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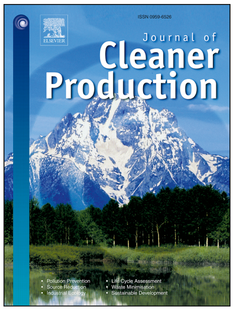

Recent Technical Advancements, Economics and Environmental Impacts of Floating Photovoltaic Solar Energy Conversion Systems

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Recent Technical Advancements, Economics and Environmental Impacts of Floating Photovoltaic Solar Energy Conversion Systems

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Table 1. Distribution of FPV potential on man-made reservoirs (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Continent	Total Available Surface Area (km^2)	Number of Water Bodies Assessed	FPV Potential (GWp)			Possible Annual Energy Generation (GWh/y)		
			Percentage of Used Total Surface Area					
			1%	5%	10%	1%	5%	10%
Africa	101130	724	101	506	1011	167165	835824	1671648
Middle East and Asia	115621	2041	116	578	1156	128691	643456	1286911
Europe	20424	1082	20	102	204	19574	97868	195736
North America	126017	2248	126	630	1260	140815	704076	1408153
Oceania	4991	254	5	25	50	6713	33565	67131
South America	36271	299	36	181	363	58151	290753	581507
Total	**404454**	**6648**	**404**	**2022**	**4044**	**521109**	**2605542**	**5211086**

Table 2. Comparison of capacity factor and annual power generation of sole hydropower and hybrid FPV-hydropower plants in Brazil (Silvério et al., 2018)**.**

Reservoir	Peak Power (MW)	FPV area (m^2)	Reservoir area (m^2)	Capacity Factor (Hydro alone) %	Capacity Factor (Hydro and PV) %	Annual Power FPV (MWm)	Annual Power Hydroelectric (MWm)
Queimado	105.00	1.04	39.43	29.0	46.5	18.4	30.4
Retiro Baixo	82.00	0.81	22.58	16.7	34.3	14.5	13.7
Tres Marias	396.00	3.90	1090.00	20.7	38.5	70.8	81.8
Sobradinho	1050.00	10.35	4214.00	18.8	35.8	178.5	197.7
Itaparica	1479.60	14.59	828.00	26.9	43.8	250.3	397.3
Xingo	3162.00	28.98	60.00	32.7	49.5	529.8	1034.4

Table 3. Estimated values of environmental impacts on a FPV plant (Choi, 2014a).

Deep Water Estimate	SMB Method					Willson Method				
Wind Speed (m/s)	5	10	20	30	40	5	10	20	30	40
Wind Drift Distance (km)	Significant Wave Height (m)									
1	0.1082	0.2288	0.4708	0.7132	0.9555	0.1112	0.2555	0.5869	0.9547	1.3483
2	0.1464	0.3161	0.6580	1.0005	1.3432	0.1467	0.3371	0.7744	1.297	1.7791
3	0.1735	0.3804	0.7985	1.2178	1.6374	0.1726	0.3964	0.9108	1.4816	2.0924

Table 4. Essential parameters in site evaluation for floating and land-based PV systems (Pimentel Da Silva and Branco, 2018; *Where Sun Meets Water : Floating Solar Market Report - Executive Summary*, 2018).

	Floating PV	**Ground-mounted PV**
Land/water surface use	• Does not compete with agricultural, industrial, or residential projects; • Ground excavation is less detrimental to the environment; • Often easier to find sites near densely populated areas; • A promising solution for archipelago countries; • Potential integration with aquaculture.	• Suitable/ affordable land may be far away from load centers, thus requiring costly transmission infrastructure; • Land excavation is generally energy/time intensive; • Competes for land with city dwellings, industrial development, and agriculture though in certain cases integration is possible.
Power system benefits	• Adaptability with current electrical infrastructure (e.g. hydropower plants); • High potential to be incorporated with hydropower.	• Costs of grid interconnection are often borne by the project developer and can be prohibitively high.

Table 5. Comparative insight into the operating features of PV application for land- and water-based regions (Golroodbari and van Sark, 2020; *Where Sun Meets Water : Floating Solar Market Report - Executive Summary*, 2018).

Type of PV System	**Floating PV**	**Ground-mounted PV**
Operating Environment	• Open and flat surface; • Low reflected diffuse light from water surface; • The general presence of evaporative cooling and higher wind speed; • Presence of dynamic movement; • Less seasonal temperature fluctuations.	• Terrain type may vary; • Albedo depends on ground type; • No movement; • The average temperature difference between the PV panel and the environment is higher.
Losses	• Lower module temperature (magnitude depends on climate); • Nearly no shading from nearby objects; • Less soiling from dust, but potentially more from bird droppings; • Potential mismatch loss from temperature inhomogeneity and misalignment in module facing; • Winter season causes enormous variation in	• More temperature loss hot and arid lands; • More sources of shading and string mismatch.

	the tilt angle.	
Performance	• Overall higher initial performance ratio (5-10%, climate-specific); • Higher energy production in all seasons with the highest in summer by 6% increase, and the least in winter with nearly 2% growth. The annual average performance can be more as much as 13%; • Long-term degradation (e.g., potential induced degradation) is still uncertain	• Higher potential for tracking, bifacial modules, and optimum tilt angle/ row spacing; • Yield prediction is better understood.

Table 6. Different features of floating and ground-mounted PV systems (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Item	Floating PV	Ground-mounted PV
Technical	• More difficult to reach parts and replace them; • Bio-fouling likely; • Higher humidity increases corrosion/oxidation of metal parts; • More replacement for structural components; • Easier access to water for cleaning; • Lower risk of vandalism and theft.	• Easier to access parts for repair and replacement; • More vegetation; • Easier to implement automated cleaning routines; • Less maintenance for civil work and ground foundations.
Safety	• The constant movement of floats poses walking hazards; • Risk of personnel falling into the water.	• Generally safe, with the stable ground for walking.

Table 7. Comparison of evaporation rate predicted by models with experiment values (Bontempo Scavo et al., 2020).

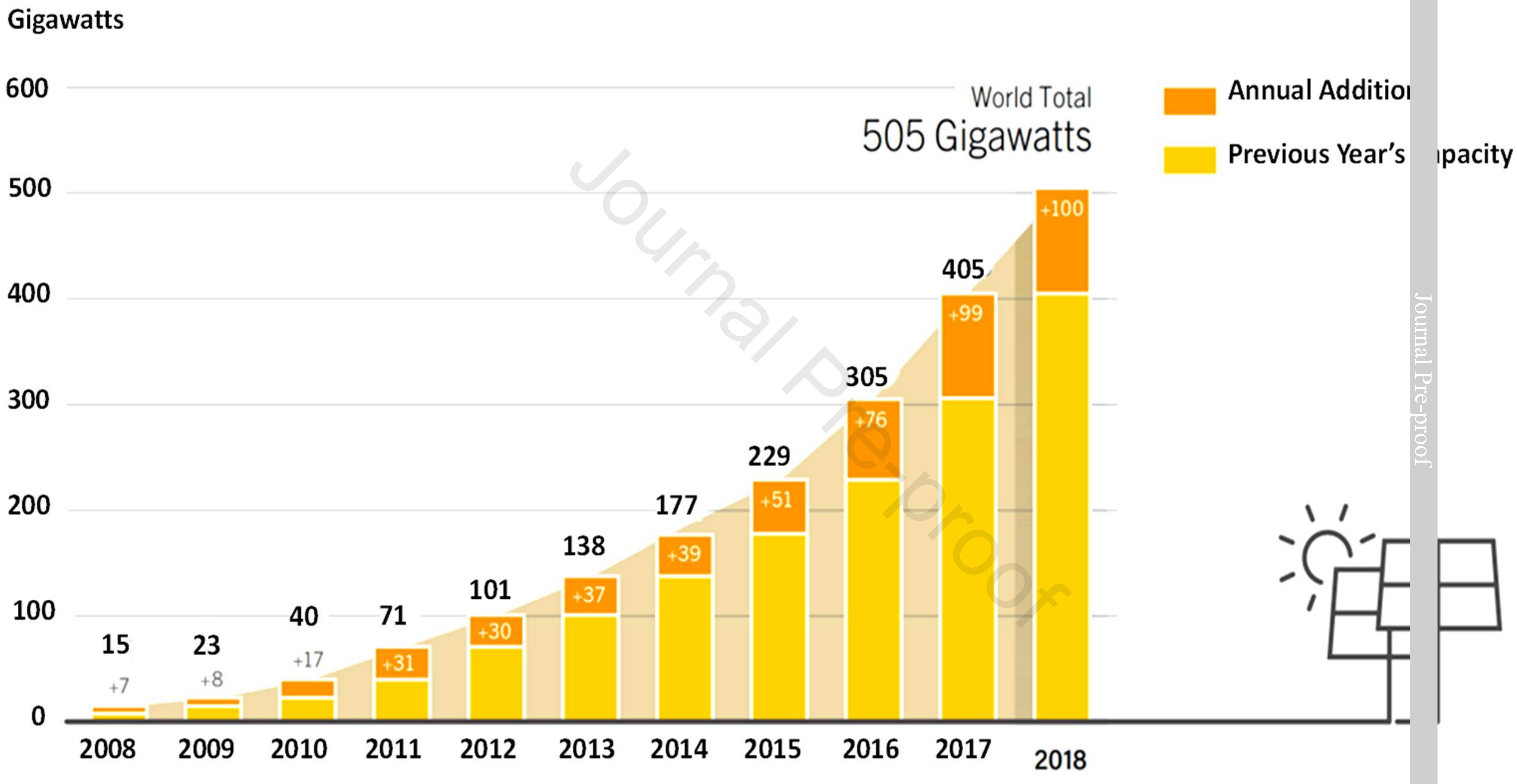
Models/Measurement	E (mm/150 days)	ΔE (%)
Measurement	303.21	0.00
Penman Monteith	309.82	-2.18
Penman Monteith modified	291.24	3.94
Valiantzas	293.99	3.04
Rohwer	268.49	11.45
Mc Guinness Bordne	297.35	1.93
Hargreaves	313.39	-3.36

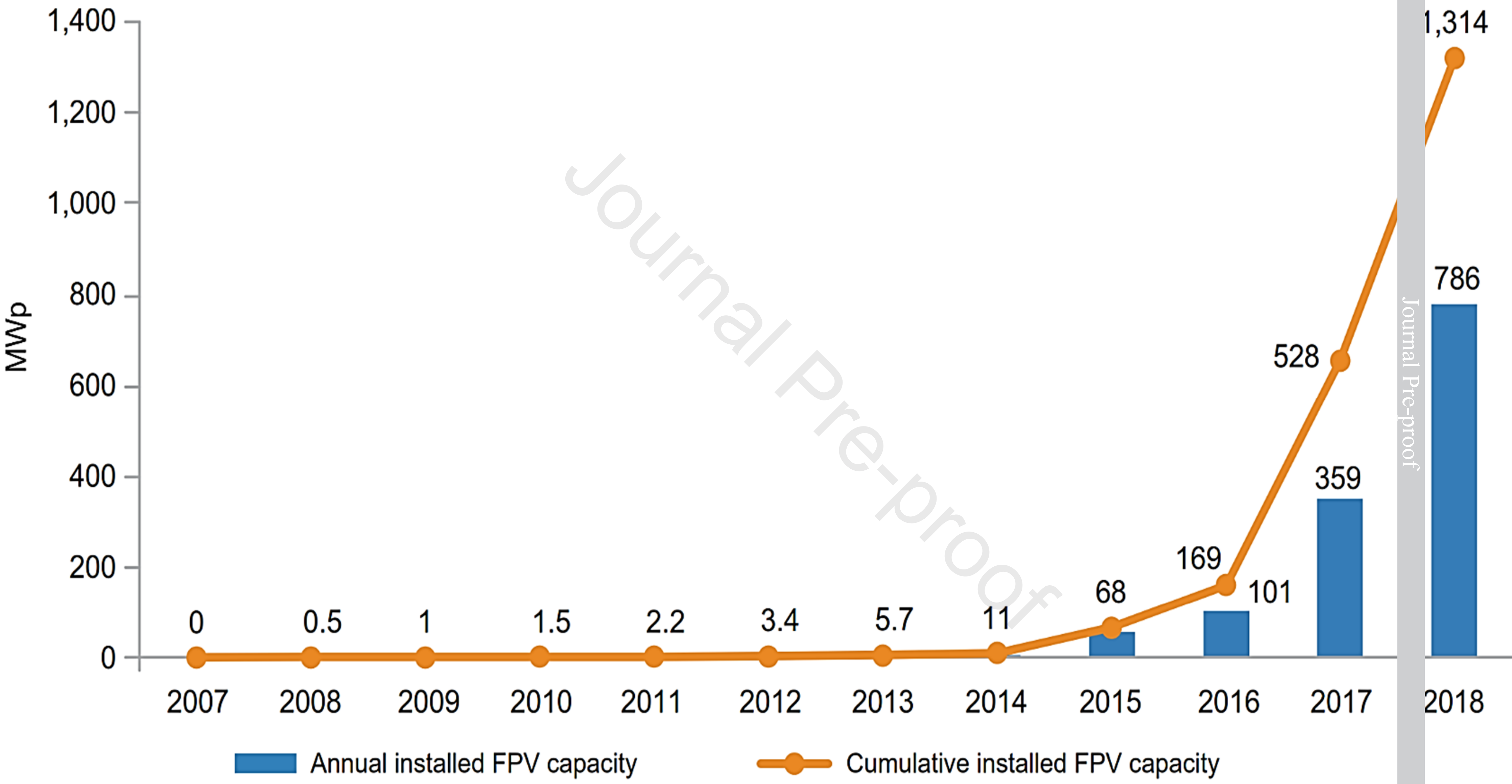
Table 8. Percentage savings in water due to the adaption of FPV over the water body (Bontempo Scavo et al., 2020).

Cover %	Suspended FPV	Floating FPV on Pontoons	Flexible FPV
0	0.0	0.0	0.0
10	6.0	18.0	15.0
30	18.0	49.0	42.0
50	30.0	73.0	64.0
70	42.0	89.0	82.0
100	60.0	100.0	100.0

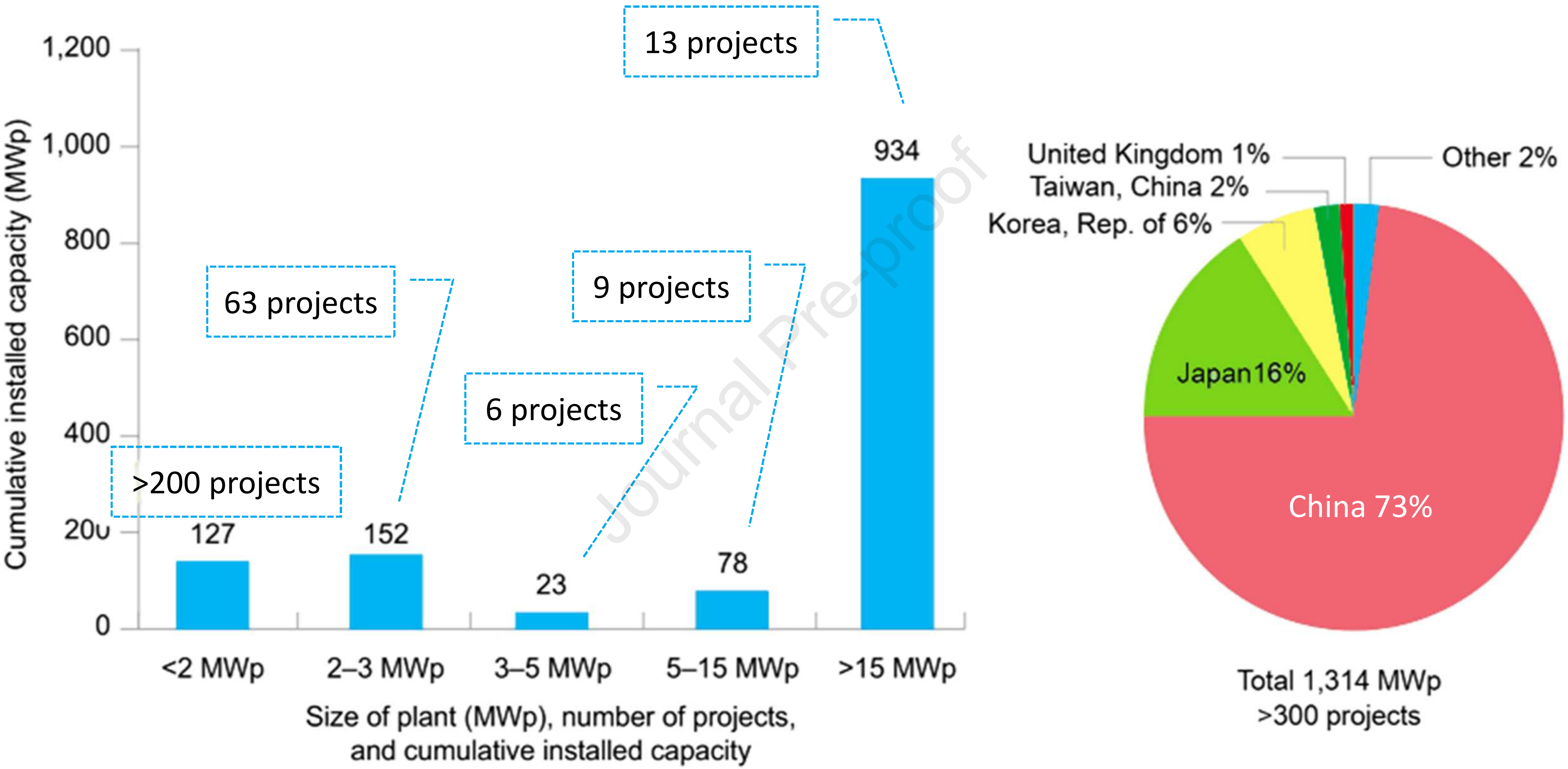
Table 9. LCOE of a 50 MW power plant evaluating different scenarios (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

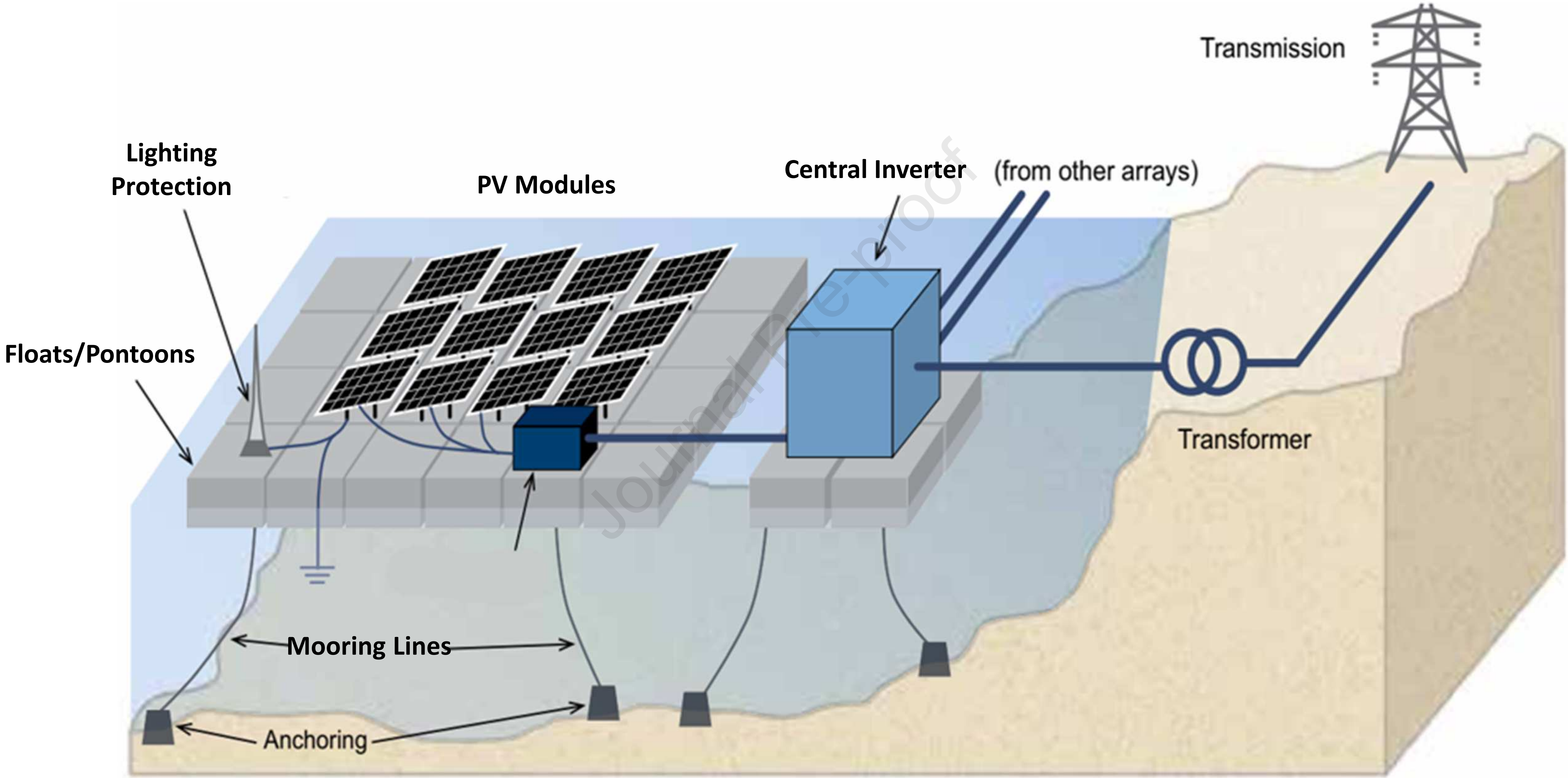
LCOE ($cents/kWh)			Ground-mounted PV (50 MWp)	Floating PV (50 MWp)	
				Conservative (+5% PR)	Optimistic (+10% PR)
Tropical	WACC	6%	6.25	6.77	6.47
		8%	6.85	7.45	7.11 base case
		10%	7.59	8.28	7.91
Arid/desert	WACC	6%	4.52	4.90	4.68
		8%	4.96	5.39	5.15
		10%	5.51	6.01	5.74
Temperate	WACC	6%	6.95	7.53	7.19
		8%	7.64	8.30	7.93
		10%	8.49	9.26	8.85


Gigawatts
600
500
400
300
200
100
0
World Total
505 Gigawatts
Annual Additio
Previous Year's pacity
15
+7
23
+8
40
+17
71
+31
101
+30
138
+37
177
+39
229
+51
305
+76
405
+99
+100
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

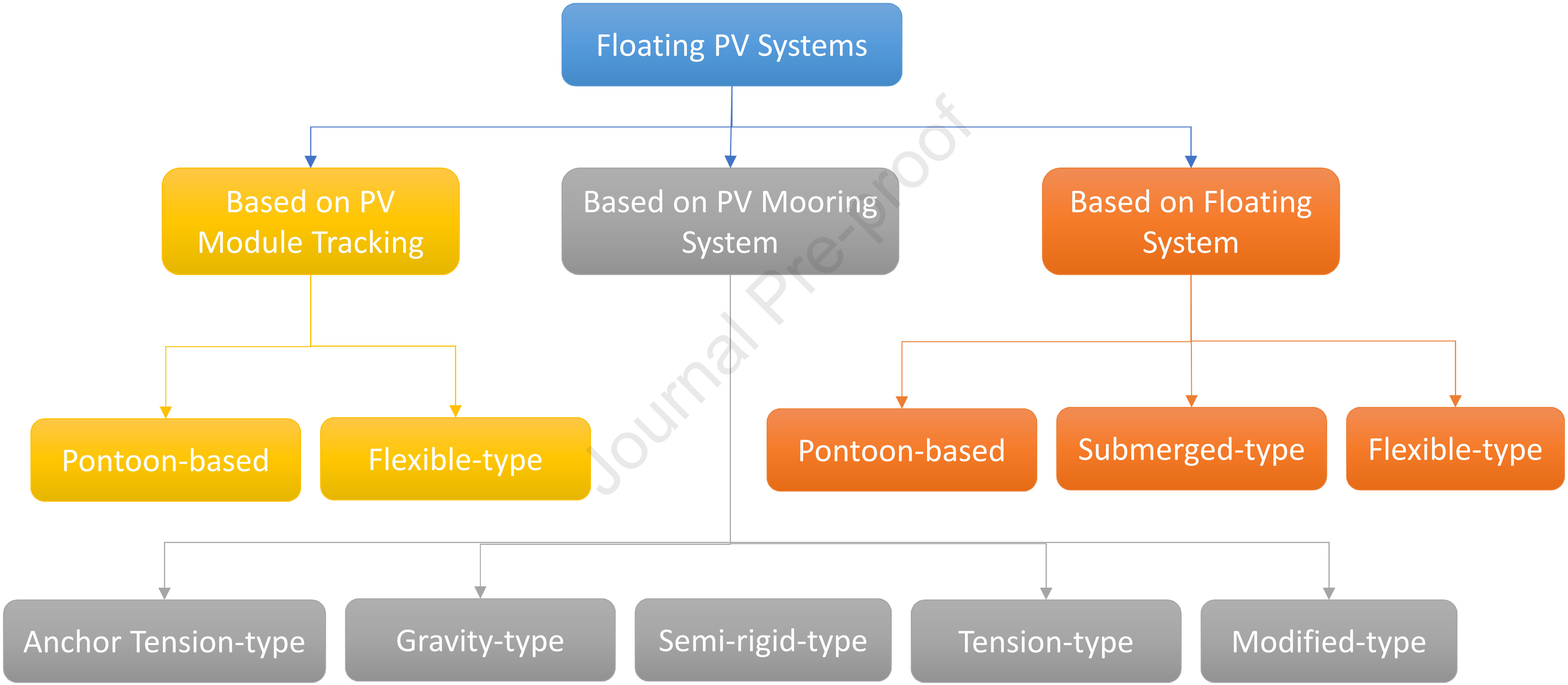


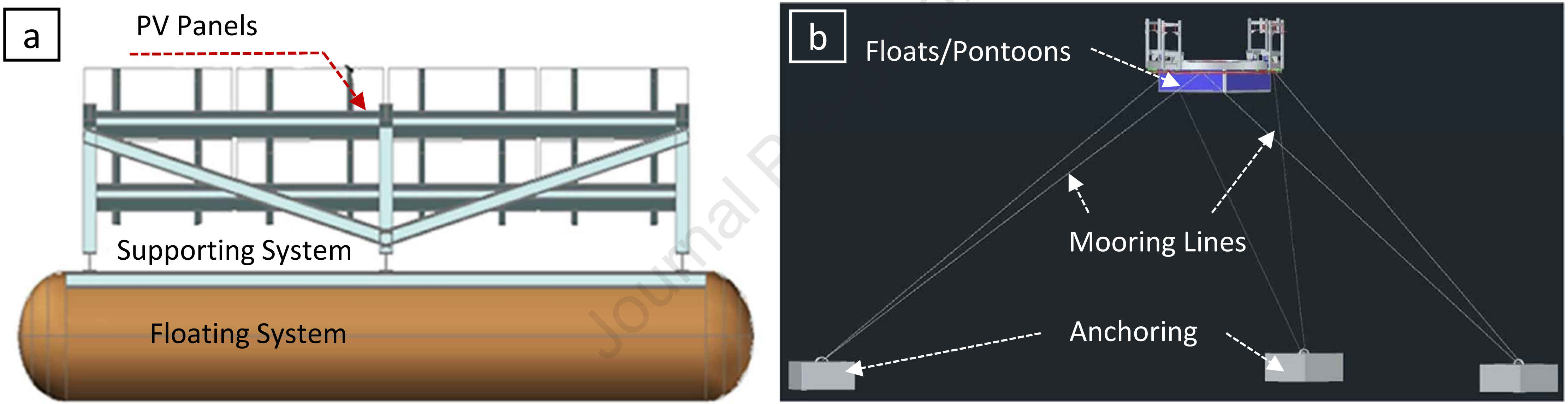
MWp
1,400
1,200
1,000
800
600
400
200
0
0
0.5
1
1.5
2.2
3.4
5.7
11
68
169
101
528
359
1,314
786
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Annual installed FPV capacity
Cumulative installed FPV capacity

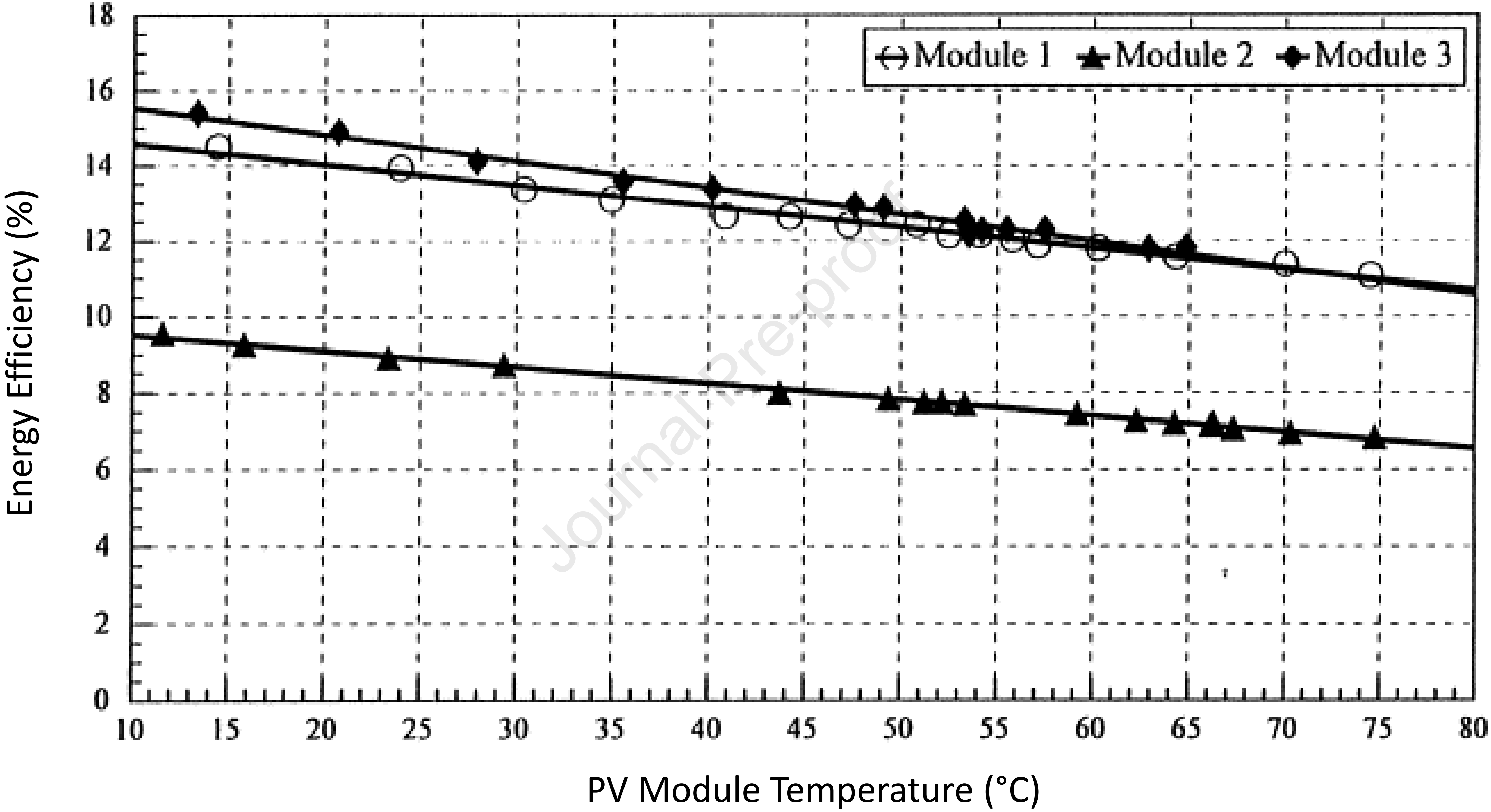

13 projects
63 projects
9 projects
6 projects
>200 projects
1,200
1,000
800
600
400
200
0
Cumulative installed capacity (MWp)
934
127
152
23
78
<2 MWp
2–3 MWp
3–5 MWp
5–15 MWp
>15 MWp
Size of plant (MWp), number of projects,
and cumulative installed capacity
United Kingdom 1%
Taiwan, China 2%
Korea, Rep. of 6%
Other 2%
Japan16%
China 73%
Total 1,314 MWp
>300 projects

