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Aquavoltaics: Synergies for Dual Use of Water Area for Solar Photovoltaic Electricity Generation and Aquaculture

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Abstract
Bodies of water provide essentials for both human society as well as natural ecosystems. To expand the services these water provide, hybrid food-energy-water systems can be designed. This paper reviews the fields of floatovoltaic (FV) technology (water deployed solar photovoltaic systems) and aquaculture (farming of aquatic organisms) to investigate the potential of hybrid floatovoltaic-aquaculture synergistic applications for improving food-energy-water nexus sustainability. The primary motivation for combining electrical energy generation with aquaculture is to promote the dual use of water, which has historically high unused potential. Recent advances in FV technology using both pontoon and thin film structures provides significant flexibility in deployment in a range of water systems. Solar generated electricity provides off-grid aquaculture potential. In addition, several other symbiotic relationships are considered including an increase in power conversion efficiency due to the cooling and cleaning of module surfaces , a reduction in water surface evaporation rates, ecosystem redevelopment, and improved fish growth rates through integrated designs using FV-powered pumps to control oxygenation levels as well as LED lighting. The potential for a solar photovoltaic-aquaculture or aquavoltaic ecology was found to be promising. If a U.S. national average value of solar flux is used then current aquaculture surface areas in use, if incorporated with appropriate solar technology could account for 10.3% of total U.S. energy consumption as of 2016.

Keywords: photovoltaics; Floatovoltaics; aquaculture; food energy water nexus; aquavoltaics; renewable energy

1. Introduction

The burning of fossil fuels has resulted in increasing atmospheric green house gas (primarily carbon dioxide) concentrations causing a net rise in global temperature, the melting of polar ice caps, and an increase in water levels, which can be summarized as climate change [1-4]. If this process is allowed to continue, the partial pressure of carbon dioxide absorbing into the oceans will cause a drop in global water pH of up to 0.5 units by the year 2100 [5] resulting in a process called ocean acidification, which will cause profound detrimental ecological shifts by way of aquatic species extinction [6-7]. There are many other negative effects of climate destabilization including, but not limited to: melting glaciers, flood risk, declining crop yields, increase in human deaths and spread of vector-borne diseases, rising sea levels, more extreme weather events, displacement of populations, increased in ecosystem vulnerability, and negative economic impacts [1-3]. These negative effects have burdened humanity with the necessity of decarbonization [8] by moving to clean and renewable sources of energy generation [9-12]. Solar photovoltaic (PV) technology is the most widely accessible sustainable and clean source of energy that can be scaled to meet humanity's energy needs [13-15]. This potential is being realized with explosive PV growth such that the International Energy Agency estimates approximately 6000 TWh of PV electricity will be generated in 2050, which is roughly 16% of the total global electricity demand [16]. To accomplish this feat, large surface areas are needed due to the diffusion of solar energy through the atmosphere. Much of this need can be met via rooftop PV or building integrated PV (BIPV) [17-20], and much more through land based PV farms [21-24]. However, as global population increases 1.15% per year [25], attractive flat land or water will become more valuable, especially in densely populated areas or remote areas like mountains or small islands. In addition, this demand also will increase due to increasing resource demands per capita as quality of life improves globally. This creates competition for limited land and water resources between food and energy demand [26-28]. 850 million people live undernourished already, indicating further reductions in agriculture land is an unacceptable during a world food crisis [29]. These coupled land and food challenges may seem insurmountable, but through use of agrivoltaics (dual use of land for both solar PV and agriculture) [30,31,32] as well as aquavoltaics (dual use of water for both solar PV and aquaculture) and some clever international and interdisciplinary engineering, they can be partially amelerated. Such dual use leads to greater efficiency of the overall combined and interconnected global system.

In addition to worsening climate change, the energy sector also consumes water a large amount of water. As of 2012 in the United States, the energy sector consumed 27% of the nation's water [33]. Traditional coal plants consume on average 687 gal/MWh [34]. Conventional PV during normal operation requires minimal water(to wash off modules), and solar concentration photovoltaic (CPV) only requires 4 gal/MWh [35,36]. Thus a shift to solar power would allow reallocation to improve citizen quality of life. The implementation of floatovolatics (FV), which can be defined as a PV system floating on any sized body of water, could mitigate water losses in primarily two ways:

1) PV plants consume less than a hundredth of the water used by fossil fuel based power plants per unit energy [33], and 2) by covering water bodies such as reservoirs FVs assist in the reduction of water loss due to evaporation by up to 70-85%. [33,37-39]. FVs have been increasingly implemented globally in the last few years [40,41]. In addition, FV systems have the potential to form agrivoltaic type systems by merging with aquaculture, which is the farming of aquatic organisms such as fish, crustaceans, mollusks and aquatic plants, to form food-energy-water nexus webs. This nexus demonstrates the interconnected nature of the production of food, energy, and water for life on Earth, including non-human ecosystems humans depend on such as wild fishing. A sustainable approach such as green energy strengthens the web, while inefficiency in resource use weakens the web.

To analyze the potential for a floatovoltaic-aquaculture, or aquavoltaic system this paper will first present the concept of aquavoltaics. Secondly, a review of the theoretical and experimental work of FV and aquaculture which provides the backbone of this aquavoltaic concept will be presented. Specifically, a focus will be on the synergistic relationship between the two technologies and how they benefit from being combined. The potential for a solar photovolotac-aquaculture or aquavoltaic ecology will be presented and conclusions will be drawn.

2. Aquavoltaics

When the concept of floating photovoltaics is combined with aquaculture, aquavoltaics is realized. The goal of aquavoltaics is the efficient use of water withthe dual use for both food and energy generation. While solar panels above the water or on its surface provide the electrical energy, the aquatic organisms living within the water below provide a sustainable food source. The concept of aquavoltaics has both scalability for industrial sized farms and the capability for off-grid remote location individual farmers. The following are synergistically beneficial and potentially detrimental elements created when aquavoltaics is implemented.

2.1 Potential Synergies between FVs and Aquaculture

2.1.1 Increase in water conservation

As stated previously, water loss from reservoirs with FV is reduced 70-85% [33,37] and utilizing this effect on aquaculture could be extremely beneficial. In order to maintain clean water and cycle nutrients water flow is needed, this is especially important for biofilters such as seaweeds [42,43]. Larger quantities of water are necessary for the larger the aquaculture systems. As a general rule, the minimum flow rate for a surface km^2 of water is about 12000 liters per minutes[44]. For systems which are isolated from large water sources recycling water is essential to maintaining production. If a 400,000 Liter capacity system exchanges 10% of water daily, that is a flow of 40,000 liters of water per day at minimum [44]. Any reduction in evaporation of water would reduce the economic and environmental costs of maintaining such large volumes. While reservoirs benefit greatly from both FVs and water conservation, implementing an aquaculture system in a reservoir is an attractive prospect for efficient land use. There is particular benefit with hydroelectric dam and reservoir pairs. Combining aquavoltaics with hydroelectricity provides dedicated energy generation during the day (PV), the availability of energy generation at night (hydroelectric), water conservation that maintains water levels, as well as food generation (aquaculture). The synthesis of these systems would reduce costs because of the existence of a grid wired area around the reservoir, and the presence of a pumping system to store energy [45] when below max load.

2.1.2 Controlled aquatic environment

More control of growth factors such as nutrients, temperature [46,47], pH [46,47], salinity[46,47], turbidity [48] and photoperiod [46,47] will lead to greater optimization of production and costs associated with the aquaculture of aquatic species. By precisely monitoring the growth factors mentioned previously, systems can be tuned for the ideal growth conditions of particular aquatic organisms for various locations be they warm or cool water cultures.

