage:

Soil sequestration or formally known as carbon sequestration is the method of managing lands, for example, farmlands to store as much carbon as possible. These methods for carbon storage include: low-till or no-till practice, altering the plant rotation schedule, and applying crop residues to fields. These applications capture carbon dioxide from the atmosphere and store it in soil. These procedures are critical in slowing down the rapid rise of carbon dioxide into the atmosphere-doing so avoid catastrophic impacts on climate change.[1]

It is estimated that the concentration of carbon dioxide during the pre-industrial era is near 280 parts per million, and in recent years this number has risen to 380 parts per million. To combat this sudden environmental impact, carbon sequestration can be used to absorb an additional 1.85 gigatons of carbon per year.[3]

Soil carbon sequestration occurs because ecological processes like photosynthesis, respiration, and decomposition contribute to the results of carbon storage. Firstly, photosynthesis draws the carbon out of the air to make carbon compounds located in the plant's biomass. The carbon that is utilized combines with water and sugar to encourage plant growth, the excess carbon is secreted through roots and into the soil and is utilized by other microorganisms. Some of the carbon is released back into the atmosphere when roots or plants decompose, and other carbon is stored for the long term.[2]

"Stable" carbon secreted from the soil can accumulate and be stored underground for several thousand years to come, and "active" carbon, found in topsoil, can float in between the microorganisms and the atmosphere.[2]

"Stable" carbon has many benefits, for example, carbon sequestration helps degrade soil and improves its agricultural productivity, healthier soils allow farms to become more resilient against droughts and rainfall, and require less usage of fertilizer, which saves farmers money and reduces environmental impacts.[3]

Co-location of solar installations and vegetation has the benefit of providing electricity output and promoting agricultural production. Depending on the solar system height installation and spacing, the crops are shade tolerant and the smaller height plants can be ideal for production in one area. For example, in a pasture landscape, a solar system that is elevated can promote more shading and cover the livestock while not having a big impact on productivity. However, on the other hand, if the agricultural activities require big machines then that could mean limited options for co-locations.[4]

Case Study I:

In this case study, the researchers from NREL (National Renewable Energy Laboratory) hypothesized that if farmers adopt the practice of revegating land underneath the solar installation, they could potentially prevent the loss of soil carbon fixation capacity and actually increase deep soil carbon storage. To test this hypothesis, the researchers investigated critical soil and chemical parameters at a revegetated photovoltaic array and an adjacent grassland in Colorado, United States. After seven years, the researchers examined the soil and determined that the chemical contents present in the PV soil were lower than that of the reference soil.[5]

This study was conducted at a 1.1 MW solar PV facility in National Renewable Energy Laboratory's National Wind Technology Center. During the time, the topsoil was removed and largely degraded, to a 1% slope. Soils present at the site were paleosols, composed of alluvial/colluvial deposits. This area was rich in native grassland, specifically xeric tallgrass prairie and bluestem grass. Activities such as grazing altered the soil but the paleosols and clay subsoils remained intact. When the PV system was installed, an area of the altered area was revegetated with native grasses (Bouteloua gracilis and Poa compressa) to see if soil composition changed. The revegetation happened a year later (2010), and seven years later, soil samples were taken from the revegetated area of the PV area and the neighboring grassland in July 2017.[5]

Samples of soil in the revegetated area were taken around the solar panels specifically below the east edge of the panel, west edge of panel, and the interpace adjacent to each panel. 16 sample locations were taken, 2.5 m apart and 10 m in length, similarly to samples taken in a reference location. [5]

When surface soils were taken, and then air dried, they were subsampled and sieved to 2mm. These particles were then analyzed for their nitrogen and carbon content.[5] According to the findings, there were lower carbon and nitrogen levels in solar PV soil than in reference soil because of the topsoil being removed during arrays construction phase.[5]

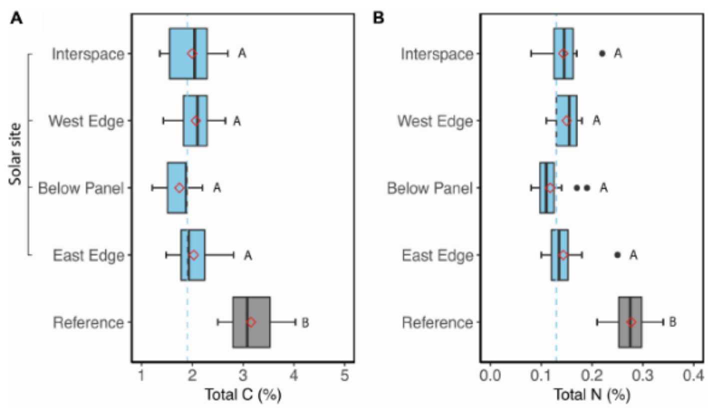

Figure 5: Results showing Total C % and Total N % in four locations near the module and in the reference location.[5]

