Distributed manufacturing of after market flexible floating photovoltaic modules

Article *in* Sustainable Energy Technologies and Assessments · December 2020

DOI: 10.1016/j.seta.2020.100830

Joshua M Pearce
The University of Western Ontario

Preprint: Pierce Mayville, Neha Vijay Patil and Joshua M.Pearce. Distributed manufacturing of after market flexible floating photovoltaic modules. *Sustainable Energy Technologies and Assessments*. 42, 2020, 100830. https://doi.org/10.1016/j.seta.2020.100830

Distributed Manufacturing of After Market Flexible Floating Photovoltaic Modules

Pierce Mayville 1, Neha Vijay Patil 2, and Joshua M. Pearce 1,2,3*

1. Department of Materials Science & Engineering, Michigan Technological University, Houghton, MI 49931- 1295, USA.

2. Department of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI 49931- 1295, USA

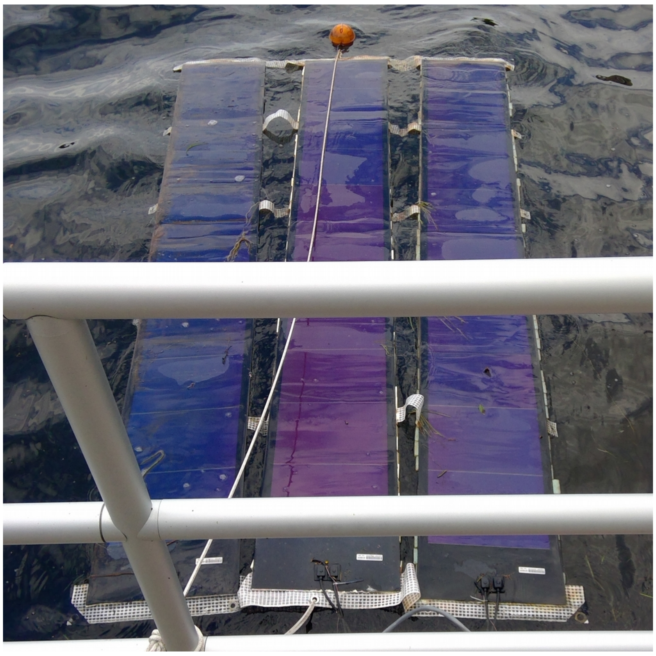
3. Department of Electronics and Nanoengineering, School of Electrical Engineering, Aalto University, Espoo, Finland.

*** contact: pearce@mtu.edu**

Abstract:

Floating photovoltaic (FPV) technology is gaining prominence as a means to alleviate land use conflicts while obtaining large solar PV deployments and simultaneously reducing evaporated water loss. In this study, an open source after-market distributed manufacturing method is proposed to be applied to large flexible PV modules to make flexible FPV systems. Specifically this study considers surface floating of flexible thin film solar PV using three types of closed-cell foams: i) neoprene, ii) mincell and iii) polyethylene. The fabricated FPV underwent indoor and outdoor tests for flotation, wave resistance, temperature and resistance to algae accumulation. The average operational temperature was reduced by 10-20ºC for the FPV compared to land-based mounting indicating substantial increases in electricity output compared to ground-based deployment of any type of PV (2-4% for amorphous silicon used here and 5-10% for crystalline Si based PV). In addition, foam-based FPV racking were also found to reduce costs of racking to $0.37-0.61/W, which is significantly lower than raft-based FPV as well as conventional land-based racking. The results of this preliminary study indicate that foam-backed FPV is exceptionally promising and should be further investigated with different foams, larger systems and more diverse deployments for longer periods to increase PV deployments.

Keywords: photovoltaic; floating photovoltaic; FPV; flexible; closed-cell foams



1. Introduction

Simple combustion of fossil fuels is increasing atmospheric CO_2 concentrations and driving climate change (Cook et al., 2016; Boko, et al., 2018; Harvey, 2018; Kellogg, 2019). To prevent dangerous temperature increases the Intergovernmental Panel on Climate Change (IPCC) suggested that carbon budget be limited (Edenhofer et al., 2015) and thus over 80% of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2°C global temperature rise (McGlade and Ekins, 2015). Numerous studies make it clear that humanity needs to move towards clean and renewable sources of energy generation (Sims, 2004; Tsoutsos, et al., 2008; Edenhofer, 2011; IPCC, 2014; Owusu & Asumadu-Sarkodie, 2016; Quaschning, 2019). Of the renewable energy sources, 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 (Pearce, 2002; Breyer, et al., 2015; Creutzig, 2017). The scale of solar PV technology demands large surface areas on both buildings (e.g. rooftop PV or building integrated PV (BIPV) and PV farms (Denholm & Margolis, 2008; Zweibel, et al., .2008; Wiginton, et al., 2010; Nguyen, et al., 2012). However, despite life cycle carbon emissions (Kenny et al., 2010) PV is more land efficient than even the best carbon capture and sequestration plans for coal (Groesbeck, et al., 2018). A substantial amount of land is still needed for PV to even replace all the current fossil fuel generated electricity and this creates competition for limited land resources between food and energy demand (Nonhebel, 2005; Calvert et al., 2013). With nearly a billion people living undernourished now further reductions in agriculture land is an unacceptable during a world food crisis (FAO, 2011).

One approach recently gaining traction in the literature and in test sites over the globe is the concept of floating photovoltaics or FPV (Dhas, 2014; Majid, et al.; 2014; Trapani & Millar, 2014; do Sacramento, et al., 2015; Trapani, et al., 2015; Patil et al., 2017; Kumar, et al. 2018). FPV installation has many advantages. As the PV in FPV are physically positioned close to or immersed in water, the operational temperature is reduced, which raises power conversion efficiency (Rosa-Clot et al., 2010; Tina et al., 2012; Ferrer-Gisbert, et al., 2013; Abdulgafar, et al., 2014; Majid, et al., 2014; Mehrotra, et al., 2014; Trapani, et al.. 2015). In regions where water scarcity is an issue, FPV has the additional major benefit that it reduces water loss because it reduces water evaporation by 70-85% (Ferrer-Gisbert, et al., 2013; McKay, 2013; Santafé, et al., 2014; Sharma, et al., 2015; Mittal, et al., 2017). FPV systems have the potential to form agrivoltaic type systems (Dinesh & Pearce, 2016) by merging with aquaculture to form aquavoltaics (Pringle, et al. 2017). Finally, FPV could also be used for drying and further reduce heat use (Osman et al., 2017).

FPV research has focused on four distinct system design strategies:

1) tilled arrays of solid modules (normally on top of pontoon structures) (Santafé, et al., 2014; Lee et al., 2014; Song & Choi, 2016; Choi, et al., 2016);

2) submerged (with and without a pontoon) (Stachiw, 1980; Rosa-Clot, et al. 2010; Sayran, et al., 2014; Mehrotra, et al., 2014; Trapani et al., 2014),

3) micro-encapsulated phase change material (MEPCM) based pontoon modules (Rathod & Banerjee, 2013; Ho et al., 2015; 2016); and

4) thin-film PV (no ridged pontoon supporting structure) (Trapani, et al., 2014;2015).