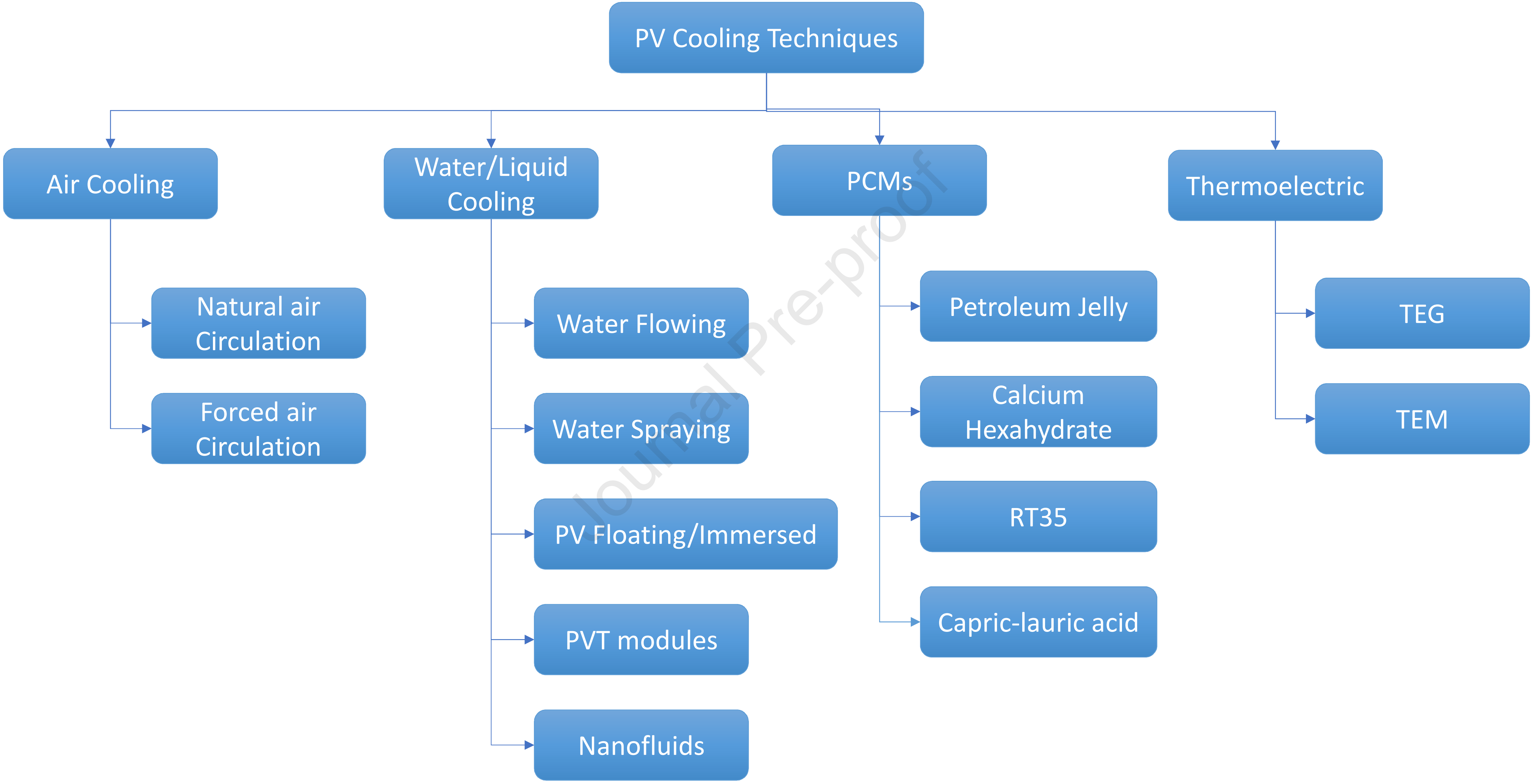


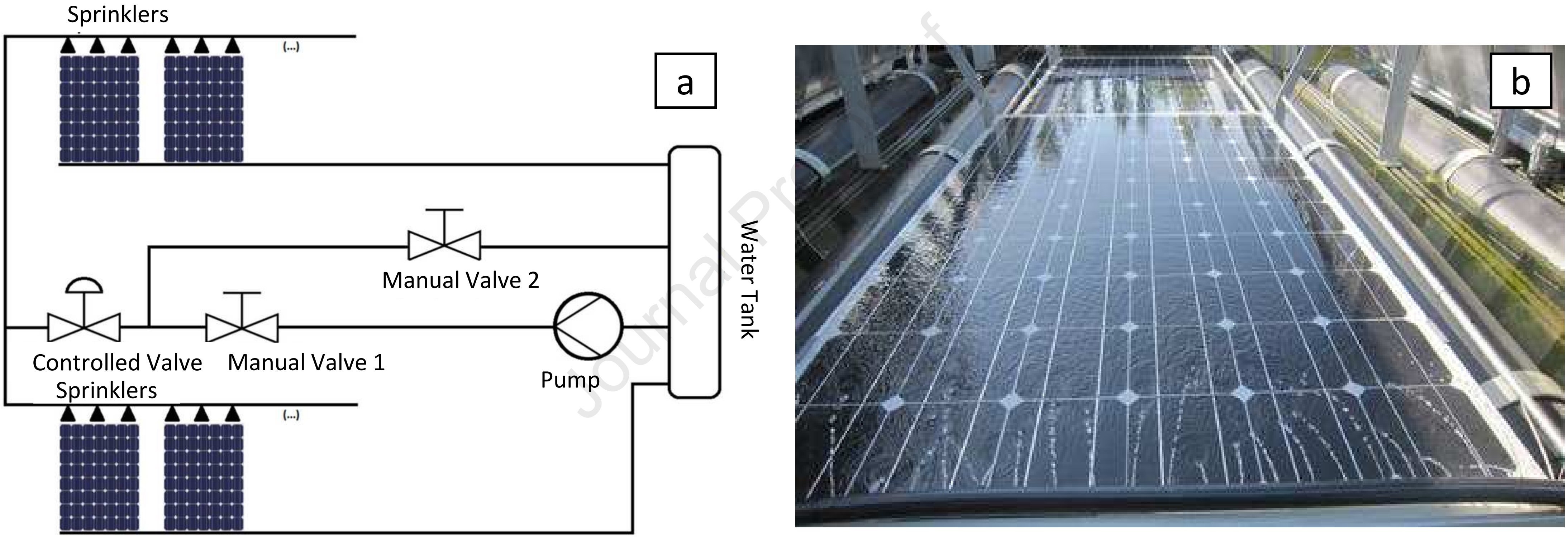
Transmission
Lighting Protection
PV Modules
Central Inverter
(from other arrays)
Floats/Pontoons
Transformer
Mooring Lines
Anchoring

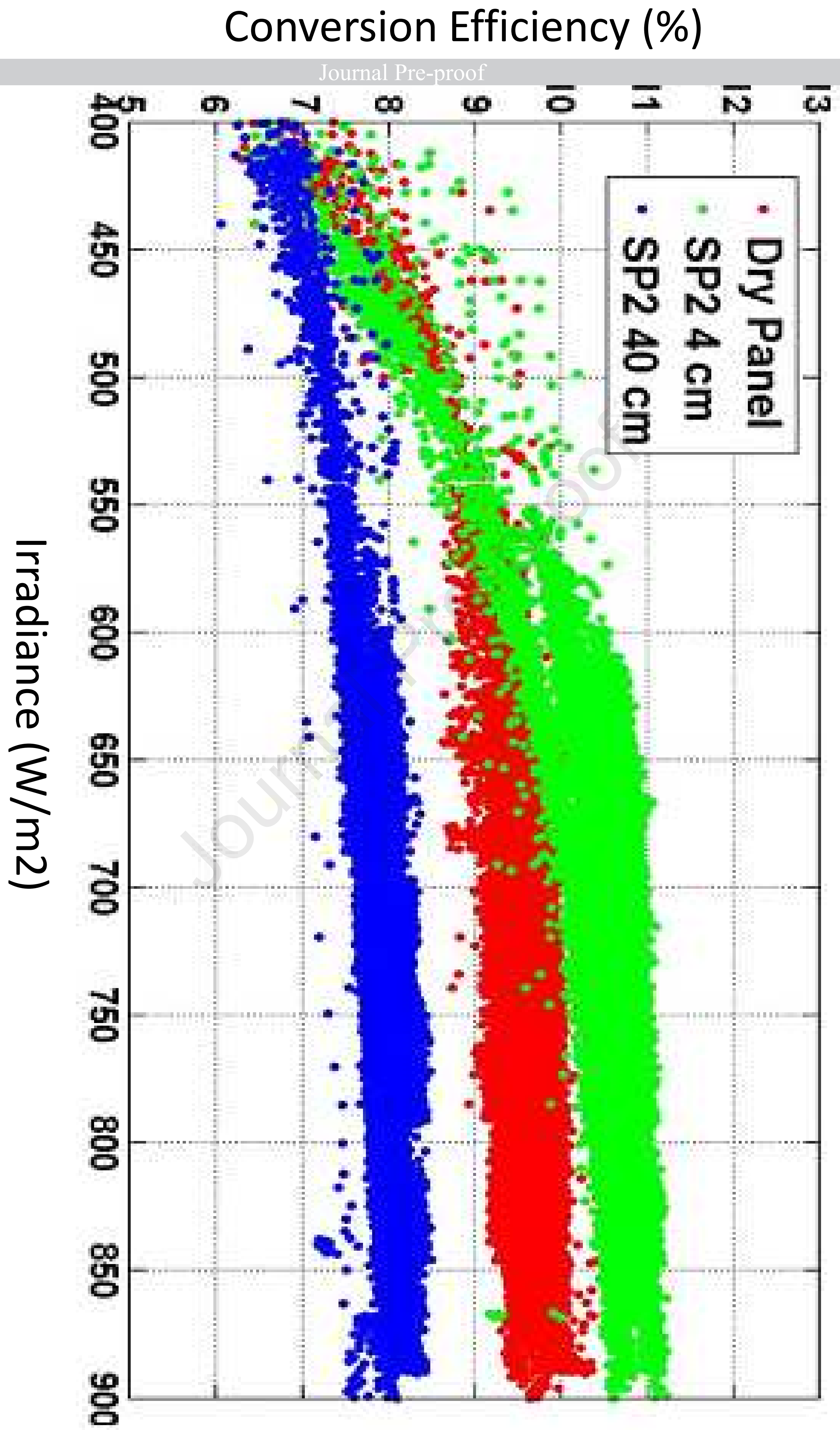

Floating PV Systems
Based on PV Module Tracking
Based on PV Mooring System
Based on Floating System
Pontoon-based
Flexible-type
Pontoon-based
Submerged-type
Flexible-type
Anchor Tension-type
Gravity-type
Semi-rigid-type
Tension-type
Modified-type

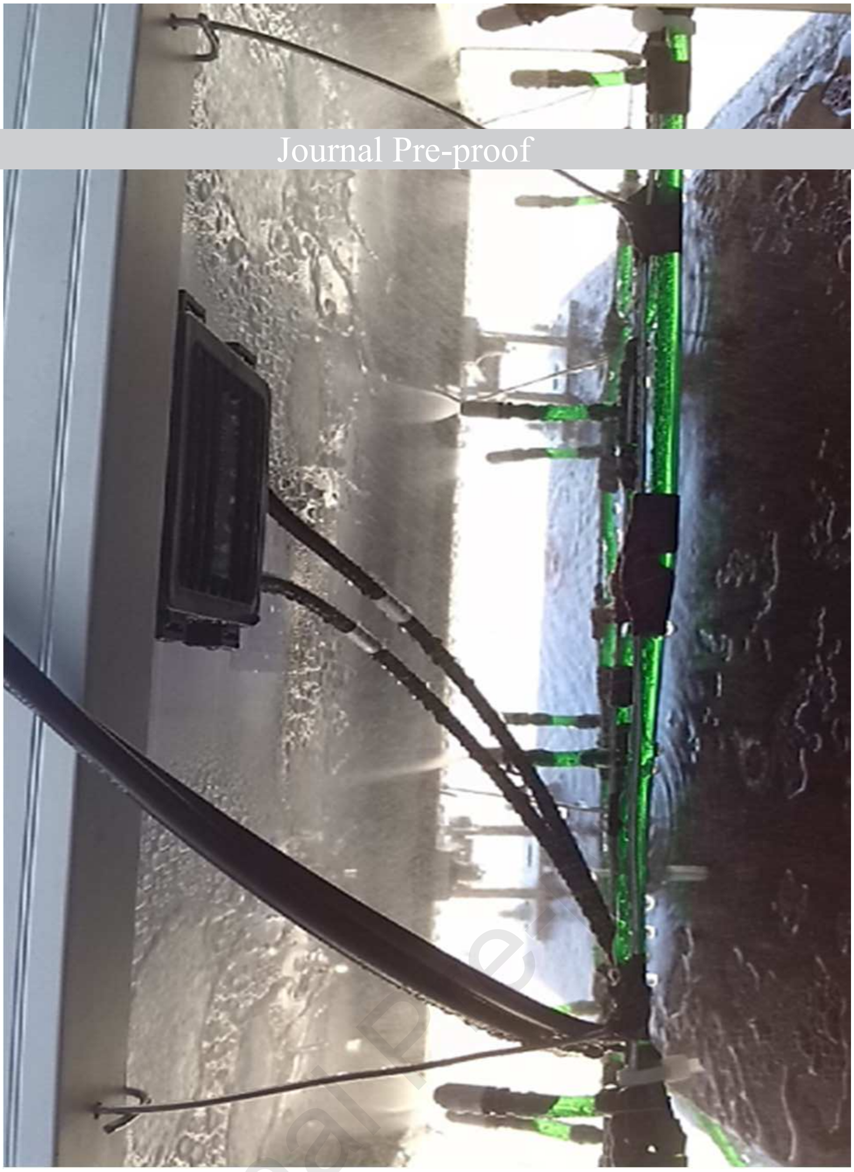

a
PV Panels
Supporting System
Floating System
b
Floats/Pontoons
Mooring Lines
Anchoring

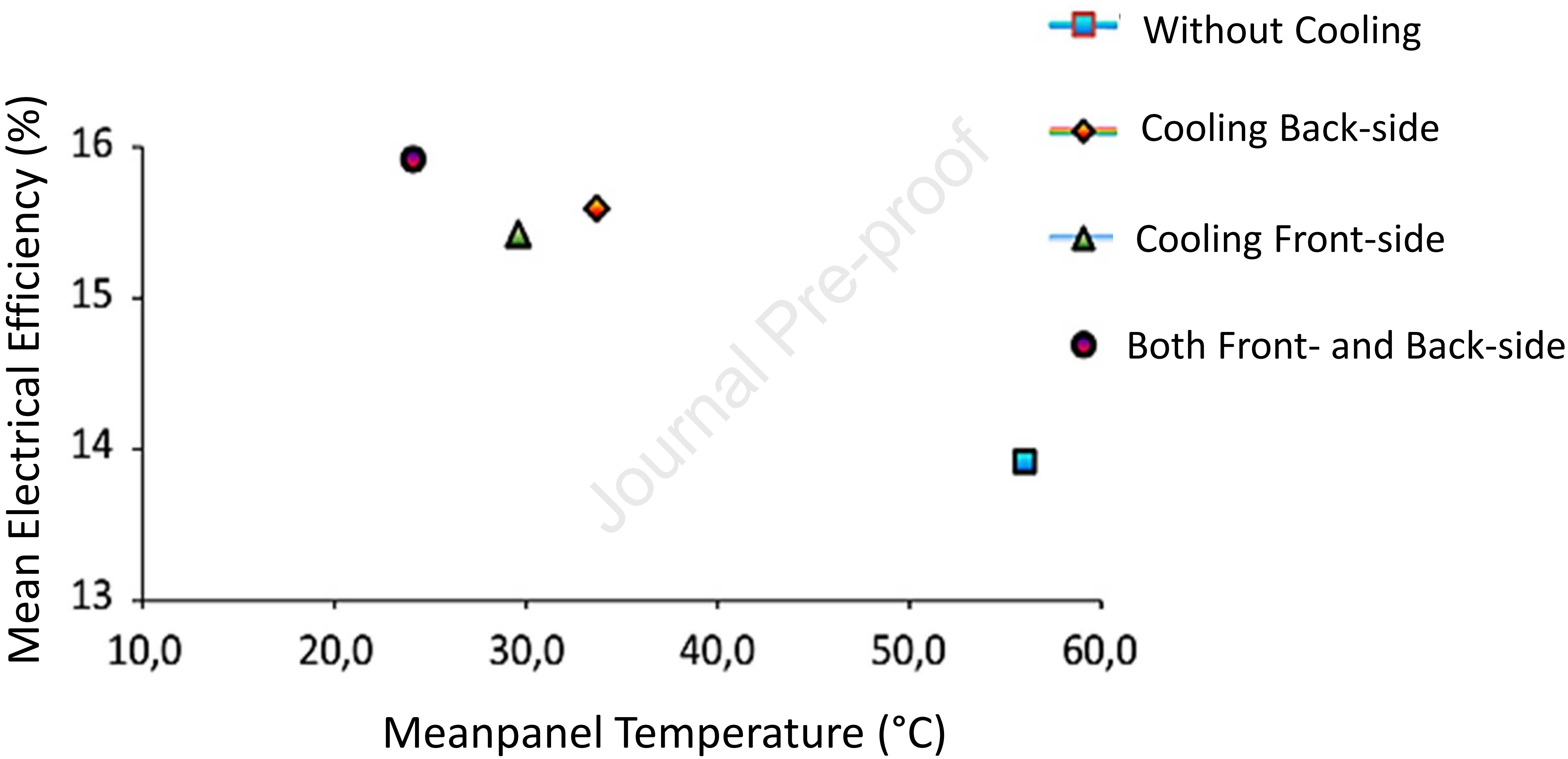

Module 1
Module 2
Module 3
Energy Efficiency (%)
PV Module Temperature (°C)
0
2
4
6
8
10
12
14
16
18
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80


PV Cooling Techniques
Air Cooling
Water/Liquid Cooling
PCMs
Thermoelectric
Natural air Circulation
Forced air Circulation
Water Flowing
Water Spraying
PV Floating/Immersed
PVT modules
Nanofluids
Petroleum Jelly
Calcium Hexahydrate
RT35
Capric-lauric acid
TEG
TEM

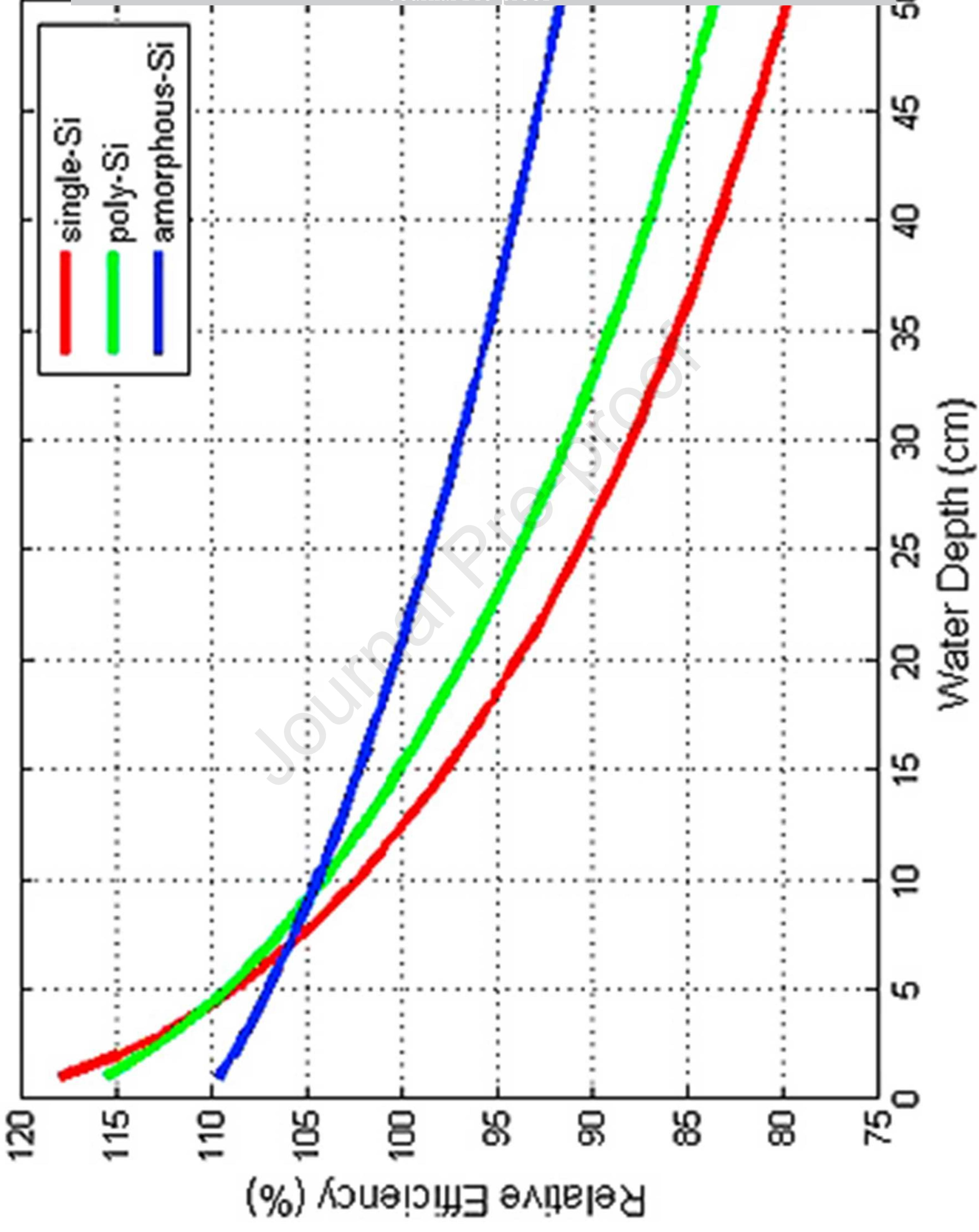

Sprinklers
(...)
a
Water Tank
Manual Valve 2
Controlled Valve
Manual Valve 1
Pump
Sprinklers
(...)
b

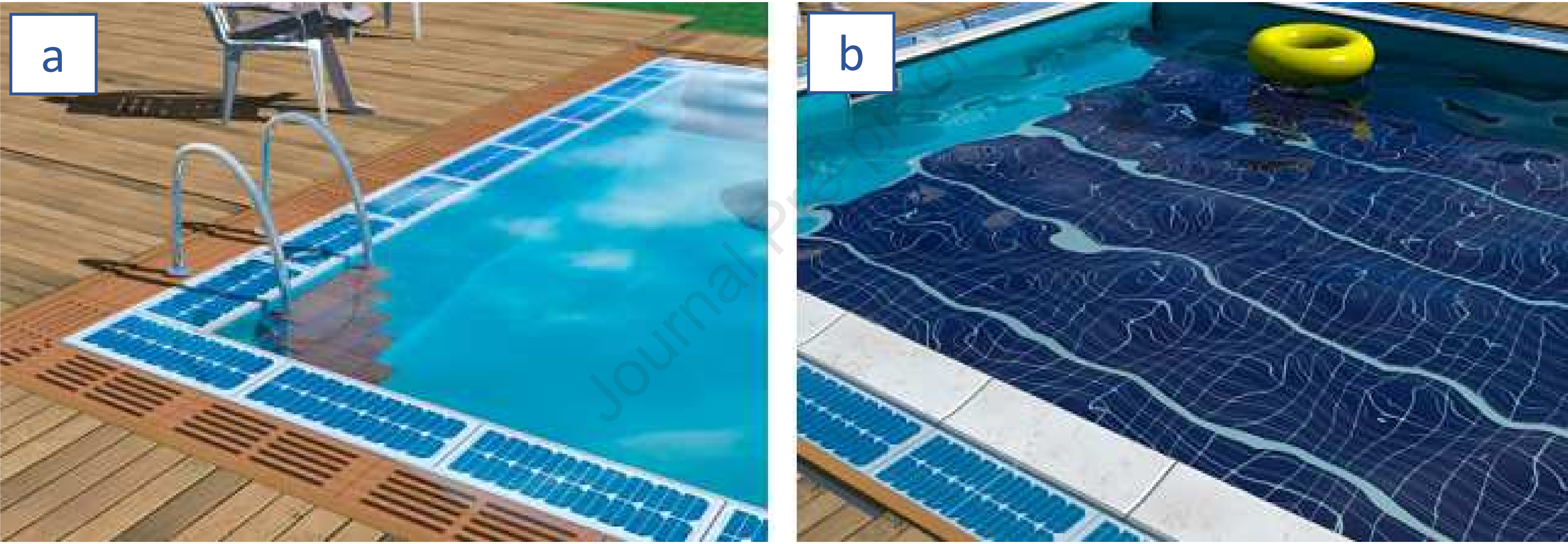

Conversion Efficiency (%)
Irradiance (W/m2)
Dry Panel
SP2 4 cm
SP2 40 cm
400
450
500
550
600
650
700
750
800
850
900
5
6
7
8
9
10
11
12
13

