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Techno-Economic and Carbon Emission Assessment of a Large-Scale Floating Solar PV System for Sustainable Energy Generation in Support of Malaysia's Renewable Energy Roadmap

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Abstract: Energy generation from renewable sources is a global trend due to the carbon emissions generated by fossil fuels, which cause serious harm to the ecosystem. As per the long-term goals of the ASEAN countries, the Malaysian government established a target of 31% renewable energy generation by 2025 to facilitate ongoing carbon emission reductions. To reach the goal, a large-scale solar auction is one of the most impactful initiatives among the four potential strategies taken by the government. To assist the Malaysian government's large-scale solar policy as detailed in the national renewable energy roadmap, this article investigated the techno-economic and feasibility aspects of a 10 MW floating solar PV system at UMP Lake. The PVsyst 7.3 software was used to develop and compute energy production and loss estimation. The plant is anticipated to produce 17,960 MWh of energy annually at a levelized cost of energy of USD 0.052/kWh. The facility requires USD 8.94 million in capital costs that would be recovered within a payback period of 9.5 years from the date of operation. The plant is expected to reduce carbon emissions by 11,135.2 tons annually. The proposed facility would ensure optimal usage of UMP Lake and contribute to the Malaysian government's efforts toward sustainable growth.

Keywords: floating solar PV; large-scale solar; feasibility assessment; LCOE; CO_2 reduction

1. Introduction

1.1. Background

In the twenty-first century, energy is a major concern in the world [1]. Due to technological advancement, industrialization, urbanization, transportation and the expansion of home appliances, final energy consumption in the form of electricity is predicted to grow at the fastest pace, at a 2.1% compound annual growth rate (CAGR) [2]. Electricity generation from fossil fuels faces significant challenges, as fossil fuel reserves are depleting and burning fuels are creating global warming, carbon emissions, acid rain, etc. [3]. Therefore, academicians, researchers and decision makers are becoming more involved with renewable energy (RE) as the perfect replacement for fossil fuels [4]. To meet worldwide carbon emission reduction goals, RE is becoming more crucial, but making the transition is difficult [5]. Between 2012 and 2020, about 1365 GW of RE capacity was added globally, accounting for 82% of global power production, according to IRENA [6]. Over the last nine years, RE installations have grown by 1359 GW. Figure 1 represents the worldwide RE production capacity from 2012 to 2020 [6].

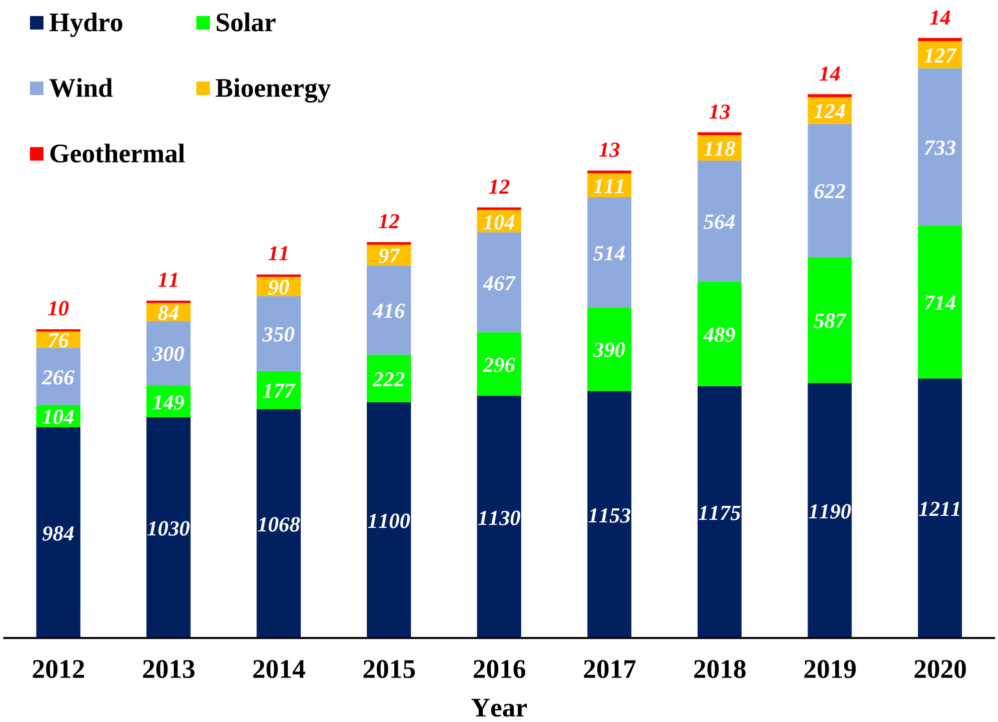


Figure 1. Year-wise global renewable energy generation capacity, 2012–2020 (GW).

The scenario of RE installation capacity in Southeast Asia (SEA) increased by approximately three times, with an annual CAGR of 8%. It has expanded from 20 GW to 87 GW from 2000 to 2020 [6]. Furthermore, the SEA nations established long-term goals and created RE policies to boost their RE installation capacity by 2050 [7]. The "National Energy Roadmap" is the name given to Indonesia's RE strategy, which sets installation capacity goals of 45 GW by 2025 and 168 GW by 2050. The "Sectoral Energy Plan and Roadmap" policy of the Philippines states that they want to guarantee the installation of 20 GW of renewable energy by 2040. Vietnam seeks to ensure its RE capacity of 32% by 2030 and 45% by 2050, and Thailand set its target of 32% RE capacity by 2037. Both named them the "Power Development Plan." Singapore wants to put up at least 2 GW of renewable energy by 2030, as stated in the "Singapore's Energy Story" RE strategy. According to the Malaysian Renewable Energy Roadmap (MyRER), by 2025 and 2035, respectively, the government of Malaysia plans to assure 31% and 40% RE capacity, as they have plenty of resources that can be used to generate RE, including enough solar radiation for solar power, as well as home, commercial and agricultural residues that may be burned or gasified to provide bioenergy, and they have rivers that can produce minor amounts of hydroelectricity. To enhance RE installation capacity and fulfill the mission, a strategic framework for MyRER was built upon four technology-specific pillars. They are the (i) solar pillar, (ii) bioenergy pillar, (iii) hydro pillar and (iv) new solutions and resources pillar, which includes energy storage and wind and geothermal technology [8].

Large-scale floating PV is one of the strategic approaches of MyRER to generate clean and carbon-less energy, which is also part of the solar pillar framework. The share of large-scale FSPV systems in the world's RE generation is currently tiny but is steadily increasing. The World Bank estimated that there would be more than 1.5 gigawatts (GW) of FSPV capacity installed across the world by the year 2020 [9]. This is a considerable increase compared to only a few years ago, and it is projected that this trend will continue as more nations try to improve their output of renewable energy from FSPV both in artificial and natural water reservoirs. A growing number of artificial lakes are being used, which contributes to one of the emerging trends in the deployment of large-scale floating solar PV systems. Large-scale FSPV is being used in water-intensive sectors, including agriculture, fishing and mining [10]. The combined utilization of water surfaces for energy production and the preservation of water may assist such companies, which consume a lot of water. The mechanisms are also being integrated with wind and hydropower, which may assist in stabilizing and generating renewable power [11]. In addition, FSPV systems may be initiated in a very short amount of time, making them an appealing choice for nations that want to swiftly scale up their output of renewable energy [12]. As a direct consequence of this, a significant number of nations, including the USA, China and Japan, are increasingly looking to large-scale floating solar PV systems as a crucial component of their respective renewable energy portfolios.

1.2. State of the Art

Compared to a ground- or land-based PV system, the installation of an FSPV system in an artificial water reservoir offers a lot of benefits. The main benefits of a large-scale FSPV system include preventing the evaporation of water, protecting the water's surface from sunlight, naturally cooling solar modules, reducing photosynthesis and algae growth and saving land for mining, agriculture and tourism. Furthermore, it is the greatest way to produce electricity for nations that lack the space to build a land-based PV system [13–15]. However, the installation of FSPV on natural water bodies may have substantial implications for the existence of aquatic organisms and may pose considerable concerns in this regard. For instance, the shade that the panels generate might lower the quantity of light that is accessible to photosynthesis in submerged algae and plant species, which can alter the ecology of the aquatic system. In addition, the installation and maintenance of the plant would disrupt the natural environment of the fish and other aquatic organisms. Despite these possible drawbacks, FSPV is a better option economically because it uses natural cooling systems more effectively and does not require any additional land for installation, which lowers the cost of generation [16]. Considering this, the FSPV system has emerged as a crucial revolutionary technology in Asia, Europe, America, Africa and Australia [17]. For the time being, FSPV merely sets out on its journey for research, but as time goes on, the exhibit grows larger and more commercial. A 175 kW FSPV system in California, USA, started producing electricity on a commercial scale in 2007, primarily to supply more energy and reduce evaporation in agricultural reservoirs [18], and the very first pilot program of floating solar installation with a 20 kW capacity was introduced by the Asian country of Japan in 2007 under the name of the Aichi Project [19]. The worldwide overall electricity generation capability from FSPV systems increased significantly over the following years. It reached the scale of 10 MW in 2014 and around 2.6 GW in 2020, of which 73% of FSPV production is dominated by China (960 MW), and the remainder is mostly attributable to Japan (260 MW), Korea and European countries. The overall worldwide electricity generation capability of FSPV systems increased significantly over the following years [20–23].

The authors of [24] discussed and assessed various FSPV plants and their operation in different water bodies, including ponds and lakes. In 2015, Japan unveiled the world's first 7.55 MW large-scale FSPV system. In 2017, China unveiled a 40 MW facility, and in 2018, it introduced the two largest plants in the mining subsidence area, with a capacity of 150 MW each. The biggest FSPV plant in China, with an output of 320 MW, began operating in January 2022 [24–26]. To discuss worldwide FSPV constructions, the authors of [27] highlighted a 465 kW FSPV installation, which was the first South Korean FSPV plant made by Solkiss in 2014. In 2018, they added a second 18.7 MW FSPV plant, and in 2019, the Korean Rural Community Corporation (KRCC) planned to build three sites with 280 MW of FSPV capacity [28,29]. The deployment of approximately 2.7 MW of capacity in different reservoirs up until 2018 reflects the fact that FSPV technology is still in the early stages of advancement in India [30]. However, the Indian government is now implementing more than fifteen large-scale FSPV projects in its huge reservoirs. Among these are a 25 MW project in Simhadri, a 20 MW plant in Auraiya and a 23 MW at Kawas, as well as 92 MW and 100 MW projects, Kayamkulam and Ramangudam, which were scheduled for completion in 2021 and 2022, respectively [31–33]. By 2022–2023, the biggest 600 MW FSPV system in the world will be installed on a reservoir at the Omkareshwar Dam on the Narmada River in India [34].

In the previous five years, Europe has seen an increase in the development of FSPV technology, which can produce 45 GW of capacity at sea and 25 GW of capacity utilizing inland waterways. The UK has the highest capacity for FPV installations among the top 30 European nations, at roughly 65.5%. Their first FSPV plant, which has a 6.36 MW capacity, was built in 2016 [29,35]. Belgium gained attention for installing a 998 kW FSPV system in 2018 [36]. In the same year, the Netherlands installed 2.1 MW of FSPV technology, marking the beginning of the nation's history regarding FSPV technology [37,38]. They constructed a 14.5 MW FSPV plant, known as the Sekdoorn project, within just six weeks in 2019, making it the fastest endeavor outside China [39]. One of the biggest and most recent installations in Europe, with a capability of 27.4 MW, was finished in March 2020 [28]. By 2023, they hope to have at least 2 GW of floating solar facilities confirmed. In 2017, Portugal assured the security of its first FSPV installation coupled with a hydropower power plant in the Alto Rabagaor reservoir with a capacity of 218 kWp [35,40]. In 2018, France's Akuo Energy company put in place a 17 MW FSPV facility in Piolenc, Vaucluse [41,42].