The latter flexible thin film PV for FPV concept is relatively new with the first flexible floating concept being developed at MIRARCO, Sadbury Canada (Trapani, et al., 2015). This type of design is extremely simple, cost-effective and potentially better suited for challenging aquatic environments. There is thus an opportunity to develop a design incorporating commercially available flexible PV modules for use in an after-market distributed manufacturing method of FPV. In this study, design considerations for developing such an open source after-market distributed manufacturing method will be applied to large flexible panels to make FPV. Specifically, this study will consider surface floating of thin film solar FPV, mechanical and electrical connections on water, floating materials, and mooring. Three types of such thin film FPV panels are tested with three different floating materials: i) neoprene, ii) mincell, and iii) polyethylene based on their buoyancy. The PV panels are peel and stick and these foams are adhered to the panels. The systems undergo indoor tests for floatation and wave resistance. Outdoor testing is performed with temperature monitoring to test the cooling effect and resistance to algae accumulation for each foam material. The system was deployed in the Keweenaw Waterway in the upper peninsula of Michigan to simulate how these arrays could be used seasonally because of their ease of deployment. The results of the FPV system design, fabrication and testing will be discussed in terms of the viability of this approach.

2. Methods

2.1 Design

This study details the design for converting Uni-Solar PVL-68 modules (Uni Solar, 2011) into FPV devices. This conversion is made possible by bonding foam to the back of the modules. The height, h, that the PV module rises above the water with a foam of known density was calculated using:

$$h = \frac{\rho_F \cdot A_P \cdot t + m_P}{\rho_f \cdot A_P} \tag{1}$$

where ρ_f is fluid density, ρ_F is foam density, A_P is the area of the PV module, t is the thickness of foam, and m_P is the mass of the panel.

Table 1 was generated using equation 1 and densities found in the physical data sheets (Foam Factory, 2019a). Using Table 1, three foam options were selected for experimental testing: 1) neoprene ½” (12.7 mm), 2) minicell T200 ¾” (19.05 mm), and 3) polyethylene 1.2 lb ½” (12.7 mm). The neoprene was chosen because of good water resistance and previous use in Miraco’s design (Trapani, et al., 2014). Mincell T200 is an extremely fine-celled, chemically cross-linked foam, which has excellent water resistance and the ¾” (19.05 mm) thickness has a roughly equivalent cost to the ½” (12.7 mm) neoprene as can be seen in Table 2. Minicell T200 is also already used in flotation applications such as life-jackets. The polyethylene (PE) was the most cost-effective way to add buoyancy, however there is a risk of water susceptibility. This susceptibility is related to water penetration into the closed cells of the foam reducing buoyancy over time. Water susceptibility should not be detrimental as the system will be undeployable. The minicell and PE were stated to be impermeable to mold and mildew (Foam Factory, 2019b).

Table 1. Calculated height of foams above water for FPV with modules.

Foam Type	Density of Foam (kg/m^3) (Foam Factory, 2019a)	Height of Foam Above Water (mm)
Air 1"	1.225	21.86
Air 1"-1/2	1.225	34.54
Air 2"	1.225	47.23
Air 3"	1.225	72.60
Air 4"	1.225	97.97
Neporene 1/8"	144.166	-0.79
Neporene 1/8"	96.111	-0.64
Neporene 1/4"	96.111	2.23

Neporene 3/8"	96.111	5.10
Neporene 1/2"	144.166	7.36
Minicel T200 1/4"	32.037	2.64
Minicel T200 3/8"	32.037	5.71
Mincel T200 3/4"	32.037	14.93
Mincel T300 1/4"	48.055	2.54
Mincel T300 3/8"	48.055	5.56
Mincel T300 1/2"	48.055	8.58
Polyethylene 2lb 1/8"	32.037	-0.44
Polyethylene 2lb 1/2"	32.037	8.78
Polyethylene 2lb 1"	32.037	21.08
Polyethylene 2lb 1-1/2"	32.037	33.37
Polyethylene 2lb 2"	32.037	45.66
Polyethylene 2lb 3"	32.037	70.25
Polyethylene 2lb 4"	32.037	94.84
Cross-linked PE 2lb 1/2"	32.037	8.78
Cross-linked PE 2lb 4"+	32.037	107.13
1.2lb Green PE 1/2"	19.222	8.95
Polystrene 1lb 1"	16.339	21.48
Polystrene 1lb 2"	16.339	46.46

Table 2. Cost of selected foams for use in FPV without tax and shipping charges.

Foam Type	**Cost for Sheet Used (USD) (Foam Factory, 2019a)**	**Cost per Volume (USD/m^3)**
Neporene 1/2"	31.99	2,266.21
Mincel T200 3/4"	32.99	1,558.04
1.2lb Green PE 1/2"	16.99	1,203.59

The properties of the three foams are detailed in Table 3. Specific values of water absorption and thermal properties are available for the neoprene and PE. The Mincel T200, is proprietary and the information for it is qualitatively provide by the manufacturer. It is a PE copolymer and should have negligible differences in material thermal conductivity to PE (Foam Factory, 2019b). Although the volume, size, and number of closed cells that are trapping air will alter thermal conductivity.

Table 3. Properties of three foam types

Foam Type	Water Absorption (Foam Factory, 2019b)	Thermal insulation
Neoprene 1/2"	5% kg H_2O/kg foam	0.0561W/mK (Bardy, et al., 2015)
Mincel T200 3/4"	"Low" (Foam Factory, 2019a)	"Good" (Foam Factory, 2019a)
1.2lb Green PE 1/2"	0.3 kg/m^2	0.03803 W/mK (Martinez-Diez, et al, 2001)

The basic experimental setup is shown in Figure 1.