FV-powered water pumping systems could also be employed to manipulate oxygenation zones, which form at different levels in bodies of water. Increasing oxygen mixing and diffusion would result in greater biomass generation [33]. Furthermore, the addition of nutrients to increase growth rates raises biochemical oxygen demand [49], thus mixing would provide a more predictable and uniform oxygen distribution. Cultured fish stock when exposed to low oxygen levels consume less fish feed due to appetite loss [50] Oxygen content can easily be monitored via sensors powered by the solar modules in the PV portion of the aquavoltaic system.

Light is essential to life for most organisms. The intensity, quality and photoperiod of light is quite variable and this shapes how ecosystems develop and grow [47]. While the intensity and specific wavelengths of light are controllable through artificial means (underwater light sources), the photoperiod of aquatic life is intrinsic and varies based on species [46,47] and can be manipulated to maximize growth for aquaculture. Typically fish are either more active in light and less in dark or the opposite [47] and this can be modified by daily changes in factors such as temperature or oxygen [46,47]. While aquatic growth in life is linked with light it is not straight forward as species are varied in their growth conditions. Fish and larvae for example, must be reared in specific light ranges depending on their specific developmental stages on a per species basis [47]. For most species growth increases with increasing day length, but in excess light can be stressful on biological functions or even lethal and there appears to be a need for a period of total darkness to obtain maximum growth [47]. Additionally, the larger the reared fish the less effect light intensity has on influencing growth [47]. However, utilizing the bottom of pontoon structures in the aquavoltaic system, light emitting diodes LEDs may be installed, powered by the PV portion of the system, for manipulation of photoperiod of the aquatic life. This design incorporation provides a powerful tool for the aquaculturist for increasing and further optimizing production for particular aquatic species.

2.1.3 Ecosystem restoration

Another use of the aquavoltaic systems is to be ecologically restorative [51]. As grass-fed land animals such as cows have been shown to be better for streams vs feedlots, so too can aquaculturists design farms to function more like a healthy aquatic ecosystem [51]. Unlike open water aquaculture with cages and pens, tank based systems that use recirculated water cannot take advantage of naturally provided services, such as tidal action, which replenishes oxygen and removes waste. These systems require large amounts of energy to pump, cleanse and oxygenate water [51], which becomes more costly the further from a water source and the larger the facility. Therefore energy demand is a barrier to industry growth. Because of the expense, farmed organisms are stocked at greater densities, which negatively impacts production and quality. These energy needs can be supplied through the use of FVs. If the energy requirements are met or exceeded with solar technology, which has the potential to leave the grid, then it allows commercial-scale aquaculture farms to be built anywhere there is sufficient sunlight. When this approach is coupled with shellfish cultures for instance (suspending cages from the floating modules), the shellfish cages are dually used for supporting the intended shellfish, but also serve as artificial reefs, while providing useful energy to culture facilities. These imitation reefs act as fish aggregation devices (FADs) around which marine species congregate as it simulates a protective environment [51]. These reefs may also be used to help re-seed coral reefs with critical species [51]. The habitat created by these dual use systems would encourage the reemergence of endangered species [51]. In contrast while the incorporation of FADs helps rebuild ecosystems, predatory birds may also return as aquaculture systems are typically open to the atmosphere and provide a potential source of food. However, if floatovolatics are utilized above water, they provide a powerful barrier to aerial predation through physically blocking access to the water from above. By embracing the approach of aquavoltaics, ecosystems can be redeveloped even in remote areas due to the freedom from the grid solar energy gives aquaculture production.

2.2 Potential detrimental elements between FVs and Aquaculture

2.2.1 Ecological impacts:

If designed and managed successfully, the aquavoltaic approach as stated above may lead to improvements within ecosystems and the environment. Policies, new practices, and strategies will need to be developed to overcome potential negative impacts to this combination of technologies. Because the floatovoltaic array absorbs light from the sun, that light is not transferred to the water ecosystem below. As many organisms need light for their natural functions or survival, a competition for light is created through imposed shading by the modules. If uncontrolled, an increase in shading decreases algal growth, general plant life, and density of microorganisms impacting the entire food chain up to fish intended for farming [33]. There are several approaches to combat this effect. As stated above, utilizing LEDs to create the optimal light environments to replace the sun's spectrum is possible via energy generated with the floating solar array. This needs further testing and the impact of energy conversion must be taken into account. Another alternative is rotating, or moving the array around the body of water in which it resides [33]. This action would limit the amount of natural light shading each given area of water would experience. An alteration to the pontoon structure itself could be to increase the distance between the modules making up an array. This change would provide a controlled amount of light to penetrate the waters below. While this approach decreases the efficiency per unit area of the array as there is a lower density of solar modules [52], but if surface area is not a constraint this is an insignificant penalty. In addition rotating an array for ecosystem protection could be incorporated into rotating the array for optimal solar absorption for an integrated tracking system. Another solution for mobile aquatic organisms is rotating their location over various time frames to non-shaded areas, similar to the agricultural idea of crop rotation. This practice is used in the salmon farming industry in Norway to reduce the biofouling and the need for anti-foulants [51]. Finding an economical and efficient solution to light competition is essential as the entire system would be impacted by the results. The addition of floating modules will most likely increase the difficulty of tending the aquaculture system, as well the aquatic life may slow or disrupt maintenance of the PV modules. To combat this effect, either rotation of the floating array can be moved into a sufficient position for maintenance, or aquatic life may be moved or herded to another location. Furthermore, there is simply a lack of research on the effects of PV modules or systems on the welfare of fish or their growth and production for industry. Due to the infancy of this field more research will be needed to understand the implications of direct contact with pontoon structures and solar arrays and aquatic life.

2.2.2 Biofouling:

The use of aquavoltaics in varied environments globally is possible with the primary requirements being sunlight and proper growth conditions for aquatic life. Due to the diverse amount of aquatic plants and animals domesticated there are many environmental conditions that allow organisms to thrive. The difficulty with biofouling in this integrated system is that there are a multitude of variables which are not well known or researched and are complicated. This is easily demonstrated with the history of biofouling prevention and its continued study since antiquity [53]. Biofouling of both FVs and aquaculture systems have been covered in this review, adding these aspects together will lead to new sources of biofouling to research and prevent. An interesting application of LEDs is potential use for antifouling by the incorporation of photocatalytic anatase titanium dioxide (TiO_2). Blue LEDs have similar effect as UV light, but cause less harm [54].

3. Water Surface Area Applications

The various types of FV technologies and designs, aquaculture advancements, and synergistic applications are discussed in the following sections. Classifications are made according to relevance and uniqueness of concept/design in promoting dual use of water.

3.1 Floatovoltaics

In the last several years, due to the success of early floatovoltaic projects there has been a call for scaling up designs of FV farms [39,41], while also characterizing the effects of the aquatic environment upon the PV modules [55]. The primary technical advantage of placing photovoltaic modules on water is is the gained cooling mechanism, boosting power conversion efficiency (PCE) due to semiconductor-based temperature dependence [37,55,-59]. It is now well established that the cooling effect of water on solar modules has been shown to increase power production from 5-22% [55-59]] depending on the method of FV deployment. In comparing FVs against identical land based solar modules there is always an increase in power output [33] due to the reduction in the operating temperature of solar modules in either direct or indirect contact with water. Additional efforts have been made in optimizing the PCE of the modules by separating focus into four distinct system design strategies: 1) thin-film (no ridged pontoon supporting structure)[57,60], 2) submerged (pontoon/no pontoon)[56,58,59,61,62], 3) tilted arrays (pontoon)[38,63-65] and 4) a new approach using micro-encapsulated phase change material (MEPCM) based pontoon modules [66-68]. It should be pointed out here that floatovoltaic systems also assist in land use change. For example, this is what drove the first solar installation at a winery in California [69]. In addition, floatovoltaics can reduce evaporation.