African countries possess many potential resources to develop floating solar plants, according to a World Bank analysis [43]. At least 100 GW of FSPV capacity can be produced using just 1% of their reservoirs [20]. The availability of reservoirs and the FSPV installation capacity of all African countries have been widely examined by Rocio Gonzalez Sanchez et al. [18]. Of nations in northeastern Africa, Egypt has the largest reservoir area and FSPV installation capacity. According to simulation research made by Ravichandran et al. [44], the High Dam and Aswan Reservoirs in Egypt can each accommodate a 5 MW FSPV plant. In 2018, Seychelles, an east African sovereign country, constructed the continent's inaugural 4 MW FSPV plant as a result of funding from the African Development Bank and the Clinton Foundation [45,46]. With capacities of 31.5 MW and 252 kW in two reservoirs, two distinct FSPV projects were constructed in California, USA, in 2017 and 2018, respectively. The largest FSPV system in the United States, however, is in Millburn, New Jersey, and is operated by the New Jersey Resources Corporation (NJR) [47,48].

The growth of RE in ASEAN member countries continues to lag behind the worldwide norm, particularly in large-scale FSPV systems. Unfortunately, as of 2019, there was less than 1 MW of FSPV installations in ASEAN nations, but they now have almost 51 MW and are planning to reach 858 MW soon [49]. However, the present efforts made by the ASEAN Center for Energy to reach the Sustainable Development Goals (SDG) are deserving of recognition. In [50], the authors evaluated and compared the effects of FSPV projects with regard to design, development, functioning and disposal in tropical environments. However, they did not find the long-term effectiveness of FSPV or humidity effects. In Singapore, a 9.8 MW FSPV and a combined FSPV with rooftop solar atop the dam of a Cambodian cement industry were expected to be completed by the Clean Tech Solar Company in 2019 to fulfill their goal of 2 GW of clean energy by 2030, and they built its biggest 60 MW FSPV facility in the middle of 2021 [51]. Indonesia has a proposal to build 60 FSPV plants in its reservoirs. Their first commercial plant in history will be the 145 MW Cirata Reservoir FSPV Project [52]. The biggest FSPV plant in Indonesia, a 2.2 GW facility, will be completed in the Duriangkang reservoir by the end of 2024 in partnership with Sunseap and BP Batam [53]. The biggest construction in ASEAN countries and the inaugural significant deployment of a floating PV plant in Vietnam, in the state of Binh Thuan, with a capacity of 47.5 MW, was completed in June 2019 as a result of finance from the World Bank [54]. Among the various renewable energy potentialities, Malaysia only has total solar resources of around 269 GW. In terms of floating photovoltaic (PV) systems, it is recognized as one of the world's revolutionary nations, with an overall surface area for water of about 2944 km^2 over 62 reservoirs, 17 hydropower dams and roughly 16.6 GW of FSPV resource potential [8]. Figure 2 displays a depiction of Malaysia's potential for floating solar photovoltaic resource development and water sources [8]. As part of a Feed in Tariff (FiT) initiative, SEDA and Tenega Nasional Berhad (TNB) have successfully launched two FSPV plants in Malaysia. In addition, 70 MW FSPV plants have already been erected in Tok Uban Lake, Kuala Langat and Kelantan, and a 30 MW FSPV project was launched for trial in 2022 at the Batang Ai hydropower project dam in Sarwak. As a result, the knowledge of potential FSPV resources, installation potential and study results has motivated the policymakers of UMP to develop a strategy to install FSPV technology in UMP Lake in the context of Malaysia. Table 1 gives an overview of the research on different floating solar plant sites around the world. Table 2 shows the limits of large-scale floating solar power plants, their goals and ranges, and the gaps in research.

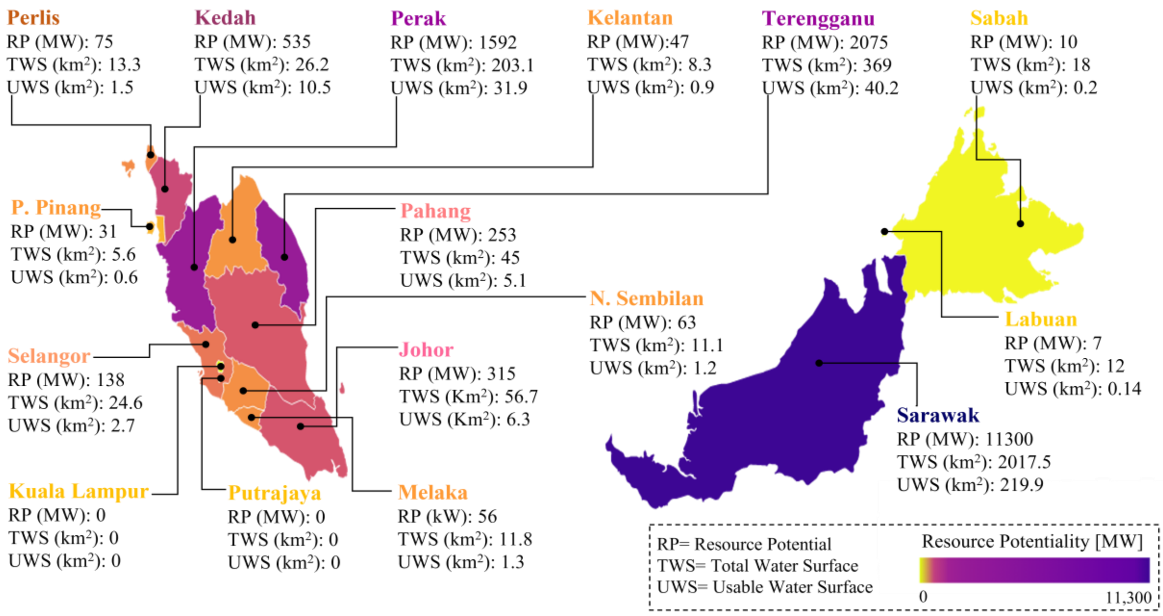


Figure 2. FSPV resource potential and water bodies in different states of Malaysia.

Table 1. Summary of some FSPV installations from all over the world.

Refs.	Plant Name	Location	Plant Size	Commission Year	Reservoir Area (ha)	Description
[19,55]	Aichi Solar Project	Central Honshu, Japan	20 kWp	2007	-	The first formal FSPV plant in the world.
[56]	Floatvoltaic	Far Niente, CA, USA	175 kWp	2008	-	The first commercial FSPV technology in the world was developed to avoid land occupation and reduce evaporative water loss.
[57]	Umenoki Floating Solar Farm	Saitama, Japan	7.5 MWp	2015	12	This plant has 27,456 PV panels with bottom anchoring technology and covers 57% of its irrigation reservoir.

Table 1. *Cont.*

Refs.	Plant Name	Location	Plant Size	Commission Year	Reservoir Area (ha)	Description
[57]	Sungrow Huainan Solar Farm	Anhui, China	40 MWp	2017	250	A massive floating solar farm by Sungrow Power Supply consisting of 166,000 PV panels. The project's initial investment was around 45 million dollars.
[25]	Three Gorges Huainan Floating Solar PV Park	Anhui, China	150 MWp	2018	320	This plant can generate 150,000 MWh of energy, which is able to supply 94,000 residences. Investment cost for this project was USD 151 m.
[26]	Dezhou Dingzhuang Floating Solar Farm	Shandong, Dezhou, China	320 MWp	2022	600	200 MW and 120 MW; two separate steps were taken to complete this plant. The facility can generate 550 m kWh and reduce CO_2 453,000 tons per year. Number of installed panels: 170,000.
[28]	Gunsan Retarding Basin Solar PV Plant	North Jeolla, South Korea	18.7 MWp	2018	17.42	The amount of renewable energy generated by this plant is sufficient to run 7450 homes. With a total price tag of USD 24.795 million, this structure uses 50,000 PV panels.
[29]	Dangjin and Goheung County Floating Solar Plant	Chungcheongnam, and Jeollanam, South Korea	280 MWp	2019	-	This project is in two different places: (i) Dangjin, 200 MW, and (ii) Goheung, 80 MW. It reduces 160,000 tons of CO_2 emissions per year.
[32,33]	NTPC Simhadri Floating Solar Project	Simhadri, Andhra Pradesh, India	25 MWp	2021	60.70	This power facility can provide renewable electricity for up to 7000 family homes. As a consequence, annual emission levels of CO_2 are reduce by 46 thousand tons. There are 109,800 unit panels in total, and the endeavor cost USD 17.45 million.
[32,33]	NTPC Kawas Floating Solar PV Park	Kawas, Gujarat, India	23 MWp	2022	-	Located in a raw water-dead lake in Gujrat, this installation is a combination of a land-based plant (33 MW) and a floating plant (23 MW). An estimated USD 39.088 m is needed to complete the construction.
[32,33]	NTPC Auraiya Floating Solar PV Project	Auraiya, Uttar Pradesh, India	20 MWp	2022	-	This plant is settled on the raw water reservoir of NTPC, and it can generate 39 million kWh of electricity and reduce 33.6 metric tons of CO_2 annually.
[31,33]	Kayamkulam Floating Solar Project	Kerala, India	92 MWp	2022	141.64	This plant is settled on the salt water body of Rajiv Gandhi gas power station, and it can generate 215.5 m units of energy and reduce 185.5 metric tons of CO_2 annually

Table 1. *Cont.*

Refs.	Plant Name	Location	Plant Size	Commission Year	Reservoir Area (ha)	Description
[32,33]	Ramagundam Floating Solar Project	Peddapalli, Telangana, India	100 MWp	2022	202.4	This plant is on the raw water lake of the thermal power plant at Telangana, and it can generate 223 million kWh per year and reduce 192 metric tons of CO_2 per year.
[34]	Omkareshwar Floating Solar Park	Khandwa, Madhya Pradesh, India	600 MWp	Under Construction	10,000	Omkareshwar is going to be the largest FSPV technology in India. The under-implementation project will cost around USD 919 million.
[58]	SPIC Thoothukudi Floating Solar PV Park	Thoothukudi, Tamil Nadu, India	14.8 MWp	2020	15.6	There are 37,632 photovoltaic panels and 1280 floating modules in the entire system. The installation cost is around USD 10.261 million, and it covers 71.31% of the body of water. It reduces 18,686 tons CO_2 per year.
[59]	Queen Elizabeth II Reservoir Solar Plant	Surrey, London, UK	6.36 MWp	2016	128	With a total of 23,046 PV panels, 61,000 rafts and 177 anchorages, QE2 is one of the biggest FSPV technologies in Europe. The entire construction cost 6 million pounds and spans 5% of the water body.
[36]	Hesbaye Frost	Wallonia, Belgium	998 kWp	2017	3	The inaugural massive floating FSPV facility in Belgium uses 3120 drifting modules to generate 1 GWh of electricity annually. About 35%of the water body is occupied by construction.
[39]	Sekdoorn Solar PV Park	Overijssel, The Netherlands	14.5 MWp	2019	-	The plant produces 13 GWh/year of energy, and the initiative provides sufficient renewable energy to run 4000 homes. The construction cost about USD 16.259 million.
[28,41]	Baywa-re Floating Solar PV Park IV	Overijssel, The Netherlands	27.4 MWp	2020	18.25	This facility uses 73,000 PV panels at an installation cost of USD 29.455 million, and it has the capacity to provide electricity for about 7800 homes. It can cut CO_2 emissions by 12,013 tons per year.
[35]	Alto Rabagao Dam Floating Solar	Montalegre, Portugal	218 kWp	2017	795.3	The world's first combined FSPV power plant with a hydroelectric dam with 220 kWp of floating solar capacity. The plant was built with bottom grounding technology, employing 840 PV panels, each of which is rated at 260 W.