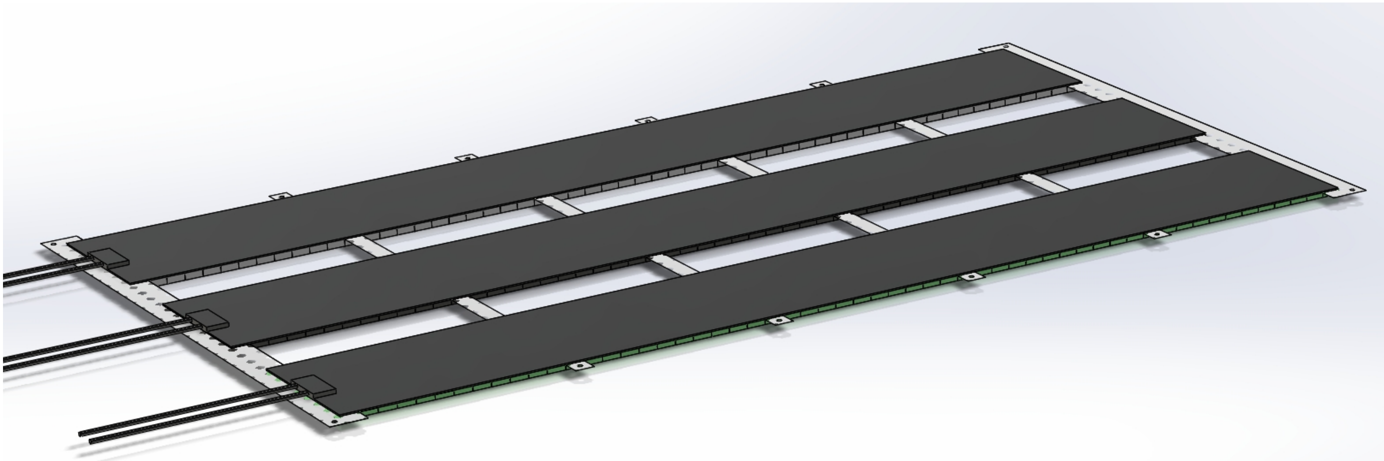
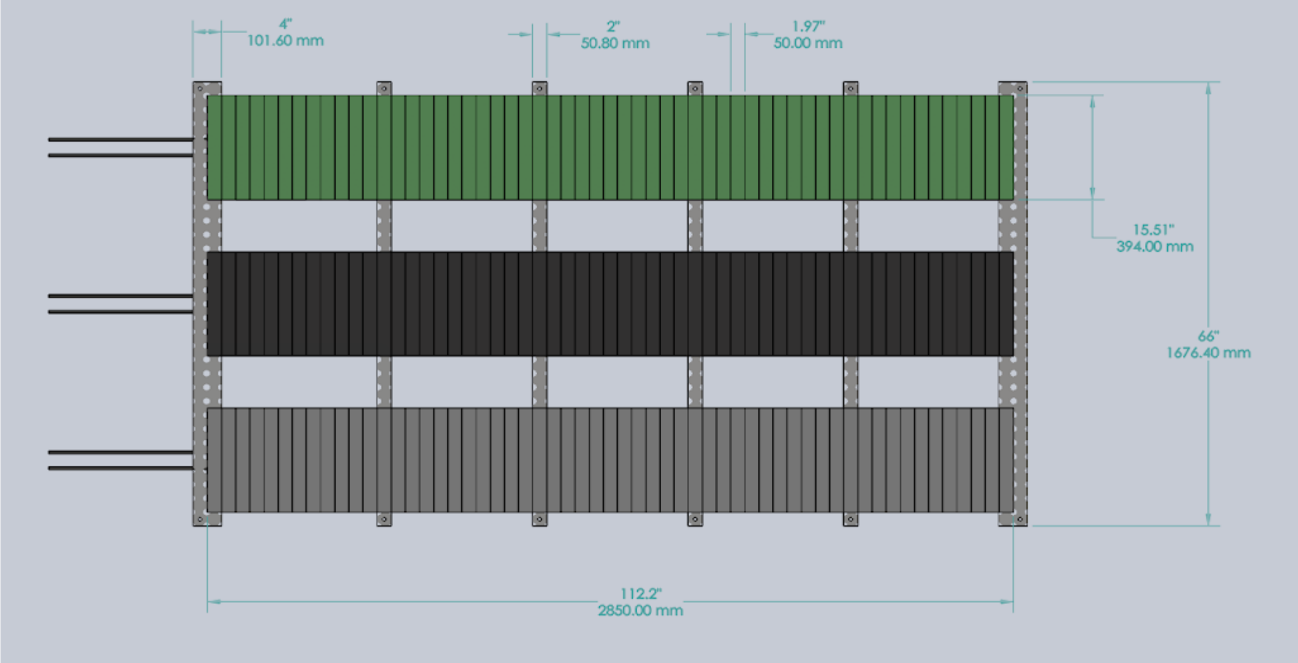


Figure 1. Design of FPV system including three panels, three foams, and tarp sections.

Equipment similar to that used to store pool swimming lane lines was designed to store the system and to deploy it for regions where the water freezes (Figure 2a). The basic mooring system design in shown in Figure 2b. Ropes connected to the two nearest corners act as mooring connection and are used to un-deploy the FPV system. The corners on the water side will be attached to a single mooring buoy with two lengths of rope connecting them at a point. The buoy is secured in place with a cement block anchor. The buoy also acts as a pulley to deploy the system. The rope is pulled from shore by being wound around the deployment structure pulling the system with it.

Figure 2. a) CAD design of FPV deployment system and basic mooring design b) side view and c) top view.



2.2 Fabrication

Each of the three foams selected was cut to the width of the modules and then into approximately 50 mm strips. Strips the same thickness were cut from a clear polyethylene tarp centred over the grommets. An extra 50 mm was added to the pieces of tarp on the ends. The strips of tarp were used to join the three panels and the grommets to secure the FPV array to mooring. With 50 mm of overhang on all tarp pieces, the panels and interior tarp strips were distributed evenly as shown in detail in Figure 3. The back of the PV modules are coated in peel and stick roofing tar. This was peeled back in sections as the foam and tarp strips were adhered along the entire length of the module. Foam strips were adhered to the tarp strips with 3M 5200 fast-set waterproof adhesive. One foam type was used on each PV module.

Figure 3. Dimensions of PV panels, foam strips, tarp strips, and tarp overhang.

The Uni-Solar installed output cables of the panels are 12 AWG in size with weatherproof rated DC quick connect terminals. The connections are only rated for water encountered on roofs and can no longer be purchased so they were removed. In order to ensure waterproof electrical connections, the 14 AWG wires were soldered on and covered using adhesive lined shrink tubing. All electrical connections were made using solder and double walled heat shrink tubing. The inner adhesive layer of the double walled heat shrink melts during heating providing a watertight seal. The FPV modules are connected in parallel to each other. The voltage across each panel is the same and the current will be additive in nature, so the output current will be additive of the currents flowing in the three panels.

2.2 Testing Methods

2.2.1 Indoor Testing and Float Height Quantification:

After assembling, the three prototype systems were tested for flotation and wave resistance in an indoor pool. This allowed the flotation height calculation to be verified by comparing it to the measured height. The height of the foam above the water was measured using a ruler. The 0 mm mark of the ruler was placed at the water's meniscus similar to the way a volumetric flask is read.