Crystallized silicon (c-Si) is the most popular and commercially available PV material [70] and results in a PV efficiency loss with temperature of around 0.5%/ºC [59]. As of the writing of this article, c-Si PV has a PCE of 18-21% at STP and is primarily used for tilted/flat designs and amorphous silicon (a-Si), which has a better temperature coefficient and is also the most popular format adopted for thin film FV technology with efficiencies from 5-10% [71]. The benefits of floatovoltaics in regards to PV performance will remain even as new PV devices improve the overall conversion efficiency in the future. Although a-Si PV is available as rigid modules, its lower efficiencies demand a larger balance of systems (BOS) (the lower efficiencies mean more racking and other systems components are needed per unit of power) cost in land-based applications, but these extra costs can be avoided using a thin film air pocket approach for on water use [60]. Additionally, other forms of efficiency loss, such as dust accumulation or geographical shading, are mitigated through natural wave motion and the flatness of water bodies, respectively [60]. For land-based PV systems, dust settles on modules, which can result in daily energy losses between 4-7% seasonally in some regions [72], and during long periods in extreme circumstances without rain or washing, daily irradiation losses could be higher than 20% [73]. Additionally, special care must be taken to ensure the land based PV will not be shaded by nearby trees or hills. While floating PV may still be shaded, they are in general less so and can be orientated away from these geographical sites due to the flatness of water bodies.

In addition to conventional PV system design considerations, other areas to be considered for FV are the flotation support structure for the modules, the mooring system for the array, and the electrical components to the system. These aspects will vary, especially the size of the support structure and mooring system based on the site location's weather and general wave motion, and size of PV modules. In a floating PV system, design considerations to be taken into account include buoyancy forces [74] and environmental forces such as wind or wave action [57,75,76]. Each pontoon would need to support at least one module, with most designs such as Figure 3 supporting two. Module weight and support structure (on pontoon) will vary based on supplier and module size. The lighter the module-pontoon system the more effect environmental forces will have on the array. Typical crystalline modules range in weight from 12-22 kg with the support structure less than a few kg [77]. The support structure material must be robust and buoyant to account for the density of solar modules while minimizing cost and resisting long-term deterioration in water. Materials used for pontoon structures have been high and medium density polyethylene or polyvinyl chloride (PVC). Most materials are naturally buoyant with densities less than 1.0g/cm^3 making them ideal for pontoon use. However, in the case of materials such as PVC with a greater than water density, geometric components are utilized to increase the buoyancy force generated such as trapping air within the pontoon. These pontoons can be hollow, solid, or filled with closed cell foam [57]. Stainless steel struts or frames may be used to withstand the weight of the system and distribute it over the pontoons if particularly heavy solar modules are used [78]. Arrays are typically held together via metal or plastic couplings providing a rigid framework, while maintaining vertical and horizontal displacement [78]. In essence the constructed system must allow modules to move relative to each other to adapt to different water conditions and levels without causing damage to either the modules or the water body. In addition, the system is either tethered to land based structures via ropes (polyester or nylon nautical ropes are commonly used) for stability on varying water levels [78] or anchored via reinforced concrete piles in open water [78]. Regardless, either a rigid or flexible anchoring is necessary to resist lateral forces [78]. Finally, most pontoon designs include a walkway for maintenance and installation [57].

FV design specifications also depend on the tilt angle of the array. Modules mounted at higher tilt angles provide more wind resistance, requiring a stronger support structure as the wind may also rotate the array, thereby reducing the solar flux incident on the PV [75]. This phenomenon also makes it possible to use entire array solar tracking in water [75]. However, if the array is flat, then such array tracing has minimal energy generation impact. Tilted designs must have a sufficient mooring system (multiple contacts) to prevent array drift and rotation, otherwise electrical output may have significant variance in day to day operations [75]. Additionally, care must be taken in order to safely insulate electrical lines and systems away from the array and towards the grid. Pontoons should be designed to be modular with cable management in mind for ease of maintenance, as well as the capability of adding further solar modules. Design of floating apparatuses need continued improvement towards optimization, especially on the material selection for long term use and to minimize negative environmental impacts.

There are currently four distinct strategies for floating PV that are detailed below. All three systems can be cooled by running water over modules to increase efficiency [55,86].

3.1.1. Thin-film FV

Thin-film FV, as shown in Figure 1, has several benefits over other FV strategies, namely its low mass and flexible nature [40,57,60]. The low mass allows a significantly diminished supporting structure and the flexible nature allows the system to yield to oncoming waves while maintaining its electrical performance [60]. This overcomes the primary limitation of thin film PV – that relatively low efficiencies drive up the BOS costs. In this case the cost of BOS for thin film FV can be much lower than on land-based systems. This enables FV to take advantage of the superior net energy production of thin film PV materials like amorphous silicon [79]. In addition to improving the net energy production and environmental impact, low mass also reduces the loads required to moor the floating modules [80]. To maintain the flexibility and long term structural integrity of the module, thin-films should be encapsulated by a polymer with high transparency, low rigidity, and of a waterproof nature [57]. During the encapsulation process, air pockets or voids can be purposefully introduced to increase buoyancy without increasing mass [40,60]. Additionally, thin-film modules use less material and are cheaper than crystalline modules on a per Watt basis [36]. As thin modules are in motion on a body of water they benefit from self-cleaning due to natural motion of water [40,60]. This makes thin-film modules ideal for offshore application, potentially in large-scale solar farms. Additionally due to the flexibility, the thin-film modules could be rolled and transported easily and deployed in emergency situations for reliable power generation [57]. Because the modules are on the surface they benefit from the cooling effect of the water underneath resulting in an increased efficiency of about 5% [57].

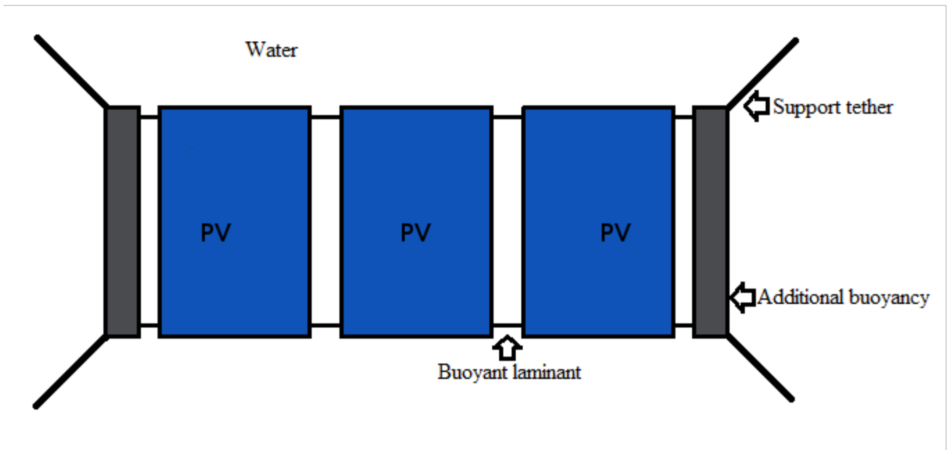

Figure 1: Top down schematic of a floating thin-film PV with three modules

3.1.2. Submerged FV

The structure of a submerged FV arrays differs based on if they are c-Si or thin-film modules. A pontoon based structure would securely hold a rigid module at a short height below the waterline as shown in Figure 2. A thin-film design would tether the module to the seabed to be below the surface of the water. Submerged modules match the surrounding temperature of the water and conversion efficiencies have increased due to natural cooling at various depths by 11% at 6cm depth [56], 11% at 4cm [40], 18% at 4cm [58], and 17.8% at 1cm depth [59]. In addition, while leaves, dust, or bird droppings can strongly reduce the efficiency of a PV system, this is largely eliminated with submerged PV [58,62] due to the natural motion of waves.