Table 1. *Cont.*

Refs.	Plant Name	Location	Plant Size	Commission Year	Reservoir Area (ha)	Description
[60]	O'Mega 1 Solar PV Park	Piolenc, Vaucluse, France	17 MWp	2018	17	The facility's yearly output of 23,035 MWh produces enough renewable energy to operate 4733 residences and prevents the release of 1093 tons of CO_2 into the atmosphere. The total estimated expenditure for this undertaking is USD 14.2 million.
[45]	Seychelles Solar PV Project	Mahe, Seychelles	4 MWp	2018	-	The LCOE of this plant is USD 0.095/kWh.
[61]	Sayreville	Middlesex, NJ, USA	4.4 MWp	2019	19.66	This bank-anchoring-based FSPV system comprises 3792 units of PV modules (345 W each) and covers 21% of the lake's surface area, installed in a water treatment reservoir.
[51]	Sembcorp Tuas Floating Solar Project	Tengeh Reservoir, Singapore	60 MWp	2021	45	This first LSS in the nation utilizes 122,000 photovoltaic panels and has the potential to offset 32,000 tons of CO_2 yearly.
[53]	Duriangkang Dam Floating Solar Plant	Duriangkang Reservoir, Indonesia	2.2 GWp	Under Construction	1600	A total of 2,600,000 MWh of energy and 1800 K tons of CO_2 are produced and eliminated annually, respectively. The estimated price tag for the endeavor is USD 2235.2 million.
[62]	Da Mi Floating Solar PV Park	Binh Thuan, Vietnam	47.5 MWp	2019	50	This initiative is projected to generate 70,000 MWh of electricity per year. The total installed cost is USD 66.44 million, and the structure uses 143,940 PV modules.
[63]	Wisewood Floating Solar Plant	Phetchaburi, Thailand	1.26 MWp	2019	2.62	A total of 3275 PV modules were used in this bank-anchoring-based construction, which spans 43% of the lake area.
[64]	Sungai Labu	Sepang, Malaysia	108 kWp	2015	4.2	A total of 432 PV modules were used in this bottom-anchoring-based construction, which spans 4% of the lake area.
[65]	Ulu Sepri	Negeri Sembilan, Malaysia	270 kWp	2016	18	A total of 900 PV modules were used in this bottom-anchoring-based construction, which is settled in a water retention dam. It spans 1.5% of the dam's area.

Table 1. *Cont.*

Refs.	Plant Name	Location	Plant Size	Commission Year	Reservoir Area (ha)	Description
[64]	Solarvest Selangor Floating Solar PV Park	Selangor, Malaysia	13 MWp	2020	53	A total of 16,640 MWh of energy is produced by this LSS facility, providing enough renewable power for 5800 dwellings at an LCOE of USD 0.051 per kWh. The annual CO_2 reduction is 11,548 tons, and the estimated cost for this plant is USD 24.886 million.
[66]	Saemangeum Floating Solar Energy Project	North Jeolla, South Korea	2.1 GWp	Under Construction	3000+	This project is going to be the world's largest FSPV plant to date. The investment for this plant is more than USD 515 million.

Table 2. Summary of a literature survey based on limitations of large-scale FSPV, goals and scopes, and research gaps.

Ref.	Goals and Scopes	Research Gaps	Limitations of Large-Scale FSPV
[67]	To assess the cooling impacts of different FSPV technologies and analyze FSPV plant energy generation.	Inadequate simulation tools and techniques for estimating the generation of energy.	Inadequate information on the cooling effects of various technologies, reliance on technology, and location.
[68]	To identify the performance of an FSPV chimney plant in Isfahan, Iran, and to assess its viability based on the return of finance rate, net price value and finance payback duration.	Lack of information on the feasibility analysis of FSPV at Isfahan, Iran.	The need of a significant number of water bodies as well as the possibility of environmental harm.
[69]	To assess the economic and environmental viability of a 10 MW FSPV facility.	Lack of explanation of appropriate places for FSPV plants and the payback period.	Increase in levelized cost of energy (LCOE) and the impacts of environmental stress factors.
[27]	To offer a global assessment of FSPV systems.	Lack of design studies and applications of FSPV.	Existence of land, its development and purchase, substation capacity and evacuation.
[29]	To present a quick summary of onshore and offshore FPV systems, to analyze their pros and cons and to predict their future.	Lack of information about installation and levelized cost for offshore FSPV plants.	Wind and wave loads.
[70]	To focus on FSPV technology, including varieties and studies of floating solar farms. The research also examines 1 MW floating PV plants at Kota Barrage and Kishore Sagar Lake in Rajasthan and calculates energy, water saved from evaporation and CO_2 emissions.	The discussion is restricted to the reliability of the grid, payback time, capital expenditure and operational expenditure.	Insufficient evidence on long-term performance and the possibility for adverse effects on the environment.
[71]	To describe the hybrid floating PV system and list merits and drawbacks.	There is no discussion about the applicability of hybrid FSPVs to manmade lakes.	The absence of a suitable site and the possibility of having an influence on the environment.
[72]	To analyze the simulations, theoretical groundwork, calculations, per unit cost and advantages of FSPV.	Insufficiency of information pertaining to design optimization, floating structures, anchoring and mooring systems.	Demand for a massive number of water bodies and dependence on the power grid.

Table 2. *Cont.*

Ref.	Goals and Scopes	Research Gaps	Limitations of Large-Scale FSPV
[24]	To present an assessment of previous endeavors in confined water bodies, including reservoirs, ponds and small lakes.	Its coverage is restricted to confined waterways completed before 2013.	Effects associated with the environment.
[55]	To analyze the latest FPV research's pros, cons and future.	The effect of FSPV on aquatic ecosystems and sea water quality.	Difficulties of the marine environment in contrast to the freshwater one.
[73]	To identify essential technologies, analyze the FSPV literature and explore new, big and distinctive installations.	The absence of norms and guidelines for the design.	An increased starting cost, water body bathymetry features and a high corrosion rate at a saltwater reservoir.
[74]	To study FSPV effectiveness, to breakdown and debate possible design ideas to increase the efficiency and cost-effectiveness of FSPV facilities and to summarize experimental findings.	The impact of tracking, cooling and focus on FSPV efficiency is ignored.	Seawater installations face the difficulties of corrosion, wave and wind impacts and algae growth. Costs for offshore FSPV rafts and mooring systems are more than those for a freshwater reservoir.
[50]	To evaluate and compare the effects of projects throughout the design, developing, functioning and disposal in tropical environments.	On the long-term effectiveness of FSPV, humidity effects are absent.	FSPV maintenance is difficult if the body of water is often subjected to strong winds, waves, or storms.
[75]	To examine various technologies, to conduct a comparative analysis between FSPV and land-based PV, to analyze FPV plants' economics and environmental consequences and to explain the technology's principal obstacles and opportunities.	Less information about the long-term effects of putting FSPV modules on water bodies. Salt buildup and algae blooms can damage the modules, and FSPV systems cost more to build.	Salt accumulation could make it harder to choose the best PV panels for an offshore FSPV plant.

1.3. Key Contributions

In Malaysia, solar PV has the highest potential advantages because of its proximity to the equator, and it receives around 1575–1812 kWh/m^2 of yearly irradiation from the sun, which is comparable to the average irradiation of SEA (1500–2000 kWh/m^2) [76]. However, land availability is one of the major obstacles in Malaysia facing large-scale solar PV. A ground-mounted solar PV installation typically requires between 0.5 and 0.7 MWp/ha of land. Additionally, throughout the deployment phase, deforestation, bird death, erosion, overflow and microclimate changes also occur [50,77]. To mitigate the challenges of land-based PV systems [71] and enhance large-scale solar auctions, floating solar PV (FSPV) is one of the strategic pillars of MyRER's solar initiatives. According to the LSS strategy of the Energy Commission (EC) of Malaysia, the Universiti Malaysia Pahang (UMP) has intended to construct a 10 MW FSPV plant in its large on-campus water reservoirs. This paper, therefore, does a structural, environmental and techno-economic feasibility analysis of an FSPV plant in UMP Lake, considering energy generation potentiality, generation cost and carbon emission reductions. The main contributions of this article are as follows:

- To find an alternative solution to the challenges of securing land for Large-Scale Solar (LSS) in Malaysia.
- To prepare a case study for the suitability of FSPV systems on the reservoir of UMP Lake.
- To design and simulate an FSPV plant in UMP Lake.
- To assess the capital cost, LCOE for the LSS auction, payback period, CO_2 reductions and grid integration.
- To assess the feasibility of the LSS strategy of MyRER.

The article is organized as follows: Section 2 describes the FSPV technology. In Section 3, a case study on the proposed location and a climatic investigation are carried out. Section 4 focuses on FSPV design and simulation studies. Section 5 performs a financial assessment, LCOE, economic and CO_2 emission mitigation assessment and grid integration. Finally, conclusions to this study are reached in Section 6.

2. FSPV Technology Overview

Conventional FSPV technology typically consists of (i) PV modules to harvest the solar radiation and convert it into electricity, (ii) the support frame to hold the PV modules and other necessary things along with the inverter, (iii) the floating structure to provide buoyancy, (iv) the mooring system to prevent the plant from moving about freely and (v) electrical components to convert the DC electricity into AC and to transfer the power away [15]. The subsequent sections provide descriptions of these components. Figure 3 presents a scenario of the FSPV system briefly.

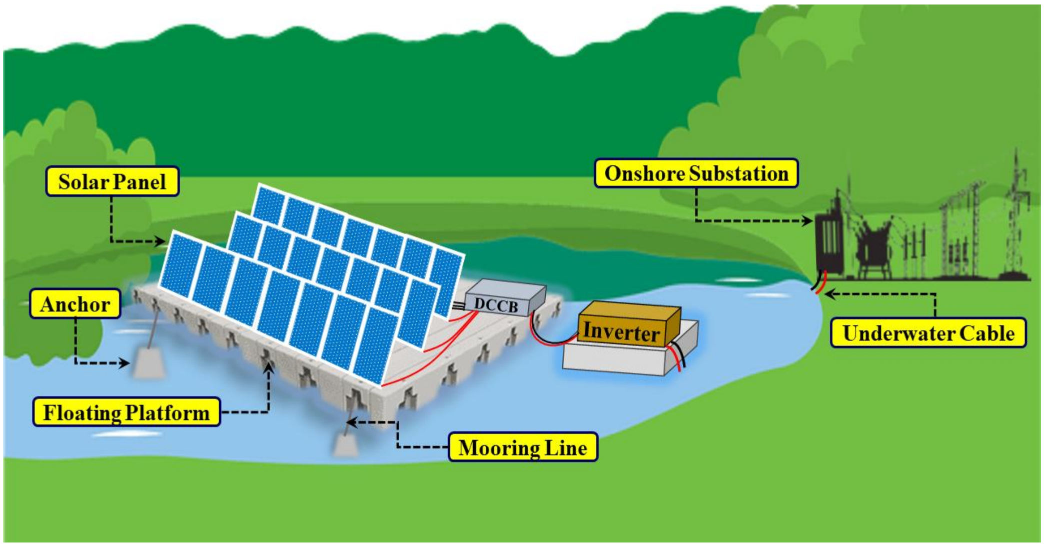


Figure 3. Architecture of an FSPV power plant.