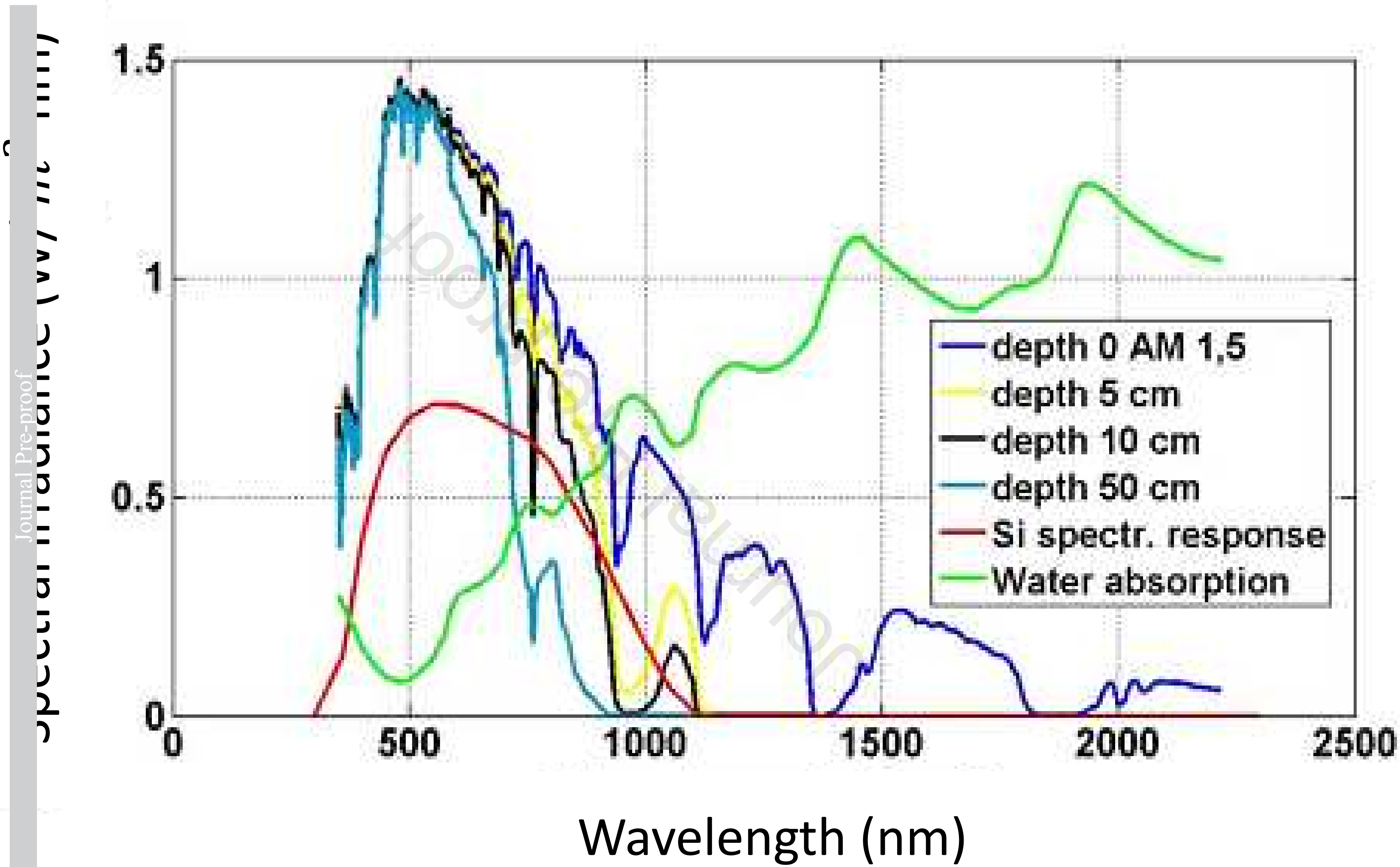


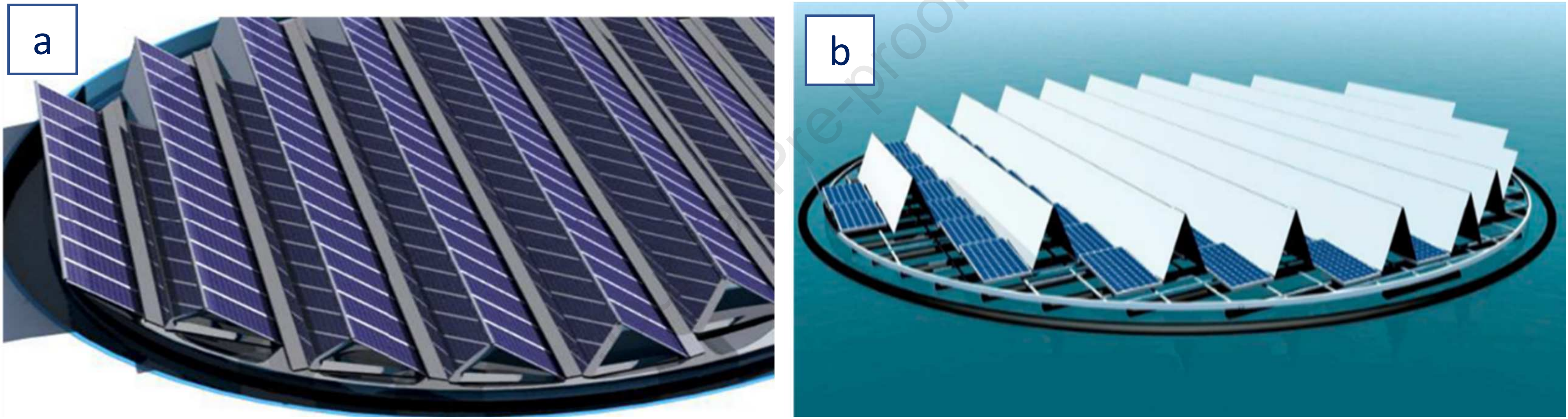


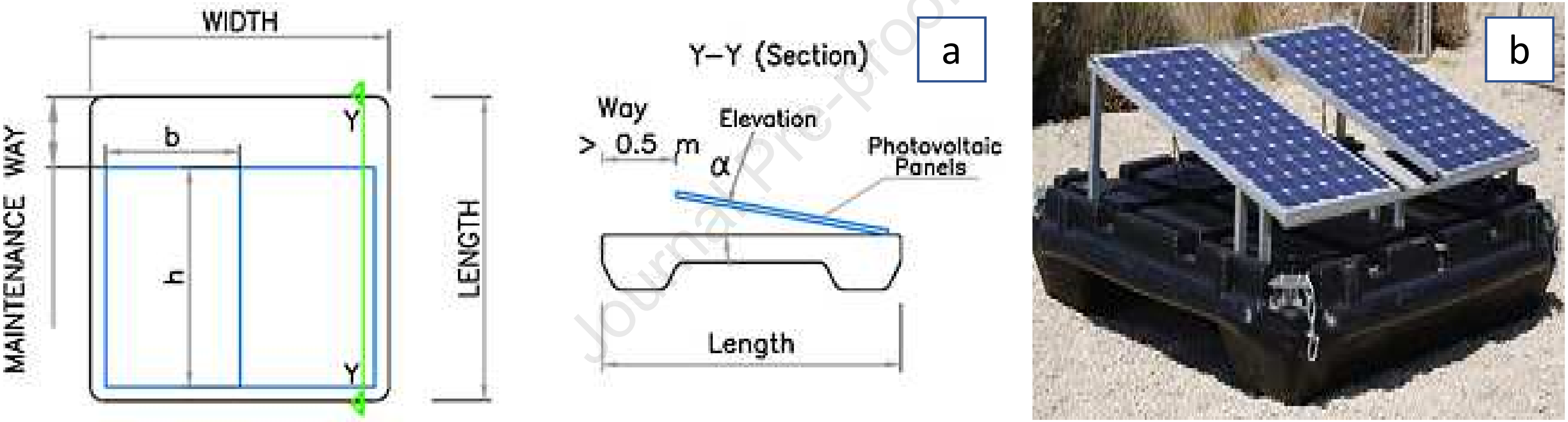
Mean Electrical Efficiency (%)
16
15
14
13
10,0
20,0
30,0
40,0
50,0
60,0
Meanpanel Temperature (°C)
Without Cooling
Cooling Back-side
Cooling Front-side
Both Front- and Back-side

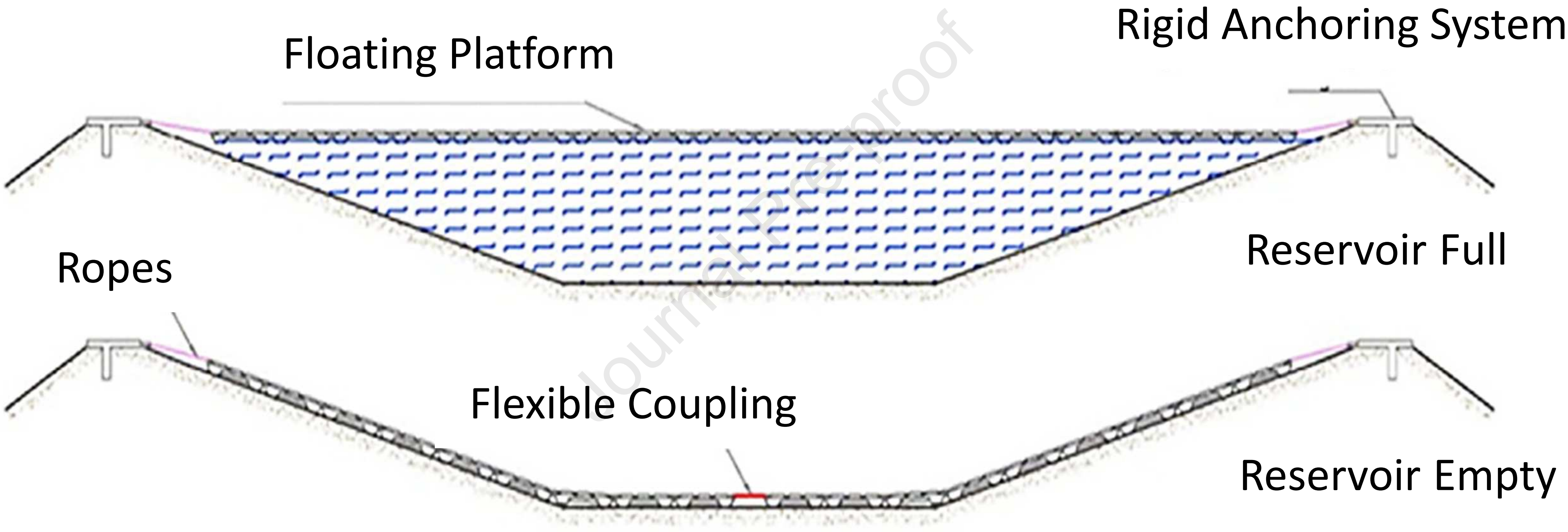

single-Si
poly-Si
amorphous-Si
Relative Efficiency (%)
Water Depth (cm)
120
115
110
105
100
95
90
85
80
75
0
5
10
15
20
25
30
35
40
45
50

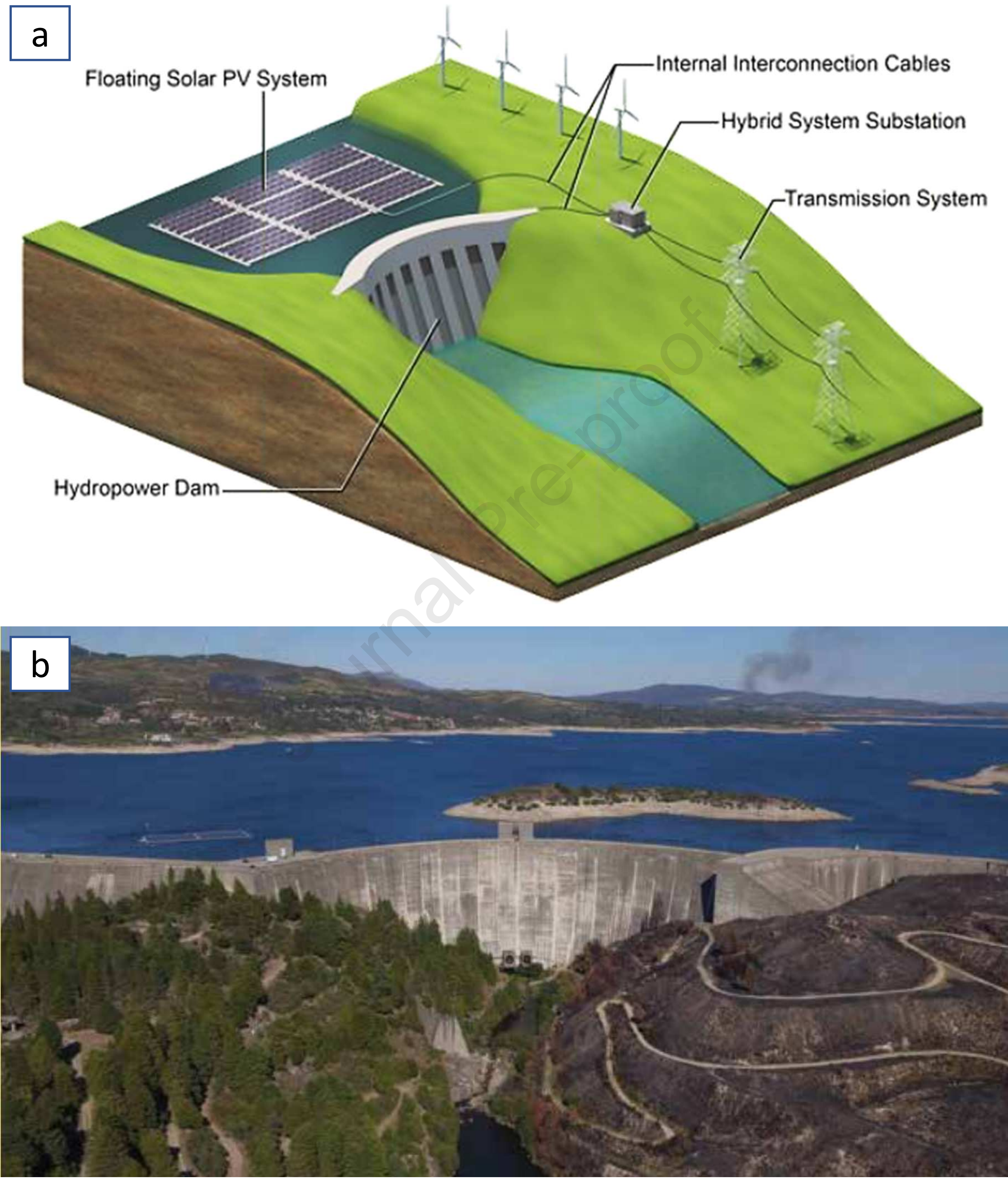

a
b

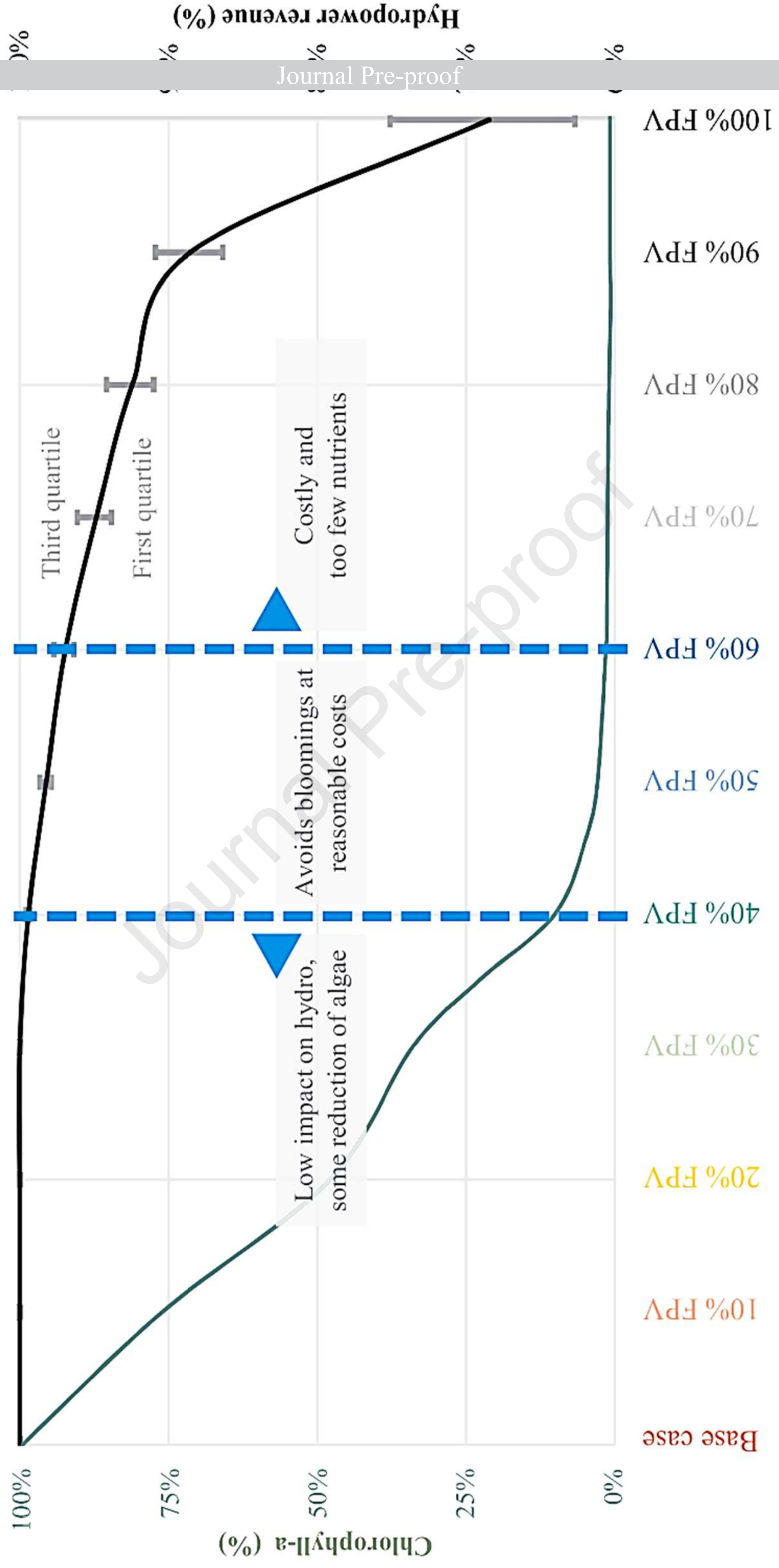

1.5
1
0.5
0
0
500
1000
1500
2000
2500
depth 0 AM 1,5
depth 5 cm
depth 10 cm
depth 50 cm
Si spectr. response
Water absorption
Wavelength (nm)

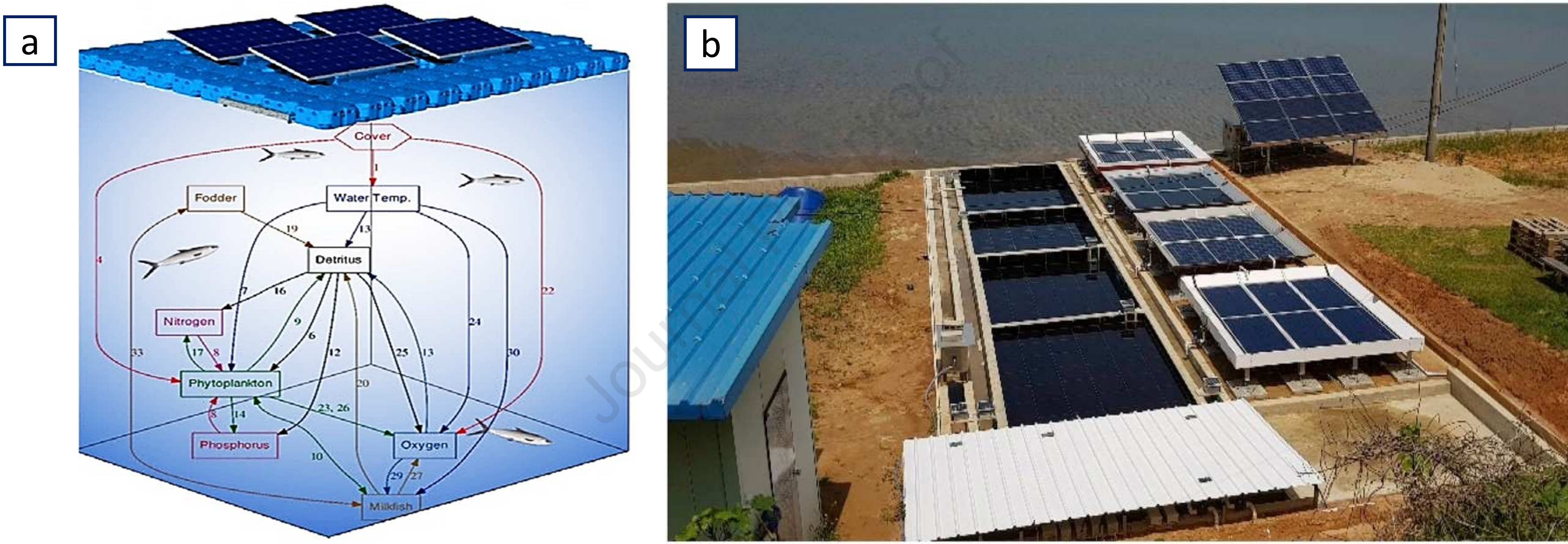

a
b

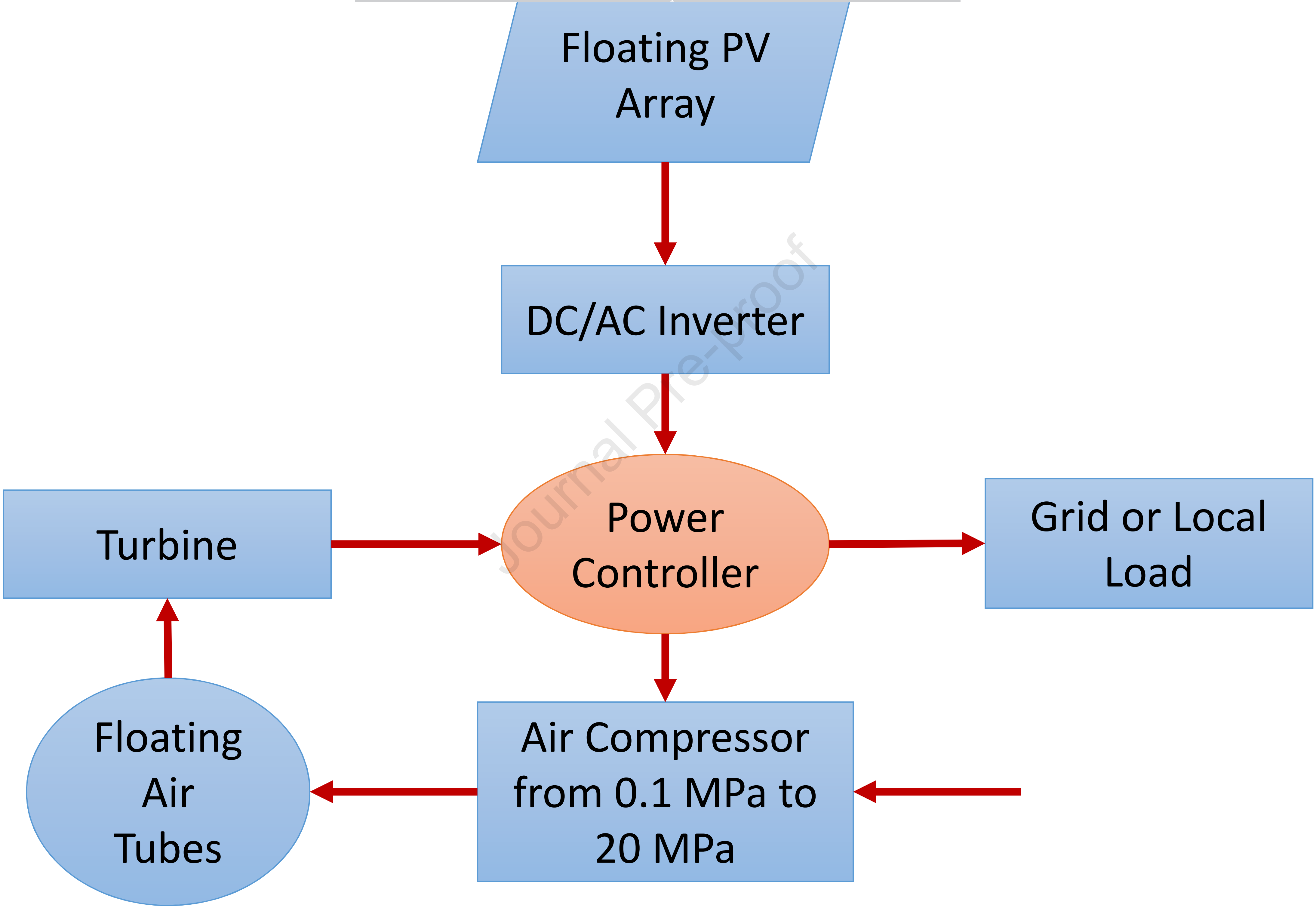

WIDTH
MAINTENANCE WAY
b
h
Y
Y
LENGTH
Y–Y (Section)
a
Way
> 0.5 m
Elevation
α
Photovoltaic Panels
Length
b

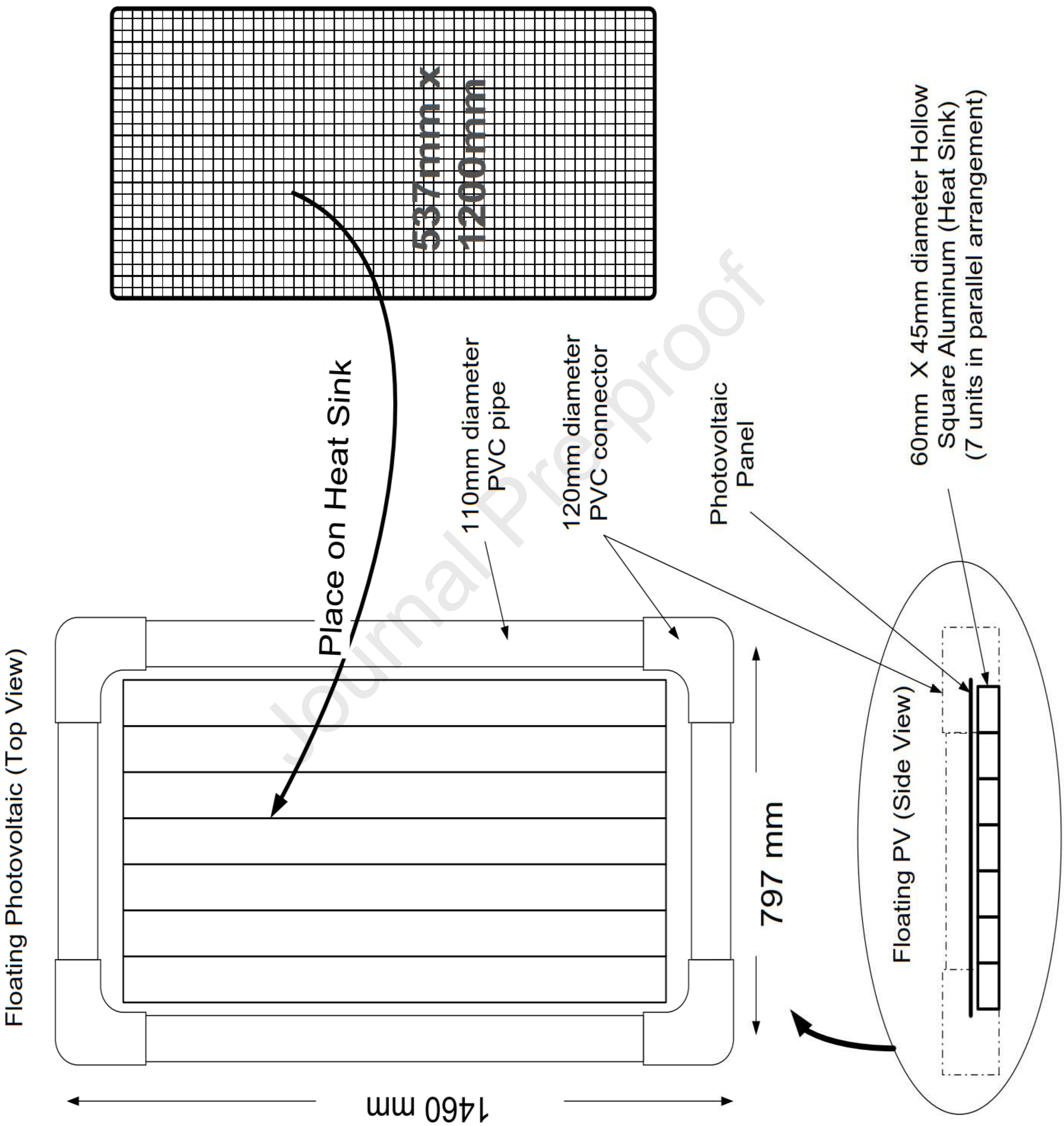

Floating Platform
Rigid Anchoring System
Reservoir Full
Ropes
Flexible Coupling
Reservoir Empty

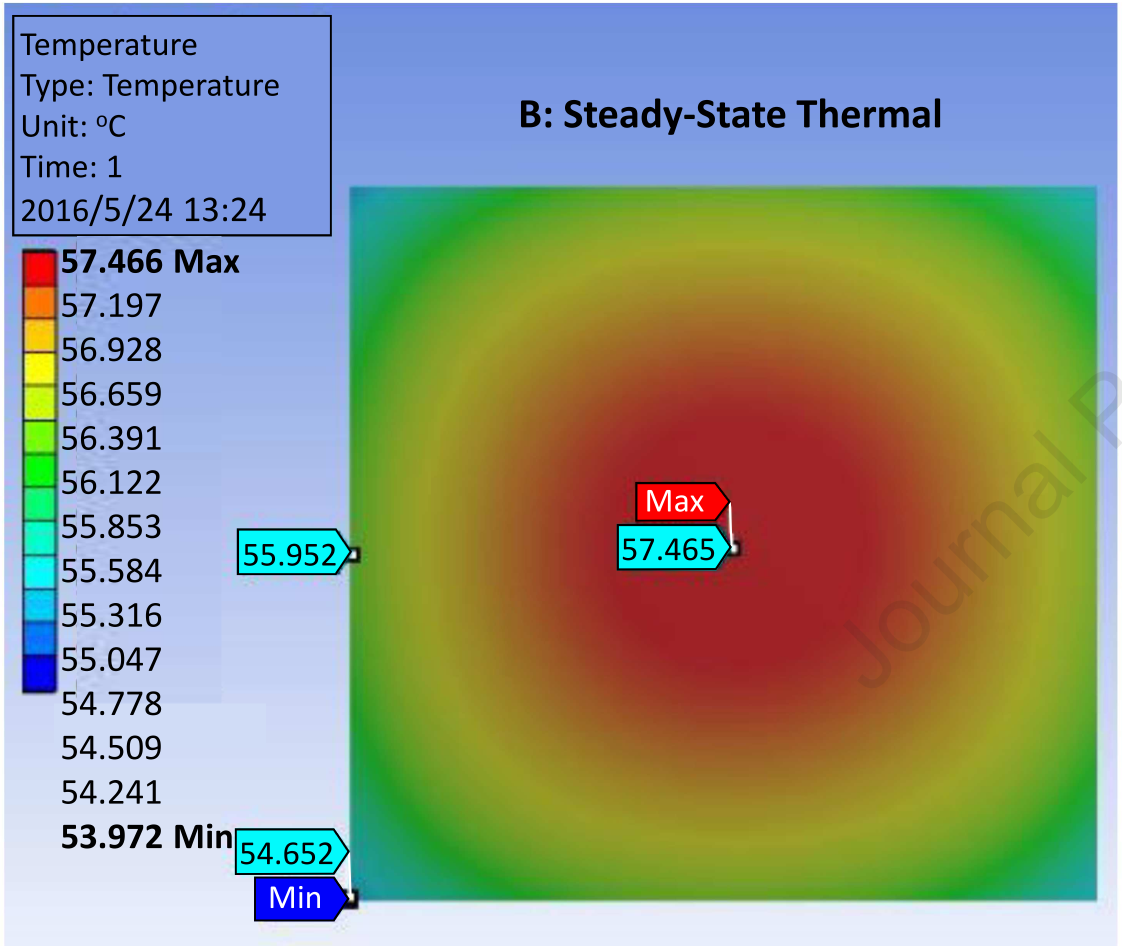

a
Floating Solar PV System
Internal Interconnection Cables
Hybrid System Substation
Transmission System
Hydropower Dam
b


Hydropower revenue (%)
Chlorophyll-a (%)
100%
75%
50%
25%
0%
Base case
10% FPV
20% FPV
30% FPV
40% FPV
50% FPV
60% FPV
70% FPV
80% FPV
90% FPV
100% FPV
Third quartile
First quartile
Costly and too few nutrients
Avoids bloomings at reasonable costs
Low impact on hydro, some reduction of algae