High water quality is essential when implementing submerged arrays. The turbidity of water varies with season, location, and weather conditions. As a guideline, in motionless water 1.0 mm diameter particles settle by 30 cm in 3 seconds and 0.01 mm particles take 33 minutes, while 0.0001 mm particles take up to 230. days [81]. Light attenuation from suspended matter is strongly dependent upon the distribution of particle sizes and is most easily understood through the geometrical cross-section (projected area) per unit volume [48].This implies that in turbid waters, submerged modules of shallow depth (>6cm) would not experience much irradiance loss due to particle scattering as the attenuation of light is minimal [48] and normal wave motion would allow the removal of larger particles. Recent developments in open source turbidity meters [82] enable low-cost determination of appropriate water clarities, of which 40 nephelometric turbidity units (NTU) is the threshold for light attenuation to have an impact [48].

Water is a powerful light absorber itself [58]. As light penetrates water wavelengths are absorbed and the spectral composition changes [62]. Thus, the deeper a solar cell is placed, the less total radiance it will receive and the specific value for each wavelength can also vary considerably, which lowers the potential energy output. Wavelengths around 480nm (blue light) are transmitted in clear water with little attenuation, while wavelengths outside of the 450-550nm range filter out completely within 25 meters [58,62]. In addition, the prevalence of dense fog in coastal regions can also reduce energy output of PV systems [62]. However, the optics of water can also provide benefits as light retention increases due to the lower refractive index of water (n = 1.33) compared to n = 1.53 for glass. The water can thus act as an anti-reflection coating and reduces the reflection losses from 4.4% to 2.0% [58]. However, if the surface of water is calm then more light is reflected as the angle of incidence moves from normal incidence (0 degrees with the vertical) towards total reflection at 90 degrees to the vertical [62]. However, it is important to note that overcast skies or wave motion does reduce the amount of light reflected by the surface of water due to the diffusion of light through those mediums [62]. On the other hand, PV efficiencies improve because non-uniform cell temperatures are avoided, which then results in lower cable power losses and a more effective inverter sizing [58]. Submerged cells demonstrate higher efficiency gains than thin film and would also be less susceptible to wave, wind, and other detrimental environmental factors.

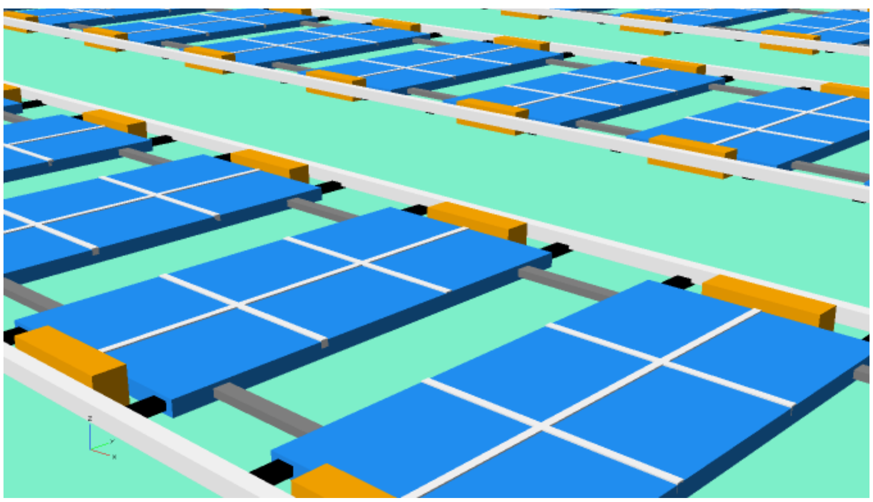

Figure 2: A schematic of a submerged FV system.

3.1.3 Surface Mounted FV

PVs on the water surface maintain approximate thermal equilibrium with the water body if there is sufficient contact [40]. Moving water can have a large effect on both module cooling as well as cleaning, and both would increase efficiency [57]. Due to the heat capacity of water, it takes more energy to change temperature than air, thus leading to a more consistent and lower temperature range for solar arrays in contact with it. Offshore arrays show at least a 5% improvement in PCE on average when compared to their onshore counterparts [40]. There are three types of surface mounted FVs: tilted, tracking and flat.

Tilted PV systems, which are set at a fixed angle usually around 20-40º tilt angle, or a variable tilt through a tracking system, allow a more ideal alignment with the sun. A 30º fixed tilt example is shown in Figure 3. A 100kW floating farm was compared to a 1 MW land farm 60 km away, experiencing similar temperatures, solar irradiance, and tilt angles of 30º and, which resulted in the FV system achieving 11% greater total efficiency over a year [74]. It is important to note that these systems were suspended above the water with no direct physical contact. A tilted PV system can be slightly submerged at the lower side of the module, this would allow the metal support to thermally equalize the operating temperature with the surrounding water to a greater degree than a system without physical contact while maintaining the optimal tilt. A pontoon structure fabricated to allow flowing water around the bottom of the module would also increase the cooling effect. Similar to land-based systems fixed tilt have a lower capital cost and involve less maintenance, but do not have as large of an output per installed unit power compared to tracking systems.

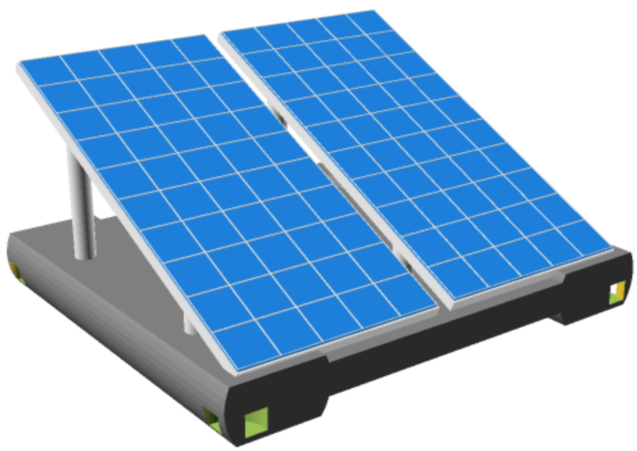

Figure 3. A representation of a floating PV pontoon with two modules at 30º tilt

Two axis tracking systems track the direction and altitude of the sun in order to form a perpendicular angle with the module surface to maximize power generation [63,83,84]. When installed on land, an increase in power generation of about 41%% is seen over fixed systems at optimal tilt [83,84]. Single axis trackers result in about 28% additional energy per year [85]. The benefit of a floating tracking system over land based is an increase in rotation capacity along the z-axis), and the structure can be made simpler for single axis tracking [63]. These improvements result in a reduction of malfunction risk which implies a decrease in operating costs [63].

Flat (0 degree tilt angle) FV systems have lower costs of supporting structure compared to fix tilted FV systems. Flat systems benefit more from water cooling due to their more uniform contact with the water surface. However, they absorb less energy per unit PV area. There is also a trade-off for optimization of the tilt of a FV system. The greater the tilt angle, the greater the spacing between modules must be to prevent inter-row shadowing. If the modules are tilted less, then they can achieve greater packing density at the expense of overall systems output per unit power for locations away from the equator.