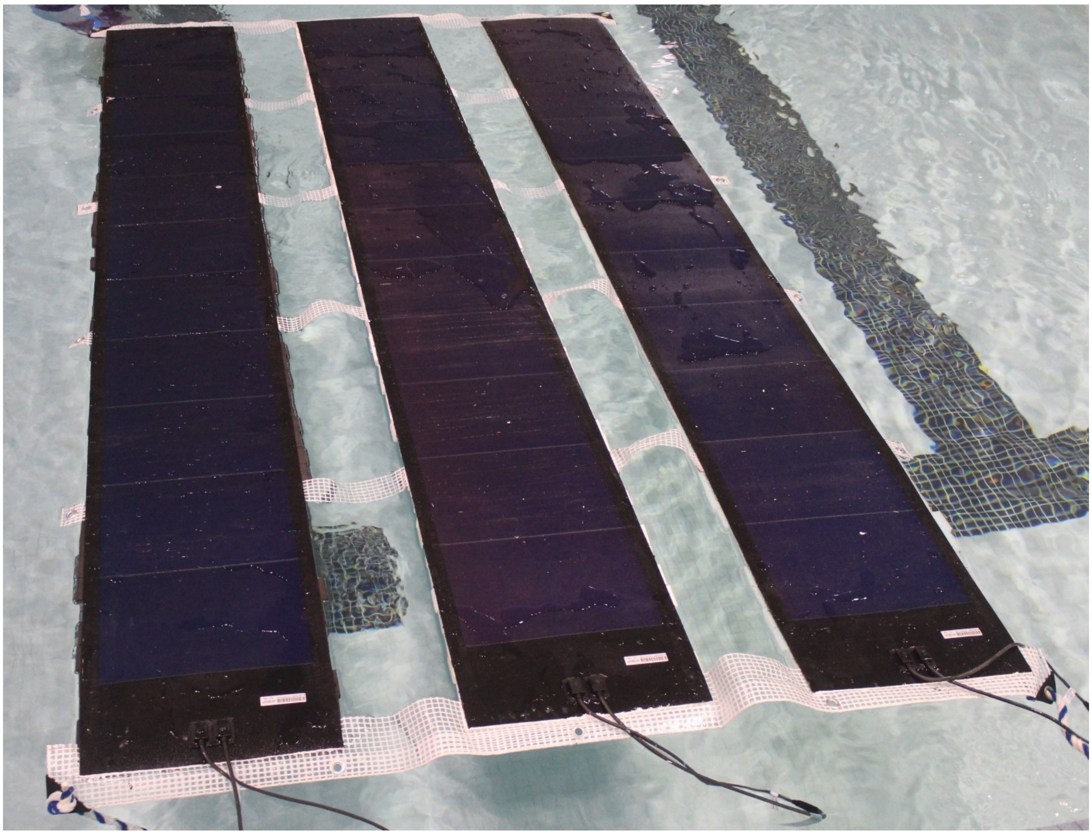


Figure 4. Testing for flotation in an indoor pool.

2.2.1 Outdoor Testing

After this initial proof of design of the system, in order to determine how algae could effect the three prototype FPV systems they were deployed in the Keweenaw Waterway at the Great Lakes Research Center (GLRC). The GLRC mooring was more than adequate for this small system and could be replicated for small home (e.g. cottage) FPV systems. Future work is needed to investigate mooring for large systems. Algae growth and sediment deposits on the top of the modules can have a negative effect on FPV performance due to light blocking. Due to the shading from the FPV, the sunlight entering on the water is reduced and this in turn reduces the photosynthesis process. This has been reported to help in the reduction of algae growth in the water (Sharma, et al., 2015; Sahu, et al., 2016).

The GLRC supplied the buoy, anchor, rope, and docking that was used. A rope was looped through a carabineer on the buoy before placing the buoy and anchor assembly in the water. With the buoy in the water, the rope was tied to the center grommet in the tarp piece on the water side. The system was set in place after passing the prototype through the dock’s railing. The other end of the rope was looped through the center grommet on the dock side. Both ends of the rope were then tied to the railing to secure the system in place, see Figure 5. The system was deployed at the end of July and left until the beginning of October as snow began to fall.

The temperature of each panel, the water, and the air was measured using a total a five temperature probes at 15-minute intervals. The temperature monitoring was preformed using a NanoDAQ board (Oberloier et al., 2020) using uxcell NTC thermistors resistors MF58 3950B 10K Ohm glass sealed temperature sensors (B Value: 3950 +/-1%). The NanoDAQ was protected from water using a Tupperware container. Electrical wires were passed through holes drilled in the Tupperware and sealed with 3M 5200. The representative days and more specifically time for wet and dry temperatures were chosen based on having the same air and water temperature.

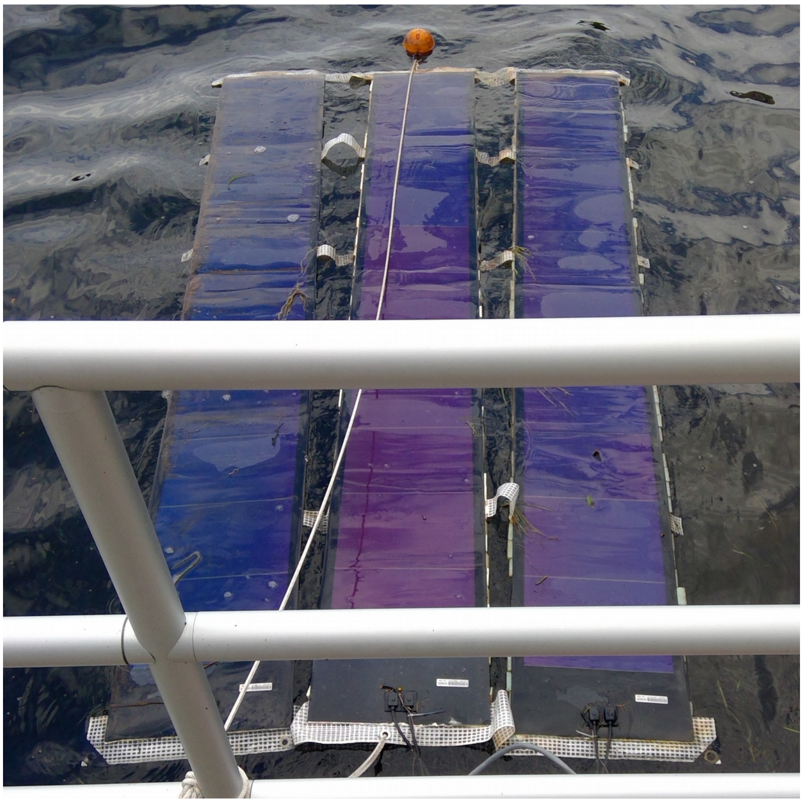


Figure 5. FPV test system deployed in the Portage outdoors.

3. Results

Testing the flotation in the indoor pool found that the measured height was lower than the calculated value but was the closest for the 1.2lb PE as can be seen in Table 4.

Table 4. Measured height of each foam type above water and deviation from calculated value

Foam Type	Measured Height of Foam Above Water (mm)	Deviation from Calculated Value (mm)
Neoprene 1/2"	6.0 ± 0.5	-1.4
Mincel T200 3/4"	13.4 ± 1.4	-1.5
1.2lb Green PE 1/2"	8.2 ± 0.5	-0.7

After the testing the flotation in the pool it was deployed at the GLRC. Algal growth was clear on the tarp but not on the top surface of the modules (Figure 6). On the underside (foam side) there was significant algal growth as shown in Figure 7. The neoprene experienced very little algal accumulation and had mostly solids stuck to it. The Mincel T had the thickest algal layer and was challenging to remove. The PE experienced a similar amount of algal accumulation to the Mincel, but also had internal accumulation. This is the dark spots seen on the green foam in Figure 8, which shows details for each of the foams tested. As shown in Table 3 because these materials are the same the similar results are expected. The tarp had a thick algal layer that was easily removed. The pH of North portage entry averaged from 11/13/19-11/19/19 was 8.11 (Michigan Tech, 2017). Algae prefer a pH around 8 (Algae Research and Supply, 2020), which explains the growth