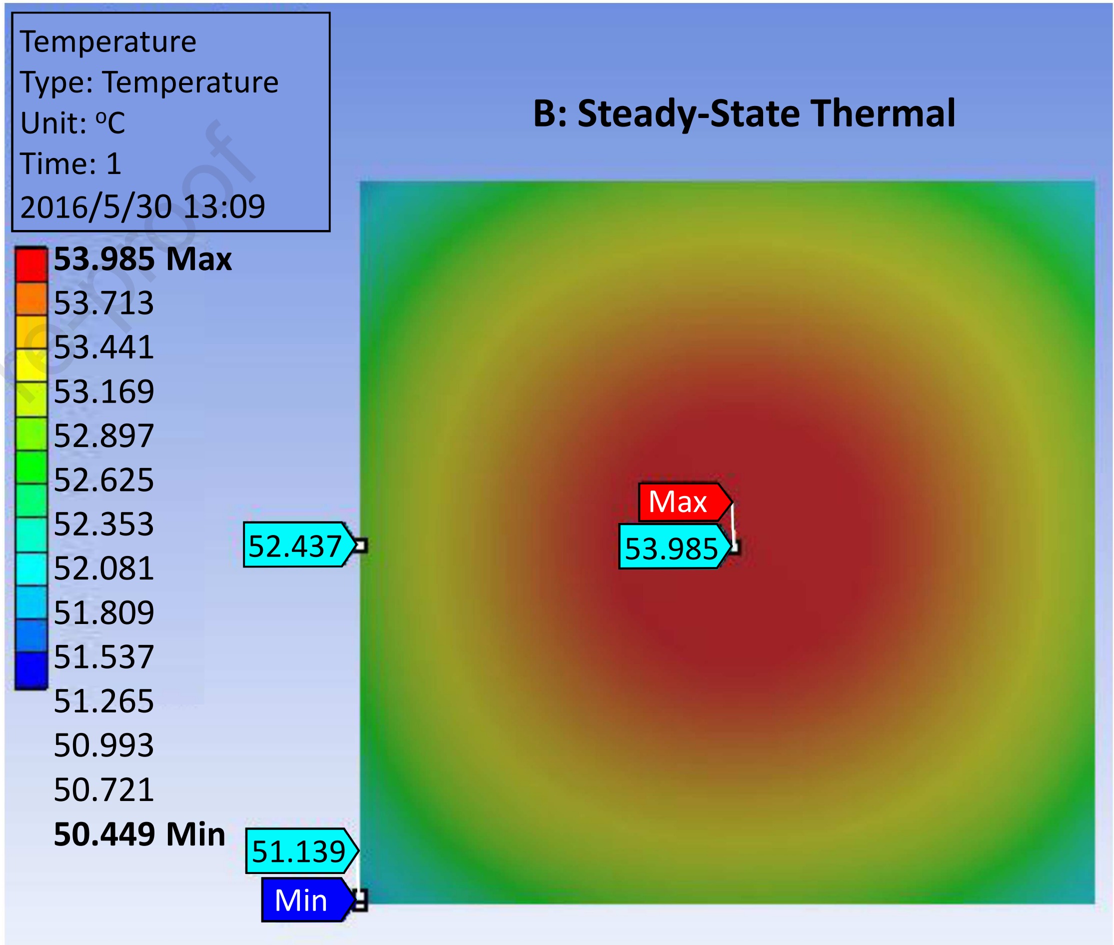

a
Cover
Fodder
Water Temp.
Detritus
Nitrogen
Phytoplankton
Phosphorus
Oxygen
Milkfish
b


Floating PV Array
DC/AC Inverter
Turbine
Power Controller
Grid or Local Load
Floating Air Tubes
Air Compressor from 0.1 MPa to 20 MPa

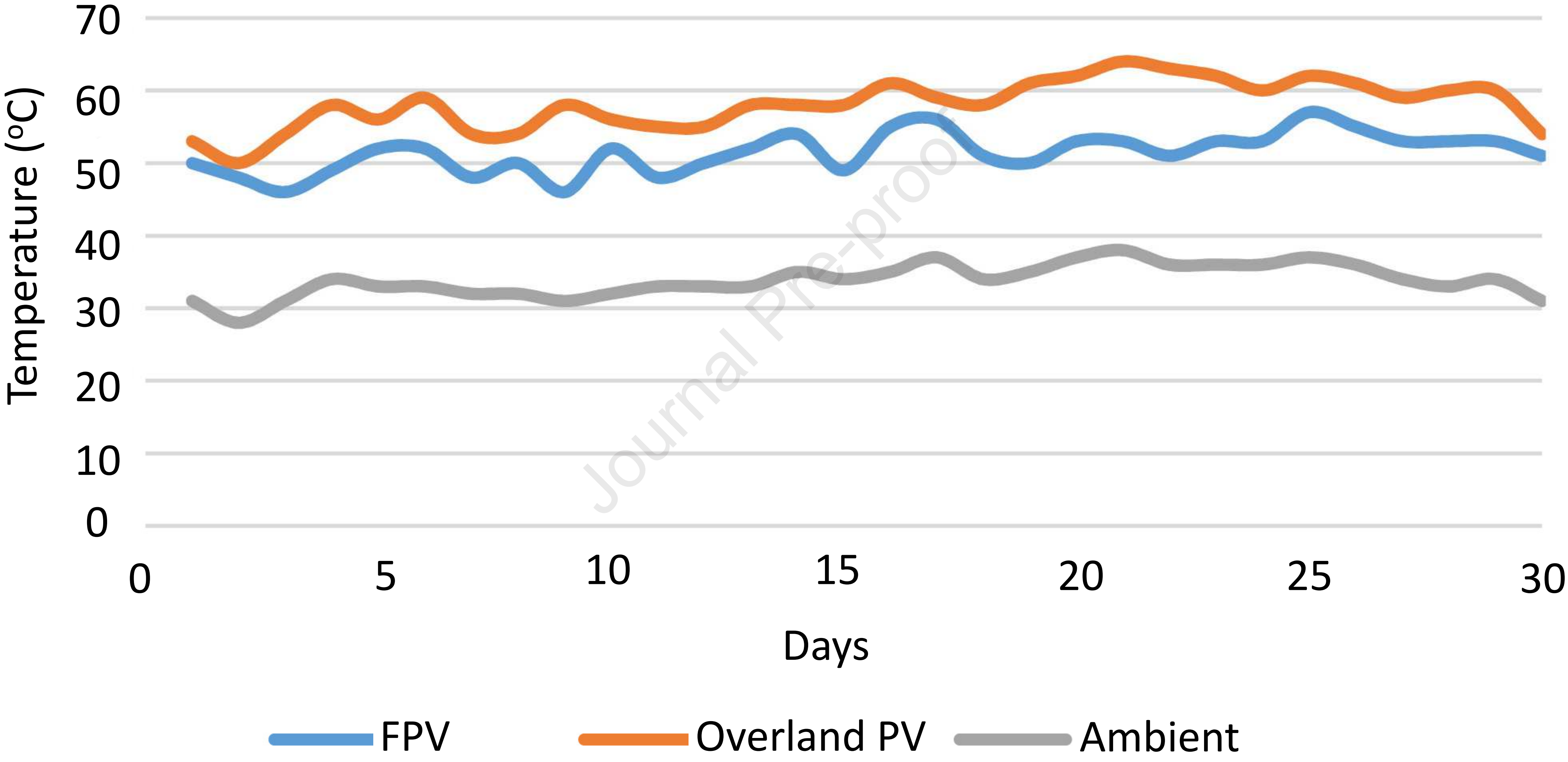

Floating Photovoltaic (Top View)
Place on Heat Sink
537mm x
1200mm
110mm diameter
PVC pipe
120mm diameter
PVC connector
Photovoltaic
Panel
60mm X 45mm diameter Hollow
Square Aluminum (Heat Sink)
(7 units in parallel arrangement)
797 mm
1460 mm
Floating PV (Side View)



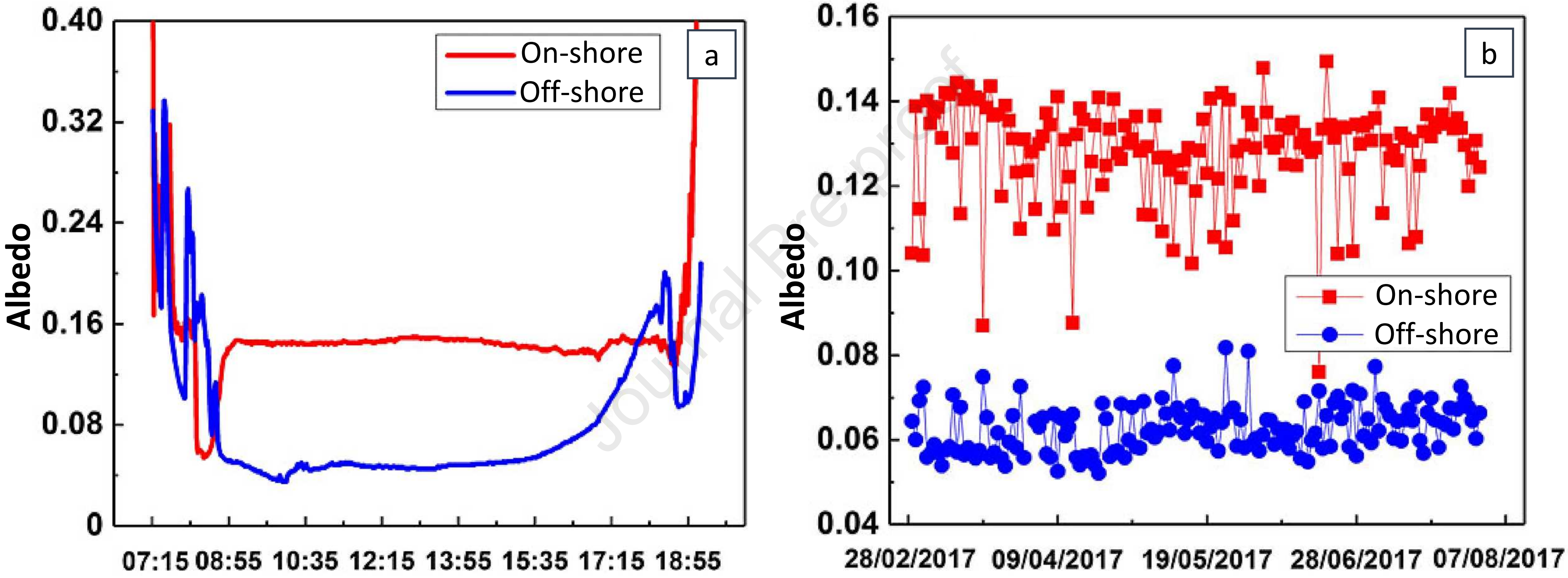
Temperature
Type: Temperature
Unit: ºC
Time: 1
2016/5/24 13:24
B: Steady-State Thermal
57.466 Max
57.197
56.928
56.659
56.391
56.122
55.853
55.584
55.316
55.047
54.778
54.509
54.241
53.972 Min
55.952
54.652
Min
Max
57.465



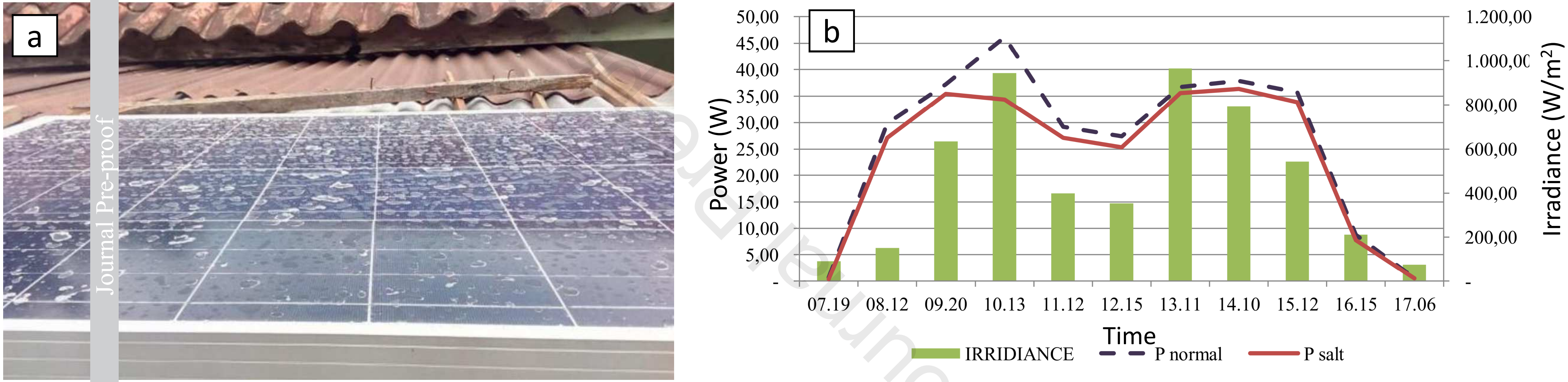
Temperature
Type: Temperature
Unit: ºC
Time: 1
2016/5/30 13:09
B: Steady-State Thermal
53.985 Max
53.713
53.441
53.169
52.897
52.625
52.353
52.081
51.809
51.537
51.265
50.993
50.721
50.449 Min
52.437
51.139
Min
Max
53.985



70
60
50
40
30
20
10
0
Temperature (°C)
0
5
10
15
20
25
30
Days
FPV
Overland PV
Ambient



0.40
0.32
0.24
0.16
0.08
0
Albedo
On-shore
Off-shore
a
07:15
08:55
10:35
12:15
13:55
15:35
17:15
18:55
0.16
0.14
0.12
0.10
0.08
0.06
0.04
Albedo
b
On-shore
Off-shore
28/02/2017
09/04/2017
19/05/2017
28/06/2017
07/08/2017


a
b
50,00
45,00
40,00
35,00
30,00
25,00
20,00
15,00
10,00
5,00
-
Power (W)
1.200,00
1.000,00
800,00
600,00
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Irradiance (W/m2)
07.19
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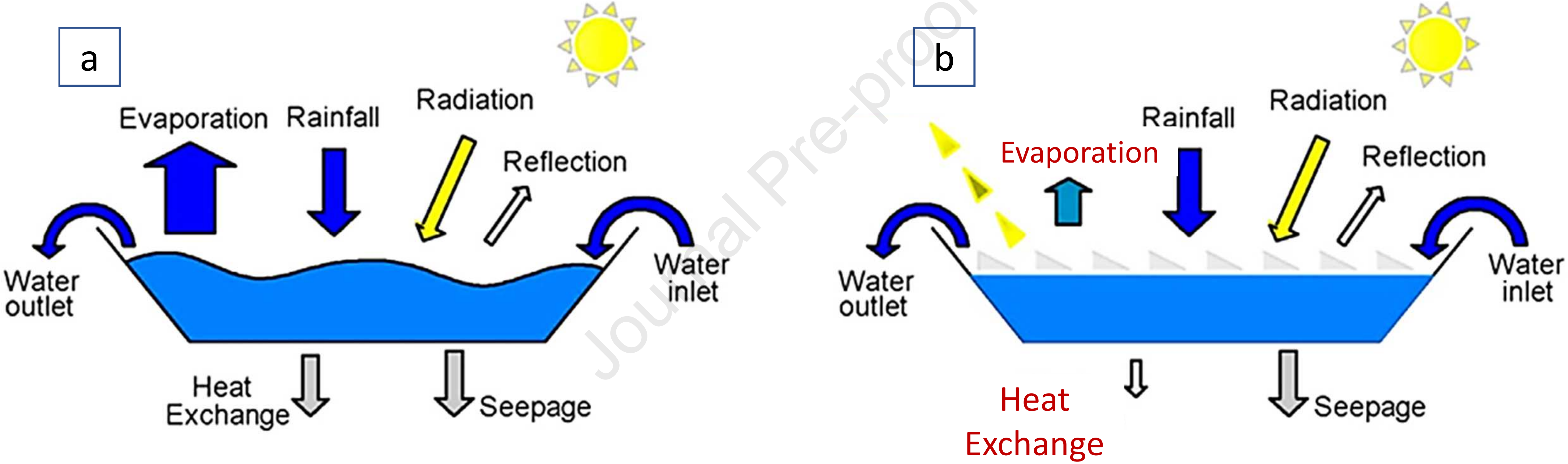
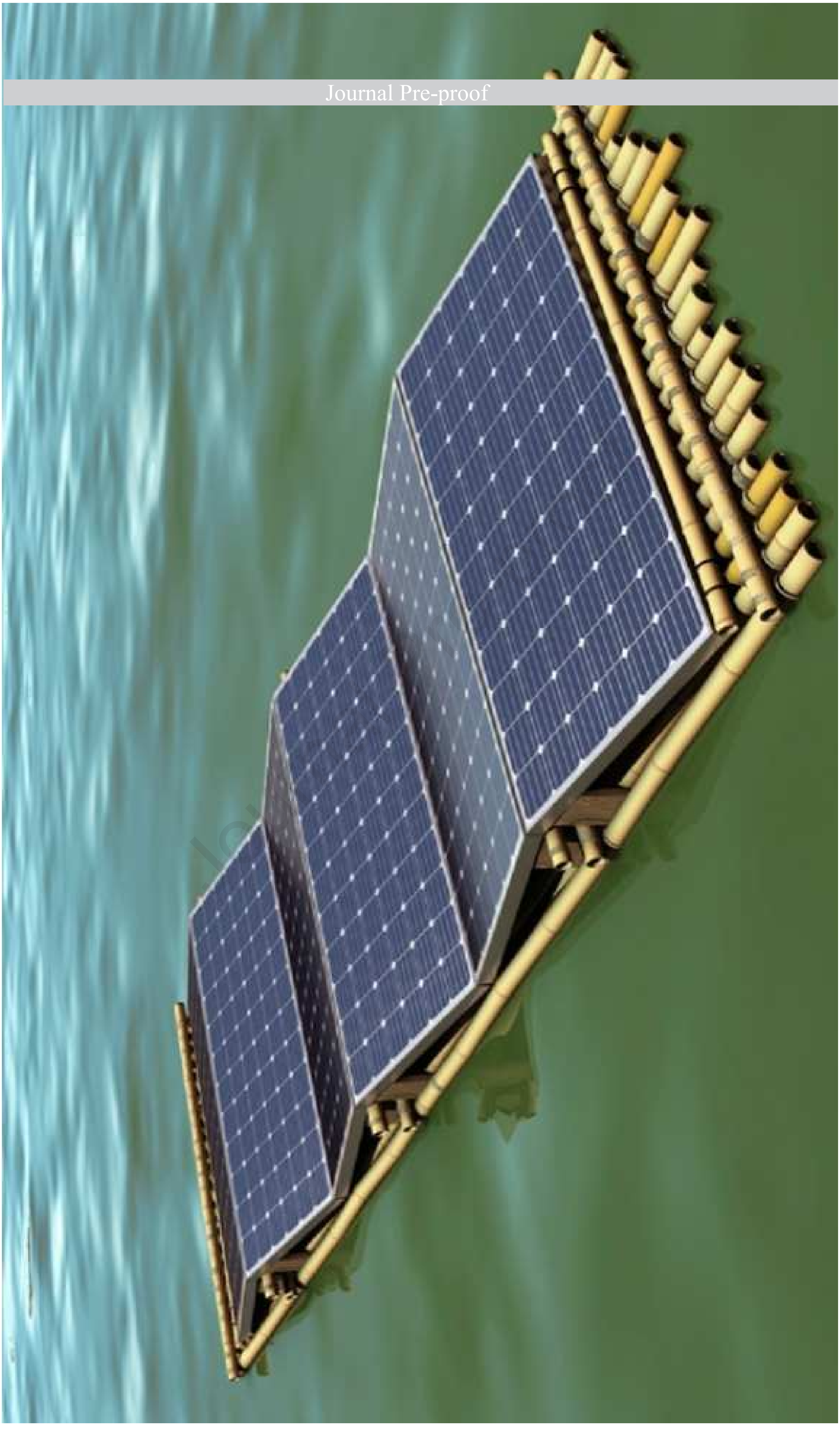
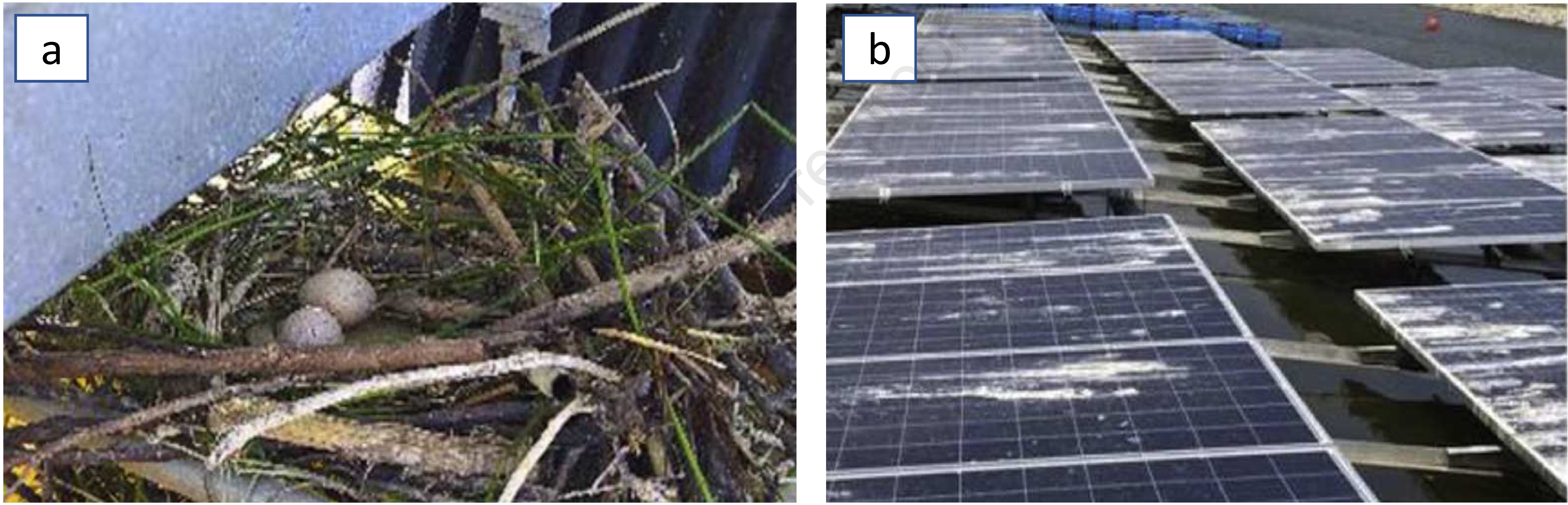

a
Evaporation
Rainfall
Radiation
Reflection
Water outlet
Water inlet
Heat Exchange
Seepage
b
Evaporation
Rainfall
Radiation
Reflection
Water outlet
Water inlet
Heat Exchange
Seepage


a
10 MW CANAL TOP SOLA
b

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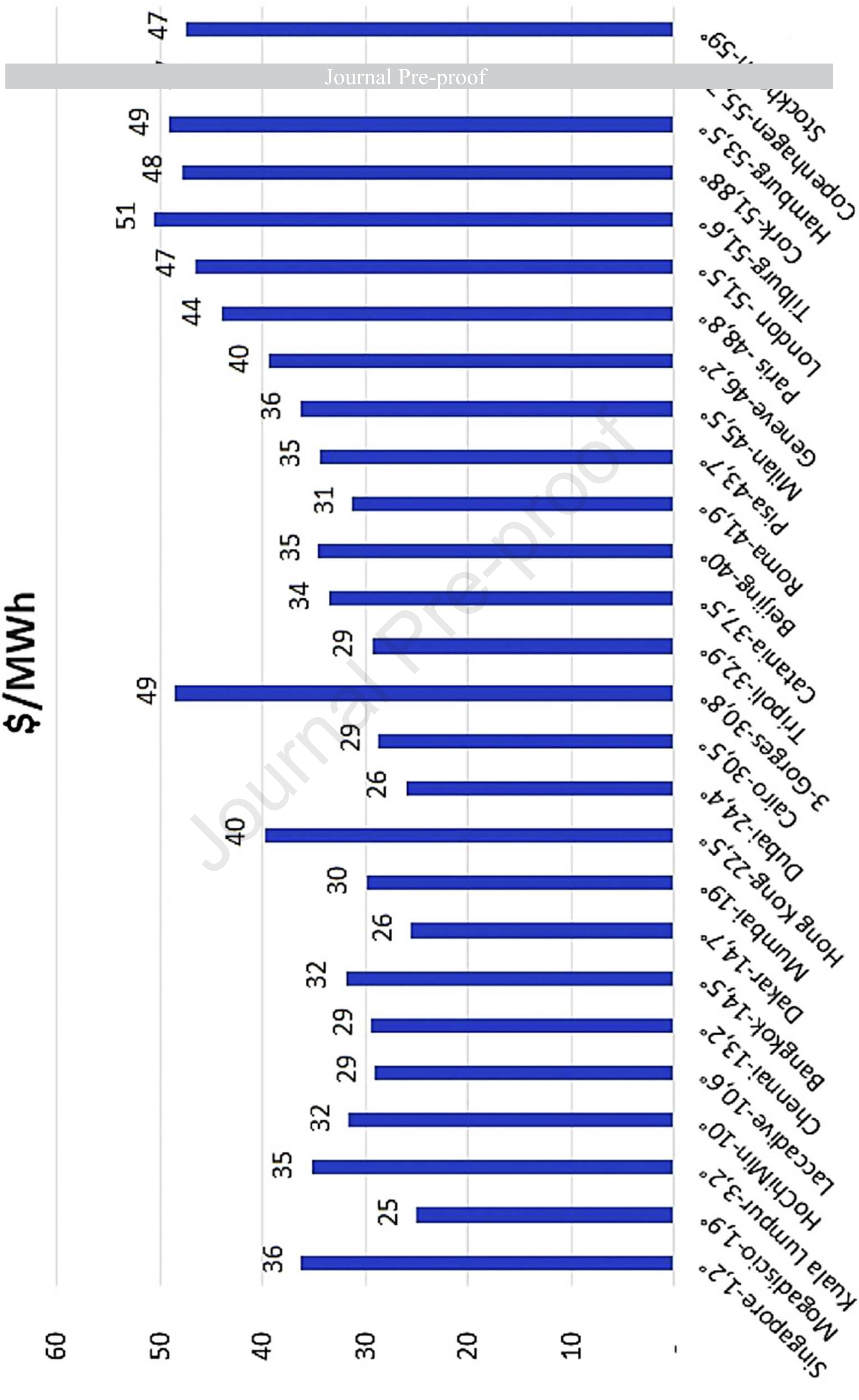

$/MWh
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40
30
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Singapore-1,2°
Mogadiscio-1,9°
Kuala Lumpur-3,2°
HoChiMin-10°
Laccadive-10,6°
Chennai-13,2°
Bangkok-14,5°
Dakar-14,7°
Mumbai-19°
Hong Kong-22,5°
Dubai-24,4°
Cairo-30,5°
3-Gorges-30,8°
Tripoli-32,9°
Catania-37,5°
Beijing-40°
Roma-41,9°
Pisa-43,7°
Milan-45,5°
Geneve-46,2°
Paris-48,8°
London-51,5°
Tilburg-51,6°
Cork-51,88°
Hamburg-53,5°
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Words Count: 16,584

Recent Technical Advancements, Economics and Environmental Impacts of Floating Photovoltaic Solar Energy Conversion Systems

Abstract

Floating Photovoltaic (FPV) is an emerging technology that has experienced significant growth in the renewable energy market since 2016. It is estimated that technical improvements along with governmental initiatives will promote the growth rate of this technology over 31% in 2024. This study comprehensively reviews the floating photovoltaic (FPV) solar energy conversion technology by deep investigating the technical advancements and presenting a deliberate discussion on the comparison between floating and ground-mounted photovoltaic (PV) systems. Also, the economics and environmental impacts of FPV plants are presented by introducing the main challenges and prospects. The FPV plants can be conventionally installed on water bodies/dam reservoirs or be implemented as multipurpose systems to produce simultaneous food and power. Installing FPV modules over water reservoirs can prevent evaporation but penetration of solar radiation still remains an issue that can be eliminated by employing bifacial PV modules. The salt deposition in off-shore plants and algae-bloom growth are other important issues that can degrade modules over time and adversely affect the aquatic ecosystem. The capital expenditure (CAPEX) for FPV systems is about 25% higher than ground-mounted plants, mainly due to the existence of floats, moorings, and anchors. It has been stated that the capacity increase of FPV plants (ranges from 52 kW to 2 MW) can intensely decrease the levelized cost of energy (LCOE) up to 85%. It is estimated that FPV technology can become more affordable in the future by further research, developments, and progress in both technology and materials.

Keywords: Floating PV modules, Water cooling, Multipurpose generation, Environmental impacts, Energy cost.

1 Introduction

Energy transition emerged to revolutionize the energy sector has facilitated a significant shift from carbon-based to renewable power stations in forthcoming decades. During this pathway, carbon reduction is the main goal to be achieved through substantial transitions in technology, market, policies, and research in the energy field. According to the World Energy Outlook released by the International Energy Agency

(IEA) (IEA, 2019), the only way to decrease the current emission trend is not only the downturn in coal-fired power plants but also the provision of new sustainable infrastructures. In this perspective, it is expected that solar photovoltaic (PV) and wind technologies will lead the renewable energy market to overtake fossil-based sources by mid-2020s and meet more than half of the world's electricity requirements by 2040 (Gorjian et al., 2020c, 2019; Gorjian and Ghobadian, 2015a). The annual PV industry shows stable growth in recent years, surpassing 100 GW (including on/off-grid capacity), and reaching a total capacity of 505 GW compared to the global total of 15 GW only a decade ago. With the exponential growth in the mixed market, PV stations totaled 505 GW electricity generation in 2018, led by China, the US, Japan, Germany, India, and the rest of the world (Gorjian and Ghobadian, 2015b; Masson et al., 2018). However, the low energy efficiency of PV modules (around 14%), which roots in a 66.7 Wp/m^2 land unit conversion, reduces the investment incentives and makes the deployment rate slowdown (Rosa-Clot and Tina, 2020a). Therefore, the advent of floating photovoltaic (FPV) technology can be a turning point to give an impetus for more substantial penetration of PV technology, avoiding land occupancy issues. In recent years, FPVs have gained substantial traction not only for their immense potential of the installation on bodies of water, but also for bringing some co-benefits such as higher efficiency compared to PV systems (Liu et al., 2017), significant financial outcomes (Durković and Đurišić, 2017), developments to the aquatic environment (Pringle et al., 2017), and enhancements to irrigation systems (Santafé et al., 2014). The utilization of FPV technology for power generation was initiated in 2007 by installing a 20 kWp power plant (Kurokawa et al., 2008) and reached 1.3 GWp in 2018 (*Where Sun Meets Water : Floating Solar Market Report - Executive Summary*, 2018) referring to the high availability of water surfaces with an estimated technical power potential[1] of 1,526, 1,832, and 2,176 GWp for tropical, temperate, and cold zones respectively (Rosa-Clot and Tina, 2018a). Solar electricity generation has opened a new market with tremendous potential and the highest cost reduction from an average of 0.10 USD/kWh in 2018 to nearly 0.04 USD/kWh in 2030. This 58% drop will dominate other significant cutbacks in peer renewables such as 55% in wind off-shore, 35% in concentrating solar power (CSP), and 25% in wind on-shore for the same period (Gorjian and Ebadi, 2020; Gorjian and Shukla,

[1] When only 1% of these areas is used.