These results as shown in the figure above illustrate that approximately a little over than 2% total carbon was measured in each of the four solar site locations meanwhile there was 3 % of carbon measured in the reference location. After seven years, the composition of periodic elements diminished and depleted the carbon storage by 38 %. Thus, the PV's soil ability to sequester carbon has been hindered compared to the original soil.[5]

Case Study II:

There are practices that can be considered to promote carbon storage. For example, if the utility PV are co-located with vegetation and with managed grazing then substantial benefits such as increased carbon sequestration can be seen.[5]

In this study, there were 6 commercial PV sites investigated for certain years including: Albany (2017-2020), Lawrence Creek (2017, 2019, 2020), Lake Pulaski (2017, 2019, 2020), Chicago (2019, 2020), Montrose (2019,2020), and Annandale (2020). Additionally, there was native pollinator vegetation under the panels and 500-700 sheep grazing treatments for 2-3 weeks per year.[6]

Soil was sampled only once a year, and then additional measurements were taken from a total of 15 soil cores from each of the top 5 cm from grazed and ungrazed sites. The samples were taken at depth levels of 0-30cm, and the soil compaction was made using a penetrometer. [6] The soil was analyzed for total organic carbon, total carbon, total nitrogen, ph, organic matter, and other periodic elements.[6] Based on those results, the productivity of different biomasses can increase based on the shading percentage.

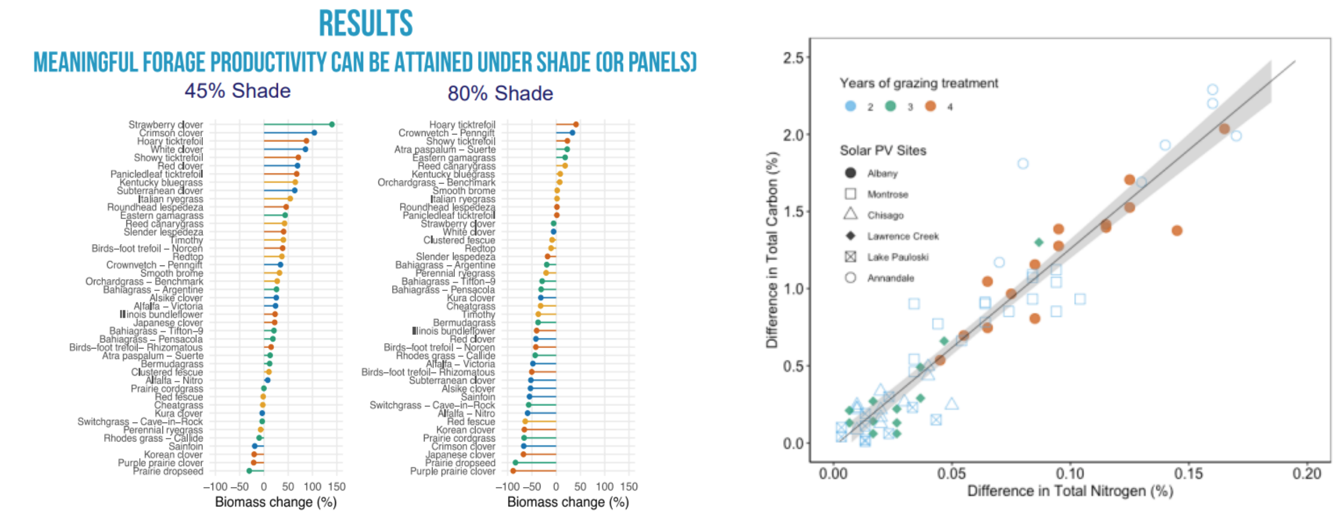

Figure 6: (Left)Forage productivity/Biomass change in 45% versus 80% shade. (Right) Differences in Carbon & Nitrogen (%) following years of grazing treatments in Solar PV Sites[6]