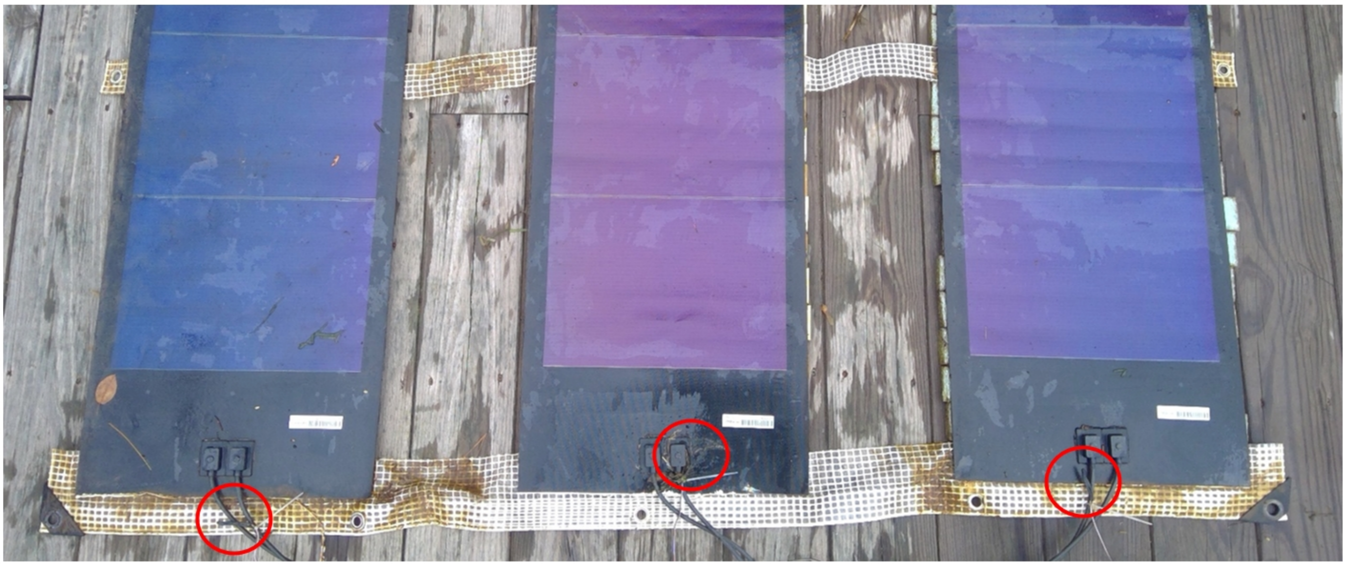


Figure 6. Top surface of FPV array after three months of deployment in the Portage waterway with temperature sensors circled in red.

Figure 7. Algal accumulation after deployment on the underside of the foam. Foam types left to right: PE, Mincel T, neoprene.

Figure 8. Details of algal growth for a) PE shows surface and internal algal accumulation b) Mincel T shows surface accumulation c) neoprene shows solids stuck to the surface

8.a.)

8.b.)

8.c.)

The operating temperatures in both land and water deployed FPV are shown for representative days of partial sun and overcast weather in Table 5. As can be seen in Table 5 the temperature reduction from the FPV was between 10-20ºC compared to the same modules on land depending on the solar conditions. These temperature reductions for the FPV drove power (and thus energy performance) improvements even for the amorphous silicon PV modules used here. These changes would be expected to be on the low end for PV materials as the temperature coefficients range are -0.2%/ºC for amorphous silicon (used in this study so a 2-4% gain in output would be expected compared to land-based deployment) up to -0.46-0.48/ºC for crystalline and polycrystalline silicon (e.g. 5-10% increase in output expected) to -0.60/ºC for CIS-based solar cells (e.g. 6-12% increase in output expected). Thus, this type of after-market foam racking would be expected to have a much larger impact on the performance of CIS and crystalline silicon-based PV.

Table 5. Temperature recorded for the FPV made up of different closed cell foams compared in and out of the water.

	Neoprene	Mincell	PE
Partial Sun, Air Temp 31 ºC, Water Temp 23 ºC			
Dry Panel Temp (ºC)	52	52	57
Wet Panel Temp (ºC)	41	38	43
Delta Temp (ºC)	11	14	14
Overcast, Air Temp 27 ºC, Water Temp 19 ºC			
Dry Panel Temp (ºC)	47	50	52
Wet Panel Temp (ºC)	35	32	37
Delta Temp (ºC)	12	18	15

4. Discussion

4.1 Performance and Economic Advantages

FPV is advantageous to land based PV system deployments. Flexible FPV like the one designed in this study are even more advantageous. Non-flexible FPV systems incorporate commercially available metal framed modules. These panels are supported by racking built into rafts. In most designs, the water would need to be pumped on to the panels to cool and clean them (Trapani, et al., 2015). Flexible FPV does not needs this as its modules are in direct contact with the water allowing for continuous cooling. Also being so close to the water, waves will clean the panels of dust and cool them further. Past studies have shown the same panels experienced an 8ºC reduction in temperature and a 40% boost in efficiency by being used in a FPV design (Trapani, et al., 2014). Data from the outdoor deployment in this study supports these past results as a 10-20ºC reduction in temperature was observed with the modules were in the water. Flexible FPV takes advantage of foams for flotation as opposed to the rafts utilized in non-flexible FPV systems. Using foam for flotation significantly reduces the cost per watt of the racking, as is quantified in Table 5. The cost per watt of raft-based racking was determined based on a simple prototype FPV system made of metal framed panels connected by metal supports to HDPE pontoons which are connected by rubber and metal couplings and anchored by ropes connect to concrete piles (Santafé et al., 2014). To determine the cost per Watt of the foam racking one third of the tarp's cost was added to the cost of each foam type. This value was then dived by the maximum power at STC (68W) from the technical data sheet for the panels used. The results in Table 5 for the cost of foam FPV racking costs are conservative. This is because the flexible PV used in this study are amorphous silicon-based PV modules, which have lower conversion efficiencies than most other thin film PV on the market as well as flexible crystalline based silicon PV modules. The most expensive closed cell foam, the Mincel T matched the cost of the lowest cost land-based rack, while the polyethylene decreased the cost by 40%. It should also be noted that these economic values for the after-market FPV conversion were based on retail costs of foams. Industrial production of FPV with foam would be expected to reduce the costs further with economies of scale. PV system designers considering the comparison between foam-based FPV can utilize the values in Table 6 with their selected PV modules and routine simulations to obtain a $/kWh to compare to conventional tilted racking and the same PV.

Table 6. Material cost per Watt of standard PV, non-flexible and flexible FPV racking without shipping

	Land Based Racking (TyconOnline, 2019)	Raft Based FPV Racking (Ferrer-Gisbert et al., 2013)	Foam FPV Racking (Foam Factory, 2019a)		
			Neoprene	Mincel T	Polyethylene
$ (USD)/W	0.61-1.70	~0.78	0.59	0.61	0.37

4.2 Limitations and Future Work

This study successfully tested three types of foams and found them to be valid candidates for post-production prosumer fabrication of FPV with flexible PV modules. It also offers the potential for future businesses to sell “FPV in a box” by integrating the PV with the floating racking. Although, neoprene performed the best in this deployment using PE for a large-scale deployment may be more desirable due to its low cost. Neoprene had the lowest amount of algal growth and was relatively easy to clean, but considering that algal accumulation does not impact performance of the PV it would make the most economical sense to use PE. The design concept is promising and should be easily scale-able. This, however, was a very preliminary study limited in that the outdoor monitoring, size of the system, the types of PV modules and foams studied as well as the location and times deployed.

First, multi-year studies of varying weather patterns for different types of bodies of water (and biodiversity) are needed to determine the optimal foam type for a given location. This will be a balance between the benefits of being closer to the water (lower temperature and higher PV efficiency) weighed against the cleaning potential of the front surface as waves flow over the modules as shown in Figure 9 against the probability of having debris deposited on the modules and thus reducing output from partial shading as shown in Figure 10. To specifically determine the algae related losses two identical FPV systems would be needed 1) deployed in the target water body with algae and 2) a second system that is either mechanically cleaned daily or deployed in an outdoor pool in the same location that used chemical treatments to eliminate algae.