2020). This can be attributed to a significant market shift towards more advanced and efficient PV cells, including PERC (passivated emitter rear contact) technology, manufacturing optimization, and higher adoption of bifacial cells and modules (Gorjian et al., 2019; International Renewable Energy Agency (IRENA), 2020). However, in 2018, the solar power growth rate became slower after China and undermined the market by 16% with an installed capacity of 44.4 GW compared to 52.8 GW in 2017. The European solar energy market grew by 21% in 2018 compared to the previous year making PV technology the most deployed power generation method among others as shown in Fig.1. It is estimated that the total installed capacity of solar power will expand two times, reaching the capacity of 1.1 TW by the end of 2022 from its 0.5 TW in 2018 (*Global Market Outlook 2019-2023*, 2019).

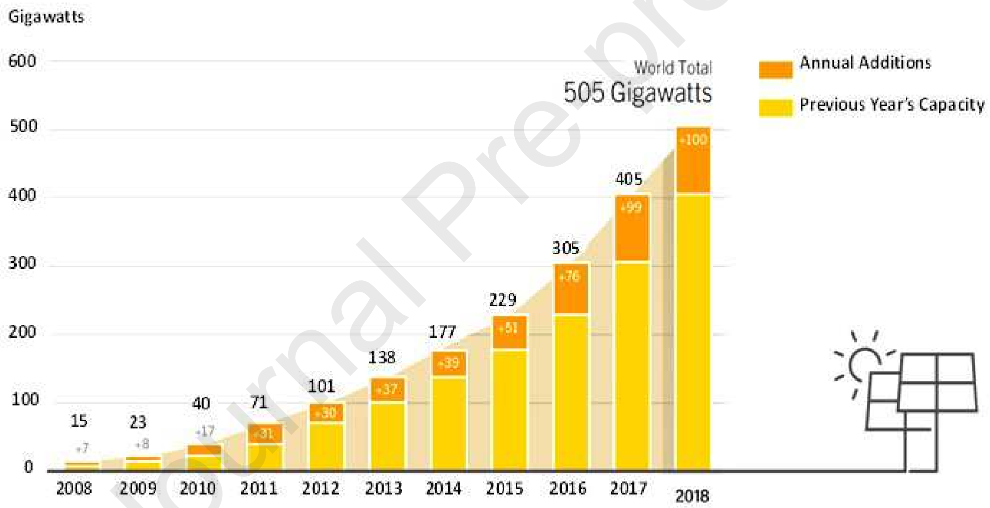

Figure 1. Global capacity of solar PV and its annual addition (Gorjian and Ebadi, 2020), Source: Becquerel institute, and the IEA Photovoltaic Power Systems Programme (PVPS).

The floating solar market emerged in 2007 by installing a 20 kWp system in Aichi, Japan, and has got a speedy growth, reaching its first-megawatt capacity within two years. In 2010, the first tracking FPV plant with 200 kWp capacity was developed in Italy, while the total cumulative power was 2.2 MWp. The first larger-scale FPV plant with a capacity of 1.18 MWp was installed in Japan in 2013. Consequently, more floating plants with peak capacity in tens and hundreds of megawatts were added to the global market, which drastically accelerated the technology deployment (Fig.2). In 2016, Japan introduced the first FPV plant working with micro-inverters and provided 300 kWp to the global capacity to hit 169 MWp. Attaining tremendous attention especially in highly populated places with limited land area and showing high adaptability with existing hydropower plants, the FPV market grew larger, especially in Eastern China, Southeast Asia, and India. Therefore, the first hydro-PV plant was developed in Portugal in 2017, while the global capacity culminated more than 0.5 GW (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Figure 2. Total capacity of FPV plants installed around the world (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Increasing R&D investments combined with new governmental initiatives for FPV promotion is expected to reach a Compound Annual Growth Rate (CAGR) of 30.7% from 2018 to 2024, reaching 4127.567 MW cumulative installed capacity where the commercial segment accounts for the highest share compared to other applications (*Global Floating Solar Energy Market*, 2019). The current market has been influenced by several large plants in recent years, most of which were emerged in China. The photographic timeline of developed FPV plants is presented in Fig. 3. As illustrated in this figure, nearly 300 projects have been documented around the world, and there are five different categories based on peak power capacity. China with a total share of 73% for installed FPV plants (950 MWp) in 2018 shrunk its size to improve the transition from traditional feed-in tariff incentive schemes (*Global Market Outlook 2019-2023*, 2019). Although Japan is the second-largest country in terms of the market for FPV plants with a total share of 16% (180 MWp), in contrast to China, the majority of the installed capacities in this country is below 3 MWp. The photo of the largest FPV power plant in the world installed in Huainan, China is shown in Fig.4. Statistics show that most of the installed FPV plants around the world are small-scale (< 3 MWp) while larger installations were on the rise after 2017. South Korea with 6%, Taiwan with 2% and the UK with 1% of total global FPV installations are ranked as the next markets in the world, while rest of the countries account for only 2% out of the total capacity of 1.3 GWp by the end of 2018 (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

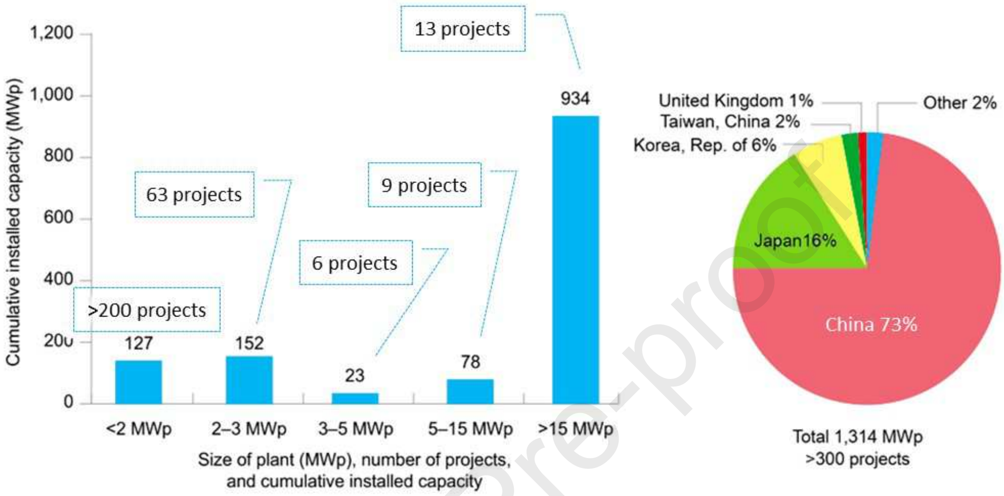

Figure 3. Global distribution of FPV systems concerning the size and location by the end of 2018 (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Figure 4. The largest FPV plant (40 MW) installed at Huainan, China (Abid et al., 2019).

Opportunities of the market are mainly based on the geospatial factors, including location, size, and other parameters representing the complexity of the deployment which may be equal or more expensive compared to ground-mounted systems (Gamarra and Ronk, 2019). Studies have estimated the amount of possible power generation through the FPV deployment on available man-made water bodies, and the results are presented in Table 1 over three different scenarios in which the use of 1, 5, and 10% of available surfaces are considered. Referring to Table 1, North America, with nearly 34% of total water bodies and 32% of the total available water surface area, offers the greatest market capacity of 1,260 GWp when the area factor is 100 Wp/m^2 and performance ratio of solar irradiance is 80%. Asia (28%), Africa (25%), South America (9%), Europe (5%), and Oceania (about 1%) occupy the rest of the possible FPV market in the world (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Table 1. Distribution of FPV potential on man-made reservoirs (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Continent	**Total Available Surface Area (km^2)**	**Number of Water Bodies Assessed**	**FPV Potential (GWp)**			**Possible Annual Energy Generation (GWh/y)**		
			Percentage of Used Total Surface Area					
			1%	**5%**	**10%**	**1%**	**5%**	**10%**
Africa	101130	724	101	506	1011	167165	835824	1671648
Middle East and Asia	115621	2041	116	578	1156	128691	643456	1286911
Europe	20424	1082	20	102	204	19574	97868	195736
North America	126017	2248	126	630	1260	140815	704076	1408153
Oceania	4991	254	5	25	50	6713	33565	67131
South America	36271	299	36	181	363	58151	290753	581507
Total	**404454**	**6648**	**404**	**2022**	**4044**	**521109**	**2605542**	**5211086**

In a study conducted by Spencer et al. (2019), it was found that 27% of the area of human-made water bodies that existed throughout the US is suitable for PV integration. However, the incorporation of FPV systems into only 27% of the appropriate area could result in 2,116 GW electric power generation which can meet 9.6% of national electricity demand in 2018. In another estimation based on the climatic conditions and 1% usage of water surfaces, the possible potentials of 1,526, 1,832, and 2,176 GWp were concluded for tropical, temperate, and cold zones, respectively (Rosa-Clot and Tina, 2018a). Wästhage (2017) showed that the integration of a 200 kWp FPV system into a shrimp farm in Thailand could offer 100% reliability. Song and Choi (2016) opened a new path by introducing the considerable potential as 971.57 MWh/y that can be exploited by FPV technology from a mine pit lake. Although the deployment of thin-film flexible floating PVs (T3F-PV) in the open sea is in progress (Trapani and Millar, 2014), there are still several threats, including intense wind loads, high waves, and corrosive salt waters that usually appear in the marine environment (Sudhakar, 2019). Other water bodies that can be used for FPV purposes are wastewater and industrial basins, natural lakes, lagoons, and freshwater rivers (Manoj Kumar and Mallikarjun, 2018).

FPV installations have opened new opportunities for scaling up the capacity of solar electricity generation especially in locations with land constraints. FPV systems have several advantages over ground-mounted installations with the most important ones including enhanced energy yield because of water cooling effects, reduced dust accumulation, decreased water evaporation of water bodies, elimination of major site preparation operations, and a high degree of modularity. In previous studies, the FPV concept has been well explored by researchers, and real-world experiences have been presented in detail. However, like any other technology, FPV is evolving with time, and the present study is aimed to give a comprehensive review of this technology by considering technical features and investigating the most recent advancements in this power generation technique. In this regard, different designs of FPV plants are studied and compared with ground-mounted PV plants from different aspects. The economics and environmental impacts of FPV systems are also studied and deliberately discussed. In the end, the most important challenges and prospects of FPV plants are presented based on the obtained results of the previously conducted studies. This study can also be considered as a guide for researchers, policymakers, private practitioners and developers to become knowledgeable about technical advancements, market potentials, environmental impacts, and costs of the FPV technology to overcome associated challenges of this technology, assisting to pave the way for future exploration and expansion of this emerging and in-progress power generation technology.

2 Concept of floating PV systems

Solar PV modules are generally installed over ground and rooftops using rigid mounting structures. Due to the low availability of land, dense population and severe threat of deforestation interest have been directed towards the installation of PV panels over canals, lakes, reservoirs, and oceans. PV panels are installed over water bodies by making them float using suitable technology and such installations are called FPV plants. The electric power output of PV panels highly depends on incident solar radiation and the temperature of the panels. Shadow effects are negligible or nil in FPV systems and the temperature of panels can be lowered by water beneath it. The efficiency of FPV panels is nearly 11.0% higher than ground- and roof-mounted PV panels (Sahu et al., 2016). The schematic view of a FPV system is depicted in Fig.5. As shown in this figure, the main components of FPV systems are pontoon/floats, mooring systems, PV panels, and electric cables & connectors.

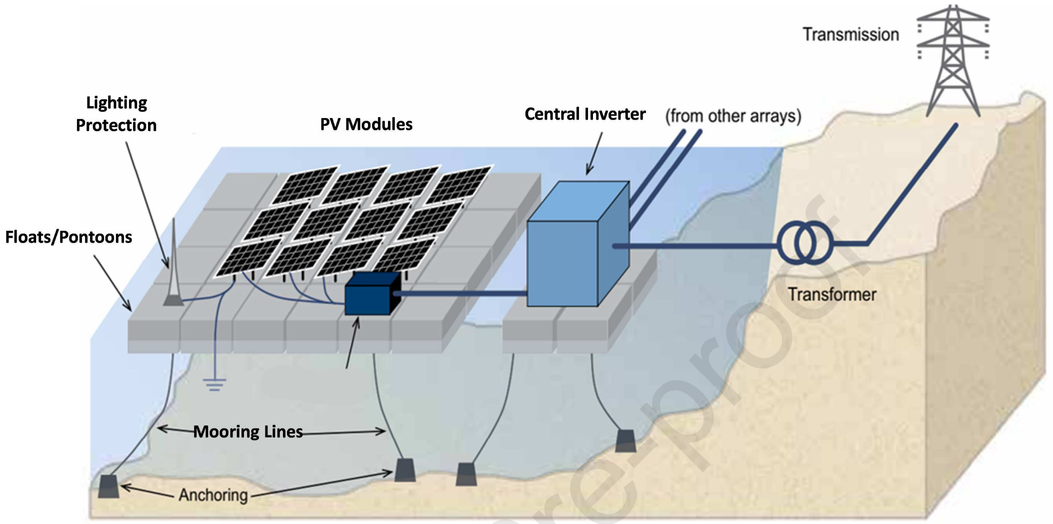

Figure 5. Schematic view of a typical FPV system and its main components (Sahu et al., 2016).

Pontoons are devices that float by itself along with PV panels by buoyancy including a space for human accessibility. Pontoons are mostly made of high-density polyethylene (HDPE) which is UV-resistant, corrosion-resistant, and has a high tensile strength (Ammala et al., 2011; Sahu et al., 2016). The mooring system is a permanent structure that is used to keep the pontoons in the desired location, position, and prevent them from moving away. Rigid supports in the form of anchorages are provided using piles along the perimeter of the reservoir to take care of dead loads and lateral forces (Ferrer-Gisbert et al., 2013; Rosa-Clot et al., 2010). Generally, rigid flat-type PV panels are used in FPV systems, however, flexible panels which are adjustable according to wave movement are more attractive (Cazzaniga et al., 2018). Trapani and Millar (2014b) developed a FPV array containing T3F-PV modules. In this case, they manufactured a small-scale prototype of a thin-film based FPV system installed on an enclosed water body in Sudbury, Canada. The results of the 45-day operation indicated a 0.5% reduction in electric efficiency mainly because of sediment blockage on FPV modules, while an average electric improvement of 5% was reported because of the water-cooling effect for three months. The use of bifacial PV modules was also proposed by Hasan and Dincer (2020) for use in FPV systems. They reported that bifacial modules can capture the reflected solar irradiance from the water surface and therefore, increase the efficiency. The results indicated that the north/south facing bifacial modules can produce a maximum of 55% growth in exposure to irradiance in comparison with conventional modules when operating on the water surface. Fig. 6 represents a broad classification of various FPVs reported in the literature.

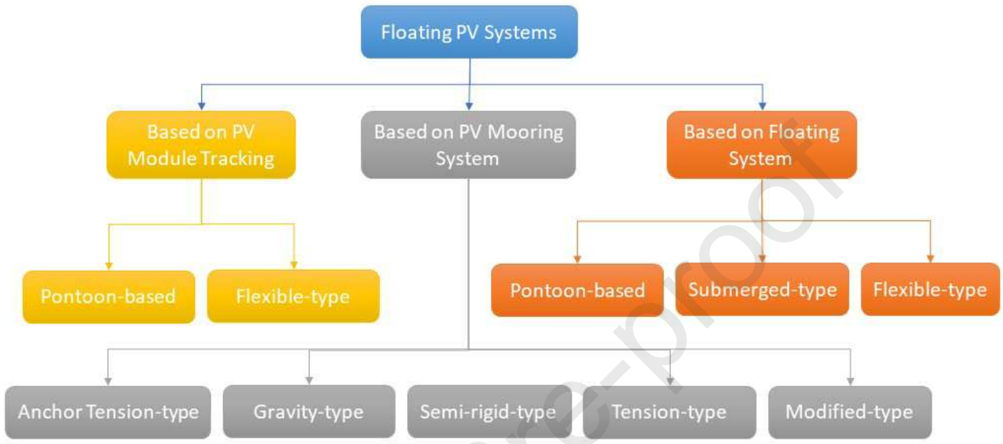

Figure 6. Various FPV systems according to the design of their main components.

A typical FPV module consists of a PV module, a supporting system, and a floating system as shown in Fig.7a (Lee et al., 2014). Strong winds and uneven surface are two significant factors imposing threats on rigid PV panels in this type of arrangement (Kajari-Schröder et al., 2011). Mooring is an essential part of both fixed and tracking floating plants to keep the platform in place (Fig.7b). However, the floating platform can also be anchored to the bottom or banks within the shallow ponds. The panel structure is mounted on floating platforms, including pontoons, modular rafts, and plastic rafts (Rosa-Clot and Tina, 2018b). Most of the water bodies have salinity which may affect the PV panel frames, hence polymer-based frames and supports are desired for longer life of panels. Electricity produced from FPV panels over water bodies is transported to the land through electric cables, hence waterproof, high-temperature resistance cables and junction boxes are required for the long life of the system (Oliveira-Pinto and Stokkermans, 2020a; Rosa-Clot and Tina, 2018c). Dust accumulation over FPV and temperature rise of panels is the major reason which reduces the performance of the FPV system. Water cooling helps to reduce radiation reflection and temperature of FPV panels and therefore, the electric output of the system can be increased by about 10 to 12%. Energy consumed for this method is only about 0.25% of the total energy output (Cazzaniga et al., 2018).

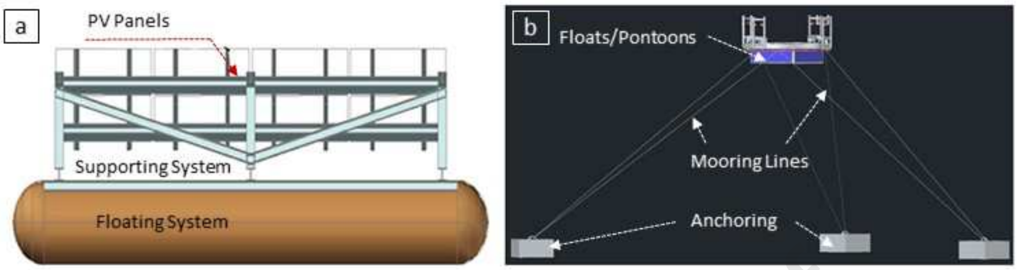

Figure 7. Supporting structures and related components for various PV systems; a) Different components of a typical FPV module (Lee et al., 2014), b) Mooring system used in FPV plants (Cazzaniga et al., 2018).

FPV plants over water bodies provide the following benefits (Ferrer-Gisbert et al., 2013):

- Reduced silt deposition;
- Improves water quality;
- Longer life of geo-membranes;
- Reduced filtering cost;
- Reduced evaporation losses;
- Improves the water and power efficiency of reservoirs;
- Generates additional income to reservoir owner;
- Saves land area which can be used for agricultural activities.

And, FPV plants have the following disadvantages over ground-mounted PV systems (Sahu et al., 2016):

- Cannot withstand heavy waves, high tides, cyclones, and tsunami;
- They are subjected to fluctuating wind loads and vibrations hence cracking and orientation change of PV modules are possible;
- Salinity of water body can deteriorate panel component and reduce its performance;
- Transmission of sunlight into a water body is prevented and hence it may affect the aquatic ecosystem;
- Cleaning of FPV panels might be more difficult hence automatic novel cleaning mechanism needs to be designed;

- Safe transport of power from FPV to land will be challenging and it requires expensive investments;
- Electricity generation cost of FPV is at least ten times higher than conventional fossil fuel unit;
- Fishing, boat/ship movement can affect the livelihood of communities living in coastal and banks;
- Detailed environmental impacts of FPVs are not fully known up to now.

3 An overview of PV modules cooling techniques

Depending on the conversion efficiency of PV modules, only a part of received solar radiation is transformed into electricity and the remained portion is wasted as heat which increases the module's temperature, resulting in a reduction in the electric efficiency. Until now, several cooling methods have been utilized to retain the temperature of PV modules close to their nominal operating values. In this section, an overview of PV modules cooling techniques along with a detailed description of adopted methods for use in FPV modules is presented.

3.1 Efficiency drop due to thermal drift

The electric conversion efficiency of a PV module depends on several factors including ambient temperature, solar intensity, convective and radiative heat losses to the ambient, accumulated dust, and relative humidity (Gorjian et al., 2020a; Kant et al., 2016). It has been demonstrated that the overall efficiency of PV cells reduces significantly with a rise in temperature. Every 1°C growth in the surface temperature of the cell prompts a 0.5% decrease in efficiency (Rosa-Clot and Tina, 2020b). Several researchers have focused on investigating new solar cell materials and on retaining low operating temperatures to enhance conversion efficiency (Elsheikh et al., 2019; Gorjian et al., 2020b). Fig.8 represents the effect of operating temperature on the electric efficiency of three crystalline silicon (c-Si) modules (Brinkworth et al., 1997). It can be seen from the figure that for all three modules there is a linear dependence of efficiency on the maximum module's surface temperature. The gradients are in the range of 0.4% to 0.5% of the nominal (25°C) value per K of temperature increase. The impact of temperature on the solar module's electric efficiency can be calculated as:

$$\eta_{PV} = \eta_{T_R}\left[1 - \beta_{ref}(T_c - T_R) + \gamma log_{10} I_0\right] \quad (1)$$

where η_{PV} is the reference PV module efficiency derived at standard test condition (STC) (T_R=25°C), β_{ref} is the temperature constant for cell efficiency ranging usually 0.004-0.005/°C (Hove, 2000), I_0 (W/m^2) is the incident solar radiation on the PV module at nominal operating temperature, T_c(°C) is the operating temperature of the PV modules, and γ is the radiation-intensity coefficient for cell efficiency which is generally assumed to be zero (Evans, 1981; Siegel et al., 1981), simplifying the Eq. 1 as below:

$$\eta_{PV} = \eta_{T_R}\left[1 - \beta_{ref}(T_c - T_R)\right] \quad (2)$$

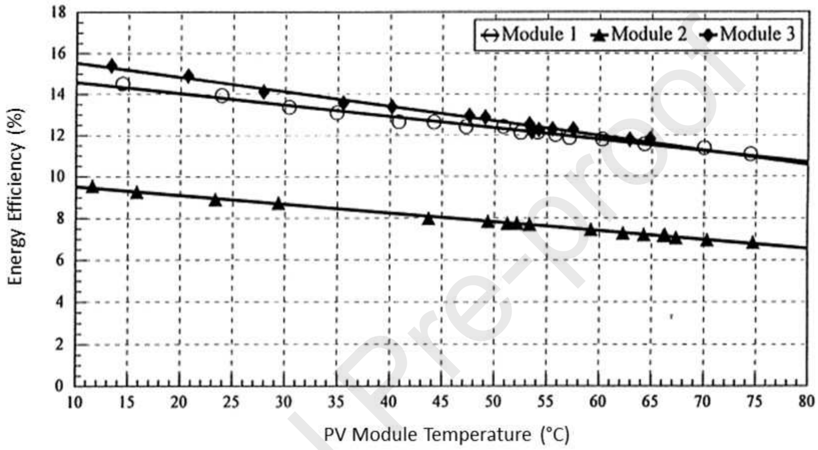

Figure 8. The efficiency of three PV modules at different operating temperatures (Brinkworth et al., 1997).

Hence, owing to the increase in temperature, merely a fraction of solar energy is used to generate electrical energy, and the remaining part is converted into the heat (Shakouri et al., 2020; Siecker et al., 2017). In recent years, various methods for thermal management of PV modules have been explored including air cooling, water/liquid cooling, phase change materials (PCMs), and thermoelectric as presented in Fig. 9. In active air- and liquid-based cooling methods usually pumps or fans are utilized to keep a flow of cooling medium over the front or back surface of the PV module. This method improves heat dissipation from the PV module, leading to advanced electric performance rates as compared with the passive methods (Gorjian et al., 2020d; Reddy et al., 2015). In passive cooling methods, heat transfer depends on natural heat exchange mechanisms (Gorjian et al., 2020b; Siecker et al., 2017). The main benefit of using passive techniques is their low maintenance costs due to the lack of any moving or energy-consuming parts.

3.2 Efficiency enhancement methods for FPV modules

Water availability along with low power consumption for pumping can favor the utilization of water as an effective medium to cool PV panels and is highly suitable for FPV. One of the important benefits of floating PV modules is that the basin water can be considered as a thermal bath to cool down PV modules on-site and increase the electric efficiency of the modules. The most common performance enhancement techniques utilized in FPV systems are cooling methods of "*water veil cooling*" and "*water sprinkler cooling*" and a recent method of applying both cooling methods and installing concentrators as "*Floating tracking concentrating cooling (FTCC)*" which are discussed here.

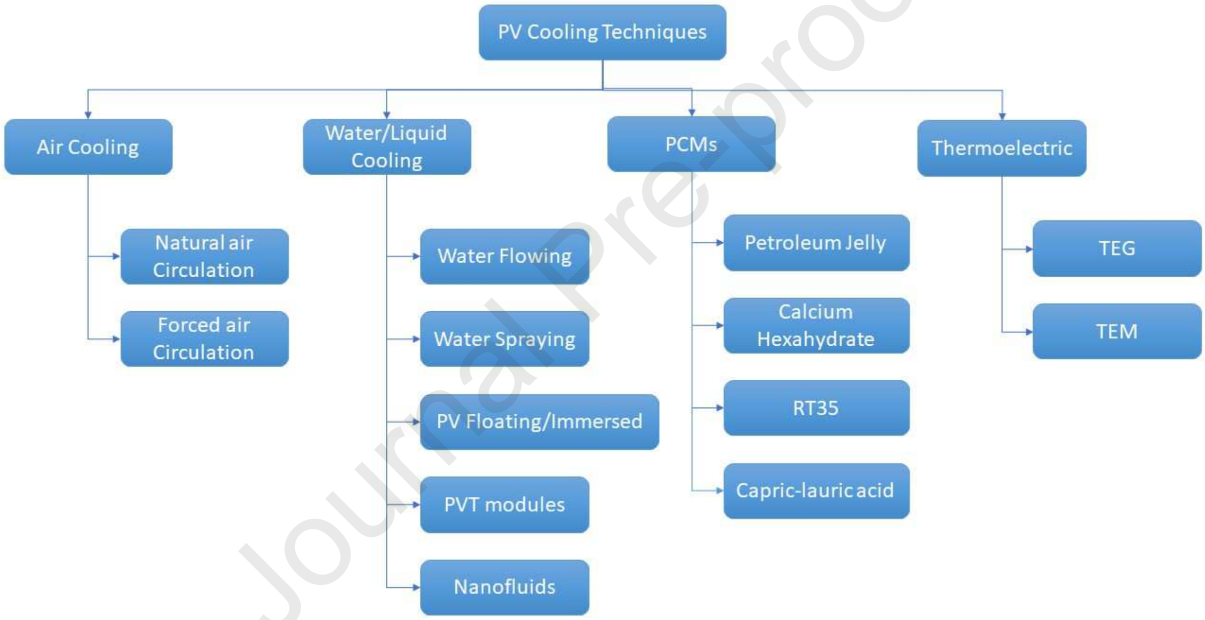

Figure 9. Classification of cooling technologies utilized in PV modules (Cotfas and Cotfas, 2019; Shukla et al., 2017).

3.2.1 Water veil cooling (WVC)

A water veil cooling (WVC) system is composed of two main parts of a pump and an irrigation system made of polyethylene pipes mounted above each PV panel. In this method, a temperature control system is used to switch on the pump when the PV panel temperature runs over a fixed threshold (Fig.10a) (the maximum temperature is typically 30°C) (Siecker et al., 2017). The photo of a water veil assisted PV cooling system positioned on a FPV plant in Pisa (Italy) is shown in Fig.10b. The presence of a thin layer/veil of water over the PV panel can help to reduce its temperature while it also minimizes the reflection of incident solar radiation. The reflection loss avoided by incorporating water veil is about 2%

and 6% for 0° and 30° incidence angles, respectively (Castanheira et al., 2018). It is estimated that using the WVC system can increase the efficiency of a solar panel up to 15% at peak radiation conditions. The conversion efficiency of a PV panel with and without water veil above the panel is shown in Fig.11. As can be seen in this figure, the conversion efficiency of the panel with 0.04 m water veil is higher than the PV panel with no water and PV panel with 0.40 m thickness of water veil. This observation justifies the fact that visible solar spectra reaching the PV panel with lower water depth remains unaltered and cooling effect caused by water veil is also fruitful (Lanzafame et al., 2010).

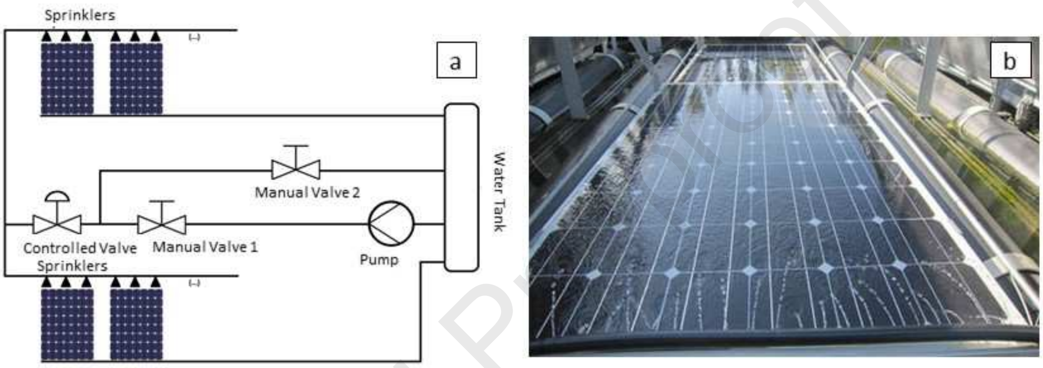

Figure 10. a) Schematic of a WVC system (Cazzaniga et al., 2018), b) Photo of Water WVC system for FPV installed in Pisa (Italy) ("Floating solar," 2020).