In the above figure to the right, as many years of grazing treatment is applied to PV sites, there is a chance in total carbon sequestration as well as increase in nitrogen concentration. Also, from the figure, it can be determined that the most biomass change can be seen in strawberry clover in 45% shading and Hoary tick trefoil in 80% shading. These biomass statistics are a good indicator of using this vegetation under the modules. Higher contents are present for both in grazed sites compared to control sites, and there is no correlation between grazing frequency. [6]

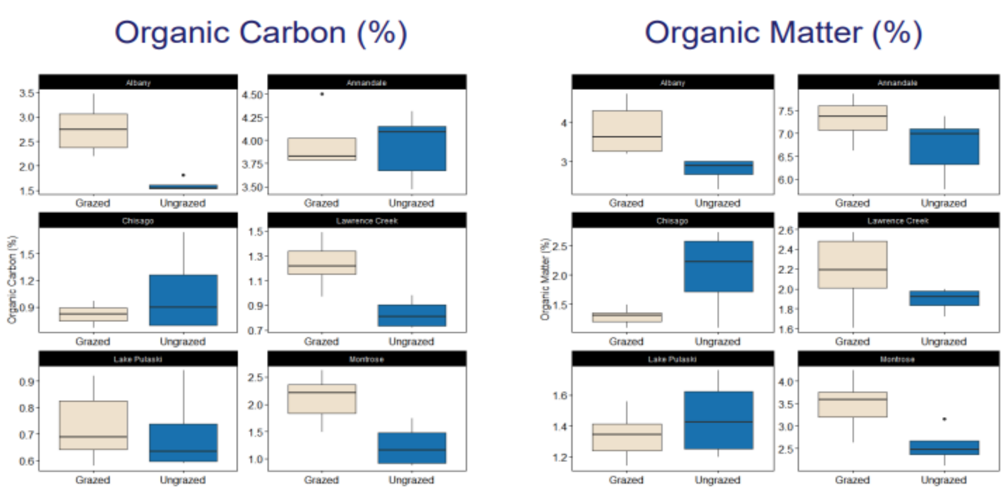

Figure 7: (Left)Organic Carbon % in Grazed versus Ungrazed territory. (Right) Organic Matter (%) in Grazed versus Ungrazed territory.[6]

Following this treatment, there is more abundance of carbon in grazed sites compared to the ungrazed sites, but also there is more organic matter present in sites where there was grazed treatment involved.[6] The presence of nitrogen indicates that fertilizers were used in this treatment.

Clearly, when you pair grazing with re-vegetation you can make significant improvements in carbon sequestration and vegetation management practices. However, long term research suggests more studies are necessary to better understand soil carbon capacity[6] It's also important to pair the vegetation with the amount of shading provided from the modules to meet the peak performance of biomass productivity.

References:

[1]*Fact sheet: Soil carbon sequestration* (no date) *American University*. Available at: https://www.american.edu/sis/centers/carbon-removal/fact-sheet-soil-carbon-sequestration.cfm (Accessed: December 14, 2022).

[2]Digital, M. (no date) *Soil Carbon Sequestration*, *Regenerative Energy*. Available at: https://regenerativeenergy.org/soil-carbon-sequestration-what-is-it-and-why-is-it-important/ (Accessed: December 14, 2022).

[3]Wall, N. (2022) *Everything you need to know about soil carbon sequestration*, *DGB Group*. Dutch Green Business Group. Available at: https://www.green.earth/blog/everything-you-need-to-know-about-soil-carbon-sequestration (Accessed: December 14, 2022).

[4]*Overview of opportunities for co-location of solar energy ... - NREL*. (n.d.). Retrieved December 14, 2022, from https://www.nrel.gov/docs/fy14osti/60240.pdf

[5] *Effects of revegetation on soil physical and chemical properties in ...* (n.d.). Retrieved December 14, 2022, from https://www.researchgate.net/publication/343578893_Effects_of_Revegetation_on_Soil_Physical_and_Chemical_Properties_in_Solar_Photovoltaic_Infrastructure

[6]Towner, E., Karas, T., Janski, J., Macknick, J., & Ravi, S. (2022, January 13). *Managed sheep grazing can improve soil quality and carbon sequestration at Solar Photovoltaic Sites*. TUScholarShare. Retrieved December 14, 2022, from https://scholarshare.temple.edu/handle/20.500.12613/7254