2.1. PV Modules

To produce electricity from the radiation of the sun, solar PV modules are manufactured from a defined set of linked solar cells [78]. The amount of energy generated from PV modules highly depends on various internal and environmental factors, such as sunlight duration, irradiance, clarity index, temperature, etc. [79]. PV modules made on crystalline silicon wafers are often employed in large-scale FSPV installations. However, to avoid saltwater vapor penetration, offshore FSPV plants need a distinctive design of modules. In addition to using thin-film, organic and polymer cells, as well as cadmium telluride, cadmium sulfide and hybrid PV cells, PV panels are also made using these technologies [80]. To effectively absorb sunlight, the front side of the module is covered by transparent glass with a small concentration. The rear side is covered with a protective film made of ethylene vinyl acetate (EVA) to provide the best protection possible against the inclement environment. The aluminum structure's durability against rust and tension guarantees that the deployment is acceptable. The top of the aluminum alloy has punched slots to ensure proper placement. The junction box located at the rear of the panel is where the positive and negative terminals of the panel are linked [81].

2.2. Support Frame

A metal frame is often employed in most FSPV systems as a structural support to hold the PV modules and transfer tension to the elements, and it is composed of galvanized steel, high-durability steel or aluminum [82,83]. However, in certain instances, the architecture is constructed such that a single PV module is supported only by a float. Because corrosion is a challenge for steel or aluminum frames, experts are increasingly recommending the use of fiber-reinforced polymer (FRP) composite materials as support frames in FSPV construction, owing to their exceptional resistance to corrosion [84,85].

2.3. Floating Structure

A floating structure is the most essential component of an FSPV system and has traditionally distinguished floating solar technology from ground-mounted technology. Usually, it is composed of several disposable empty plastic floats that are joined together to make a substantial pontoon and to provide enough assistance to hold the solar panel, which is typically mounted with predefined tilt angles. The floats are constructed using a variety of substances and shapes depending on factors such as where they are installed, environmental circumstances, the quality of resources, the cost and convenience of moving the vehicles, the architectural design and a host of other factors. These materials are Fiber-Reinforced Plastic (FRP), High-Density Polyethylene (HDPE), Medium-Density Polyethylene (MDPE) and Fero-cement in the FSPV system [21]. There are two primary forms of floating structures that have been introduced in FSPV technology: pure floats and modular rafts or membranes and mats [86]. They are (i) the pontoon type and (ii) superficial. Figure 4 illustrates a categorization of floating FSPV technology structures based on their configuration [87].

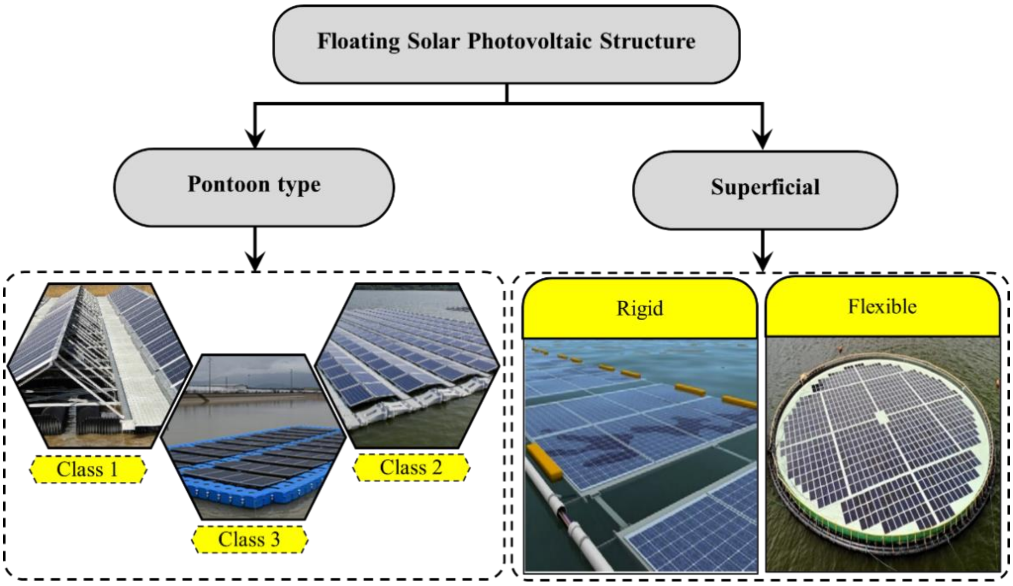


Figure 4. Categorization of floating structures of FSPV systems.

2.3.1. Pontoon Type

The FSPV system's pontoon-type structure has been developed to create a sturdy floating platform over the water's surface on which the PV panels are dependent. There are three other sorts of pontoons available. Based on the floater shapes, materials, PV panel support structures, placement of panels, and walkways, they are divided into three classes: 1, 2 and 3. Class 1 floating structures were designed by Terra Moretti in partnership with Koine Multimedia and utilize several of their initiatives [74]. The class 2 structure was initially suggested by Ciel and Terre, and it continues to be the most implemented FSPV technology [20]. In 2009, NRG Energia installed its first assignment in Bubano, Italy, where it created the first class 3 structure in the world [88].

2.3.2. Superficial

In PV technology, only a limited amount of solar radiation is turned into electricity, and the remaining light is crucial in increasing cell temperature and lowering panel efficiency.

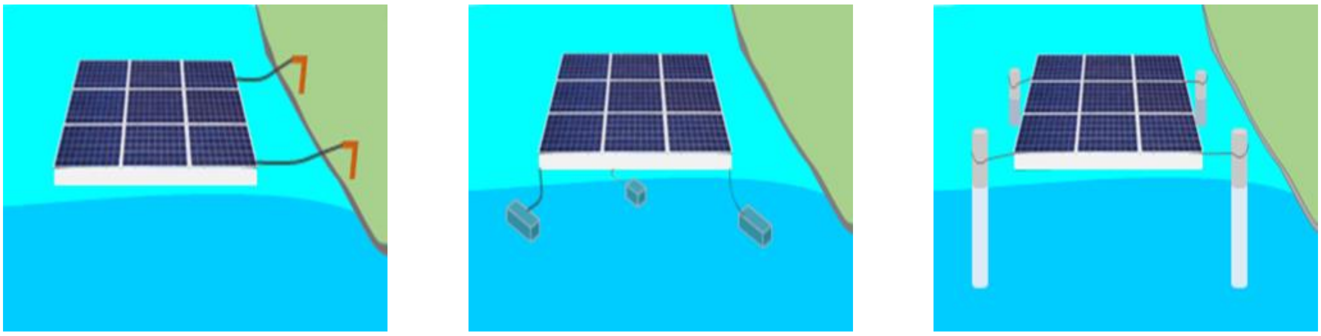
To keep the panel cool and boost efficiency, semi-submerged floating solar technology called the superficial structure has been developed [89]. The literature demonstrates that, in addition to providing cooling, a partly submerged floating structure may enhance power production, minimize the impacts of wind and wave loads, and extend its lifetime by up to 4 cm when submerged [90,91]. A comparative description of the three classes of pontoon-type structures and two superficial floating structures is provided in Table 3.

Table 3. Description of class 1, 2 and 3 structures and rigid and flexible floating structures.

Structure Type	Description
Class 1	• In most cases, HDPE piper floaters are used to make the rafts, and steel, aluminum or FRP materials are employed to build the support framework [48]. • It has little physical contact with the water body, and the construction procedure is simple [92]. • The structure is quite buoyant and can be walked upon [93]. • Despite being sturdy and adaptable, it is more expensive than similar products. • It has significant shortcomings in offshore locations because it can endure waves up to 2 m high [93].
Class 2	• In class 2 structures, full HDPE floats of modest diameters, mainly single modular, are attached with the help of appropriate connectors [48]. • Class 2 floating structures are designed in such a way that each PV module may fit inside a separate float with an integrated support structure. Therefore, the modules do not need any extra support frames [93]. • In addition to supporting PV modules, this structure also supports electrical components and makes catwalks [67]. • This technology is relatively less expensive and relieves strain, and by utilizing minimal metals, corrosion may be mitigated [92]. • Despite being straightforward in design and execution, customization is not feasible. As a result, applications have become less efficient [93]. • PV panels and wires are more exposed to a humid environment due to a wider distance between the water level and the panel, which causes faster deterioration. • The rafts experience significant wind pressure and wave stresses due to their small weight. Therefore, they can be injured in a marine environment.
Class 3	• By constructing many floats and addressing the drawbacks of class 2 structures, class 3 floating structures provide a vast area for PV panels and electrical items [48]. • Such sturdy construction offers enough space for walkways, which facilitates maintenance and operation [93]. • Although the cost is somewhat higher than that of class 2 structures, class 3 structures try to optimize structural stability [92]. • Some designs are offered and add some complexity to the construction because customization is feasible.
Rigid	• It can function just below a light layer of water and can handle medium waves, and PV modules can only be submerged to a depth of two meters [94]. • It is uncertain if this structure holds up in a marine environment [93].
Flexible	• A flexible structure may be created by employing crystalline or thin-film solar modules that are supported with foam [95,96]. • Installation and upkeep of the structure are simple. The self-cleaning and cooling processes are made simple by water immersion, which also reduces the rate of module deterioration [57]. • Even though the framework is less expensive, the PV modules cannot be tilted by the system [92].

2.4. Mooring System

A mooring system is a crucial part of FSPV technology that ensures the safety of the plant by restricting its freedom of movement. It tries to safeguard the floating platform from any risk or harm [14]. Typically, the mooring line for an offshore FSPV plant comprises steel chains or cable ropes, and synthetic material rope, elastic rubber rope or a combination of both is used in the Sweetwater FSPV facility [97]. The area and position of the plant, the composition of the soil in the reservoirs, and the level of water nearby all play a role in how the mooring system is set up for the floating system. There are primarily five different types of anchoring systems that are noticeable. They are the gravity type, anchor-tension type, semi-rigid type, tension type and modified type. However, FSPV technology mostly uses anchor-tension-type mooring systems [20,98]. The mooring line is often attached on one end to a floating platform, and the other end is attached to anchors. When choosing an anchoring method for a floating body in an FSPV system, factors such as plant size, distance from the shore, waves and wind loads, as well as cost, are typically considered. A short description and classification of anchoring systems are shown in Figure 5 below [92].



(**a**) (**b**) (**c**)

Figure 5. Anchoring systems of FSPV plants: (**a**) bank anchoring; (**b**) bottom anchoring; (**c**) piling anchoring.

(a) Bank anchoring: This option is best suited to small, shallow ponds with shorelines that are relatively near the floating body. It costs extremely little to build, run and sustain.

(b) Bottom anchoring: This option is the most practical anchoring solution for freshwater FSPVs because it has a stronger tensile strength and lessens stress and harm to floating docks.

(c) Piling anchoring: For installations with distinctive characteristics, such as monitoring and emphasis, this option is very helpful. It costs more because piling anchoring involves digging below the water's surface at various depths.