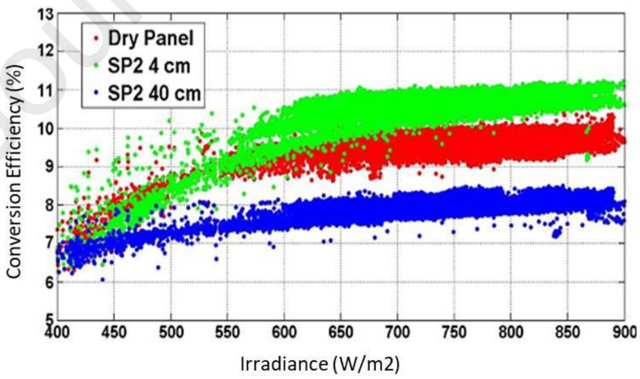

Figure 11. The conversion efficiency of PV panels with different depths of water over it (Lanzafame et al., 2010).

3.2.2 *Water sprinkler cooling*

The water sprinkler cooling system is simpler than the WCV system and instead of irrigation pipes, it uses high-pressure sprinklers to perform at a pressure of 2 to 3 bar. Therefore, this system would come far cheaper than the WVC system. Using this technique can increase the annual power production by 10%.

In this method, spray time can be arranged for a very short period to minimize the energy waste of pumping and loss of solar radiation due to the shadowing effect caused by water jets (Siecker et al., 2017). Spraying water over PV modules can reduce the operating temperature and reflection losses by about 26°C and 2-4%, respectively (Sargunanathan et al., 2016). Nižetić et al. (2016) investigated the effect of water spraying on both sides of the PV panels on its efficiency and temperature (Fig.12). According to the experimental results, it was found that the simultaneous cooling of the front and back sides using water spray reduces the PV panel temperature and increases electric output and efficiency by about 30°C, 16.3%, and 14.1% respectively, while causes additional power consumption due to spraying. It was reported that back-surface cooling alone enhances power output by about 14.0% in comparison to the panel with no cooling. A comparison of mean temperature and electric efficiency of a PV panel using various cooling options is depicted in Fig. 13.

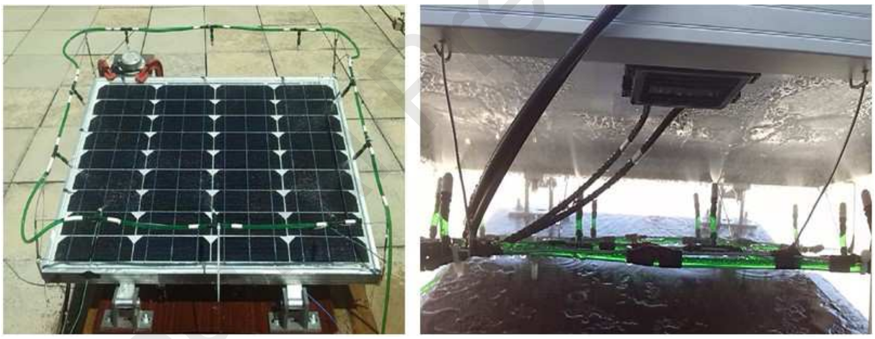

Figure 12. Simultaneous front and back surface cooling of the PV panel by water spraying (Nižetić et al., 2016).

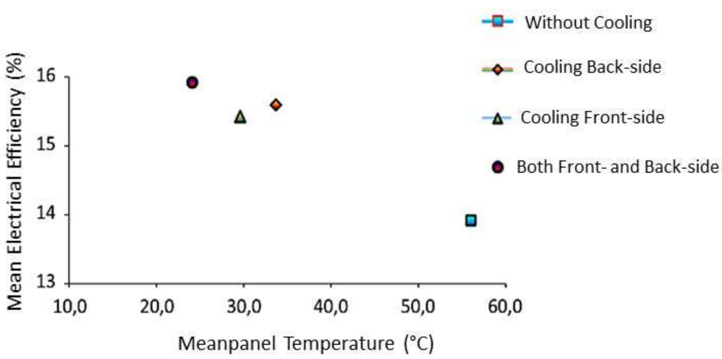

Figure 13. Variation of panel temperature and its electric efficiency under various cooling conditions (Nižetić et al., 2016).

3.2.3 Submerged PV systems

Submerged PV (SPV) systems are of great interest as they help to meet the heating demands of swimming pools and produce additional power by utilizing the base area of the pool. PV panels can be installed around the edges of the swimming pool or on the base of the pool (Tina et al., 2012). As presented in Fig.14, single- and poly-crystalline PV modules are more suited for instillations around the edge of the pool while amorphous PV modules are more suited for installations on the base of swimming pools because of their high relative efficiency at high depths (Rosa-Clot et al., 2010). The installation of PV panels over the edges and bottom of a swimming pool is also shown in Fig.15. The efficiency of PV panels installed around the edges of the overflowing type swimming pool increased by about 10 to 20% due to the cooling effect caused by water flowing over them. The power output of PV panels installed 1.2 m below the water surface of the pool reduced by about 10.0% in comparison with the ground-based PV modules. However, PV panels installed at the bottom of the swimming pool can produce both the required power and heat for warming the water inside the swimming pool without affecting the pool structure (Rosa-Clot et al., 2017). From Fig.16, it can be concluded that for water layer thickness below 0.05 m, the solar spectra reaching the SPV panel is more or less similar to the solar spectra at no water case (Lanzafame et al., 2010). It can also be confirmed that water absorbs most of the infrared radiation (IR) rather than visible radiation and the negative effect of water temperature rise due to this can be neglected because in WVC/partially SPV panels only thin layer of water will be above the PV panel and the water is re-circulated after mixing with bulk water from lakes, ponds or reservoirs. The lack of thermal drift and reduced radiation reflection losses both help to increase the power conversion efficiency of SPV panels by about 15.0% compared to dry panels. SPV installations are more suitable in regions with high ambient temperature and high solar radiation intensity and therefore, are highly recommended in regions located within 30° latitude as nearly horizontal installations are possible in these locations for enhanced year-round power production (Tina et al., 2012).

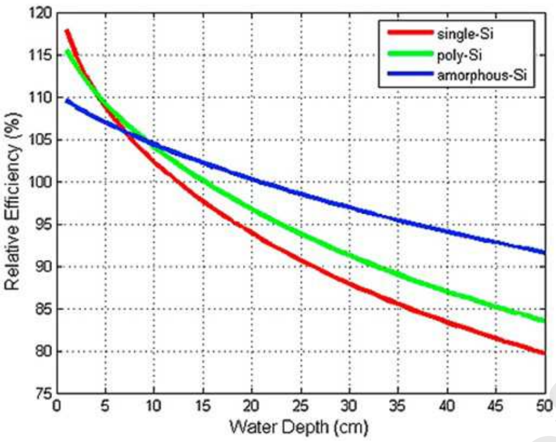

Figure 14. Variation of the relative efficiency of various PV panels at different water depths (Rosa-Clot et al., 2010).

However, some drawbacks associated with SPV systems are as follow (Rosa-Clot et al., 2017):

- Reduced power output at high depth installations;
- Reduced performance because of frequent shading effects caused by swimmers/moving objects;
- Algae and silt deposition may occur frequently over SPV modules;
- Long-term real-time data regarding the reliability and economics of SPV systems is not available.

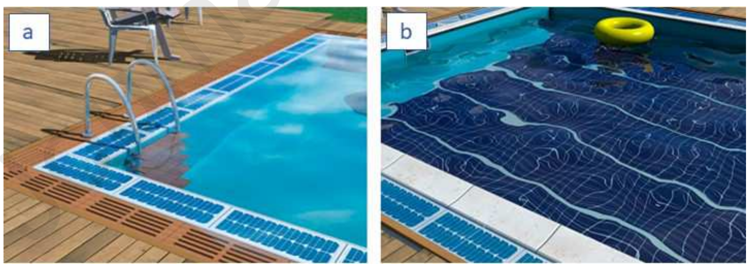

Figure 15. PV panel installation on swimming pool; a) Around edges of the pool, b) Inside the pool (Rosa-Clot et al., 2017).

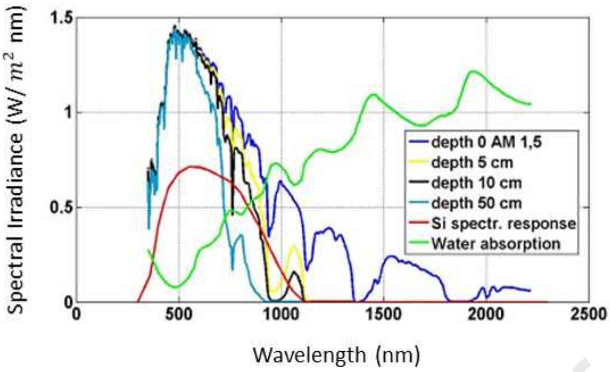

Figure 16. Variation of solar radiation spectra for different water depths (Lanzafame et al., 2010).

3.2.4 Floating tracking concentrating cooling (FTCC) systems

One method to accomplish the optimal power output of a PV module is to use artificial basins for installing FPV plants. These water-based plants comprise a platform with PV modules, an array of reflectors, and a solar tracking system. These systems which are known as floating tracking concentrating cooling (FTCC) also use a sprinkler or veil cooling system to control the operating temperature of the panel with water while employing reflectors to enhance solar radiation incidence. The implementation of reflectors to concentrate solar radiation increases the energy intensity for more energy harvest. The floating platform allows a very efficient system for a one-axis tracking system with the positioning of reflectors which raise the amount of solar energy absorbed by the PV panels.

Cazzaniga et al. (2011) suggested a solution for controlling the operating temperature of floating tracking concentrating PV plant by building circular floating platforms on small basins and lakes, with a set of reflectors installed on a structure in polyethylene tubes and cooled with the basin water as shown in Fig. 17. The diameter of the platform ranges from 20 to 40 meters and has a power output from 25 to 100 kW. A careful application of planer reflectors was analyzed by (Cazzaniga et al., 2012) to improve the system efficiency and cost. From the detailed analysis, it was found that the annual yield is considerably improved compared to a fixed ground-mounted PV plant. Further, it was found that the costs of the supporting structure and the cooling, tracking, reflector systems were competitive with those of land-based plants, while a 30% increase in the annual energy yield is expected in the FPV plant. According to this study, the FTCC increases the life cycle and reduces the thermal stresses of PV panels, while it has no fixed structure that can be decommissioned with less than 1.0% of the total cost for the plant without affecting the natural environment of the water body.

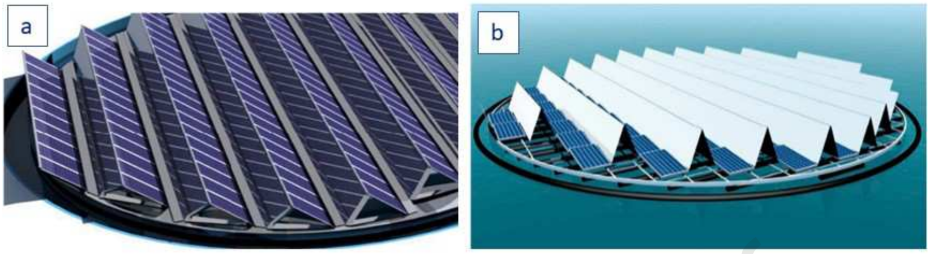

Figure 17. Outline of an FTCC plant: a) Reflectors on the rear of PV panels, b) V-shaped reflectors (Cazzaniga et al., 2011).

Tina and Rosa-Clot (2011) conducted an experimental study to optimize and assess the electrical efficiency of a FPV plant with reflector, tracker, and water veil cooling arrangement. The veil of water was composed of a set of irrigators positioned on the top of the panel. From the study, it was found that the average yearly yield per kWp installed increases by 60-70% compared to a fixed plant under similar climate conditions.

4 Commercial designs of FPV systems

Several researchers have suggested the installation of FPVs over abandoned mining lakes (Rosa-Clot and Tina, 2018b; Song and Choi, 2016), tanks of fish farms (Pringle et al., 2017), irrigation ponds for agriculture, and storage basins of hydroelectric power plants (Cazzaniga et al., 2019) which are often of artificial type and without constraints. Other water bodies that can be used for the installation of FPV systems are natural lakes, wastewater and industrial basins, lagoons, and freshwater rivers (Manoj Kumar and Mallikarjun, 2018). According to the application, FPV plants are classified as "*Conventional FPV systems*", "*Multipurpose FPV systems*", and "*Hybrid floating solar-hydropower systems*".

4.1 Conventional FPV systems

In conventional FPV systems, the water surface is covered by floating modules which are in turn connected by pins. The factors affecting the performance of FPV systems installed above reservoirs are (Redón Santafé et al., 2014):

- Structure of the floating platform;

- Varying water level and layout of the reservoir;
- In-situ work for construction and exploitation.

Designing adaptable floating modules for reservoirs is highly challenging as most of the reservoir's layout, walls, and internal geometry are highly variable. Floating modules are designed to accommodate standard PV panels and to cover maximum water areas to prevent evaporation losses (Siecker et al., 2017). The size of floating modules is determined by considering the gap between panels to prevent shading and walkways for easy operation and maintenance where the access way of at least 0.5 m is highly recommended (Fig. 18) (Redón Santafé et al., 2014).

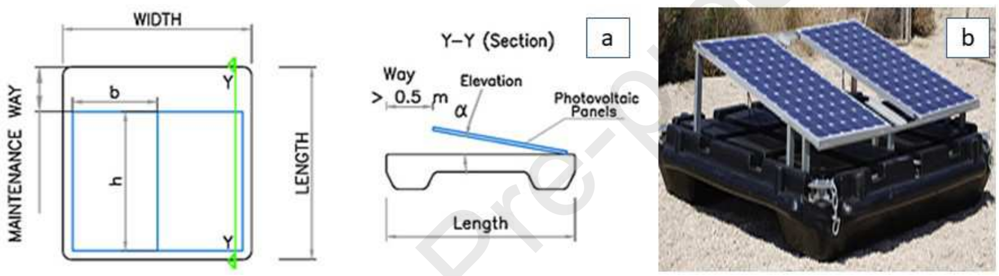

Figure 18. a) The layout of a typical floating PV module (Redón Santafé et al., 2014), b) Photo of a FPV module (Ferrer-Gisbert et al., 2013).

The tilt angle of panels corresponding to local latitude is more optimum for increased electricity production per year. However, the low tilt angle is highly preferred in the case of FPV systems for the following reasons (Redón Santafé et al., 2014; Rosa-Clot et al., 2010):

- Reduced gap between rows to prevent shade hence more area is utilized;
- Reduced wind uplift and drifting;
- Improvement of the structural behavior of the system due to reduced wind forces.

The top portion of pontoons has a large number of rectangular gutters which make it stiffer to withstand dead, live and wind loads and it also facilitates the installation of electric wiring. Pontoons are joined together with the help of metal rods and pinned joints which helps proper fitting of them over the reservoir and also facilitates the transmission of horizontal forces and vertical rotation as shown in Fig.19 for Kagawa's FPV plant with a total capacity of 696 KWp (Barbuscia, 2017; Ferrer-Gisbert et al., 2013).

Figure 19. Kagawa's FPV plant (696 KWp) installed by Ciel et Terre (Barbuscia, 2017).

Elastic joints are used between pontoons to adjust variations occurring during the times of full and empty reservoirs. When the reservoir is full, elastic joints are closed and the surface of the water is fully covered, but for the empty reservoir, elastic joints are opened where pontoons cover internal walls of the reservoir (Fig. 20). Rigid supports and anchorages for floating modules are necessary and must be installed along the perimeter of the reservoir to withstand the dead loads and forces caused by wind and waves. FPV systems are found to be a suitable candidate to provide electricity at reasonable costs along with a huge cut-off in CO_2 emission. An increase in the cost of fossil fuel-based electricity and declining PV costs have increased the potential of FPV systems in reservoirs of arid and semi-arid areas (Trapani and Millar, 2013).

4.2 Hybrid floating solar-hydropower systems

Drought and fluctuations in rainfall patterns have a huge impact on the power generation capacity of hydropower plants. These uncertainties have led to installations of a large number of thermal power plants in most of the regions which in turn significantly increased carbon emissions. These issues can be averted possibly by integrating hydropower plants with PV plants (Silvério et al., 2018).

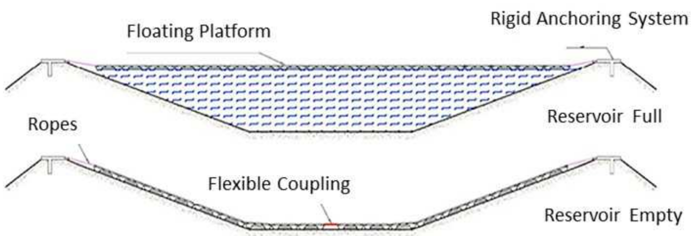

Figure 20. Status of floating platforms during full and empty reservoir conditions (Redón Santafé et al., 2014).

FPV plants are effective candidate compared to ground-mounted PV units for integration with hydropower plants as locations closer to dams will have uneven surfaces, forests, animal issues, etc. Deployment of FPV systems over hydroelectric power plant reservoirs and therefore, their combined operation has the following advantages (Silvério et al., 2018):

- Power variation in FPV due to intermittent solar radiation profile can be avoided;
- The power output quality of the FPV can be improved;
- FPV output can compensate power reduction from hydropower plants especially during droughts;
- Power output from FPV prevents the consumption of water from hydropower plants which can be otherwise used during peak load conditions.

A schematic view and photo of a hybrid floating solar-hydropower plant are shown in Fig.21. Silverio et al. (Silvério et al., 2018) investigated the potential of implementing FPV in hydroelectric power plant reservoirs in various parts of Brazil. The levelized cost of energy (LCOE) and horizontal force due to wind load were found to be increased with an increase in PV panels tilt angle with the optimum tilt angle of 3°. A list of hydroelectric power plants, their peak power, installed FPV area, annual power generation capacity, and capacity factor are presented in Table 2. It can be seen that the mean energy gain by combining FPV with hydroelectric power is about 76.0% and it has also increased the capacity factor by around 17.3% in comparison to sole hydropower unit. Cazzaniga et al. (2019) analyzed the effect of implementing FPV in the 20 largest hydropower plants around the world. It was identified that covering 10.0% of hydropower plants' surface area with FPV can enhance the total hydropower generation capacity at least 65%, while evaporation losses can be reduced by more than 18%.

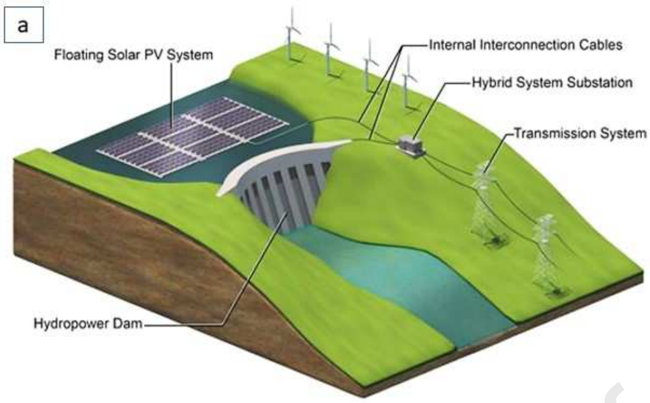

Figure 21. a) Schematic of a hybrid-floating solar-hydropower plant and its main components, b) Photo of the first hybrid floating solar-hydropower installed in Montalegre, Portugal (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Table 2. Comparison of capacity factor and annual power generation of sole hydropower and hybrid FPV-hydropower plants in Brazil (Silvério et al., 2018).

Reservoir	Peak Power (MW)	FPV area (m^2)	Reservoir area (m^2)	Capacity Factor (Hydro alone) %	Capacity Factor (Hydro and PV) %	Annual Power FPV (MWm)	Annual Power Hydroelectric (MWm)
Queimado	105.00	1.04	39.43	29.0	46.5	18.4	30.4
Retiro Baixo	82.00	0.81	22.58	16.7	34.3	14.5	13.7
Tres Marias	396.00	3.90	1090.00	20.7	38.5	70.8	81.8
Sobradinho	1050.00	10.35	4214.00	18.8	35.8	178.5	197.7
Itaparica	1479.60	14.59	828.00	26.9	43.8	250.3	397.3
Xingo	3162.00	28.98	60.00	32.7	49.5	529.8	1034.4

Haas et al. (2020) investigated the impact of deploying FPV in the Rapel hydropower reservoir, Chile on microbial growth and operation of the hydropower plant. Very large FPV plants over hydropower plant eliminated algae which in turn affect the reservoir's ecology and it also affects hydropower plant revenue as shown in Fig. 22. Recommended optimum cover % of FPV over hydropower reservoirs are found to be within 40 to 60% such that the acceptable level of algal concentration is maintained along without any loss of hydropower revenue. FPV has more ability to provide high power output compared to hydropower plants for a cover ratio of about 25%. Batteries and storage facilities are highly necessary for FPV-hydropower plants. In some FPV-hydropower plant cases especially near Siberia and Amazon jungle, availability of power is more but the population to consume it is very low (Farfan and Breyer, 2018). Hence, effective and essentials policies/actions are required to make these systems more utilizable. Integrated FPV-pumped storage power systems reduce energy imbalance and save lots of land and water. The load during the night is provided by a pumped storage unit, while at sunshine hours it is taken from the FPV. Additionally, the FPV helps to pump water to a higher level when FPV power generation is higher. Thus the excess energy is stored and utilized in an effective manner (Liu et al., 2019).

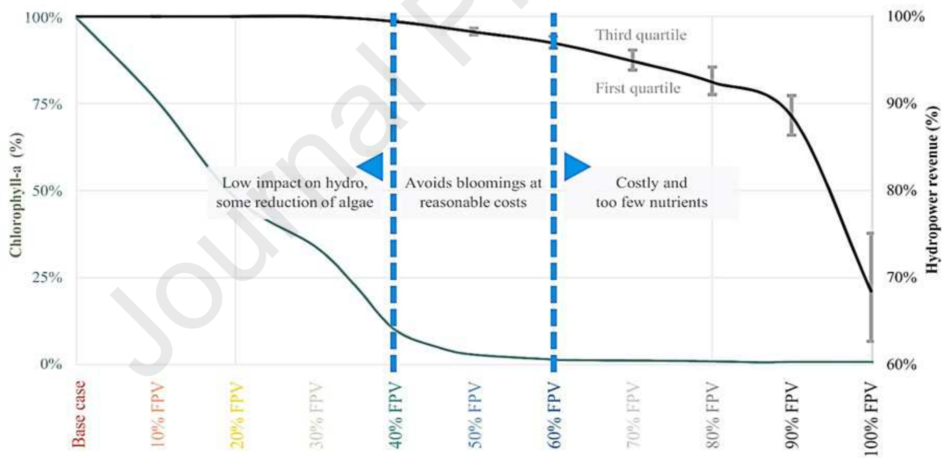

Figure 22. FPV's cover% on the water reservoir and its effect on algae concentration and hydropower revenue (Haas et al., 2020).

4.3 *Multipurpose FPV systems*

According to the Food and Agriculture Organization (FAO), *aquaculture* (also known as *aquafarming*) is defined as the farming of aquatic organisms such as fish, mollusks, crustaceans, and aquatic plants under a controlled environment. Currently, over 40% of seafood devotes to aquaculture farms (Gorjian et al., 2020d; Naylor et al., 2000). The combination of FPV with aquaculture form the concept of aquavoltaics, bringing the benefit of efficient water use for both food and energy generation, while simultaneously assisting in land-use change. The systems can be both implemented in industrial-sized farms as well as small remote-located villages. The FPVs can also perform as fish aggregation techniques which suggest a controlling framework for the behavior of fishes by protecting them, and presumably improve the yield (Christoffel Prinsloo, 2019; Xue, 2017).

Château et al. (2019) developed a dynamic model to study the principal biochemical processes in a milkfish (*Chanos chanos*) pond covered by FPV panels (Fig.23a). Some experiments were also conducted and data were recorded from ponds with and without FPV cover within two production seasons of summer and winter. Results indicated that the FPV system may display some mild negative consequences for fish production due to the reduction of dissolved oxygen (DO) levels. Also, it was concluded that the energy gained from this integration (with the capacity of about 1.13 MW/ha) is significant which could compensate for the losses in fish production.

Kim et al. (2020) proposed the concept of a FPV system for co-harvesting of salt and electricity. In this case, a fiber-reinforced plastic (FRP) seawater vessel was prepared where the PV modules were installed on. The test rig of the proposed system is shown in Fig.23b. The results from the experimental tests indicated that the water temperature and depth do not have a strong correlation and each can independently affect the performance of PV modules, while the impact of water salinity on the performance of the PV module is insignificant in a short time. They claimed that the electric performance of the FPV system is higher than the ground-mounted PV modules mainly due to the cooling effect of the seawater.

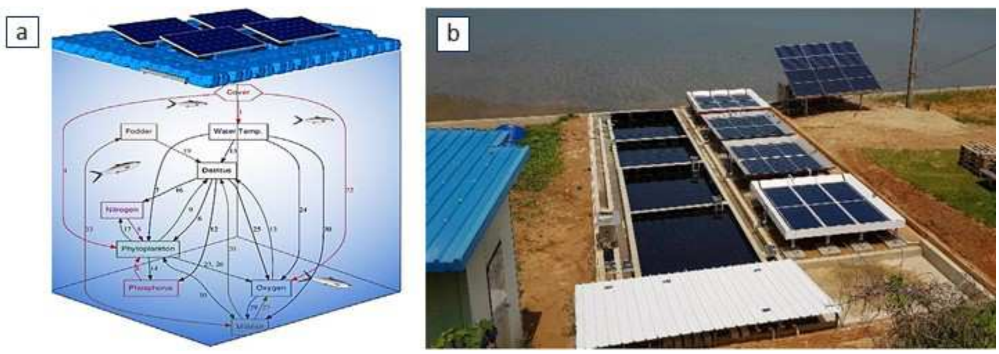

Figure 23. a) A developed model simulating the fish pond ecosystem covered with FPV panels (Château et al., 2019), b) Developed aquavoltaic system for simultaneous salt and electricity harvest (Kim et al., 2020).

In aquavoltaic systems, the mounting method of the PV panels is important as they are usually installed on floating cages, and therefore require specific structures to ensure their endurance under dynamic environments. Salinity is the other threat that requires special sealing and cabling for PV systems to work properly in the marine areas. Besides, restrictions in solar tracking systems, power storage facilities, and power distribution are other challenges in aquavoltaic systems that need to be considered (Menicou and Vassiliou, 2010; Pringle et al., 2017).

5 Comparison of ground-mounted and floating PV systems

The PV technology used for floating and ground-mounted solar systems is different and it depends on several factors that arise from the variations in the working environment and other relevant conditions. Also, the performance of both the systems are not similar and must be evaluated based on the cumulative effects of all influencing parameters (Golroodbari and Sark, 2020). Some of the main factors are presented here to give a comparative insight into the features of each PV technology.

5.1 Design and installation

5.1.1 Structure

The structure used for PV modules is aimed at supporting the panel weight, resisting dynamic wind and static snow loads, and providing a tilt angle. In some roof- and ground-mounted PV systems, cleaning apparatus (Qdah et al., 2019), tracking mechanisms (Huang et al., 2011), cooling systems (Elbreki et al., 2020; Kabeel et al., 2019), and reflecting tools (Malik and Chandel, 2020) are mounted to the main PV structure. Having whether moving structures or fixed-frames, ground-mounted solar systems are installed on a concrete base. Zn-coated steel frames, aluminum sheets and profiles, stainless steel, and copper fasteners are generally employed to meet normal corrosion environments to have an expected lifespan of 25-30 years (Pierozynski and Bialy, 2018).

According to Bödeker et al. (2010), 72% of the aluminum used in the PV industry devotes to the construction and mounting facilities, while panel frames and inverters consume 22% and 6%, respectively. The superiority of aluminum alloys over steel is attributed to their lighter weight, higher strength, and more corrosion resistance using a thin oxide layer (Farzaneh et al., 2012). Whereas floating systems need particular components to secure their sitting on the water which varies with location morphology. Sahu and Sudhakar (2019) demonstrated the durability of HDPE material for FPV application after observing reliable stability in its mechanical properties under accelerated UV exposure. After several developments, modular rafts with the ability to connect together are implemented for small to large-scale plants (Cazzaniga et al., 2018). Pultruded fiber reinforced polymeric plastic (PFRP) materials suggested by researchers (Lee et al., 2014) are also utilized in FPV systems due to their lighter weight and higher corrosion-resistance compared to other conventional materials. As a unique feature, pontoon pipes can be modified to store compressed air up to an internal pressure of 20 MPa and then release it to produce energy through a turbine whenever it is needed. Fig. 24 shows a block diagram of the isothermal compressed air energy storage (ICAES) integrated into the pontoon structure of a FPV system (Cazzaniga et al., 2017).

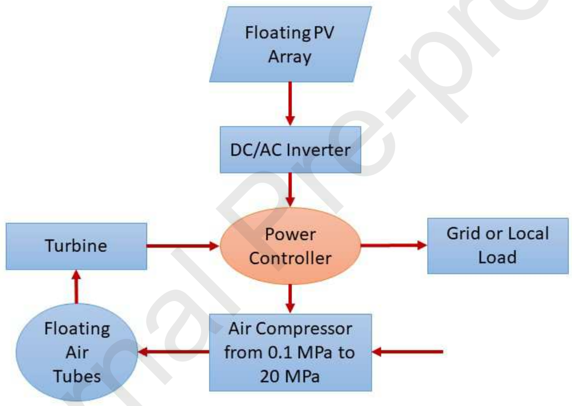

Figure 24. Block diagram representing the process of an ICAES coupled with a FPV system (Cazzaniga et al., 2017).

FPV structures are usually prone to frequent waves and winds, followed by the changes in the plant direction. Choi (Choi, 2014a) investigated the effects of wind speed on the power generation potential of a 100 kW FPV plant and found that as the wind speed increases, the FPV structure starts to rotate, which decreases the solar energy absorption and results in significant drops in power generation. Wave and other external forces that cause high levels of stress and vibration are more common in FPV systems than ground-mounted projects, which bring possible micro-cracks in modules and decrease their durability (Sahu et al., 2016). Furthermore, off-shore FPV plants undergo much higher mechanical stress than those installed above freshwaters (*Where Sun Meets Water: Floating Solar Market Report - Executive Summary*, 2018). Table 3 summarizes the simulated data for wind speed, wind drift distance, and wave height for a location with mid-climatic conditions using Sverdruv Munk Bretschneider (SMB) and Willson methods (Choi, 2014b). Although wind is active on both systems, static loads induced by snow accumulation in the winter season are more highlighted in a ground-mounted PV plant where several incidents have been reported in the literature (Köntges et al., 2014).