A specialized type of PV system, which until the advent of the FV concept was too expensive due to tracking system costs to be economically viable, is the floating tracking cooling concentrating (FTCC) system [45]. This design can be either tilted, or flat, but always is accompanied by mirrors to concentrate luminescence towards the modules [45]. This focusing of light with simple booster reflectors is well known to increase output of PV systems [86-91]. However, simple booster reflectors cause non-uniform temperature across the module which can lead to a decrease in the life cycle due to thermal stresses [92] as well as a reduction of open circuit voltage and a softening of PV cell fill factor [93]. This effect has been found to be small for 1.5X reflectors [94], but it is mitigated completely due to the use of flowing water over the modules maintaining them at ambient water temperature [45] resulting in benefits to uniformity mentioned previously [58]. The tracking component can be utilized through a twin motor system to create torque for rotation of the array [45]. The primary problem with tilted is the lack of homogeneity of solar radiation on the modules primarily due to mirror misalignment, this is has less of an effect on the more simple flat module [45]. On the flat module resting on the water surface flanked by two mirrors at 62 degree from the horizontal [86,45]. When compared to conventional fixed-ground installation, a 60-70% increase in annual yield is suggested for systems with mirrors [86]. However, upon optimization this type of system leads to comparable costs (an increase of 10%) to a ground mounted system and an increase of 10-30% in annual energy yields [86].

3.1.4 Micro-encapsulated phase change material (MEPCM)

The last type of floating PV discussed is the phase change material (PCMs), which are categorized as eutectics (organic and inorganic), organic (paraffins and non-paraffins), and inorganic (salt hydrates and metallics) [66]. These types provide a unique approach to improving FV economic performance. While most PCMs used have melting points between 20-60°C [66], PCMs used in FV applications have utilized a melting point as low as 16°C to beneficial effect. Micro-encapsulated PCM layers are attached to the back of a module to form a MEPCM-PV module. The benefit is thermal diffusion from the module to the PCM as the module heats up. Overall, this approach shows an increase in efficiency by up to 2.1% compared to untreated PV modules [67,68]. To date, this technology has not been implemented in water based systems of floating PV. The PCMs could also provide buoyancy for the module which could reduce support structure costs of FV systems. Furthermore, the PCM added onto the PV module could act as an additional thermal sink for shallow water FV deployment. This technology is relatively new and more research is needed to maximize the gains from MEPCMs.

3.2 FVs Challenges

There are several challenges in FV technology which need to be resolved with future research. If the floating PV array is located in a body of water with no wave motion sediment accumulation may be a significant problem as overtime sediment would weigh down modules and cover them resulting in less light hitting the PV surface [40,60]. Cleaning thin-film PV showed a 1% improvement (from 3% to 4%) [60]. However, with proper water flow the sediment should be removed and cause no negative impact on modules [60].

There is an unknown potential for biofouling of the module surface in different aquatic ecosystems.

The exposure of polymers to water leads to biodeterioration and biodegradation causing a change in physiochemical properties [95]. Ecosystem components or microorganisms could contaminate the module components and lead to PCE reduction and eventually module failure if not properly maintained. A potential solution is hydrophobic or hydrophilic photocatalytic coatings [57]. A perfectly smooth laminated module surface being hydrophobic in nature would allow water droplets to shed. Utilizing a photocatalytic coating (such as TiO_2) would break down surface contamination [57]. Anti-biofouling techniques have been investigated, but so far are not satisfactory for long term functionality [40,57]. The main concern with current biofouling techniques is the potentially negative ecological effect of unknown magnitude. Such as anti-fouling paints and coatings, which leach biocidal compounds such as organic biocides or heavy metals onto the surface, producing a toxic layer preventing biofouling. Many of these leached compounds are dangerous to environment, by negatively impacting the growth of shellfish and fish [96] explained further below. However, hydrophobic surface coatings tested for snow-removal on PV modules could also be applied to pontoon structures [94]. An interesting direction for further research would be investigating non-reactive surface treatments for FV to physically hinder biofouling organism settling.

4. Below Water Area Applications

4.1Aquaculture

The development of aquaculture is driven by the needs of the people through local employment, food security, poverty reduction, as well as the needs of industry through profits, productivity and quality improvement [97]. Farmed aquaculture provides a secure, controllable, and a sustainable supply of fish both on industry scale as well as to rural farmers [50,98,99]. While demand for fish products increases yearly, aquaculture can more reliably meet that demand than capture production [51]. Capture production is maintaining stagnated growth at roughly 91.3 million tonnes annually, while aquaculture has an on average annual growth rate of 6.1% for the last decade [100]. However, even as dependency on farmed fish increases, several issues will need to be resolved, which may endanger the future of this industry. Poor practices in aquaculture can create “biological pollution” [99,101] in the form of excess feed and manure, escaped fish and pathogenic diseases which can devastate wild fisheries [51]. This biological pollution, which is magnified where large quantities of fish are grown, can have profoundly negative ecological impacts by contributing to algal blooms, leading to eutrophication of water bodies. Increases in fish waste and algal biomass can also increase turbidity, reducing spectral penetration, which hinders aquatic plant photosynthesis and changes in behavior of fish and their predators due to visual response limitations [48]. If water turbidity is sufficiently high then fish may sustain damage to their gills and benthic (lowest level in an aquatic environment) suffocation may occur, leading to cascading ecological damages [48]. In many cases modern aquaculture is currently a net drain on the world's seafood supply through “reducing” fish practices (feeding smaller fish to larger fish) [51]. Through implementing aquaculture in the form of artificial reefs, integrated ecosystems, and using sustainable practices aquaculture can become a source of environmental construction and bio-conservation rather than degradation and destruction [51,102,103].

As of 2012, 45.5% of all aquatic organisms were produced in a freshwater culture environment totaling 41.1 million tons, 47.7% in marine with the remainder in brackish water [100]. Accessible freshwater constitutes less than 1% of the global surface area, and marine and brackish water cultures are currently marginally utilized when they cover roughly 71% of global surface area [104]. With about 0.17% of aquatic plants and 0.13% of aquatic animals domesticated, compared to only 0.08% of land plants, and

0.0002% of land animals, aquaculturisits have domesticated a wider range of species than farmers on land [51]. This amounts to 0.09% more plant species, and 0.13% more animal species.   This diversity of species leads to more flexibility in adapting aquaculture to differing regions and allows for more intricate farming practices. Improving the biological production of fish, shellfish and seaweeds is an important part of increasing future aquaculture production [104]. Understanding these three groups of aquatic life will help prevent the undernourishment of the human species as global populations continue to increase and even under extreme circumstances [105,106,107].

There are several different types of aquaculture cultures used in industry [97]:

- Direct Water-based systems (cages, pens, rivers, and oceanic)
- Land-based systems (ponds, irrigated systems, flow-systems, and tanks)
- Recycling systems (recirculation based, or highly controlled closed and isolated systems)
- Integrated farming systems (aquaponics) for both shellfish and seaweed.

All of these types may employ single or multiple species of aquatic life to allow varied complexity in aquaculture farming.