2.5. Electrical Components

In large-scale solar power plants, electrical components are essential for electricity storage, conversion, transmission and distribution. The same electrical components used in ground-mounted PV systems are employed in FSPV. They consist of the DC combiner box, the inverter, the transformer, the wires and the connectors.

- DC Combiner Box (DCCB): The DCCB distributes power in a box with DC breakers and protective devices, creates a single output from numerous DC inputs from the solar PV array and allows lengthy lines to decrease transmission voltage dips between the PV array and inverter.
- Inverter: The inverter transmits solar PV-generated DC to power system utility as AC [99]. With unique functionality, voltage and current management, it is put over floaters or the nearest land or beach. Large power factors, mild short-circuit currents, excellent efficiency, prolonged reliability and little maintenance make a good inverter [100].
- Transformer: The transformer transmits energy from utility-connected PV power plants, which affects business and technology [101]. The system uses power transformers to increase or decrease voltage, and high-rated transformers are used for facilities with large outputs [102].

- Cables and Connectors: Multiple cables carry PV panel electricity to shore. The FSPV system places the most wires under water. FSPV cables must resist corrosion, mechanical stress, severe UV radiation, and considerable temperature changes. The connections enable easy cable connection and carry a lot of electricity [27].

3. Case Study: FSPV at UMP Lake

3.1. Lakes Location and Resource Potential

Universiti Malaysia Pahang (UMP) is one of the top public technical universities in Peninsular Malaysia, located in the Pahang state with a latitude of 3.545° N and a longitude of 103.429° E. The campus of UMP, Pekan, encompasses 642 acres collectively and includes four small and large lakes with a combined area of around 110.73 acres [103]. Among the four lakes, there are two lakes on the south-east side of the campus, namely Lake C, which has an area of 8.11 acres (38,220 m^2), and Lake D, which has an area of 21.16 acres (85,632 m^2). According to design and modeling studies, Lakes C and D have potential resources of 3.4 MW and 6.6 MW, respectively, for installing a 10 MW floating solar photovoltaic (FSPV) plant on their water surface.

3.2. Local Weather

The biggest province in Peninsular Malaysia, Pahang, has one of the hottest climates. The meteorological information for UMP, Pekan, is taken from Meteonorm V8.1.4.25305 and includes information on air velocity, solar irradiation, surface temperature, humidity, etc. The data in Table 4 show UMP, Pekan's monthly air temperature (Ta), global radiation horizontal (H_Gh), diffuse radiation horizontal (H_Dh), sunshine duration (Sd), relative humidity (RH) and snow depth (Snd). In Pekan, the yearly average temperature is 27°, with a maximum temperature of 28° in May. As a tropical nation, Malaysia experiences rain from September to January, with December seeing the most precipitation. Sometimes, a month's worth of rain lasts more than twenty days. The area of UMP, Pekan has the most sunshine in February, with seven hours a day. Sunlight is the least abundant in December. The humidity levels between 40% and 60% feel comfortable overall. November is typically the most miserable and moist month, with humidity at around 88%. On the contrary, Pekan in February is more tolerable. The most satisfying fact is that there is no snow impact on PV modules because there is no snowfall in Malaysia. The daily temperature, monthly precipitation, precipitation days and sunlight duration for the UMP Lake region are shown in Figure 6a–c.

Table 4. Meteorological information of UMP Lake, Pekan, Pahang.

Month	Ta	H_Gh	H_Dh	Sd	RH	Snd
	[°C]	[kWh/m^2]	[kWh/m^2]	[h]	[%]	[mm]
January	25.6	136.8	72.7	159	86.9	0
February	26.2	152.6	77.3	185	83.9	0
March	27.1	177.1	77.9	205	83.0	0
April	27.8	169.4	78.8	203	82.5	0
May	28.0	166.8	75.7	206	83.6	0
June	27.8	146.2	78.2	188	83.1	0
July	27.5	154.9	82.7	296	83.0	0
August	27.4	154.2	87.6	193	82.8	0
September	27.2	152.6	77.7	171	83.4	0
October	27.0	154.1	89.5	160	84.8	0
November	26.4	115.9	72.8	119	88.0	0
December	25.8	104.2	70.2	114	88.3	0

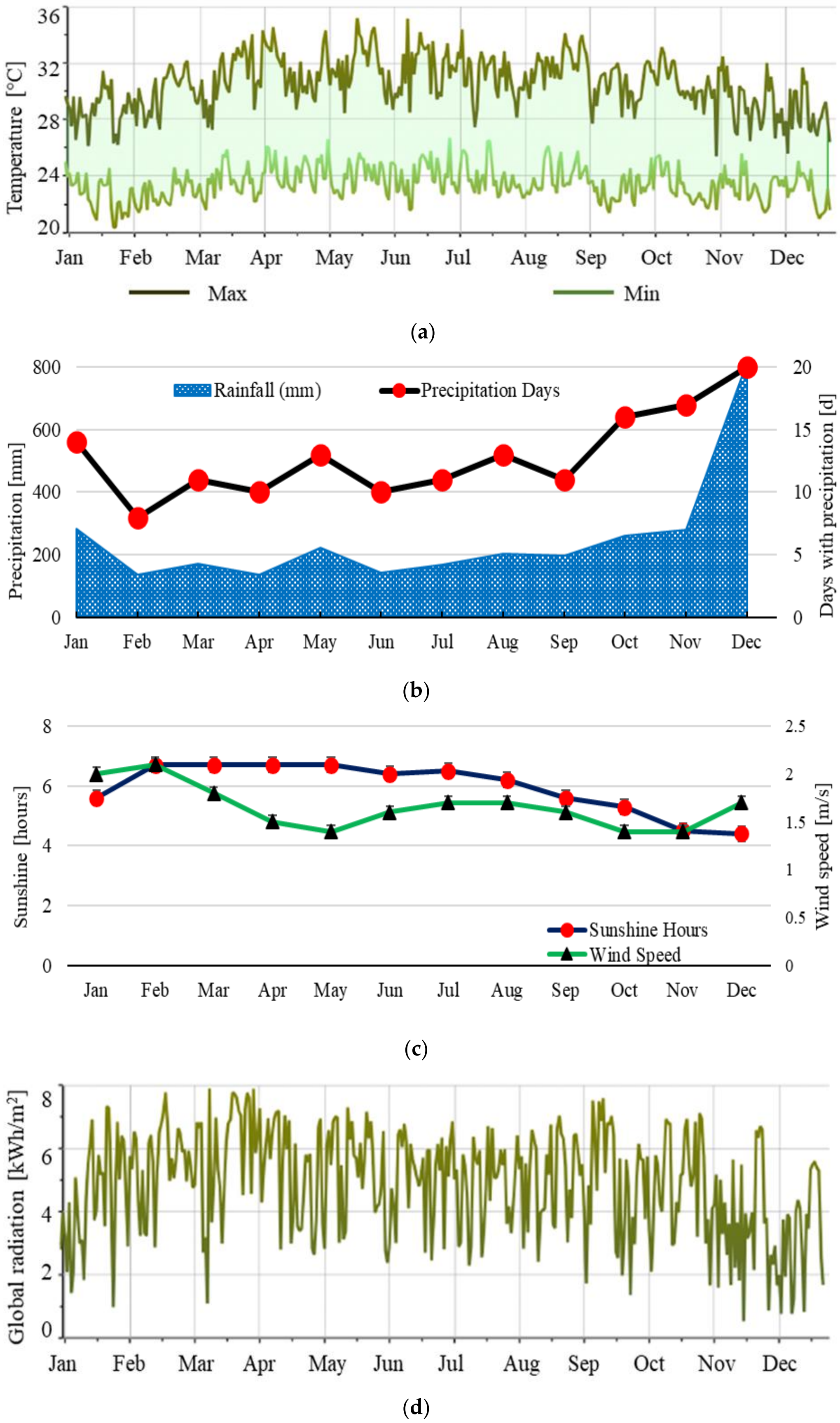


Figure 6. Climatic data of (**a**) daily temperature, (**b**) monthly precipitation, (**c**) average monthly sunshine hours and mean wind speed and (**d**) daily global radiation at UMP, Pekan.

3.3. Solar Irridation

Malaysia is a multiracial nation in coastal Southeast Asia, and the West Malaysia region has a varied geographic layout in which uniform solar irradiation ranges from 1487 to 1572 kWh/m^2 for lesser sunny hours [104]. The area around UMP in Pekan experiences 1786.2 kWh/m^2 of horizontal global solar radiation every year, with the greatest values in March (177.1 kWh/m^2) and the lowest values in December (104.2 kWh/m^2). The gross estimated diffuse solar radiation throughout this region is 941.2 kWh, with the greatest and lowest values occurring in October and December, respectively, at 89.5 kWh and 70.2 kWh. The daily global radiation of UMP, Pekan, Pahang is shown in Figure 6d.

3.4. Wind Speed

For the construction of FSPV technology in any reservoir, wind speed is regarded as one of the most essential criteria. Depending on the season, various parts of Malaysia experience diverse wind speeds, specifically when the southeast and northeast monsoons occur between May and September and between November and March, respectively. In Malaysia, the mean wind speed is often less than 3 m/s, whereas the highest wind speed is between 6 and 12 m/s [105]. The mean annual wind speed in the UMP Lake area is 1.7 m/s, with a mean maximum of 2.1 m/s in February. The mean wind speed at UMP, Pekan, Pahang, is depicted in Figure 6c. The wind speed threshold for FSPV plants typically falls within the range of 9 to 15 m/s. If the wind speed exceeds this threshold, the floating structures may begin to shift, putting additional strain on the anchoring systems and raising the possibility of solar panel damage. Therefore, based on the data we have, it can be expected that an FSPV in UMP Lake would not be impeded until a big storm occurs.

3.5. Summary of the Site Investigation

On 1 and 2 January 2023, a practical assessment was conducted to evaluate whether UMP Lake is suitable for installing FSPV. The subsequent comments in Table 5 are made in addition to using the literature, data from the university website, practical measurements and the authors' best understanding. The position of the FSPV plant is shown specifically in Figure 7 in the Google Earth image. The FSPV plant at UMP Lake is therefore technically and legally feasible to install given the appropriateness of the lake's conditions, water depth, stability of the lakebed, site wind speeds, solar resources, the impact of the FSPV plant on the lake's ecosystem and the technical and regulatory requirements.

Table 5. Site inspection details of UMP Lake.

Criteria	Sub-Criteria	Consequence of Observation
Topography	Geospatial suitability of architecture	The south-east corner of the university, next to Kuala Pahang, is where FSPV installation, operation and maintenance are suggested. In Pahang, sand and clay are the predominant types of soil. However, the projected lake's soils are clay and loam, descending in the direction of the water [106].
	Adequate space for storage and transportation of materials	It is feasible to transport materials via huge trucks from any region of the country because the road near the lake is around 40 feet wide, and there are enough spaces for storing goods inside.
	Stable, appropriate and sufficient area for a floating base	The proposed location is favorable for constructing a floating platform because lakes C and D have enough space and water basins.
	Limitations due to construction work	The adjacent lake road would stay congested during the construction period, and the lake's beauty would be temporarily affected, but it would return after the work is over.