Table 3. Estimated values of environmental impacts on a FPV plant (Choi, 2014a).

Deep Water Estimate	**SMB Method**					**Willson Method**				
Wind Speed (m/s)	**5**	**10**	**20**	**30**	**40**	**5**	**10**	**20**	**30**	**40**
Wind Drift Distance (km)	**Significant Wave Height (m)**									
1	0.1082	0.2288	0.4708	0.7132	0.9555	0.1112	0.2555	0.5869	0.9547	1.3483
2	0.1464	0.3161	0.6580	1.0005	1.3432	0.1467	0.3371	0.7744	1.297	1.7791
3	0.1735	0.3804	0.7985	1.2178	1.6374	0.1726	0.3964	0.9108	1.4816	2.0924

5.1.2 Site characteristic

Proper site selection is a crucial step in any project and can ensure the success of the plant, regardless of its future effects. Therefore, identification criteria may vary depending on the location, type of PV systems, and other design parameters. Table 4 provides a comparison between the crucial considerations for both ground-mounted and FPV systems in terms of site selection.

Table 4. Essential parameters in site evaluation for FPV and ground-mounted PV systems (Pimentel Da Silva and Branco, 2018; *Where Sun Meets Water : Floating Solar Market Report - Executive Summary*, 2018).

	Floating PV	**Ground-mounted PV**
Land/water surface use	• Does not compete with agricultural, industrial, or residential projects; • Ground excavation is less detrimental to the environment; • Often easier to find sites near densely populated areas; • A promising solution for archipelago countries; • Potential integration with aquaculture.	• Suitable/ affordable land may be far away from load centers, thus requiring costly transmission infrastructure; • Land excavation is generally energy/time-intensive; • Competes for land with city dwellings, industrial development, and agriculture though in certain cases integration is possible.
Power system benefits	• Adaptability with current electrical infrastructure (e.g. hydropower plants); • High potential to be incorporated with hydropower.	• Costs of grid interconnection are often borne by the project developer and can be prohibitively high.

5.1.3 PV panels

Silicon PV panels are the most common type used in ground-mounted and floating PV systems. However, in floating structures where the lighter mass and flexibility are more critical than conventional

PV systems, the flexible thin-film PV modules have shown promising advantages by floating on the waves and eliminating pontoon structure (Trapani and Millar, 2014; Trapani and Redón Santafé, 2015). To increase the flexibility and durability of thin-film modules integrated with floating systems, solar cells, air pockets, and ducts are embedded inside high transparent layers and then laminated tightly (Nagananthini et al., 2020). In a model proposed by Majid et al. (2014), a multi-crystalline PV panel attached with a hollow square aluminum heat sink at the bottom was encased inside a polyvinyl chloride (PVC) frame, which was equipped with hollow square aluminum as a heat sink. In this design, the trapped air inside PVC pipes keep the module float on the water surface and the aluminum heat exchanger was attached to the bottom of the PV, as shown in Fig. 25. Results indicated that the module is corrosion-free, durable, and viable to be used for floating systems in large-scale. One of the technical challenges of floating panels is Cadmium Chloride ($CdCl_2$), which is one of the most expensive and toxic materials that existed in PV panels and is easily replaced by Magnesium Chloride ($MgCl_2$) inside seawaters. This interaction could influence both the manufacturing process and the PV panels' price in off-shore projects (Sahu et al., 2016).

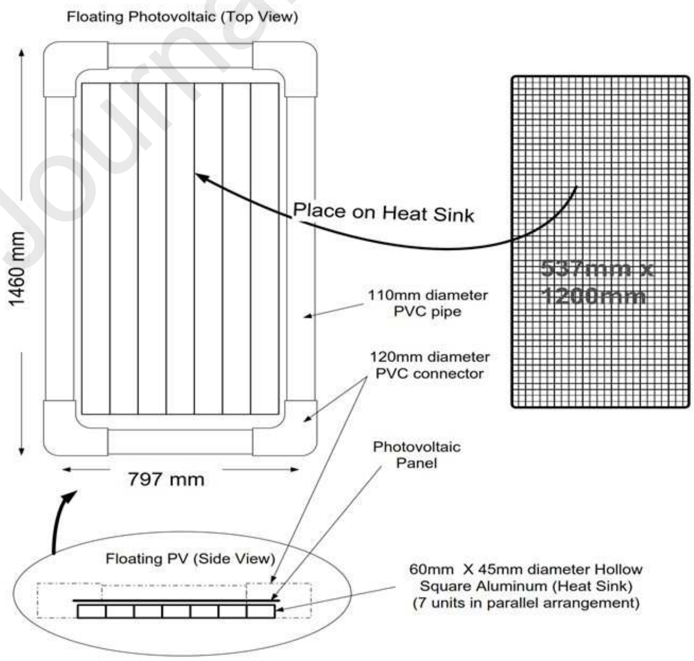

Figure 25. A FPV module incorporated with a PVC frame and an aluminum heat sink (Majid et al., 2014).

5.1.4 Tracking mechanism

Solar tracking is an enhancement technique to increase solar energy absorption and, consequently augment the power generated by the system. PV panels employed tracking systems are usually highly efficient and can be classified based on the degree of freedoms, namely one- and dual-axis tracking systems (Awasthi et al., 2020). Literature abounds numerous trackers for PV systems; however, there are some distinctive differences between the mechanisms used for terrestrial and floating ones. Firstly, in the design of tracking-type FPV plants, there is an additional disturbance from the floats that must be considered as well as azimuth- and tilt-tracking (Cazzaniga et al., 2018). Besides, the number of PV panels that can be used for a single tracking system in ground-mounted structures hardly exceeds 3 kW due to the implementation of cantilever mechanism for tracking in which the cantilever length grows with an increase in the weight of the PV module and external forces. Nevertheless, in floating structures, given the buoyancy effect exerted from water, self-weight is more easily resisted and the floating platform can be relatively large. As a result, a more straight-forward mechanism with lower energy is needed to rotate the platform up to 20 kW for tracking purposes (Choi et al., 2014).

5.2 Operational factors

5.2.1 Temperature

Temperature is a governing factor in PV panels and the rise in working temperature reduces power efficiency. As was discussed in Section 3, the implementation of cooling mechanisms is a promotion to solve the accumulation of heat on PV modules. The working temperature of solar cells can vary depending on the operating conditions. In this perspective, Charles Lawrence et al. (2017) proposed a model for the prediction of working temperature as a function of ambient temperature, solar irradiance, wind speed, and water temperature. Results revealed that a FPV with an annual mean temperature of 21.95°C can display an average efficiency of 14.69%. In another study, Liu et al. (2017) compared the ability of two identical PV panels, one terrestrial and one mounted on a floating structure. Temperature analysis showed that during the operation, floating systems experience a lower temperature than ground-mounted panels as shown in Fig. 26. Furthermore, having 3.5°C less working temperature, the crystalline PV cells (with the electricity temperature coefficient of 0.45 %/°C) employed with a FPV unit produced 1.58-2.00% more electricity than ground-mounted panels.

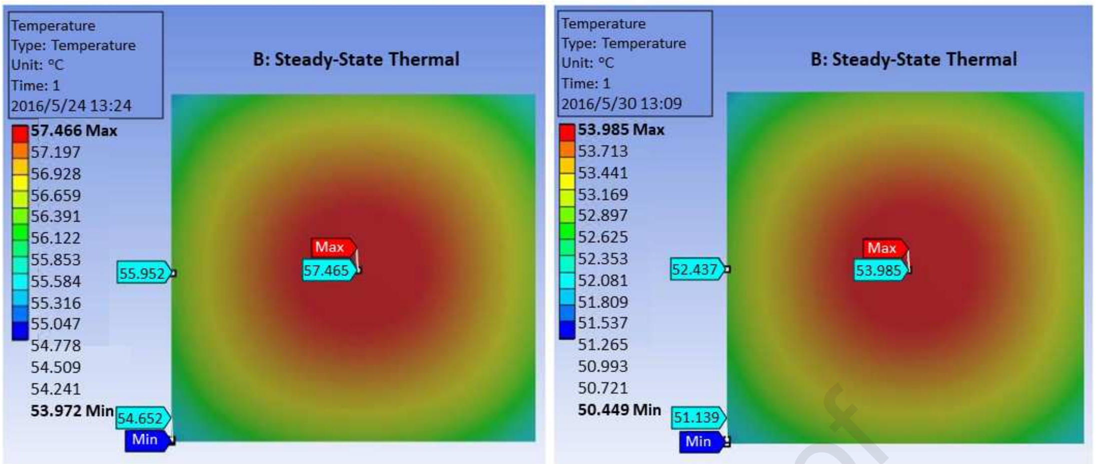

Figure 26. Temperature distribution during the operation (Liu et al., 2017); a) Terrestrial PV panel, b) FPV system.

An experimental investigation was conducted by Majid et al. (2014) to study the thermal behavior of a FPV equipped with an aluminum heat sink. Results showed that although FPV panels can cause 5.93% growth in power with a reduction of 18°C in temperature compared to conventional PVs, the implementation of a heat exchanger on the bottom side of the panel brings more enhancements up to 15.5%. Choi (2014a) demonstrated that water bodies provide a cooler environment during daytime operations hence the floating panels stay cooler than ground-mounted panels. Goswami et al. (2019) evaluated the potential of a 10 MW FPV plant and reported that "Heat Islanding"[1] which usually appears in terrestrial PV systems can be avoided with the development of floating plants. Fig. 27 shows how this effect can produce a surface temperature difference of 12°C between overland and floating PV modules.

5.2.2 *Albedo*

Albedo refers to the fraction of solar energy reflected from various surfaces in forms of direct and diffuse radiation (Rosa-Clot and Tina, 2018d). In the comparison between floating and terrestrial PV plants, this dimensionless factor can make considerable differences in power generation due to the diversity of albedo values induced by surrounding objects. In the case of ground-mounted PV systems, Schindele et al. (2020) reported that albedo factor and installation height could be highly influential on the amount of power produced by an agrivoltaic (APV)[2] plant, which can bring about 8% annual enhancement.

[1] Heat Islanding effect refers to the heat trapped between the soil and PV modules.
[2] Co-production of food and electricity on the same land.

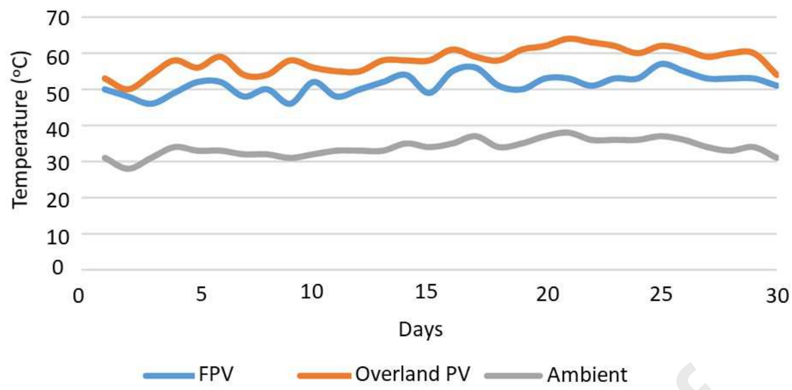

Figure 27. Temperature variations of overland and floating PV modules (Goswami et al., 2019).

Gul et al. (2018) asserted that some of the essential ground-based objects that affect the power production are aluminum foil, white tiles, whiteboard paint, white pebbles, sand, grass, and cement slabs with the albedo values range from 0.19 to 0.75. Cazzaniga et al. (2019) observed that there is an imbalance between the land albedo (high reflection) and the installed terrestrial PV panels (high absorption and low reflection), which modifies the mean radiation balance and local temperature. Due to the lower albedo factor (nearly 5%) in water, floating plants cannot possess such an effect. In another study by Cazzaniga (2018), it was concluded that when PV panels are south-oriented, the fraction of solar energy reflected from the water body could hardly enhance the power generation over 2.2%. However, a higher reflection from water in the upper direction could yield a better result with the integration of bifacial PVs. Other studies (Campana et al., 2019; Oliveira-Pinto and Stokkermans, 2020a) have echoed the positive influence of the water albedo on power production in FPV systems. Although Temiz and Javani (2020) claimed that water albedo is higher than terra, which offers an enhanced solar absorption for FPVs, other references have declined the superiority of albedo effect in floating systems over the ground-mounted systems.

Liu et al. (2018) experimentally investigated the behavior of albedo factors under land and water PV installations. Fig. 28 shows that the obtained value on the water varies between 5 to 7%, while the rooftop albedo was 13%. Patel and Rix (2019) proposed a model to estimate the albedo factor for the FPV system and observed that the value is not constant for smooth waters where temperature and wavelength had the least effects while the sun’s position was the prominent factor. Therefore, the highest albedo was recorded at early hours in the morning and late afternoon, as also demonstrated in Fig. 28a. Accordingly, the average albedo value of 2%, which is mostly recommended in the literature, is claimed to be higher than those obtained during the simulations. However, Rosa-Clot and Tina (2018d) argued that in addition to the light wavelength, wind speed and the characteristics of water surface (water turbidity, waves, and sunlight) are influential on water reflection (roughly 5%) which is far less than land albedo (20-60%). Table 5 presents other distinctive differences in the operating characteristics of floating and ground-mounted PV systems.

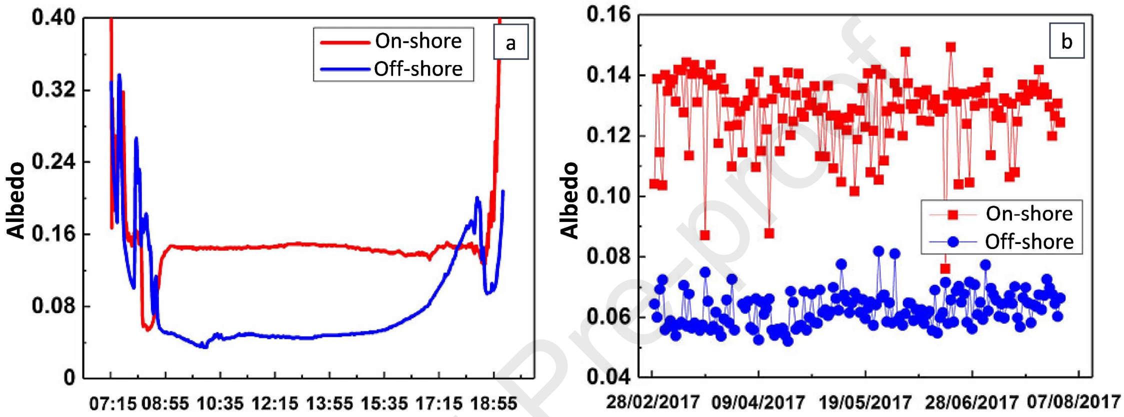

Figure 28. Comparison of albedo for on-shore and off-shore PV installations; a) Daily profile, b) 4-month profile (Liu et al., 2018).

Table 5. Comparative insight into the operating features of PV application for land- and water-based regions (Golroodbari and Sark, 2020; *Where Sun Meets Water : Floating Solar Market Report - Executive Summary*, 2018).

Type of PV System	Floating PV	Ground-mounted PV
Operating Environment	• Open and flat surface; • Low reflected diffuse light from water surface; • The general presence of evaporative cooling and higher wind speed; • Presence of dynamic movement; • Less seasonal temperature fluctuations.	• Terrain type may vary; • Albedo depends on ground type; • No movement; • The average temperature difference between the PV panel and the environment is higher.
Losses	• Lower module temperature (magnitude depends on climate); • Nearly no shading from nearby objects; • Less soiling from dust, but potentially more from bird droppings; • Potential mismatch loss from temperature	• More temperature loss hot and arid lands; • More sources of shading and string mismatch.

	inhomogeneity and misalignment in module facing; • Winter season causes enormous variation in the tilt angle.	
Performance	• Overall higher initial performance ratio (5-10%, climate-specific); • Higher energy production in all seasons with the highest in summer by 6% increase, and the least in winter with nearly 2% growth. The annual average performance can be more as much as 13%; • Long-term degradation (e.g., potential induced degradation) is still uncertain	• Higher potential for tracking, bifacial modules, and optimum tilt angle/ row spacing; • Yield prediction is better understood.

5.3 Maintenance factors

Cleaning is one of the essential practices during the operation of PV systems, which not only boosts the efficiency of the plant to a great extent but also increases the lifespan of the module. According to the literature (*Where Sun Meets Water : Floating Solar Market Report - Executive Summary*, 2018), soiling is a location-dependent issue and the presence of substances such as dust, dirt, biomass particles, leaves, bird droppings, salt, and scale deposits can significantly affect the PV conversion efficiency. The salt deposition is one of the specific conditions that refer only to off-shore systems and its corrosive nature can bring damage to the balance of system (BOS) of PV power plants (Setiawan et al., 2019). Although the PV panels are usually protected from rust, the deposition of salt can block the light path and mitigate power efficiency. Gretkowska (2018) investigated the effects of salt accumulation on PV panels by simulating FPV modules working in a marine environment. Results indicated that after 30 days of wetting with saline water, power performance shrunk by 14 to 28% and 13 to 25% respectively for simulation procedures of immersion and dripping. Moreover, it was recommended that those PV modules employed in floating projects must be protected from direct contact with saline water, and the selection of adequate PV technology is critical as Copper Indium Gallium Selenide (CIGS) PV technology showed the most impact from the salt deposition.

In another effort, Setiawan et al. (2019) explored the behavior of PV panels under the off-shore floating conditions by splashing seawater on the modules. As shown in Fig. 29, the accumulation of salt particles after three days of treatment could result in a drop of 1.3778 W and 0.948 in power and efficiency respectively, which may be more pronounced in long-term operation. Like most ground-mounted projects, floating plants could benefit from cooling systems for cleaning purposes as well. However, despite the conventional PV systems, water availability and energy requirement for pumping in FPV plants are more convenient and justifiable (Cazzaniga et al., 2018). On the other hand, maintenance operation may be more expensive due to the costs of specialized required equipment such as workboats and winches (Menicou and Vassiliou, 2010). Weeding is a prominent problem that emerged in the ground-mounted PV system which implies drastic costs for cleaning and maintenance duties. However, in terms of installation on water surfaces, this is not an issue to be considered (Cazzaniga et al., 2018). Humidity is the other threat posed exclusively to the long-term operation of FPV systems installed above both freshwater reservoirs or seawaters. In environments with relative humidity above 70%, the risk of moisture penetration is high, which increases necrosis in the polymers and causes yellowing of the color of PV modules (Hamdi et al., 2018). A comparative insight is given in Table 6 to present the features of each technology based on the maintenance aspects.

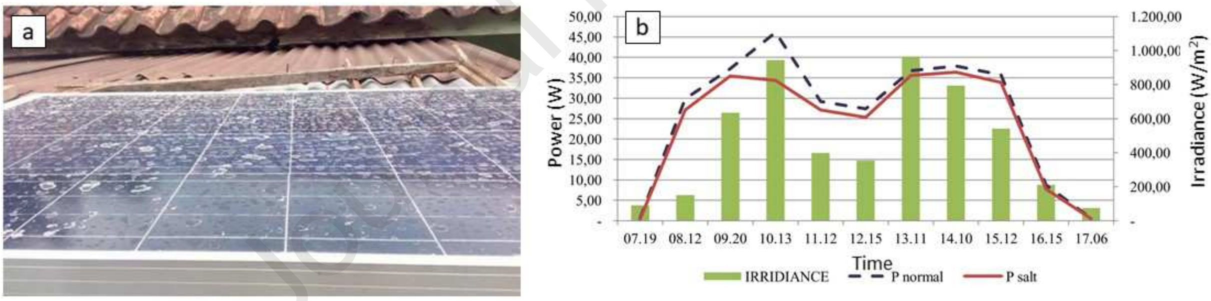

Figure 29. a) Salt deposition after three days of seawater splashing; b) Variations in power generated by normal and treated panels respect to solar radiation (Setiawan et al., 2019).

Table 6. Different features of floating and ground-mounted PV systems (*Where Sun Meets Water : Floating Solar Market Report - Executive Summary*, 2018).

Item	Floating PV	Ground-mounted PV
Technical	• More difficult to reach parts and replace them; • Bio-fouling likely; • Higher humidity increases corrosion/oxidation of metal parts; • More replacement for structural components;	• Easier to access parts for repair and replacement; • More vegetation; • Easier to implement automated cleaning routines; • Less maintenance for civil work and ground

	• Easier access to water for cleaning; • Lower risk of vandalism and theft.	foundations.
Safety	• The constant movement of floats poses walking hazards; • Risk of personnel falling into the water.	• Generally safe, with the stable ground for walking.

6 Effect of FPV panels on reducing evaporation in water reservoirs

Evaporation of water from the free surface of water bodies depends on various factors like water surface temperature, air temperature, relative humidity of the air, vapor pressure, etc. Evaporation can occur when there is a flow of energy to provide latent heat of vaporization and a heat sink for removing vapor (Sinclair, 2019). Generally, some models are used for estimating water loss from water bodies by evaporation which are discussed here.

- *Penman Monteith model – evaporation rate in mm/d* (Bontempo Scavo et al., 2020):

$$E = \left(\frac{0.404\Delta(Q^* - N) + \gamma \frac{900 u_2 (e_s - e_a)}{(T_a + 273)}}{\Delta + \gamma(1 + 0.34 u_2)} \right) \quad (3)$$

Where Q^*(MJ/m^2-d) is net radiation, N (MJ/m^2-d) is the change in heat storage in the water body, T_a(°C) is the mean air temperature, Δ (kPa/°C) is the saturation slope of the vapor pressure curve at T_a, γ (kPa/°C) is the psychometric constant, u_2(m/s) is the average hourly wind velocity, e_s(kPa) is the saturation vapor pressure, and e_a(kPa) is the average hourly actual vapor pressure.

- *Penman Monteith modified model- evaporation rate in mm/d* (McJannet et al., 2008):

$$E = \frac{1}{\lambda} \left(\frac{\Delta w (Q^* - N) + \frac{86400 \rho_a c_a (e_w^* - e_a)}{r_a}}{\Delta w + \gamma} \right)$$

(4)

Where λ(MJ/kg) is the latent heat of vaporization, Δw(kPa/°C) is the slope of the temperature saturation water vapor curve at water temperature, Q^*(MJ/m^2-d) is the net radiation, N(MJ/m^2-d) is the change in heat storage in the water body, ρ_a(kg/m^3) is the density of air, c_a (MJ/kgK) is the specific heat of the air, e^*_w (kPa) is the saturated vapor pressure at the water temperature, r_a(s/m) is the aerodynamic resistance, and γ(kPa/°C) is the psychometric constant.

In the case of Penman equations, several environmental parameters are used to estimate the evaporation rate of water bodies. But, most of the weather monitoring locations around the globe do not have facilities to measure these parameters. Net radiation and vapor pressure difference terms in Penman equations are generally calculated using several other parameters, including latent heat of vaporization, saturation vapor pressure, psychometric coefficient, atmospheric pressure, clear sky solar radiation, etc. This makes the calculation more complex and may result in some errors (Valiantzas, 2006). In this regard, Valiantzas developed the evaporation model as a function of weather data which is usually measured in most of the stations.

- *Valiantzas model – evaporation rate in mm/d* (Valiantzas, 2006):

$$E = 0.051(1-\alpha)R_s\sqrt{T+9.5} - 0.188(T+13)\left(\frac{R_s}{R_a} - 0.194\right)\left(1 - 0.00014(0.7T_{max} + 0.3T_{min} + 46)^2\sqrt{\frac{RH}{100}}\right) + 0.049(T_{max} + 16.3)\left(1 - \frac{RH}{100}\right)(0.62 + 0.53u_2)$$

(5)

Where α is the reflection coefficient of albedo (0.08 for open water surface), and T(°C) which is the mean air temperature is generally estimated by $0.5(T_{max} + T_{min})$, R_a (MJ/m^2-d) is the extraterrestrial solar radiation, R_s (MJ/m^2-d) is the measured solar radiation, and RH(%) is the relative humidity.

- *Rohwer model – evaporation rate in inches/d* (Rohwer, 1931):

$$E = 0.44(1 + 0.27u_{10})(e_s - e_d)$$

(6)

Where e_s is the mean saturation vapor pressure at the temperature of water surface (inches of Hg), e_d is the mean saturation vapor pressure at the dew point of air (inches of Hg), and u_{10}(miles/h) is the mean wind velocity.

- *McGuiness and Bordne model – evaporation rate in mm/d* (McGuinness, 1972):

$$E = (0.082T - 0.19)\left(\frac{R_s}{1500}\right)2.54$$

(7)

- *Hargreaves model – evaporation rate in mm/d* (Hargreaves and Allen, 2003):

$$E = 0.408 \times 0.0025(T + 16.8)(T_{max} - T_{min})^{0.5} R_a$$

(8)

The accuracy of various evaporation models has been reported by (Bontempo Scavo et al., 2020) using the experimental data collected from Lentini Lake, Italy which has a depth and surface area of about 10 m and 12,000,000 m^2, respectively (Table 7). Results indicated that Penman Monteith's model is more accurate in predicting values. Yearly water loss from the lake by evaporation was about 1,743 mm/y and it corresponds to 20,920,000 m^3/y.

Table 7. Comparison of predicted evaporation rates with experiment values (Bontempo Scavo et al., 2020).

Models/Measurement	**E (mm/150 days)**	**ΔE (%)**
Measurement	303.21	0.00
Penman Monteith	309.82	-2.18
Penman Monteith modified	291.24	3.94
Valiantzas	293.99	3.04
Rohwer	268.49	11.45
Mc Guinness Bordne	297.35	1.93
Hargreaves	313.39	-3.36

The loss of water can be prevented by installing FPV systems over the lake thereby the conserved water can be used for other useful purposes (Sahu et al., 2016). Energy and mass balance for uncovered and FPV-covered reservoirs is shown in Fig.30. For FPV installed water bodies, the total evaporation rate is estimated by summing up evaporation on the free water surface and evaporation on the area covered by FPV. It can be mathematically expressed as (Bontempo Scavo et al., 2020):

$$E_{FPVS} = (1 - X)E + XE_{cover}$$

(9)

Where X is the fraction of water surface covered by FPV and Q* is the net radiation on the free surface of the water which is given by,

$$Q^* = SW_n + LW_n$$

(10)

Where,

$SW_n = (1-\alpha)(R_d + R_b)$, and (11)

$LW_n = \sigma(T_w)^4(0.56 - 0.0092(e_a)^{1/2})(0.10 + 0.90C)$ (12)

Where C is the cloudiness function, σ is Stefan-Boltzmann constant, T_w(°C) is the mean daily temperature of water, SW_n(MJ/m^2-d) is the net contribution by short wave radiation, and LW_n(MJ/m^2-d) is the net contribution by longwave radiation, R_b and R_d are direct and diffuse horizontal solar radiation (MJ/m^2-d). For suspended PV covers, only diffuse component of solar radiation reaches the water surface beneath it. Similarly, for estimating longwave contribution full cloudy condition is assumed hence the value of C is equal to 0.30. Canal top PV system and buoyancy supported modules come under suspended PV covers which are shown in Fig.31. Net radiation reaching water surface beneath suspended PV covers is given by (McJannet et al., 2008),

$$Q^* = (1-\alpha)(R_d) + \sigma(T_w+273)^4(0.56 - 0.0092(e_a)^{1/2})(0.10 + (0.90\times0.30)) \quad (13)$$

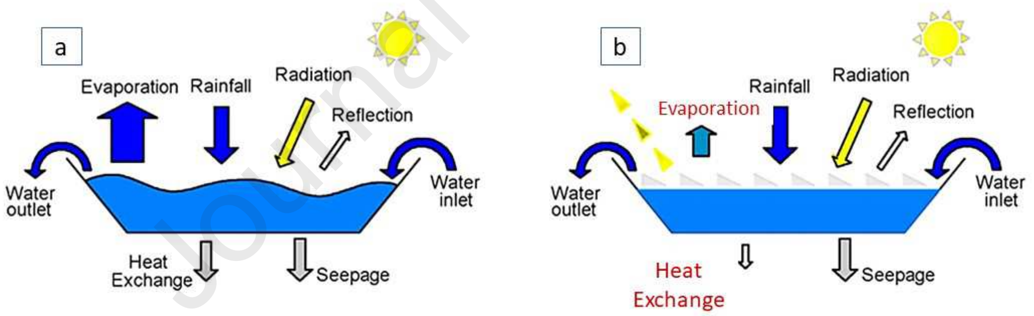

Figure 30. Energy and mass balance for: a) Uncovered irrigation reservoir and, b) FPV covered irrigation reservoir (Redón Santafé et al., 2014).

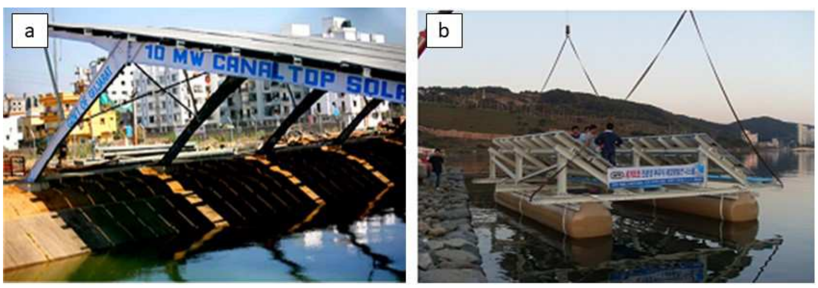

Figure 31. a) Canal top FPV system (suspended type) (Kumar et al., 2020), b) PV modules anchored to a buoyancy system (suspended type) (Lee et al., 2014).

The net radiation received the water surface in the case of flexible floats is estimated as (Bontempo Scavo et al., 2020),

$$Q^* = 0.40(\alpha_{PV}\ (1-\eta_{el})\ (R_b + R_d)) + \sigma\ (T_w + 273)^4(0.56 - 0.0092(e_a)^{1/2})\ (0.10) \quad (14)$$

Where η_{el} (%) is the electrical efficiency, and α_{pv} is the absorptivity of the PV panel. In the case of flexible floats, the contribution of shortwave radiation is not zero as 40.0% of the reduced solar radiation incident over the flexible PV panel is transferred to the water surface. Floating PV covers do not allow any radiation to reach the water surface below it. Therefore, short wave contribution is eliminated, and for longwave radiation case, the C value is equal to zero. In these cases, the net radiation is estimated as (Bontempo Scavo et al., 2020):

$$Q^* = \sigma\ (T_w + 273)^4(0.56 - 0.0092(e_a)^{1/2})\ (0.10) \quad (15)$$

Net radiation at the water surface estimated from the above equations can be used to predict evaporation loss with cover for various types of floats using the Penman Monteith model/modified model. Percentage reduction in evaporation rates due to the adaption of different types of FPV over the “Biviere di Lentini” basin Catania is presented in Table 8.