4.1.1 Direct Water-based systems

Water-based systems are primarily open-pens or cages located in natural waterways, or near-shore coastal marine environments [99]. In a pen based system, the pen is moored to the seabed and buoyancy tubes provide floatation. This approach is primarily used with finfish based aquacutures. This design allows fish waste to fall through to the seabed as well as clean oxygenated water to flow through the pen [99]. Clean water, the volume of which increases with system size, is essential for healthy production and is provided by natural currents of waterways[99]. There are high risk issues with this method including: the potential for escape and breeding with wild populations (leading to the introduction of invasive species and a decrease in biodiversity [49]), disease and parasite transmission, reduced water quality that may lead to increased pollution (accumulation of fecal waste, excess nutrient use, and antibiotic use), and potential use of toxic chemicals, and the use of fish feed [50,99,108]. While there are studies being done to remedy these risks, many countries still discharge untreated water into natural waters loading them with nutrients and waste products that upset balanced ecosystems and cause ecological shifts [49]. Furthermore, most finfish species produced in aquaculture are carnivorous and are fed a diet that can require up to 5 kg of fishmeal to produce 1 kg of marketable fish [99]. There is a definite need to reduce the reliance on fishmeal to move the industry towards more sustainable practices with the implementation of adequate government controls. In general, open-pens or cages are not beneficial to the local ecosystem

[113][51][113][113][51][114][113][42][43][51][42][42]

4.1.2 Land-based Systems & Recycling

Land-based aquaculture systems are typically either semi-closed or closed, similar to open pen, or cage design with the primary difference is that land based are not located directly in the waterway. In a semi-closed system water is exchanged between a farm and a natural waterway [97]. This results in waste water from the farm being traded for freshwater in the natural waterway, which can result in pollution of the waterway, harming local ecosystems, however this is reduced compared to open pen structures

[97]. A closed system rears aquatic species in tanks or ponds with water, which is continuously recirculated through the system and isolated from waterways eliminating direct pollution[97]. Biological and chemical methods, similar to conventional wastewater treatment, are often employed to remove nutrients and other constituents that would harm the fish at elevated levels [109]. While land-based systems reduce the environmental impact of the farmed fish by reducing the potential for escapes and nutrient releases, it can place a high demand on fishmeal production for feeds, depending on the species of fish being grown [97,110]. For commercial-scale fish production, solid waste management, nutrient recycling and feed conversion enhancement can be more easily addressed on land than in open-water systems [42]. Another sustainable application of land based systems is integrating aquaculture into rainwater or livestock storage systems [97,98]. Doing so allows the water to be used in a way that benefits two systems, once for aquaculture production, and then for livestock, irrigation, or as fertilizer [98,51]. This ultimately allows more products (crops, fish, or livestock) to be produced per unit of water and conserves water by utilizing it more efficiently. These systems are also preferred for exotic species and genetically modified organisms in order to keep them contained [97,101].

4.1.3 Integrated Aquaponics Farming Systems

Integrated farming is combining aquaculture with hydroponics, which results in systems such as aquaponics that utilizes farmed aquatic animals in conjunction with plants and mediating bacterial systems [111]. Integrated systems can provide an overall risk-reduction in production, a decrease in ecological pollution, and a boost to environmental conservation because multiple species are involved; unfortunately this potential is largely untapped [51,98]. In an efficient system, as many species would be incorporated serving as many functions as possible [51]. The basis of this system relies on integrating species which use the waste from one species to improve the productivity of another. This type of system not only optimizes growing conditions for one organism, like many other aquaculture methods, but for the entire system. Since seaweeds and mussels do not need to be fed, they are in relation to finfish relatively low maintenance, and less time-sensitive to raise [51]. Vegetables such as aubergines (eggplant), tomatoes, lettuce, spinach and cucumbers can be grown alongside fish species such as tilapia and perch [111,112]. In some areas the combination of fish and rice cultivation is well established and has a long history in practice, which on average increases rice production by around 12% [104]. For intensely integrated cultures 1-ha of land-based fish-shellfish-seaweed farm can produce 105(25+50+30) tons of aquatic life annually [42]. Other systems with notable synergy include fish-phytoplankton-shellfish, and fish-seaweed-macroalgivore [42]. Selectively integrated shellfish or seaweed may reduce fish cage colonization, biofoulment, and damage which not only decreases maintenance costs, but lowers the likelihood of water flow impediment and food competition of the farmed fish [51]. Utilizing these approaches can achieve minimal negative environmental impact and potentially even positive environmental impacts.

4.1.4 Shellfish Integrated Systems

Another aquaculture practice with promising benefits similar to finfish aquaculture, which may also be conducted simultaneously, is the aquaculture of shellfish species [51,99]. Because these species (mostly mussels and oysters) are filter-feeders, they extract their nutritional requirements from the water column, requiring no external inputs such as fishmeal. Overfishing of oysters have led to the extensive loss of natural oyster reefs and clam beds which significantly impacts water quality of affected areas [113]. When one aspect of an ecosystem is removed, it often has a cascading effect. An adult oyster can filter up to 200 liters of water per day [51], which controls the levels of phytoplankton by removing them from the water column, which increases its quality [113]. If not controlled, blooms of phytoplankton can block sunlight as well as reduce oxygen in the water potentially leading to fish death and ecosystem decline [113]. While oysters not only improve water clarity, they also help reverse the growth of oxygen-depleted “dead zones” around the world [51], which in turn may help restore aquatic environments. Mussels can be a critical component of the food chain as macrobenthic epifauna (such as shrimp) can develop from and thrive upon bivalve waste, which in turn are fed upon by populations of fish and crab [114]. If maintained correctly, healthy shellfish populations can help promote healthy finfish populations [113]. These are just a few examples of combining aquaculture cultures in a symbiotic relationship, which leads to the enhancement of the overall system.

4.1.5 Seaweed Integrated Systems

Another sustainable practice utilizing hydroponics (growing plants using mineral nutrient solutions without soil in water), is the integration of seaweed into other aquaculture systems [42]. Seaweed biofilters have been shown to reduce feed use and the environmental impact of maricultures (seawater-based cultures) through water recirculation of fish culture effluents due to a reduction in pumping in of clean water and effluent discharge while maintaining other ecosystem balances(ammonia and oxygen levels)[42,51]. In addition, some species such as gracilaria (red algae) showed up to a 30% improved growth in the presence of salmon culture installations [43]. Seaweeds grown in this proximity help reduce waste and excess nutrients from cage systems [51]. Seaweed biofiltration also reduces nutrient release into the native ecosystem by sequestering nutrients into the seaweed, which is later harvested, which effectively increases the nutrients available in the environment at any given time [42]. For implementation towards developing a nutrient-balanced aquaculture system the use of several aquatic species (both plant and animal) could be complementary to optimize biofiltering and reduce net wastes [43,51]. Thus, plant biofilters have the potential to stabilize the culture environment as well as reduce the overall environmental impact of aquaculture [42].

4.2 Benefits of Aquaculture systems

There are positive impacts of aquaculture on the environment. Specifically, production of aquatic species can reduce the pressure on wild stocks allowing the recuperation of those populations [49,115]. Additionally, effluents from aquaculture can increase production, abundance, and diversity of local species, if used correctly [49,102]. This can be done by the use of floating structures either rigid or flexible to act as both artificial reefs and/or fish aggregation devices, which have been shown to restore damaged ecosystems, thus creating effective marine protected areas [71,97,102,116]. With the continued growth of aquaculture, less dependence falls on other protein generation sources such as confined animal feedlot operations (CAFOs) and their concomitant environmental externalities, such as reducing acreage for field crops, and posing risk to environmental quality and public health [117]. Additionally, sustainable aquaculture practices such as culture ponds could even replace destructive land-based practices like slash-and-burn agriculture helping to preserve arable land for future use. [49].

4.3 Aquaculture Challenges

4.3.1 Perseverance in Small Scale Farms

While aquaculture has been practiced for several millennium, its industrialized development has really begun within the last five decades [115]. On the industry level aquaculture has been successfully imperfectly implemented, standardization and more sustainable practices are necessary for true success[97]. Most non-industrial scale aquaculture production takes place in the developing world where the challenge of environmental sustainability is greatest [115].There is difficulty in prolonged implementation of local and small scale aquaculture systems [118]. Small scale farms require a wider range of agri/aquaculture topics and practices for a given individual to know compared to large scale farms. Where a single farmer way need to know about fish cultures, bacteria nutrient cycling, fluid pumping, and water quality, an industry size farm would have a dedicated expert on each given area. Among small scale implementation, farm size must also be large enough to generate sufficient income to sustain the farm [118]. Otherwise, adoption of aquaculture technology may be abandoned. Small farmers often lack the capital for investment in multiple sources such as combining shrimp, catfish and salmon farming [115], which would increase the ease of scaling up production. These aspects increase the complexity and difficulties of small scale aquaculture farming.