Table 5. *Cont.*

Criteria	Sub-Criteria	Consequence of Observation
Hydrology	Level of water of the lake	A practical measurement was taken on 2 January 2023 and revealed that the lake's water level is around 9 m in the middle and 2.5–3 m closer to the coast. The water level fluctuates between 0.5 and 2 m due to seasonal precipitation.
	Determination of the hydrological rate and outflow mechanism	It should include a precise mechanism for measuring the water flow rate to calculate the loads on the floats and anchors. However, regrettably, there are currently no measurement facilities available. When the lake's water level climbs above its threshold, however, the systemic sewage gates are there to release the water.
	Water quality and pH level	According to a visual inspection, the surface water is not as good as the groundwater [107]. The experimental investigation [108] determined that the water in the lakes has an average pH of 6.64.
	Risk of floods and cyclones	The lower region of Pahang seems to have a 20% [109] chance of flooding due to various reasons. Despite being one of the higher locations above sea level, an uncertain flood or cyclone may develop in the lakes due to rainfall with a minimal amount of South China Sea wave action.
	Height of waves at the lake	At UMP Lake, no observable large waves are seen. However, sometimes, especially during the northeast monsoon season, a small number of waves might be visible, owing to strong storms or wind.
Geology	Soil quality of the lake region	Due to the UMP Lake's proximity to the South China Sea, sandy soil is expected to be present there. Its soil around the lake is quite good sand with Cu > 4, with a soil sample of almost 2.63 mg/m^3 [107].
	Probability of earthquakes	In Pahang, Pekan is in seismic risk region 2 [110]. There is a significant danger of earthquakes in the installation region because Pahang has previously seen many earthquake incidents [111].
	Risk of land erosion	The potential annual soil erosion for the surface is 9551.93 tons/ha/year at the installation region [106].
Roads and Networks	Connecting road at the worksite	At the worksite, there is a suitable connecting road for both large and light transportation.
	Appropriateness of grid integration	To integrate the generated electricity into the national grid, there is a 33/11 kV substation at UMP, which is around 2.3 km away from the plant.
	Protection of the site	The installation site is located inside the university area; thus, the region is always extremely secure.

Figure 7. Location of FSPV installation in Google Earth images.

4. Design Studies

As part of the LSS strategy of the Energy and Natural Resources Ministry under MyRER, our goal is to implement a 10 MW FSPV plant in the water bodies of UMP Lakes; thus, design studies for the plant are crucial. According to the simulation, UMP Lakes C (4000 kWp) and D (8000 kWp) each have a combined 12,000 kWp DC FSPV system to achieve the target of 10 MW AC as the DC to AC conversion ratio of 1.2. This section describes the design of the proposed plant, the numerical calculation of FSPV technology, the specifications of the PV arrays and plant, and simulation studies.

4.1. Architecture of Floating Platform

Typically, the floating platform includes coupling elements, floating devices for buoyancy, support systems for PV modules and PV panels themselves. We are already familiar with the numerous floating structures according to the literature. For our proposed plant, we chose HDPE materials as floats and FRP materials as the support frame of PV modules to make a floating structure based on the location, shipping, reliability, environment and other factors. The floating structure and the floating PV energy generation platform are depicted in Figure 8. Although the comparative prices for both HDPE and FRP materials are high, both seem to have strong chemical and corrosion resistance, comparatively high stiffness and rigidity and a light weight, each of which is vital for FSPV renovation; thus, these materials are thought to be suitable for manufacturing [112]. Additionally, the platform pathway is composed of fiber-reinforced plastic (FRP) materials, and indeed, the unit connector is built with stainless steel [113]. Usually, for 18 PV modules, around 15 floats are needed. Therefore, to complete this project, at least 18,017 pieces of HDPE modular pontoon floats measuring 50 cm × 50 cm × 40 cm are utilized [114]. The overall power of the PV array under Standard Test Conditions (STC) is 12,000 kW, with a total of 21,620 PV modules, each rated at 555 Wp. Every string has 23 series-connected modules, and there are a total of 940 strings. In lakes C and D, there are five and six floating platforms, respectively, which hold all the PV modules.

Shading is one of the key contributors to the external factors that influence the performance degradation of solar PV. PV arrays may experience partial shading because of one module or string casting a shadow on another. Considering this, inter-row space between two strings is a major consideration in the construction of PV plants. To ensure minimal space between the two rows, Equations (1)–(4) are very well designed to produce maximum electricity from PV arrays during sunlight. The latitude (φ) of the UMP Lake area, tilt angle (β), solar declination angle (δ), and module length (l) are all considered in the determination of the inter-row spacing [115].

$$D1 = lcos\beta \tag{1}$$

$$D2 = lsin\beta\cdot \tan(\delta + \varphi) \tag{2}$$

$$D = D1 + D2 \tag{3}$$

$$Height = lsin\beta \tag{4}$$

$$Total\ occupied\ area = No.\ of\ modules \times D \times module\ width(w) + W \tag{5}$$

The optimal tilt angle, β = 10°, which is often used to install the PV panels, is taken into consideration in our project because the tilt angle in Malaysia ranges from 0° to 15° [116]. The other variables include solar declination angle δ = 23.5° for the longest day of the year [110], UMP Lake latitude φ = 3.545 and module length l = 2.384 m and width w = 1.096 m. Thus, based on the calculations, the array's active area is $D1$ = 2.348 m, the free space is $D2$ = 0.211 m, its height difference is 0.412 m, and its minimum inter-row space is D = 2.559 m. According to the design, there must not be any gap (W = 0) between any two modules in a string. Therefore, the total occupied area of the plant is 60,637 m^2.

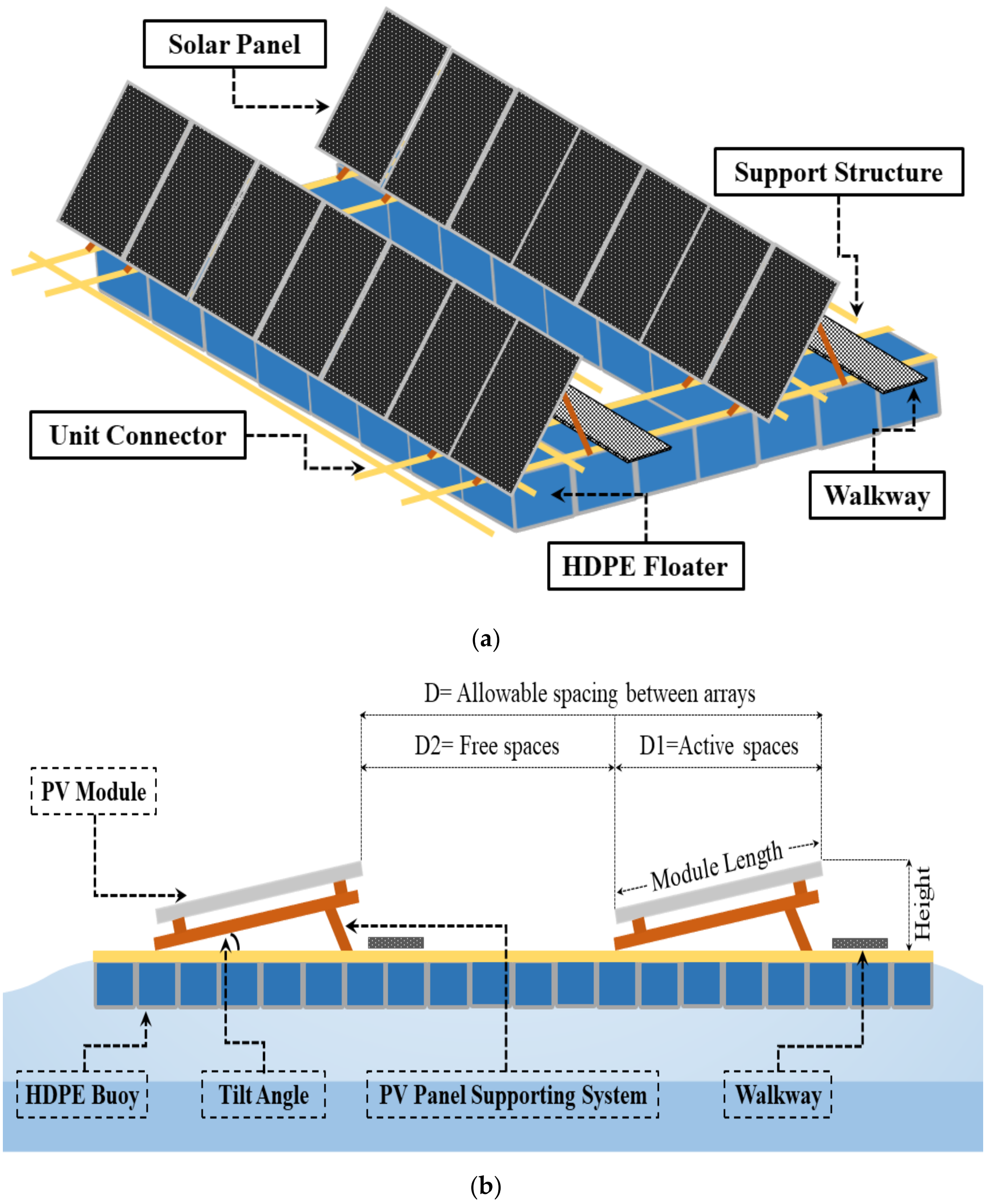
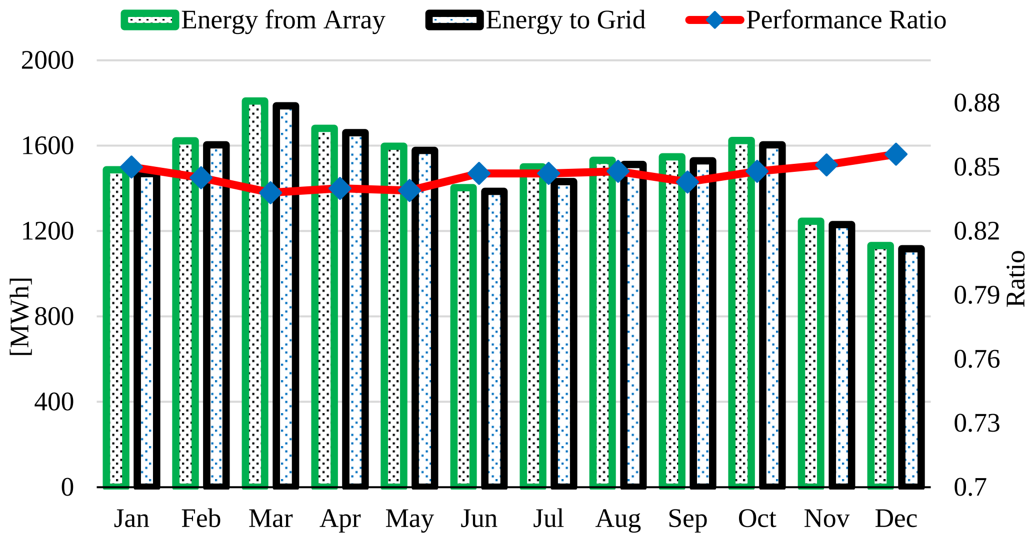


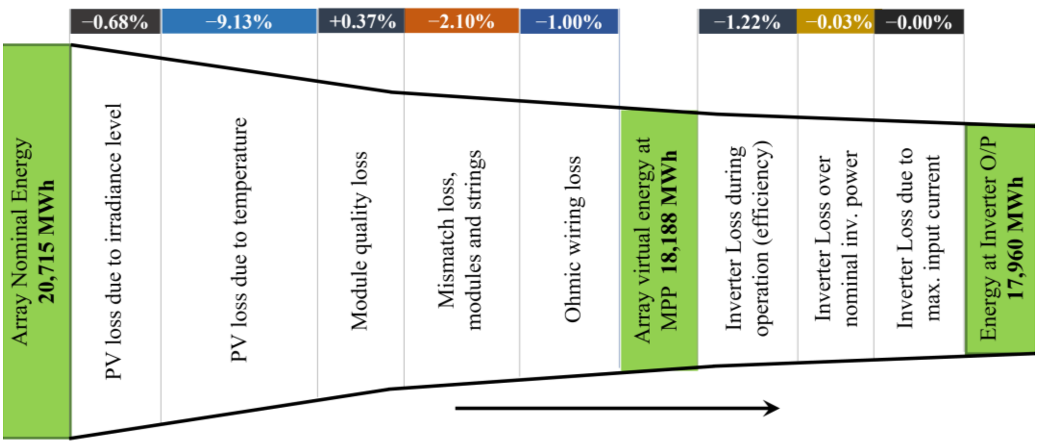
Figure 8. (**a**) Energy generation platform; (**b**) Unit structure of proposed FSPV.