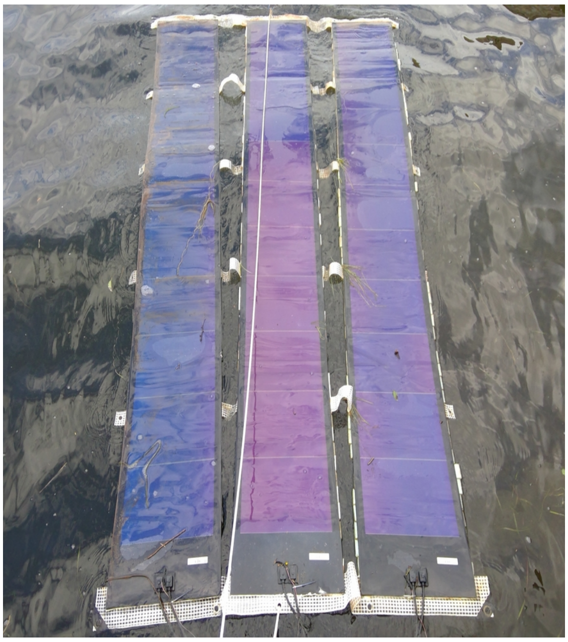


Figure 9. Waves cleaning the front surface of the modules.

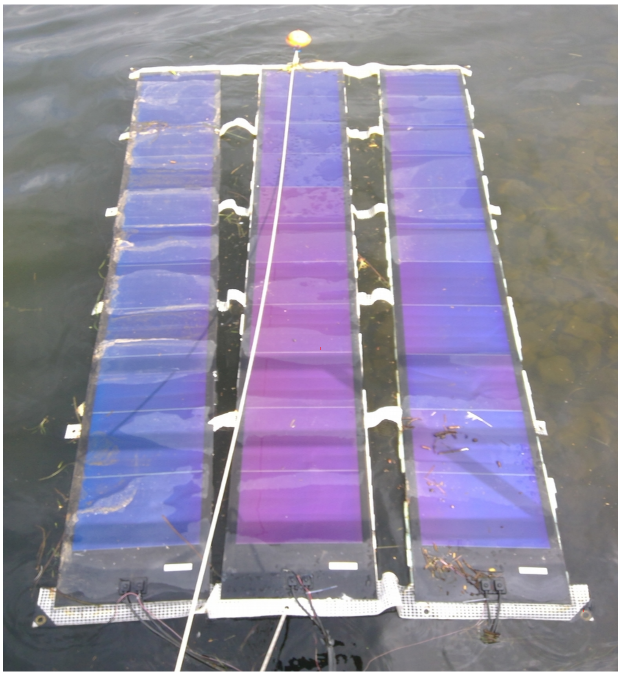


Figure 10. Debris deposited on the front surface of the modules indicated by orange circle.

Future work could investigate larger systems and determine the potential on other types of commercially available flexible modules that could be incorporated into these designs are summarized in Table 7.

Table 7. Commercially available flexible modules that are candidates for foam-backed FPV.

Manufacturer	Model Number	Watt	Type	Flexibility	Current (I)
Uni Solar	PVL-68	68	Thin Film	Flexible	4.1
	PVL-136	136			4.1
	PVL-144	144			4.1
Powerfilm Solar	R28	28	Thin Film	Flexible, Rollable	1.8
	R42	42			2.7
	R60	60			3.9
SunPower	SPR-E-Flex-50	50	Thin Film	Flexible	2.8
	SPR-E-Flex-110	100/110			5.9
	SPR-E-Flex-170	170			5.84
Solopower Systems	Model SP1	70	Thin Film	Flexible	3.4
		75			3.4
		80			3.5
		85			3.5
		90			3.6
Global Solar	PowerFLEX+BA PV	100	Thin Film	Flexible	3.2
		105			3.2
		110			3.3
		200			3.2

Future work is needed to determine the economics for a partial year deployment as demonstrated in this study in the upper peninsula of Michigan where modules would be destroyed if not able to be taken out of the water as it freezes and shifts. In addition, future work is needed to deploy these types of systems in other locations. As examples three locations were selected where a large-scale FPV plant could be installed (e.g. close to power station) and remain in use year round (no freezing) rather than partial use case shown here.

Based on an assessment of the technical potential of PV on man-made water bodies in the U.S., New Mexico has potential FPV generation that exceeds the current total energy production (Spencer et al., 2018). The Navajo Lake is a man-made water body formed by the Navajo Dam, which is for the Colorado River Storage Project. The Navajo Dam hydro power plant with capacity 30 MW is operated by City of Farmington (Bureau of Reclamation, 2019). Installing the FPV on the Navajo lake appears to be a good option as power generated from FPV can be tied to the power generated by the hydroelectric power plant as well as increasing the hydro capacity by reducing evaporation. Similarly, the Sobradinho Basin in Brazil is formed a hydroelectric dam on the São Francisco River. The Sobradinho Dam has the capacity to install 1050 MW of PV power if 0.25% of the basin's surface area of 4214 km^2 would be covered if the total power capacity was installed with raft FPV (Silvério et al., 2018). The basin already has a 1 MW raft based FPV plant in place that would allow for a direct comparison to foam based racking. The capacity of FPV plant is planned to be increased to 2.5 MW by January, 2020. Even with this increased production, the raft FPV plant will only use 0.24% of the dam's capacity allowing a foam FPV plant of equal or greater capacity to also be installed (Sunlution, 2019; Ciel & Terre, 2019). This FPV concept may also be appropriate for aquavoltaics (Pringle et al., 2017). So, for example, the total area for aquaculture in Taiwan was approximately 40 thousand hectares as of 2015 (Fisheries Agency, 2019) that could be used. Previous work has shown that with 60% FPV cover more than 70% of fish production could be maintained as well as generating 5 times the profit (Châteaua et al., 2019). To move forward with the FPV proposed here on such a system, the impact of salinity on the FPV modules and foams would need to be tested for brackish or marine aquaculture systems. Finally, future work is needed to look at locations where such temporary deployment of FPV would be most beneficial (e.g. summer homes, cabins, research stations etc.) and where a system as described here could be rapidly and easily undeployed when freezing weather occurs.

5. Conclusions

In this study, an FPV system was designed using an open source after-market distributed manufacturing method that could be used for making small systems to power individual devices or applications like solar power for off-grid cottages. The ability to easily deploy or store such systems could make them available for partial year use in seasonal homes. The results were promising and could be developed to be applied to larger arrays of flexible PV modules in regions where ice and snow would not preclude year round deployment. Flexible FPV systems were successfully fabricated using commercially available PV panels and closed cell foams following the open source designs. Three different floating materials were tested based on their buoyancy and all were found to adequately deploy the PV. The average operational temperature was reduced by 10-20ºC indicating substantial increases in efficiency regardless of PV material used as the absorber. The lowest-cost foam tested, PE, provide racking costs of \$0.37/W even at home-sized retail scale. PE foam used in FPV showed a 14-15ºC temperature differential so would be expected to provide a 7% boost in energy over flat land-based systems. Overall, such foam racking would reduce costs of racking to \$0.37-0.61/W, which is significantly lower than raft-based FPV at any scale as well as land-based racking. PV developers can use the results of this study to calculate the \$/kWh for such foam-backed FPV and compare this value to other FPV racking designs or more conventional fixed tilt systems to optimize site design. The results of this preliminary study indicate that foam-backed FPV is exceptionally promising and should be further investigated with different foams, larger systems and more diverse deployments for longer periods of time to scale the idea up.