4.3.2 Environmental Challenges

Aquaculture systems are generally sustainable on the small scale, but as the number and size of farms increase, so does the potential environmental damage [49]. Not all species of aquatic life can be farmed on a sustainable basis [108,115]. Closed system aquaculture, which is possible for many species, is the most environmentally sustainable practice due to its isolation from local ecosystems [115]. In contrast, water-based systems along the coast or oceanic located devices absorb energy from tides and represent a threat to intertidal adapted species [119] as it modifies their specific environment. This effect is regional over dozens of square kilometers [119]. Ultimately, the goal of coastal construction should be to avoid altering current speeds or heights to any significant degree. Also, regional effects of any structure should be considered before implementation to prevent potential habitat loss [108,119]. Extreme caution should be used when converting a local area such as coastal wetlands to aquaculture production. This transformation often results in the loss of essential ecosystem services (organism protection, flood control, sediment trapping, and water treatment) which in some cases of shrimp farming resulted in a wild fish biomass loss of 447 g for every 1 kg of shrimp farmed [108]. Biological diversity conservation of ecosystems is increasingly important as the aquaculture industry grows. This invokes a responsibility to comprehend the ability of aquatic environments to sustain fishing yields, aquatic operations, and other multiple use benefits [99].

Other issues impacting the environmental sustainability of aquaculture include higher than necessary production costs, and inefficiencies (i.e. feed practices, nutritional regulation, among others) with raising fish [115]. In some cases natural populations have been intentionally restocked with bred fish, which influences the genetic structure of the involved breeds [49]. Costs increases from unreliable supply of fishmeal is prevalent primarily in small scale or remote aquaculture producers. Both the environmental and economic costs of using fishmeal can be reduced if an effective substitute (protein-based meals) is used.

Policy decisions

Due to the rapid growth of the industry, policy changes are of significant importance to the future direction and profitability of aquaculture. This will in turn determine if aquavoltaics will prosper. To curtail unsustainable, or environmentally damaging practices, such as wild fingerling harvesting (compared to producing from a domesticated stock), international import bans may be imposed [115].

Trade barriers, if used, would through cost prevent market access to farmers forcing them to access aquaculture through unsustainable and damaging practices [115]. As nations become more industrialized, more regulation [42] of industry is observed. One large driving factor of the industry is the legislation imposed on anti-fouling technology and coatings [122][120] as these provide a tradeoff between reducing operation costs and safeguarding the environment as they are often damaging to aquatic life [96][53]. Any technology with an uncontrolled impact is not sustainable in this field.

4.3.3 Biofouling Control

Reducing or eliminated the biofouling (accumulation of microorganisms, plants, or animals on surfaces) of aquaculture presents a significant economic and technological challenge. The particular fouling community developed and its effect in the aquaculture system is primarily dictated by the properties of the fouling surface [96] as when organisms settle they modify both the surface chemistry and morphology [120]. Thus, the key to reducing and controlling biofouling is the protection and understanding of these surfaces within their respective environments. In a shellfish-based system the objective is focused around maintaining clean shells, because biofoulers negatively impact the appearance, marketability, growth rate, and general condition of the shellfish [96,120]. The primary negatives of biofouling for finfish cultures result when water flow is restricted due to fouling organisms causing net occlusion [96,120]. This results in less water flushing, which may lower dissolved oxygen, and increase the difficulty in removing excess feed and waste. If left unchecked there is a greater vulnerability to disease due to the potential harboring of pathogenic microorganisms by fouling species [96,120]. Additionally, as growths occur either on shellfish or in the case of finfish aquaculture upon nets and cages the weight supporting structures are forced to bear also increases, which can lead to heightened maintenance costs [96,120].

To control these negative effects of biofouling, several strategies have been employed to various degrees of success. Since antiquity antifouling paints or chemicals have been used, they work by creating a thin toxic layer above their applied surface to mitigate any potential growth [53,96]. However, this toxic layer is indiscriminate against surrounding aquatic life and damages ecosystems [53]. The difficulty then resides in developing an antifouling strategy, which has the following characteristics: broad spectrum activity, low mammalian toxicity, low water solubility, no bioaccumulation in the food chain, not persistent in the environment, compatible with paint raw materials, favorable price/performance [53]. One favorable direction is research dealing with low surface energy coatings to form a non-stick surface to prevent biofouling organism adhesion [120].

4.3.4 Further investment in research

The international community has an important and positive role to encourage a successful and sustainable aquaculture industry [115]. The necessity of proper education, technical assistance, and industry-based standards is paramount to progress and efficient practices [97]. Optimization of aquatic systems, either in aquaculture or aquaponics, will require public and private resources to reduce knowledge gaps to successfully create products for public use [111]. There is also definite need for continued investigation in design and long term implementation of non-toxic antifouling coatings [122]. An interesting an environmental approach would be biomimetics, which utilizes bio-inspired designs [122]. Furthermore, the aquaculture industry should investigate processes to reduce the reliance on fish meal as an input in feed, an increased development of integrated farming systems, and an increase in low trophic level aquaculture [108].

5. Discussion

5.1 Combining the Fields: LED applications

Light emitting diodes (LED)s are ideal for applications with aquavoltaics due to several attractive qualities. LEDs have narrow spectral output that overlaps the photosynthetic absorption spectrum so they can be used specifically to enhance plant life [54]. Additionally, LEDs remove unusable or detrimental wavelengths and are durable, reliable, inexpensive, and highly efficient [54] and would be relatively easy to install and upkeep. By utilizing different wavelengths of light aquaculturists can control the behavior and reproduction of fish and other aquatic life [54]. Yellow (570-590nm) and green (495-570nm) light are useful for affecting fish behaviors, and promoting plant based biomass production [123]. Blue (450-495nm) light due to its outstanding transmission characteristics is the most impactful compared to other colors [54,124], and is the most versatile being suitable for improving plant growth, affecting fish behavior, and even controlling diseases in plants [123]. Because different wavelengths of light are absorbed by water at different depths, aquatic animals, such as squids, have adapted their retinas to be highly sensitive to particular colors [124]. Squids for instance are highly sensitive to blue light and less so towards red(620-750nm) and white [124]. Such wavelengths can be used as an excellent luring source to control their behavior [124]. This application can be easily applied towards other fish species to more directly control their actions. Other than behavior effects, blue light specifically promotes growth of algae, fish larva, and plants [54]. The photoperiod of aquatic life can easily be manipulated with broadband artificial light or particular wavelengths.

Broadband light is often used in aquaculture. One example showed after a 24 week testing period under 24 constant light, juvenile haddock were 53-60% heavier compared to normal photoperiods [125]. Additionally, experimentally adjusting the light intensity showed an additional 11% improvement in body mass [125]. Another study under artificial broadband light superimposed over natural light showed that during winter and spring (salmon were kept in oceanic cages) sexually maturing Atlantic salmon increased as much as 37.6% and a 32% increase in mass [126]. While broadband light does show improvement, specific wavelengths of light can show similar results [127]. In one study, when exposed to full-spectrum white light and under blue light (470nm) of equal intensity haddock larvae showed similar feeding success [127]. However, when comparing different intensities of light haddock larvae showed the greatest feeding success when exposed to blue light over full-spectrum or green(530nm) light [127]. Another case study on Atlantic cod investigating growth performance using blue, green, red, and white lights showed a similar trend [128]. In comparison to growth in red light the larvae depicted a 75-80% increase in dry weight when reared under blue light (455nm) [128]. LED irradiance, in particular blue light, has also been shown to be an applicable light source for coral aquaculture [129]. From the use of broadband light to specific wavelengths, it is clear that light intensity, and wavelength can positively impact aquaculture production. Furthermore, the adaptation of FVs to incorporate LEDs demonstrates a large synergistic potential with aquaculture.