4.2. Simulation Studies

A simulation using PVsyst 7.3.1 to model the FSPV system was carried out to estimate the array specifications, system production, losses, performance ratio, carbon emission reductions and other associated parameters. For simulation, PVsyst obtained metrological data from Meteonorm 8.1 for the site of UMP Lake, where the altitude is 8 m, and the time zone is +8 (GMT). The optimal tilt angle is 10°, and the appropriate azimuth angle of 23.5° was set in the software. The desired energy level of 12,000 kW was entered into the simulation software by the SEDA and EC of Malaysia, and the sizes of the solar modules and inverters were chosen based on the market's availability, reliability, cost, transport facilities, and—most crucially—the local demand. The simulation demonstrates that the effective energy at the output of the array is 18,188 MWh per year, and the injected energy to the grid is 17,960 MWh per year, which equates to daily 4.10 kWh/kWp daily with an average performance ratio of 0.845. The rest of the energy is lost because of several factors, including the array, system and inverter losses. The PV array's monthly effective energy from the array, energy injection into the grid, performance ratio and loss diagram are shown in Figure 9. Due to the greater sunshine hours and highest solar radiation of the year, March produces the most energy (1809 MWh), and December produces the least (1132 MWh). The daily array and system losses that occur in the plant are 0.7 kWh/kWp and 0.05 kWh/kWp, respectively. The PV conversion efficiency of the entire system is 21.25% at STC.



(**a**)



(**b**)

Figure 9. (**a**) Monthly energy production, delivery to grid and performance ratio; (**b**) Loss diagram of the system.

4.3. Specification of PV Array and Plant

According to the study, it is essential to select the finest PV modules, floats, support frames and electrical components when establishing an FSPV system, depending on market demand, cost, how long they last and other factors. Tables 6 and 7 provide specifications for the PV array and plant, respectively. Although the chosen DC combiner box has a maximum DC short circuit current rating of 21–32 A per input, it can be changed depending on the string current rating. Furthermore, the DCCB has a PV DC isolator, a DC surge arrester and DC fuse holders inside it with the proper protection mechanism. The system necessitates an additional AC isolator switch because the chosen inverter does not come with an integrated PV AC switch.

Table 6. Overview of the equipment for projected FSPV plant at UMP Lake.

Technical Parameters of PV Panels			
Manufacturer	Trina Solar	Max. Power Point Voltage (Vmpp)	31.8 V
Model	TSM-DE19	Short Circuit Current (Isc)	18.56 A
Technology	Si-mono	Max. Power Point Current (Impp)	17.45 A
Maximum Power (Pmpp)	555 Wp	Module size	1096×2384 mm^2
Open Circuit Voltage (Voc)	38.1 V	Number of cells	2×55
Technical Parameters of Inverter			
Manufacturer	Sungrow	Nominal AC power	2000 kW
Model	SG2000	Max. AC apparent power	2200 kVA
Protection	IP54 (NEMA3R)	Nominal AC current	3666 A
Operating mode	MPPT	Max. AC current	4032 A
Size ($W \times H \times D$)	$2.99 \times 2.59 \times 2.43$ m^3	Rated grid voltage	415 V
Weight	5700 Kg	Grid voltage range	400–460 V
Max. PV input voltage	1000 V	Nominal grid frequency	50/60 Hz
Startup input voltage	500 V	Feed-in phases	Triphased
Min. working voltage	460 V	Maximum efficiency	99%
MPPT voltage range	460–850 V	Number of MPPT	4
Max. input current	4880 A	Number of string inputs	32
Technical Parameters of Transformer			
Manufacturer	ABB	Rated Power	12.5 MVA
Model	Customized	Rated voltage (HV)	11 kV
Number of phases	Three	Rated voltage (LV)	0.415 kV
Cooling system	ONAN	Frequency	50 Hz ($\pm$5%)
Technical Parameters of DC combiner box			
Manufacturer	MOREDAY	Max. input current per channel	20 A
Model	MDXLD-PV24/1	Max. DC output current	400 A
Max. input	24 strings	Max. DC short-circuit current	21–32 A
Max. output	1 string	Protection level	IP65
Max. DC input voltage	1500 V	Dimension ($W \times H \times D$) (m^3)	$1.2 \times 0.75 \times 0.25$

Table 7. Summary of the projected FSPV plant at UMP Lake.

Plant Summary			
System nominal DC power	12 MWp	Rough panels area	56,490 m^2
System Max. DC power	11.828 MWp	Sensitive cells area	52,428 m^2
System AC power,	10 MW	Plant occupied area	60,636 m^2
Pnom ratio (DC:AC)	1.20	Number of DC combiner boxes	50 pcs
Vmpp (STC)	663 V	Number of inverters	5 pcs
Impp (STC)	16.568 kA	Number of transformers, 2.5 MVA	5 pcs
Number of PV panels	21,620 pcs	Number of AC isolator switches	5 pcs
Number of panels per string	23 pcs	Substation	1 pc
Array size	940×23	Weather station	1 pc
Number of floating pontoons (min)	18,017 pcs	Switchgear and protection	1 pc

The complete array is split into two lakes. Lake C hosts a 313×23 array with 7199 modules and 17 DCCBs. On the other hand, a 627×23 array is formed in lake D using the remaining 14,421 PV modules and 33 DCCBs. The DCCBs' output is linked to inverters that are placed next to the grounds of the lakes (see Figure 7), and to link with the grid, the output from the inverters is boosted to an 11 kV AC utilizing five 2.5 MVA transformers. This 11 kV high voltage relates to the grid of Tenaga Nasional Berhad (TNB), Malaysia. To track the generation and distribution of energy throughout time, the plant employs a SCADA-based monitoring system.

5. Analysis and Assessment

To analyze and assess the feasibility of FSPV in UMP Lake, some significant aspects that affect the implementation of the plant were carefully considered. This section includes a technical and financial assessment, emission reductions, a grid integration analysis, and the viability of LSS's connection to TNB's grid.

5.1. Budgetary Evaluation

Due to the usage of additional equipment, including pontoons, submerged wires, anchoring and mooring systems, expertise labor costs during installation and regular inspection costs of underwater elements, the construction of FSPV technology is always 20–25% more expensive than the construction of a land-based PV plant. However, it is still less than a rooftop solar installation [30,117]. Typically, the total capital investment of an FSPV installation lies between USD 0.8 and USD 1.2 per Wp, depending on the place, the level and diversity of the water surface and the size of the plant [20,118]. Following the guidelines of ADB Financial Management and Analysis of Projects 2005, the budget for the FSPV plant at UMP Lake was calculated [118]. The financial information in Table 8 was created while taking into account both recent scholarly investigations [92,119–121] and the current market value of the products from online retailers (such as Alibaba, Amazon, IndiaMART and others). A corporate tax rate of 24% and the VAT rate of 6% in Malaysia were considered according to the year 2021. The physical and price cost contingencies were counted as 5% and 3.1%, respectively, of the overall base cost. The cost estimate was performed in US dollars using a conversion of 1 MYR to 0.23 US dollars.

Table 8. Detailed budget estimation for FSPV plant at UMP Lake.

SL No.	Purpose	Parameters	Total Cost (Million USD)
1	Civil works	Anchoring and mooring system	0.19
		Floating structure	0.90
		Wage cost of labor (construction period)	0.40
2	Equipment	PV panels	1.78
		Inverters	0.30
		DC combiner box	0.01
		Weather station	0.01
		DC and AC Cables	0.26
		Grid substation (transformer, switchgear, SCADA and others)	1.26
		Testing and commissioning	0.01
		Water storage, supply, repair boats and water monitoring sensors	0.07
		Profit edge	0.60
3	Miscellaneous	Accessories, fasteners, wiring, PVC flexible pipe, SDB board, fitting–fixing, energy meter, monitoring and display, UPS, lan tools and others	0.03
4	Planning, consultation and inspection	Grid system analysis	0.02
		Feasibility analysis	0.20
		Performance analysis	0.01
		Geological analysis	0.01
		Hydrographic inquiry	0.01
		Ecological impact analysis	0.02
		Engineering simulation and design	0.10
		Explanation of the methodology, assessment strategy, paperwork, and guarantee setup	0.02
		Comprehensive engineering assessment	0.04
		Budget of finance (from planning to completion)—independent engineer	0.02
5	Inland transportation	Logistics	0.38

Table 8. *Cont.*

SL No.	Purpose	Parameters	Total Cost (Million USD)
6	Taxes and duties	Total tax incidence on solar panels (24%) VAT (6%)	0.07 0.45
7	Additional investment expenditures	Land development and construction Environmental and social cost Project management, construction and supervision	0.02 0.25 0.25
8	Contingency	Physical and price	0.60
9	Costs related to the execution	Interest upon installation Fees for committing	0.64 0.01
		Initial investment cost (without replacement and O&M)	**8.94**
10		Replacement cost	1.40
11		Operation and maintenance (O&M) cost (21 years)	9.39
		Total cost of the system (CTS)	**19.73**

5.2. Energy Generation Cost Estimation

Equation (6) was used to estimate the cost of per unit energy generated by the proposed FSPV project, where Egn represents the net electricity generated during the plant's lifetime (21 years), *Cts* represents the system's total cost, and *Egc/kWh* represents the per kilowatt-hour energy generation cost. The overall cost covers the capital cost and OPEX, with CAPEX including the cost of civil works; the cost of FSPV equipment; various survey, design and analysis costs; contingency costs; and other costs. OPEX includes the cost of operation, repair, and replacement. The system might require 19.73 million US dollars in total. Each year, the plant produces nearly 17,960 MWh of energy, and during its 21-year lifespan, it produces nearly 377,160 MWh of energy. Therefore, according to Equation (6), the per unit (kWh) energy generation cost is USD 0.052.

$$Egc/kWh = Cts/Egn \tag{6}$$

5.3. Economic and CO_2 Emission Mitigation Assessment

To assess the economic evaluation of the planned FSPV project, Equations (7) and (8) were used. Here, the annual savings is the profit made by the FSPV system expressed in US dollars, annual energy production is expressed in kWh, and LCOE denotes the levelized cost of energy per kWh. The initial investment seems to be the capital cost of the plant in dollars necessary for establishing the intended plant, and the payback period in years is the amount of time it takes for it to produce enough electricity to recoup its original investment expenditures. As the annual energy production from the proposed plant is 17,960,000 kWh and the LCOE is USD 0.052/kWh, according to Equation (7), the annual savings of the PV plant would be approximately 17,960,000 kWh × 0.052/kWh = USD 933,920, and according to the Equation (8), the payback period for this FSPV plant would be approximately 8,900,000/933,920 = 9.5 years because the initial expenditure (total CAPEX) of this project is 8.9 million dollars.