6. Acknowledgments

This research was funded by the Witte Endowment. We would like to thank the Great Lakes Research Center and the Coordinator of Marine Operations at the GLRC, Jamey Anderson, for providing us with a place to deploy the prototype FPV system and for helping us deploying it.

7. References

Abdulgafar, S.A., Omar, O.S. and Yousif, K.M., 2014. Improving the efficiency of polycrystalline solar panel via water immersion method. *International Journal of Innovative Research in Science, Engineering and Technology*, *3*(1), pp.96-101.

Algae Research and Supply , 2020. Algae Culture and pH, Available: https://algaeresearchsupply.com/pages/algae-culture-and-ph (visited on 6.8.2020)

Boko, M., Niang, I., Nyong, A., Vogel, A., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R. and Yanda, P.Z., 2018. Africa Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Bardy, E., Mollendorf, J., and Pendergast, D., 2005. Thermal conductivity and compressive strain of foam neoprene insulation under hydrostatic pressure. J. Phys. D: Appl. Phys., 38 (20) 3832.

Breyer, C., Koskinen, O. and Blechinger, P., 2015. Profitable climate change mitigation: The case of greenhouse gas emission reduction benefits enabled by solar photovoltaic systems. *Renewable and Sustainable Energy Reviews*, *49*, pp.610-628.

Bureau of Reclamation, Navajo Dam, Available: https://www.usbr.gov/uc/rm/crsp/navajo/ (visited on 12.6.19).

Calvert, K., Pearce, J.M. and Mabee, W.E., 2013. Toward renewable energy geo-information infrastructures: Applications of GIScience and remote sensing that build institutional capacity. *Renewable and sustainable energy reviews*, 18, pp.416-429.

Ciel & Terre International, Solar & Hydro Hybridization: Ciel & Terre's Floating PV Plant on Sobradinho Hydrolectric Dam, Available: https://www.ciel-et-terre.net/solar-hydro-hybridization-ciel-terres-floating-pv-plant-on-sobradinho-hydrolectric-dam/ (visited on 12.13.2019)

Château, P.A., Wunderlich, R.F., Wang, T.W., Lai H.T, Chen, C.C., Chang, F.J, 2019. Mathematical modeling suggests high potential for the deployment of floating photovoltaic on fish ponds. *Science of the Total Environment.* 687, pp. 65-666.

Choi, Y.K., Choi, W.S., Lee, J.H., 2016. Empirical Research on the Efficiency of Floating PV Systems. Science of Advanced Materials 8, 681–685. doi:10.1166/sam.2016.2529

Cook, J., Oreskes, N., Doran, P.T., Anderegg, W.R., Verheggen, B., Maibach, E.W., Carlton, J.S., Lewandowsky, S., Skuce, A.G., Green, S.A. and Nuccitelli, D., 2016. Consensus on consensus: a synthesis of consensus estimates on human-caused global warming. *Environmental Research Letters*, *11*(4), p.048002.

Creutzig, F., Agoston, P., Goldschmidt, J.C., Luderer, G., Nemet, G. and Pietzcker, R.C., 2017. The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, *2*(9), p.17140.

Denholm, P. and Margolis, R.M., 2008. Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States. *Energy Policy*, *36*(9), pp.3531-3543.

Dhas, T.R., 2014. A Review on New Era of Solar Power Systems: Floatovoltaic Systems or Floating Solar Power Plants. *i-Manager's Journal on Instrumentation & Control Engineering*, *3*(1), p.1.

Dinesh, H. and Pearce, J.M., 2016. The potential of agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, *54*, pp.299-308.

do Sacramento, E.M., Carvalho, P.C., de Araújo, J.C., Riffel, D.B., da Cruz Corrêa, R.M. and Neto, J.S.P., 2015. Scenarios for use of floating photovoltaic plants in Brazilian reservoirs. *IET Renewable Power Generation*, *9*(8), pp.1019-1024.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C. and Matschoss, P. eds., 2011. *Renewable energy sources and* *climate change mitigation: Special report of the intergovernmental panel on climate change*. Cambridge University Press.

Edenhofer, O. ed., 2015. *Climate change 2014: mitigation of climate change* (Vol. 3). Cambridge University Press.

FAO,2011. 29. The State of Food Insecurity in the World 2011 Available at <http://www.fao.org/docrep/014/i2330e/i2330e00.htm>(accessed March 17th 2016).

Ferrer-Gisbert, C., Ferrán-Gozálvez, J.J., Redón-Santafé, M., Ferrer-Gisbert, P., Sánchez-Romero, F.J. and Torregrosa-Soler, J.B., 2013. A new photovoltaic floating cover system for water reservoirs. *Renewable energy*, *60*, pp.63-70.

Fisheries Agency (Council of Agriculture, Taiwan R.O.C.), Fisheries of the Republic of China(Taiwan), Available: https://www.fa.gov.tw/en/FisheriesoROC/content.aspx?id=2&chk=05d9ffd2-651d-4686-a2d1-a44413152366&param=pn%3d1 (visited on 11.5.2019)

Foam Factory Inc., 2019a. Closed-Cell Foam, Available: https://www.foambymail.com/closed-cell-foams.html (visited on 3.22.2019)

Foam Factory Inc., 2019b. Data sheets, Available: https://www.foambymail.com/datasheets.html (visited on 10.29.2019)

Groesbeck, J.G. and Pearce, J.M., 2018. Coal with Carbon Capture and Sequestration is not as Land Use Efficient as Solar Photovoltaic Technology for Climate Neutral Electricity Production. *Scientific Reports*, 8(1), p.13476.

Harvey, L.D., 2018. *Global warming*. Routledge.

Ho, C.J., Chou, W.-L., Lai, C.-M., 2015. Thermal and electrical performance of a water-surface floating PV integrated with a water-saturated MEPCM layer. Energy Conversion and Management 89, 862–872. doi:10.1016/j.enconman.2014.10.039

Ho, C.J., Chou, W.-L., Lai, C.-M., 2016. Thermal and electrical performances of a water-surface floating PV integrated with double water-saturated MEPCM layers. Applied Thermal Engineering 94, 122–132. doi:10.1016/j.applthermaleng.2015.10.097

IPCC., 2014. Mitigation of climate change. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1454*.

Kellogg, W.W., 2019. *Climate change and society: consequences of increasing atmospheric carbon dioxide*. Routledge.

Kenny, R., Law, C. and Pearce, J.M., 2010. Towards real energy economics: energy policy driven by life-cycle carbon emission. *Energy Policy*, *38*(4), pp.1969-1978.

Kumar, N.M., Kanchikere, J. and Mallikarjun, P., 2018. Floatovoltaics: Towards improved energy efficiency, land and water management. *International Journal of Civil Engineering and Technology*, *9*, pp.1089-1096.

Lee, A.K., Shin, G.W., Hong, S.T. and Choi, Y.K., 2014. A study on development of ICT convergence technology for tracking-type floating photovoltaic systems. International Journal of Smart Grid and Clean Energy, 3(1), pp.80-87.

Majid, Z.A.A., Ruslan, M.H., Sopian, K., Othman, M.Y. and Azmi, M.S.M., 2014. Study on performance of 80 watt floating photovoltaic panel. *Journal of Mechanical Engineering and Sciences*, *7*(1), pp.1150-1156.