5.2 FV Scale and Use

A short example of the potential capabilities of FVs is provided. Using the projected energy needs of the United States for 2016 (2.30×10^{12} kWh)[130] and the output (59.3kWh/m^2) of a recently completed large scale FV farm in Godley U.K.[41] the water coverage area needed to accommodate all of US energy consumption is about 39,500km^2. It is important to note that the solar irradiance in

Godley U.K. is about 875kWh/m^2 [41]. When compared to the US Gulf Coast, the main catfish-producing area of the country where the solar irradiance is 1,860kWh/m^2 [131], the irradiance is more than doubled (2.13times greater). Assuming everything remains constant other than the increase in irradiance, 126 kWh/m^2 may be used instead of 59.3kWh/m^2 to determine the water coverage area needed (18,200km^2). Currently 295 km^2 are utilized in the US Gulf Coast for catfish production [132]. This area if utilized for aquavoltaics would amount to about 1.6% of total U.S. energy consumption. If taken into a broader context of the entire freshwater aquaculture industry in the continental U.S., 2,000 km^2 is currently used [133]. If a national average value of 1,750kWh/m^2 [131] is taken as the solar flux, then current aquaculture waterway use, if incorporated with appropriate solar technology could account for up to 10.3% of total U.S. energy consumption as of 2016. From these calculations it is easy to see the powerful capability and untapped potential that aquavoltaics offers all of humanity. Future work, however, is needed to evaluate the use of this technology over even greater water surfaces areas by analyzing ideal locations [134] for floatovoltaics such as reservoirs by hydropower dams [134], pumped hydro storage for PV farms [135] and even temporary PV installations for nomadic people [136] for use as aquavoltaic installations.

5.3 Food-Energy-Water Nexus Approach

Through an integrated use of water it is possible to generate food and energy using an aquavoltatic system design. Reliable sources of food, energy, and water are critical for human well-being, sustainable development, and poverty reduction [137]. As the global population continues to rise, demand for all three of these essential needs will grow. The Food-Energy-Water Nexus describes the complex and networked nature of global resource systems [137].

A nexus approach supports the transition to a green economy. It focuses on the dynamic interconnections between the three essential needs so that limited resources can be sustainably managed [137]. Therefore, based on a given situation, trade-offs and synergies are developed and analyzed, then prioritized responses are formed [137]. With these responses action may be taken to improve the overall standard of living. This is possible through resource efficiency with policy coherence due to an increasing integration of management and governance between world nations [137]. Furthermore, this approach emphasizes compromise between the interests of users and their goals while preserving ecosystems [137]. The end result is improved food, energy, and water security on a global scale creating a better future for humanity.

More than 40% of seafood comes from aquaculture farms [100] and this value is increasing as over exploitation of wild fish populations result in declining catches from many wild fisheries that in turn increases the need for practical aquaculture [51]. This has resulted in the aquaculture industry being considered among the fastest growing industries worldwide [50]. Water conservation is essential for continued aquaculture production. By simply installing FVs on the surface of an aquaculture system there would be expected to be a reduction in water evaporation as solar energy that drives evaporation is absorbed via PV instead of the water and solves the well-established PV thermal management challenges [138]. FVs also provides functionality as fish aggregation devices which provide a way to control the behavior of fish, protect them and potentially increase production [71]. Finally, a potential synergy of FVs combining with aquaculture is the capability to incorporate LEDs into the underside of fabricated designs. Specific wavelength exposure through LED use can manipulate aquatic organism (fish and plant life) behavior and growth rates to increase yields [123].

Four of the questions asked at the 2016 national conference for the Food-Energy-Water Nexus regarding its vision are answered below [139]:

1. "How will we feed the 9.6 billion people expected to be alive in 2050 while also meeting their needs for water and energy and improving the environment?"
    - Aquaculture has been growing rapidly within the past decades [50], and while this growth is projected to continue, capture fisheries are overall stagnant [100]. The use of FVs can reduce the natural water evaporation of water reservoirs by up to 85% by physically shielding water from sun light. Furthermore, that blocked light then is absorbed by solar modules and is converted to usable energy. Aquavoltaics can help solve this problem.
2. "What are the opportunities to improve water and energy efficiency and reduce food waste such that every improvement in one area yields gains in all areas?"
    - Aquavoltaics can yield an improvement in all three areas. The floating PV modules generate the energy needed to cleanse water. Solar technology efficiencies are improving year to year. Additionally, if the array is installed near a hydroelectric dam, then a power grid is already in place and the aquavoltaic array can tap into it to provide supplemental energy. This can even go as far as pumping water back uphill to create potential energy when there is excess energy being generated. This synergy will reduce the load on hydroelectric power and conserve water resources. The aquaculture side of this strategy can incorporate food wastes as a dietary option to grow aquatic organisms for consumption [108]. This capability allows a more sustainable aquavoltaic process.
3. "What are the strategies for resilience in the face of increased climate variability and other environmental changes?"
    - Aquavoltaics can be utilized to conserve the environment and potentially restore ecosystems or endangered animals. With the approach of integrated farming, many species are grown together to resemble an ecosystem in contrast to traditional aquacultures where a single species is grown at max. This ecosystem resemblance yields a system more resilient to disease and environmental changes. Due to the diversity of domesticated aquatic life, and the widespread use of PV technology, aquavoltaics can be conducted in various climates. Additionally, as solar technology is a sustainable source of energy, more of its implementation will continue to phase out unsustainable methods such as coal.
4. "How do we unleash scientific talent, technological advances, human ingenuity and entrepreneurialism, with wise public policy to meet essential human needs and restore the earth's environment, both regionally and globally?"
    - Aquavoltaics is a new concept, combining two fields which have a need for substantial research. Scientific talent and the technological advances achieved in the pursuit of furthering these fields will result in a world better prepared to meet humanity's needs. Human ingenuity is needed to solve current problems limiting the industry such as biofouling. There is substantial business opportunity for the deployment of such systems [140]. Approaches such as those found in the Food-Energy-Water Nexus will lead to global commitment on passing wise policy to safeguard entrepreneurialism and the environment. Processes are simplified and become easier when knowledge is free and easily accessible to both small time users and large companies. Through the avenue of open source software and hardware, ingenuity and sustainable advancements are not only possible, but encouraged.

6. Conclusions

This review has gathered knowledge of FVs and aquaculture and has provided insight into their combined application in the novel approach of aquavoltaics. This application has powerful potential to help resolve some of the food, energy, and water problems facing the world. Floatovolatics has been shown to reduce the evaporation of water in reservoirs up to 85%. In comparison to land mounted arrays floating PV structures always offer an increase in efficiency due to the cooling effect water has in close proximity. The magnitude of this effect does change based on the orientation and amount of contact the module has with water. The greatest improvement was shown with floating tracking cooling concentrating (FTCC) systems which resulted in an annual efficiency increase of 30% and a cost comparative to tilted ground arrays. Aquaculture has been shown to be a critical future food source with significant growth likely, especially as the global population continues to rise and capture fisheries already reaching stagnating growth. Aquaculture is most sustainable when integrated with multiple species which generally include fish, crustaceans, and seaweed cultures. The combination of both fields has created several powerful synergies. These include the increase in water conservation, more direct control of the aquatic environment with respect to photoperiod, and the capability of ecosystem restoration. One of the largest unknowns is the interaction of floating PV with aquatic organisms and the potential for biofouling to occur. LEDs were also shown to have drastic beneficial effect on aquatic life to promote aquaculture production. Through a Food-Energy-Water Nexus approach aquavoltaics can help move the world to a more sustainable future, both in an economical and environmental sense.

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