$$Annual\ savings = Annual\ energy\ production\ (kWh) \times LCOE \tag{7}$$

$$Payback\ period = Initial\ investments/Annual\ savings \tag{8}$$

FSPV systems may help reduce carbon emissions by producing clean, renewable electricity from solar energy. The quantity of carbon dioxide and other greenhouse gases emitted into the environment is decreased when floating PV systems are used in place of conventional fossil-fuel-based power plants. Floating PV plants may reduce carbon emissions by providing electricity from a renewable source in lieu of energy that would have otherwise been produced from fossil fuels. Additionally, floating PV systems may contribute to the preservation of resources such as land and water that would otherwise be utilized for energy generation [69,95,122]. As PV installations cannot be entirely regarded as pure zero-emission energy production technologies, the carbon footprint of a PV plant refers to the quantity of carbon dioxide emissions created during the manufacturing, shipment, installation and operation of the plant. According to studies, a PV plant emits around 40 g of CO_2 equivalent per kilowatt-hour [123]. Equations (9)–(11) estimate the CO_2 emission reductions for the projected FSPV plant. Equation (9) depicts the total CO_2 emissions of the proposed plant, Equation (10) depicts the highest CO_2 emissions that might be reduced by the FSPV plant, and Equation (11) depicts the net CO_2 reductions. Here, to calculate the emissions, only the PV panel is considered, and the impact of floaters is neglected.

$$\begin{aligned} &CO_2\ emission\ from\ FSPV\ plant \\ &\quad = Annual\ energy\ production\ (kWh) \times CO_2/kWh \end{aligned} \tag{9}$$

$$\begin{aligned} &CO_2\ emission\ mitigation\ by\ FSPV\ plant \\ &\quad = Annual\ energy\ production\ (kWh) \\ &\quad \times Grid\ emission\ factor \end{aligned} \tag{10}$$

$$\begin{aligned} &Net\ CO_2\ reduction \\ &\quad = CO_2\ emission\ mitigation\ by\ FSPV\ plant \\ &\quad - CO_2\ emission\ from\ FSPV\ plant \end{aligned} \tag{11}$$

Therefore, assuming the emitted value of 40 g of CO_2 eq/kWh, the annual CO_2 emissions from the planned FSPV plant are 718.4 tons. Because the Malaysian grid's life cycle emissions vary depending on the fuel type, as per the literature [124], the proposed plant considers the grid's emission factor of 660 g CO_2/kWh. As a result, this FSPV plant reduces CO_2 emissions by 11,853.6 tons/year, and the net CO_2 emission reduction by this FSPV plant is 11,135.2 tons annually.

5.4. Grid Connection Analysis

The grid connection study determines the suitability and acceptability of a 10 MW FSPV plant at UMP, Pekan, in the TNB distribution network in Malaysia. It is planned that the FSPV plant will include 5 × 2000 kW inverters, 5 × 2.5 MVA and 0.415 kV to 11 kV step-up transformers placed quite close to the shore of Lake D. By means of underwater cables, the FSPV plant's generated DC power is sent to the onshore inverters, and the medium-level voltage from the transformer's HT side is sent to the UMP substation close to the UMP Property Development and Management Center (PDMC) so that it can connect to the TNB distribution network. The monitoring and security system for the facility is built close to its shoreline. There is an HT VCB panel, a PFI plant and a complete SCADA-based monitoring system. As the transmission line from the plant to the UMP substation is only around 2.3 km long, there are relatively fewer cables utilized, which reduces the transmission loss and associated costs. Figure 10 depicts the single-line schematic of the FSPV plant on the grid.

5.5. Feasibility of FSPV under LSS Strategy

Since 2012, the EC has been operating four specialized programs to promote renewable energy in Malaysia. They are (i) the Feed-in Tariff scheme (FiT), (ii) Large-Scale Solar Auction (LSS), (iii) Net Energy Metering (NEM) and (iv) Self-consumption (SELCO) program. LSS auctions were first launched in Peninsular Malaysia in 2016. With the lowest offer for off-take costs, LSS aims to facilitate the adoption of utility-scale solar power plants with sizes ranging from 1 to 100 MW. Up to 2020, about 857 MW of solar PV capacity was constructed within the LSS framework, which resulted in a significant decrease in the cost of energy. Although a rapid procedure was used to allocate a 250 MW large-scale solar plant before the start of LSS auctions, Malaysia had already held four LSS bids from 2016 to 2020 [8,125,126]. In the four LSS auctions, the cost for 10 MW to 30 MW plants varied from RM 0.1850/kWh to RM 0.2481/kWh, and the cost for 30 MW to 50 MW plants ranged from RM 0.1768/kWh to RM 0.1970/kWh [127]. A summary of the four LSS auctions is as follows:

- LSS 1: This auction took place in 2016 for the capacity of 371 MW. The lowest bid was RM 0.39/kWh.
- LSS 2: The LSS 2 auction was held in 2017 for 526 MW of capacity, with the lowest price of RM 0.34/kWh. The auction of LSS 2 was 13% less expensive than the auction of LSS 1.
- LSS 3: This auction was held in 2019 for 491.88 MW. The lowest bid was RM 0.17/kWh, 50% lower than LSS 2.
- The last auction, LSS 4, was held in 2020 for the capacity of 1000 MW, with the lowest bid of RM 0.1399/kWh. The bid for LSS 4 was 18% lower than that of LSS 3.

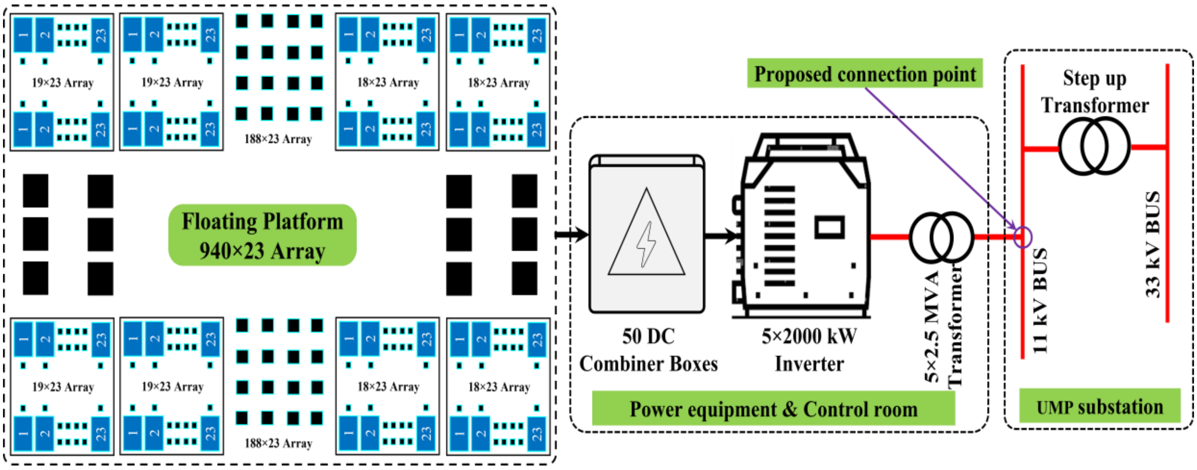


Figure 10. Single line diagram of FSPV plant to TNB grid.

The LSS scheme includes a floating solar power plant, which is an ongoing development at EC. In both east and west Malaysia, there are several floating solar power plants that are active or being constructed. A 13 MW FSPV facility in Selangor sells energy to TNB with a 21-year Power Purchase Agreement (PPA) and LCOE of RM 0.21608/kWh or USD 0.051/kWh [128]. To consider the LCOE of a 13 MW FSPV plant as a benchmark, and adhering to EC regulations to link the LSSPV to the TNB grid, a feasibility study of the FSPV under the LSS scheme is presented in Table 9. The analysis determines the appropriateness of the FSPV connection in the LSS scheme of EC.

Table 9. Status of the proposed plant according to the EC guidelines.

Term	Parameters of EC for LSS	Status of the Proposed FSPV Plant
General	The LSS program participants should be a local company/authority/owner.	UMP is a national public university of Malaysia.
	A land or water body can be used for other purposes.	Water bodies are also used for fisheries.
	Plant capacity must be between 1 MW and 100 MW.	The proposed plant is 10 MW.
	The PPA duration is 21 years.	The design and calculation of the plant were made considering its 21-year lifespan.
	Fixed and lower energy prices.	The LCOE of the proposed plant is USD 0.052, which is acceptable according to the previous LSS bids.

Table 9. *Cont.*

Term	Parameters of EC for LSS	Status of the Proposed FSPV Plant
Connection study	The connection voltage level is 0.415 kV, 11 kV and 33 kV for the distribution voltage network.	The selected transformer's output voltage is 11 kV, and it is connected to an 11 kV bus.
	The nodal point must be at a distribution license (DL) owned substation.	As UMP has a 33/11 kV DL license substation, the nodal point must be in the UMP substation.
	Must have VCB/GIS switchgear and a SCADA system.	A GIS-based HT panel and a SCADA-based monitoring system are there.
Power system study	Information related to the single line diagram, plant layout, datasheet of PV panels and inverters, site, location layout, installed and output capacity, COD and others must be sent to CE.	The maximum amount of information possible is provided in this article. More related information and documents will be sent at the time of application.
Technical study	Technical parameters, such as voltage range, steady state voltage limit, frequency, power factor, harmonics, fault level, synchronization, etc., must be harmonized with the existing TNB's network.	The design and selection of equipment were made considering the TNB network. Furthermore, an in-depth study on technical parameters will be conducted before the Request for Proposal (RFP).

6. Conclusions

In this article, the technical and economic potential of the proposed FSPV plant in UMP Lake, Pekan, Pahang, Malaysia, is evaluated based on the water bodies, environmental aspects and other available resources, and a feasibility analysis is carried out according to the EC guidelines. The UMP authorities may refer to this paper as a guideline while putting the plant into operation. The outcomes of this study may help guide future planning and decision-making initiatives targeted at accelerating the construction of large-scale solar projects throughout the nation. Put simply, the study's findings are as follows:

- The technical and financial research favorably supports the construction of a 10 MW FSPV plant at UMP Lake.
- The proposed FSPV plant may make a substantial contribution to the country's large-scale solar strategy.
- According to assessments, FSPV has a 12 MWp capacity and produces 17,690 MWh of energy annually.
- The PR of the plant of 84.5% was simulated using PVsyst software, which shows that the region has significant potential to generate additional RE utilizing FSPV technology.
- The plant only needs to use 60,636 m^2 of water bodies to generate 17,960 MWh of electricity annually with an LCOE of USD 0.052/kWh.
- The project's capital expenditure worth USD 8.94 million is recovered during a payback period of 9.5 years.
- The planned facility helps the country's initiatives to mitigate the effects of climate change by dramatically reducing CO_2 emissions, which would amount to 11,135.2 metric tons annually.

According to the research's findings, floating solar PV has substantial potential as a realistic solution for achieving Malaysia's renewable energy targets. In the end, this research emphasizes the significance of ongoing investment and innovation in the renewable energy industry to ensure that Malaysia and the rest of the globe have a sustainable energy future.

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