Martinez-Diez, J. A., Rodriguez-Perez, M. A., De Saja, J. A., Arcos Y RÁbago, L. O., Almanza, O. A., 2001. The Thermal Conductivity of a Polyethylene Foam Block Produced by a Compression Molding Process. *Journal of Cellular Plastics*, *37*(1), pp.21- 42.

McKay A. FVs: Quantifying the Benefits of a Hydro-Solar Power Fusion Pomona Senior Theses; 2013.

McGlade, C. and Ekins, P., 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 C. *Nature*, *517*(7533), p.187.

Mehrotra, S., Rawat, P., Debbarma, M. and Sudhakar, K., 2014. Performance of a solar panel with water immersion cooling technique. *International Journal of Science, Environment and Technology*, *3*(3), pp.1161-1172.

Michigan Tech, 2017. Upper Great Lakes Observing System: North Entry Buoy, Available: http://uglos.mtu.edu/station_page.php?station=45023 (visited on 6.8.2020)

Mittal, D., Saxena, B. K., Rao, K. V. S., Floating solar photovoltaic systems: An overview and their feasibility at Kota in Rajasthan, 2017, *International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, Kollam, 2017, pp. 1-7. doi: 10.1109/ICCPCT.2017.8074182

Nonhebel, S., 2005. Renewable energy and food supply: will there be enough land?. *Renewable and sustainable energy reviews*, *9*(2), pp.191-201.

Nguyen, H.T., Pearce, J.M., Harrap, R. and Barber, G., 2012. The application of LiDAR to assessment of rooftop solar photovoltaic deployment potential in a municipal district unit. *Sensors*, *12*(4), pp.4534-4558.

Oberloier et al., 2020 (to be published).

Osman, F.A., Ya'acob, M.E. and Iskandar, A.N., 2017, September. Field measurements of temperature profile for floatovoltaic dryer in the tropics. In *AIP Conference Proceedings* (Vol. 1885, No. 1, p. 020015). AIP Publishing.

Owusu, P.A. and Asumadu-Sarkodie, S., 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering*, *3*(1), p.1167990.

Patil Desai Sujay, S., Wagh, M.M. and Shinde, N.N., 2017. A review on floating solar photovoltaic power plants. *International Journal of Scientific & Engineering Research*, *8*(6), p.789.

Pearce, J.M., 2002. Photovoltaics—a path to sustainable futures. *Futures*, *34*(7), pp.663-674.

Pringle, A.M., Handler, R.M. and Pearce, J.M., 2017. Aquavoltaics: Synergies for dual use of water area for solar photovoltaic electricity generation and aquaculture. *Renewable and Sustainable Energy Reviews*, *80*, pp.572-584.

Quaschning, V.V., 2019. *Renewable energy and climate change*. Wiley.

Rosa-Clot, M., Rosa-Clot, P., Tina, G.M., Scandura, P.F., 2010. Submerged photovoltaic solar panel: SP2. Renewable Energy 35, 1862–1865. doi:10.1016/j.renene.2009.10.023

Rathod, M.K. and Banerjee, J., 2013. Thermal stability of phase change materials used in latent heat energy storage systems: a review. Renewable and Sustainable Energy Reviews, 18, pp.246-258.

Sahu, A., Yadav, N. and Sudhakar, K., 2016. Floating photovoltaic power plant: A review. *Renewable and sustainable energy reviews*, *66*, pp.815-824.

Santafé, M.R., Ferrer Gisbert, P.S., Sánchez Romero, F.J., Torregrosa Soler, J.B., Ferrán Gozálvez, J.J., Ferrer Gisbert, C.M., 2014. Implementation of a photovoltaic floating cover for irrigation reservoirs. *Journal of Cleaner Production*. 66, 568–570. https://doi.org/10.1016/j.jclepro.2013.11.006

Sayran A. Abdulgafar, Omar S. Omar, Kamil M. Yousif, 2014. Improving The Efficiency Of Polycrystalline Solar Panel Via Water Immersion Method 3

Sharma, P., Muni, B. and Sen, D., 2015, May. Design parameters of 10 KW floating solar power plant. In *Proceedings of the International Advanced Research Journal in Science, Engineering and Technology (IARJSET), National Conference on Renewable Energy and Environment (NCREE-2015), Ghaziabad, India* (Vol. 2). http://www.iarjset.com/upload/2015/si/ncree-15/IARJSET%2017%20P127.pdf

Silvério, N.M., Barros, R.M., Tiago Filho, G.L., Redón-Santafé, M., Santos, I.F.S. dos, Valério, V.E. de M., 2018. Use of floating PV plants for coordinated operation with hydropower plants: Case study of the hydroelectric plants of the São Francisco River basin. *Energy Conversion and Management*. 171, 339–349. https://doi.org/10.1016/j.enconman.2018.05.095

Sims, R.E., 2004. Renewable energy: a response to climate change. *Solar energy*, *76*(1-3), pp.9-17.

Song, J., Choi, Y., 2016. Analysis of the Potential for Use of Floating Photovoltaic Systems on Mine Pit Lakes: Case Study at the Ssangyong Open-Pit Limestone Mine in Korea. *Energies* 9, 102. doi:10.3390/en9020102

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. *Environ. Sci. Technol*. 53(3), pp. 1680-1689. https://doi.org/10.1021/acs.est.8b04735

Stachiw, J.D., 1980. Performance of Photovoltaic Cells in Undersea Environment. Journal of Engineering for Industry 102, 51. doi:10.1115/1.3183829

Sunlution, Usina Solar de Sobradinho – Bahia, Available: https://www.sunlution.com.br/portfolio-items/uhe-sobradinho-ba/ (visited on 12.13.2019)

Tina, G.M., Rosa-Clot, M., Rosa-Clot, P. and Scandura, P.F., 2012. Optical and thermal behavior of submerged photovoltaic solar panel: SP2. *Energy*, *39*(1), pp.17-26.

Trapani, K. and Millar, D.L., 2014. The thin film flexible floating PV (T3F-PV) array: The concept and development of the prototype. *Renewable energy*. 71, pp.43-50.

Trapani, K. and Redón Santafé, M., 2015. A review of floating photovoltaic installations: 2007–2013. *Progress in Photovoltaics: Research and Applications*, *23*(4), pp.524-532.

Tsoutsos, T., Papadopoulou, E., Katsiri, A. and Papadopoulos, A.M., 2008. Supporting schemes for renewable energy sources and their impact on reducing the emissions of greenhouse gases in Greece. *Renewable and Sustainable Energy Reviews*, *12*(7), pp.1767-1788.

TyconOnline.com, Solar Mt, 2x-4x 325W Panels, Top of Pole, Available: https://www.tycononline.com/Solar-Mt-2x-4x-325W-Panels-Top-of-Pole_p_248.html (visited on 10.22.2019)

Uni-Solar, 2011. PowerBond PVL-68 Technical Data Sheet, Available: http://www.uni-solar.com/products/commercial-products/pvl/index.html (visited on 2.21.2019)

Wiginton, L.K., Nguyen, H.T. and Pearce, J.M., 2010. Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. *Computers, Environment and Urban Systems*, *34*(4), pp.345-357.

Zweibel, K., Mason, J. and Fthenakis, V., 2008. A solar grand plan. *Scientific American*, *298*(1), pp.64-73.