Table 8. Percentage savings in water due to the adaption of FPV over the water body (Bontempo Scavo et al., 2020).

Cover %	Suspended FPV	Floating FPV on Pontoons	Flexible FPV
0	0.0	0.0	0.0
10	6.0	18.0	15.0
30	18.0	49.0	42.0
50	30.0	73.0	64.0
70	42.0	89.0	82.0
100	60.0	100.0	100.0

7 Economics and environmental impacts

Any newly developed technology can be implemented only if it has a low negative impact on the environment and also it is economical for large scale deployments. In this section, the environmental impacts of FPVs ranging from its commissioning to decommissioning along with various factors influencing the economics of this technology are presented and discussed based on the available literature.

7.1 Environmental impacts (EIs)

In recent years, FPVs have undergone sudden growth all over the world, specifically between 2017 and 2018 the installed cumulative power went from 528 to 1,314 MWp (*Where Sun Meets Water : Floating Solar Market Report*, 2019). This growth is also linked to their low environmental impacts (EIs). In general, the EIs of both ground-mounted and FPV systems are not nil, as the manufacturing processes of PV modules, inverters, and all the composed components require huge amounts of energy and release harmful substances in the environment (Aman et al., 2015). However, during the operating phase, a FPV system shows positive impacts such as being completely silent, allowing for a reduction in the growth of algae in the presence of eutrophication, producing clean electrical energy with no CO_2 emission, saving water resources by preventing evaporation, less water requirement for cleaning PV modules (Cazzaniga et al., 2018), saving valuable lands for agriculture, mining, tourism, and other activities due to installing PV panels over water bodies, reducing bird collision with panels compared to the ground-mounted systems (Pimentel Da Silva and Branco, 2018), and improving the quality of the water of reservoirs (Baradei and Sadeq, 2020). Pimentel Da Silva et al. (2020) proposed a multi-criteria modeling approach to assess the extent and importance of the environmental and socio-economic impacts of ground-mounted and floating large-scale PV (LSPV) systems. Liu et al. (2020) provided an assessment of both the environmental impacts and synergies between economic benefits and environmental impacts without considering CO_2 emissions. The model consisted of the cross-spectrum analysis to evaluate the coherent fluctuation between economic and environmental benefits. An empirical study was conducted by Hass et al. (2020) on a demonstration project for the integration of a fishing farm and 10 MW photovoltaics in the Chinese province of Jiangsu. The model was capable of providing the optimal sizing in terms of the interaction between the FPV system and the environment of a hydroelectric power station. They concluded that the FPV should ideally be sized between 40-60% of the lake surface.

7.1.1 EIs of plant design and allocation

In the sitting phase, it is necessary to look for potential sites whose impacts on flora, fauna, air, and water are as low as possible, because, in both construction and operating phases, local ecosystems could be altered (Gasparatos et al., 2017). Therefore, basins in unprotected areas without particular plants, protected animal species, and environmental restrictions are recommended (Choi, 2014c). Estimates on real data (Lovich and Ennen, 2011) of installations in the US indicate that for utility-scale plants the dimensions are (in ha/MW_{ac}): 2.22 for fixed systems, 3.81 for two-axis tracking systems both with power between 1 MW and less than 20 MW, while 2.34 for fixed systems and 3.64 for one-axis systems both with a power greater than 20 MW.

Unlike the soil, water has a perfectly flat and regular surface which reduces the effect of mutual shading of the rows of modules and allows for a more compact system as the spacing between the modules is not a function of the soil conformation. Besides, the occupation of land is limited to the energy transformer substations and the road cable ducts excluding the surface of modules (Gasparatos et al., 2017). The visual impact of ground-mounted PV systems can be high which can be solved through careful design by considering PV panels as architectural elements. As far as floating systems are concerned, bamboo buoyancy systems are proposed in the literature (Fig.32) that minimize both the visual and polluting impact since they are made of natural raw materials with a lifetime of more than 10 years in water (Rosa-Clot and Tina, 2018c).

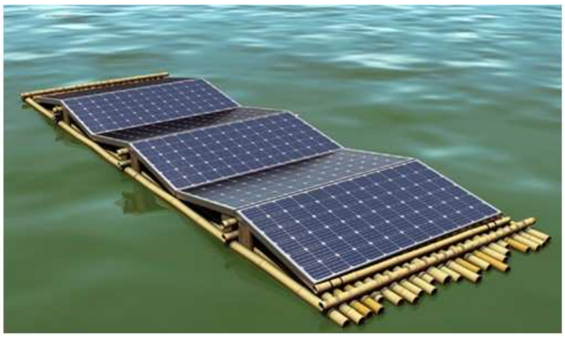

Figure 32. PV modules installed on a floating base made of Bamboo (Rosa-Clot and Tina, 2018c).

7.1.2 EIs during plant construction

In the implementation phase, the EIs that can occur are of different types and entities. For example, access to the site is a potential impact that can cause deforestation. As for floating systems, this impact could be limited since the allocation of the modules takes place on the surface of the water. The transit of heavy vehicles or boats for the construction and transportation of materials are potential causes of noise and air pollution. Although these items all generated noise, it is at lower levels in comparison with industrial noise guidelines and occupational noise levels, and therefore it doesn't cause environmental, health, or safety impacts (Guerin, 2017). Also, the impact of noise is truly negligible because the construction phase duration is much shorter than the life cycle (20 years) of the plant. Moreover, both large ground-mounted PV plants and FPV plants are often constructed far from settlements, so the impact of noise affects very few people. Also, the leakage of polluting materials in the water (such as oil, fuel, etc.) of the working machines (for example boats) can be harmful to the lake environment. The positioning of ballasts for anchors on the bottom of the basins certainly causes water mixing and therefore cloudiness which could cause loss of habitat of the fauna in the water (Pimentel Da Silva and Branco, 2018). At this stage, noise pollution is also necessary to be considered as an EI. It is mainly linked to the movement of vehicles for the construction of the plant and could harm the fauna in the surrounding environment. The time required for the installation of FPV systems has not yet been fully defined since unlike ground installations, site preparation is eliminated (suppressing vegetation and civil infrastructure). Nonetheless, the FPV installation can be complex as some working phases take place in water (Pimentel Da Silva and Branco, 2018). Usually, the construction phase for plants on the ground that vary from 1 to 5 MW of capacity lasts up to 100 days, while for plants greater than 25 MW, it lasts more than 210 days (*Solar Power Jobs : Exploring the Employment Potential in India's Grid-Connected Solar Market*, 2014).

7.1.3 EIs during plant operation

A phase that requires more attention, in the case of floating systems, is that of operation since there are no exhaustive studies that quantify/qualify the real impact and causes of the interaction between the surrounding environment and the system. This is also due to the recent birth of this technology, and therefore the absence of long-term data.

Conventional ground-mounted PV systems require a quantity of water and other chemicals to clean the modules. It is clear that chemicals are extremely toxic to the environment and could impose many negative impacts on fauna and flora during a long period (Lovich and Ennen, 2011). The potential contamination of water through these substances can result in the mortality of fishes and other aquatic species or the alteration of the water quality because of the growth of algae and loss of oxygen in the water. In FPVs, it is necessary to limit or even change cleaning methods, not using chemical materials that can contaminate and pollute the reservoir. Additionally, floating systems require less water for cleaning as the system is positioned away from the ground and the effects of dust carried by the wind are also eliminated (Rosa-Clot, 2020).

Besides, unlike ground-mounted systems (especially for those in desert environments), water is easily available and in the immediate vicinity. Bird activities and specifically bird droppings may bring some disadvantages, however, no influence has been reported from FPV on bird fauna (Rosa-Clot, 2020) (Fig.33). In this phase, there could also be the risk of contaminating water with oils, lubricants, fuels, paints, when mechanical devices for maintenance are moved, and with material scraps due to corrosion (Costa, 2017). During maintenance, it is important to also take into account waste management which mainly consists of following the management plan and guidelines for the replacement and disposal of batteries (if any), panels, and other defective equipment (Aman et al., 2015). Partial or total coverage of the water surface reduces algae growth. This positive impact could be useful for lakes where eutrophication problems occur. Eutrophication is the abnormal growth of algae (and other aquatic plants) and is sometimes referred to as "green tide" which can also lead to the establishment of highly anoxic conditions which is the main cause of fish death and foul-smelling emissions (Cazzaniga et al., 2018).

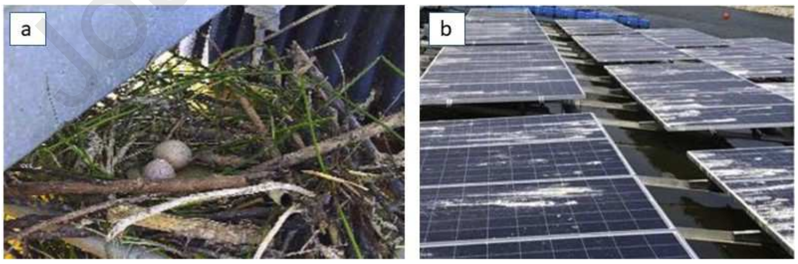

Figure 33. a) Nesting of Seagull (Suvereto FPV plant), b) Birds droppings on modules (SERIS[1] testbed) (Rosa-Clot, 2020).

Fig. 34 shows a case of excessive algae blooms on water basins. However, it is not recommended to cover the entire surface (Haas et al., 2020), particularly in lakes with living organisms, to ensure the

[1] Solar Energy Research Institute of Singapore

penetration of sunlight and the production of oxygen through photosynthetic organisms. Reducing oxygenation can even increase GHG emissions from the tank (Marco Antonio Esteves Galdino and Marta Maria de Almeida Olivieri, 2017). Hence, installations on natural lakes could create further consequences than artificial water surfaces. The environmental impact deriving from the quality of the water can be resolved by installing systems for monitoring the water state (Rosa-Clot and Tina, 2018a). To mitigate the effect of reducing the penetration of solar radiation in the basin, it is possible to adopt technologies of PV modules called "bifacial" which have a double advantage: increasing the energy produced compared to the conventional mono-facial modules, and avoiding the complete darkening of the water body as they are not completely opaque (usually the filling factor of the cells is from 80 to 90%) (Tina et al., 2020). Some associated risks can also arise from the aquatic animals on the FPV systems (Fig. 34b).

Figure 34. a) Dense bloom of algae in which interventions are required to control the water quality, b) Animal visit in FPV system (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Sometimes animals may vandalize structural components or cables. Barrier methods must be employed during the operating and maintenance (O&M) stages to prevent animal visits. Non-barrier methods such as laser-beam equipment could also be a practical technique in this way. It is also important to maintain such equipment per the supplier's recommendation. In some cases, it is essential to store anti-venom at the O&M site office and identify the nearest medical center for emergency cases to mitigate snakebite threats. It is important to maintain both the equipment and personnel safety at all times (*Where Sun Meets Water : Floating Solar Market Report*, 2019). The floating structures could also reduce the formation of waves by reducing the effect of wind on the free surface of the water. Other impacts of FPVs on lakes and the aquatic environment may involve the electromagnetic field produced by conductors installed on the bottom or surface of the lake (Costa, 2017). Most of the floating systems are made of HDPE which are in different shapes and types of floats. In reality, direct contact with water (20% or more according to the proposed technical solution) occurs mainly through HDPE pipes that support galvanized steel structures or through rafts completely built-in HDPE. Galvanized iron (or aluminum) is not in direct contact with water, but for various reasons, including rain or waves, these structures and PV modules can be wetted with water and can release small quantities of materials that can be dissolved in the water (Cazzaniga, 2020; *Where Sun Meets Water : Floating Solar Market Report - Executive Summary*, 2018).

7.1.4 EIs of plant decommissioning

The environmental impact deriving from the decommissioning phase essentially consists in the change of the geomorphology of the lake bottom caused by the removal of the ballast and the anchors of the plant; short-term change in water quality, due to mixing for handling and therefore cloudiness; increase in noise caused by the traffic of vehicles and machinery; recycling and management of waste deriving from the uninstallation process (Pimentel Da Silva and Branco, 2018). However, it should be noted that, unlike ground-mounted systems, floating systems, at least as regards the surface of the water, do not require any remediation. This aspect is important because it reduces the impact due to the noise of the vehicles, pollution, and changes in the geomorphology of the soil (Sahu et al., 2016).

7.2 Economic analysis of FPV systems

Unlike the ground-mounted PV plants, floating systems are still in the first phase of the learning curve. There are not enough installations to be able to make an accurate analysis of installation, maintenance, and operating costs. The support, mooring, anchoring, and floating systems are constantly changing, improving, and optimizing. Therefore, the assessments could undergo drastic changes, positively, in the near future when the technology of the entire system will be established as well as that of the systems on the ground.

7.2.1 Capital expenditure (CAPEX)

To evaluate the implementation costs of a PV system, the actions are required to make the system working. Below are the components of a FPV system along with some comments on costs (Sahu et al., 2016):

- **Floats*:*** they are generally made of HDPE or glass fiber reinforced plastic (GRP). Concerning the type chosen, the cost can change considerably. These components are not used in ground systems.

- **Moorings*:*** the installation of a mooring system can be expensive in deep water or where the change in water level is relatively large. These components are not used in ground systems.
- **PV modules:** they are the same as those used for ground systems, or with a higher protection index (in this case they could be more expensive) to avoid the penetration of water into them.
- **Cables and connectors:** for application in water, special cables should be installed. Even if there is no electrical component under the water, waterproof IP67 junction boxes are recommended which are more expensive.
- **Other electrical components, inverters and/or batteries:** they are installed on the ground or floating cabins; therefore, they work in normal conditions as in conventional ground systems.

The construction of FPV systems entails different costs as some works are carried out in the water with all their difficulties. In a study by Martins (2019), it was reported that labor cost for the ground-mounted system is equal to 40 US$/h, while for the FPVs it is increased as 60 US$/h. These additional costs could be offset by the fact that the system does not use the soil, which leads to overall lower costs. As mentioned above, the water surface is immediately usable without the need for levelling works as in the case of the ground. Besides, the soil resource plays an important role in terms of cost and can be relevant where there is scarcity. In particular, solar radiation measurements, bathymetry and lake bottoms, wind and wave surveys, grid connection studies, possible ship traffic surveys, and environmental impact assessments (EIAs) are considered essential on large lakes and are estimated in the range € 20-70 k per study (Barbuscia, 2017).

In a study by Galdino and Olivieri (2017), the installation cost for a 1.2 MWp plant was reported 30% higher than that of a ground-mounted system due to the utilization of a premature technology which has not been fully optimized yet for systems of this size. Teixeira et al. (2015) conducted an economic feasibility study of a hybrid hydro-FPV system in which he declared a 30% increase in costs for the FPV when compared with a ground-mounted system. An estimate made in Ref. ("Sonoma County Is Building the Largest Floating Solar Project in the US | Greentech Media," n.d.) states that floating systems with an installed capacity greater than 10 MWp would have a cost similar to ground-mounted installations. The plants described in Ref. ("K-water English," n.d.) with 100 kWp and 500 kWp capacities had a cost of US$ 6.4/Wp and US$ 4.35/Wp respectively. It was claimed that the cost reduction in the second case was due to system optimization. Oliveira-Pinto and Stokkermans (2020) indicated that CAPEX for FPV systems is generally 25% higher than ground systems, mainly due to floats, moorings, and anchors. In Ref. (*Where Sun Meets Water : Floating Solar Market Report*, 2019), it has been stated that the average total investment cost of a FPV system in 2018 ranged between 0.8 US$/Wp and 1.2 US$/Wp, depending on the size and location of the system. It was reported that the CAPEX of large-scale FPV projects (around 50 MWp) is between 0.7 and 0.8 US$/Wp in the third and fourth quarters of 2018, depending on the location and type of installed modules.

The CAPEX of a hypothetical 50 MWp FPV installation was calculated and compared with a land-based system (both with fixed inclination) in the same position. For PV modules a cost of US$ 0.25/Wp was considered, while for inverters, a cost of 0.06 US$/Wp for both the ground and floating system was obtained. For assembling systems, a cost of US$ 0.15/Wp for the FPV and US$ 0.10/Wp for the ground system, for the BOS (balance of system) US$ 0.13/Wp and US$ 0.08/Wp for the FPV and the ground system respectively, US$ 0.14/Wp and US$ 0.13/Wp, respectively was considered. These resulted in overall CAPEX of US$ 0.73/Wp for the FPV and US$ 0.62/Wp for the ground system (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

Rosa Clot and Tina (2020) made a list of the costs for building a FPV plant for various proposed technological solutions. They assumed that the cost relating to the PV modules is 0.25 US$/W, the electrical components including cables and inverters is 0.12 US$/W, the galvanized steel is 2.20 US$/kg, and finally, the cost of the HDPE is 2.40 US$/kg. Starting from this hypothesis, they proposed three types of 1 MW plant that cost respectively: US$ 803,692 the Singapore Solution, US$ 590,556 the Gable "Slender" Solution, and US$ 630,106 Gable2 Solution and compared them with a ground-mounted system with a total cost of US$ 630,700. As can be seen, only in the case of the Singapore Solution the cost of the system in the water is higher than that of the ground installation.

7.2.2 Operating expense (OPEX)

The costs related to the operational phase are for leasing or renting the space in which the system will be installed, operation and maintenance, and insurance. In the case of FPV systems, the rent could be less expensive as the water surface cannot be used for other purposes (i.e. agriculture or construction). The O&M costs of a PV system generally consist of the replacement of faulty and malfunctioning devices or objects (inverters, PV modules, electrical and electronic components), and cleaning of PV modules (*Where Sun Meets Water : Floating Solar Market Report - Executive Summary*, 2018). Generally, for ground-mounted systems, especially in desert areas where there is a presence of dust, the latter component is important and expensive. Besides, the soil may need to be periodically cleaned, as the presence of spontaneous vegetation (shrubs, brushwood, dry material) could reduce the performance of the plants and cause fires in the summer season. Therefore, the conditions in which the FPV systems are operating, in this sense, could be advantageous as there is the availability of large quantities of water near the plant and the absence of growth of wild plant species near the modules. Maintenance costs could be different between the conventional and floating systems since in the latter:

- Moorings, submarine cables, or floating platforms require different knowledge, tools, and processing times.
- It may be necessary to act on the moorings in case of a change in the level of the lake beyond the limit concerning the permitted one (a practical example is the maintenance of the floating system installed in the laboratories of the Enel Innovation Lab in Catania (IT) consists of adjusting the length of the moorings in conditions where the level of the basin has fallen beyond the minimum level).
- There may be a cleaning and cooling system that requires maintenance and cleaning of the filters of the water suction pumps due to the excessive turbidity of the water.
- Modules may need to be cleaned more frequently due to bird droppings.
- Checking for any malfunctions or wear of cables submerged in water, specialized personnel, divers, or robots capable of carrying out inspections under the water may be required.
- Maintenance takes place mainly on the water with vehicles such as boats, which could be among the items of expenditure in the OPEX phase if not already present on site.

As for insurance, it depends on many factors but also on the location and weather variables. According to Ref. (*Where Sun Meets Water : Floating Solar Market Report*, 2019), the annual cost of insurance can vary from %0.25 to %0.5 of CAPEX. Maintenance and operating costs for a conventional utility-scale ground system, declared by NREL in 2018 for the US, was 0.0154 US$/Wp/year. However, 0.009 US$/Wp/year was reported in Lazard and 2.5% of the CAPEX was reported by Fraunhofer. A study on the costs of ground-mounted PV systems, projected up to 2050, stated that OPEX in Germany in 2019 was 9.2 €/kWp/a (Vartiainen et al., 2020). It has also been shown that OPEX will decrease by about 30% and 50% until 2030 and 2050 respectively. In Ref. (Rodrigues et al., 2020), it has been stated that the plausible values for the OPEX costs for floating installation on dams are two-fold of the OPEX costs on the ground. For FPV systems, most of the maintenance is allocated to inverters which imposed costs ranging from 6.15 to 9.50 US$/kWp. In a study by Martin (2019), it was stated that the OPEX costs in the economic evaluation phase for the comparison between the ground-mounted and floating systems are 0.013 US$/Wp/year and 0.026 US$/Wp/year respectively. This is because the working conditions in the FPV could be more complex than the ground system. Rosa-Clot and Tina (2020c) stated that the maintenance costs are constant throughout the life cycle and limited for the floating system (with some increases if a localization system is implemented) and on average are higher for a ground system. Regarding the decommissioning, they declared that it is much cheaper for FPV systems since there is no fixed structure, except for the mooring blocks which can be easily moved.

7.2.3 Levelized cost of electricity (LCOE)

Numerous researches have been carried out to evaluate the LCOE of a PV system. Several scenarios were often considered, in which the variables involved were parameterized to evaluate their possible variations in the final result. Usually, sensitivity studies are carried out considering the following variables: solar radiation, climatic zone (arid/desert, tropical, temperate), PR (performance ratio), CAPEX, years of operation, system degradation rate, yearly insurance, O&M, and financial leverage.

In a study conducted by Barbuscia (2017), the following LCOE values for ground-mounted systems were reported: 48 US$/MWh in Peru in early 2016; 36 US$/MWh in Mexico; and 29.9 US$/MWh in Dubai. It was concluded that the costs depend on the installation site where the world average cost amounts are about 67 US$/MWh. A recent study by Vartiainen et al. (2020) conducted an assessment of the LCOE for ground-mounted systems according to the WACC[1] indicated the development from 2019 to 2050 for six European locations. In particular, they studied LCOE with a nominal WACC of 2%, 4%, 7%, and 10%. LCOE with 7% nominal WACC in 2019 ranged from 24 €/MWh in Malaga to 42 €/MWh in Helsinki. In

[1] Weighted Average Cost of Capital

2030, this range would be 14-24 €/MWh and 9-15 €/MWh in 2050. It should be noted that the increase in the nominal WACC from 2% to 10% doubles the LCOE. In (*Where Sun Meets Water : Floating Solar Market Report*, 2019), an LCOE calculation was made considering three geographical areas with three WACC and two PR scenarios (+ 5% and + 10% concerning the evaluation of the natural evaporative cooling of the modules in the water) (Table 9). In a recent study by Oliveira-Pinto and Stokkermans (2020), the LCOE concerning the type of used floats, and the location of installation were evaluated. The calculated LCOE was ranged from 50.3 €/MWh for Almeria to 96.2 €/MWh for Barrow Gurney for the floating system and compared with the reference values of the ground-mounted system. The LCOE was reported as 33.1 €/MWh and 59.3 €/MWh for the two mentioned locations. Barbuscia (2017) presented a sensitivity analysis of the LCOE as a function of the size of the system and type of the float. The role played by the capacity of the system on the cost of the energy was highlighted, which indicated an almost exponential decreasing trend as the installed power increases, reaching values similar to those of conventional technologies for utility-scale systems. It started from values of about 80 cUSD/kWh for the power of 52 kW up to 12 cUSD/kWh for capacities greater than 2 MW.

Table 9. LCOE of a 50 MW power plant evaluating different scenarios (*Where Sun Meets Water : Floating Solar Market Report*, 2019).

LCOE ($cents/kWh)			**Ground-mounted PV (50 MWp)**	**Floating PV (50 MWp)**	
				Conservative (+5% PR)	**Optimistic (+10% PR)**
Tropical	WACC	6%	6.25	6.77	6.47
		8%	6.85	7.45	7.11 base case
		10%	7.59	8.28	7.91
Arid/desert	WACC	6%	4.52	4.90	4.68
		8%	4.96	5.39	5.15
		10%	5.51	6.01	5.74
Temperate	WACC	6%	6.95	7.53	7.19
		8%	7.64	8.30	7.93
		10%	8.49	9.26	8.85

Sensitivity analysis was also conducted on the choice of mounting structures, among the modular and rigid ones, and it showed a 20% variation in the LCOE for a 5 MW plant. In another study carried out by Rosa-Clot and Tina (2020d), the LCOE was calculated concerning the location which is presented in

Fig.35. LCOE for Dubai with different plant configurations were obtained as 36.3US$/ MWh for Fix 20° ground-based unit, 31.8 US$/MWh for Fix 10° + cooling, 26.5 US$/MWh for Gable 10° + cooling, 26.9 US$/MWh for vertical axis tracking tilt 20°. Temiz and Javani (2020) obtained an LCOE value of 0.6124 US$/kW for a FPV system which produces both electricity and hydrogen.

The FPV systems have good prospects for further growth and development which can be seen from the continuous research, development, and deployments listed out in various above-mentioned literature. In many cases, the analysis affirms that FPVs are more expensive than conventional ground-mounted systems. At the same time, CAPEX and OPEX of FPVs will significantly be lower than the current ones due to continuous growth in this technology as expected by the 2050 projections (Vartiainen et al., 2020).

8 Conclusion and prospects

The global deployment of the FPV technology can create a new border in the development of renewable energies and bring opportunities for an extensive range of regions and markets. The FPV technology has the capability of doubling the existing capacity of the installed PV systems around the world except this technology doesn't require land like the ground-mounted PV systems.

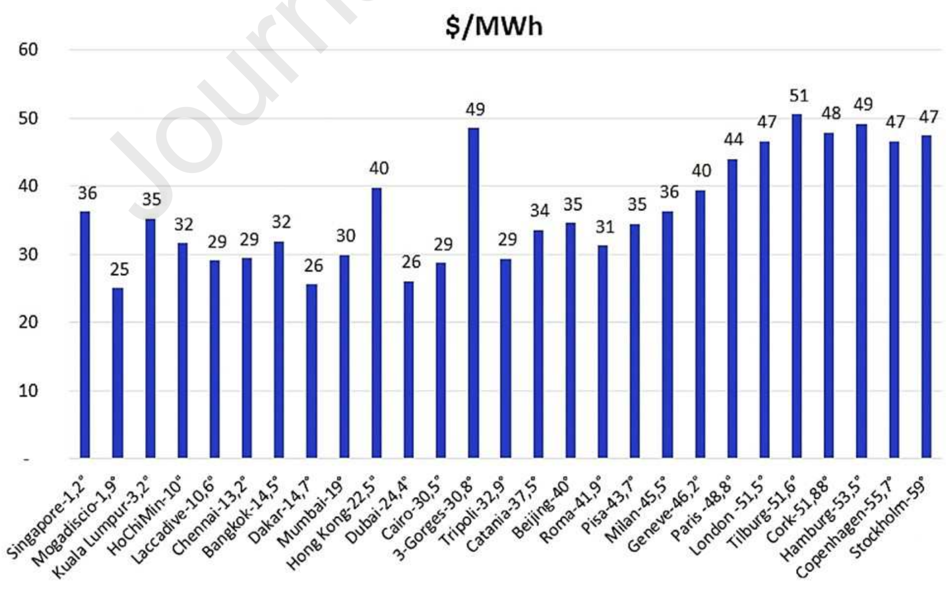

Figure 35. LCOE assessment concerning location (Rosa-Clot and Tina, 2020d).

The present study comprehensively reviews the current state of FPV technology's art with an in-depth exploration of environmental impacts and economic improvements. FPV systems are evolving based on new cell technology, biodegradable materials, and advanced tracking mechanisms, while ecological impacts, long-term assessments, and optimization of size and employed systems are still the challenges that should be further addressed. Following conclusions can be summarized from this study:

- FPV as a fast-growing technology is estimated to reach 30.7% CAGR by increasing R&D investments combined with new governmental initiatives, reaching a cumulative installed capacity of 4,127.567 MW in 2024 with the highest share for the commercial applications.
- Cooling systems are essential to ensure higher performance and longer lifetime of FPV plants, and water veil cooling is one of the straightforward techniques which can cause about 10 to 15% enchantment in electricity production. However, water depth is the critical factor to be optimized due to the possible sacrifice in visible solar spectra in higher thickness.
- The optimum FPV coverage on hydropower plants is said to be 40 to 60% in which algal concentration remains controlled, and the hydropower revenue is maintained. Although the ecological footprint has been investigated exhaustively in man-made water sources, marine life and the possible impacts on off-shore species require more studies.
- The salt deposition is a significant challenge in off-shore systems and could be a limiting factor in choosing the best PV cells in FPV power plants. Therefore, a more extensive range of PV technologies should be assessed for off-shore deployment, where so far CIGS PV technology has shown the highest sensitivity to the saline water. The development of new nano-coatings or cover material for PV panels can also be investigated in future research to reduce the risk of salt deposition and pave the way for off-shore applications.
- The effects of humidity on long-term operation of FPV systems in the environment with high relative moisture levels remain unknown, and future research must address this behavior. Current scientific data suggests a reduction of 15 to 30% in efficiency as the impact of humidity on PV cells. Thus, more advancements are required in PV cells' technology to hinder moisture penetration, especially when FPVs are subjected to a harsh environment.
- Cost analysis has demonstrated that optimization is a critical issue in FPV plants, where a 32% reduction in labor cost is expected for optimized systems. In comparison with ground-based PV systems, floatings are exhibiting a 25% rise in CAPEX while the decommissioning phase comes

cheaper. Inverters maintenance is one of the reasons for the cost increase in FPV power plants in which the addition of 6.15 to 9.50 US$/kWp can be observed compared to terrestrial PV plants.

- Geographical characteristics and the capacity of the power plant are among the influencing factors on LCOE. Studies have suggested that an increase in capacity could drastically reduce the cost of energy, where an 85% fall has been reported for the condition when the FPV power plants expand from 52 kW to 2 MW.

The benefits of FPV technology like higher energy yields, enhanced water quality, trimming down the water evaporation, and better use of existing transmission assets can transform the FPV technology to an attractive option for investors, private companies, policymakers, and stakeholders where the market deployment entails further global acquaintance with the technology, reducing costs, maximizing profitability, and minimizing negative environmental impacts of the FPV projects. Although the overall costs of FPV plants are higher than ground-based PVs with current technology, incoming data are reflecting an onward increase in its economy, which is projected to be completely cost-competitive with peer technologies by 2050. This trend could be accelerated with further research on the use of semi-transparent and flexible thin-film PV modules, adaptability with hydropower, and durability of these systems.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: