An Econo-Environmental Analysis of the Tengeh Reservoir Floating Photovoltaic Farm

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Abstract

In 2021, Singapore marked a significant milestone with the establishment of a 45-hectare floating photovoltaic (FPV) testbed in Tengeh Reservoir, aligning with the global shift towards renewable energy adoption to mitigate carbon emissions. As floating photovoltaic farms gain prominence in large-scale projects, this study aims to compare their efficiency against land-based photovoltaic (LPV) farms. Key parameters, including their albedo, heat-loss coefficient and energy capacity, were analysed to assess their performance. To evaluate the economic viability of FPVs, the study employed the present worth approach, calculating and comparing crucial indicators such as its net present value, internal rate of return, payback period, benefit-cost ratio, profitability index, unit cost of generation and weighted average cost of capital. Furthermore, the environmental sustainability of FPVs was assessed by analysing solar irradiance levels in Singapore using PVGIS-ERA5 data and quantifying CO2 mitigation and emission levels. The findings reveal that FPVs present a lucrative investment opportunity with substantial net CO2 reductions, demonstrating the benefits for developers and the environment. Although FPVs are less technologically mature than their land-based counterparts, they offer promising potential that is likely to only improve through continued research and innovation.

Key Words: Solar Energy; Floating Photovoltaics; Economic Performance; Energy Efficiency; Present Worth Approach; Renewable Energy

1. Introduction

Singapore is an island city-state situated on the southern tip of the Malaysian peninsula blessed with abundant annual solar irradiance levels, surpassing those of temperate countries like the United States of America by approximately 50% (EMA, 2022). Motivated by these favourable conditions, the Singaporean government has embarked on a path of large-scale solar power utilisation. This commitment aligns with Singapore's revised Nationally Determined Contribution (NDC) under the United Nations Framework Convention on Climate Change, where the nation pledged to cap its carbon emissions at 65 million tonnes by 2030 (NCCS, 2020). Given that the power sector contributes 40% of Singapore's total carbon emissions, the transition to renewable energy sources is imperative to achieve its NDC target. Hence, Singapore has an ambitious target of harnessing a minimum of 2 gigawatts-peak (GWp) of solar energy by 2030 (Sun et al., 2021).

Solar energy has long been an attractive alternative energy source. To date, at least 18 countries have constructed land photovoltaic (LPV) farms with a capacity greater than one gigawatt (Jäger-Waldau, 2020). Previously, concerns surrounding the cost-effectiveness of solar energy hindered widespread investments. However, since 2010, the cost of production for solar technologies has reduced by 80% (Li et al., 2017). Concurrently, the efficiency of PV modules has risen from 14.7% to 19.2% (Lugo-Laguna et al., 2021). This progress means that fewer panels are needed to generate the same wattage, thus prompting further investments in solar energy.

Singapore, with its high solar irradiance exposure, would uniquely benefit from the large-scale implementation of solar panels. However, Singapore is resource-constrained in one major way: land area; it is only 718.3 km² in landmass (Sin et al., 2016). To address this constraint, Singapore has undertaken extensive research on the feasibility of deploying FPVs.

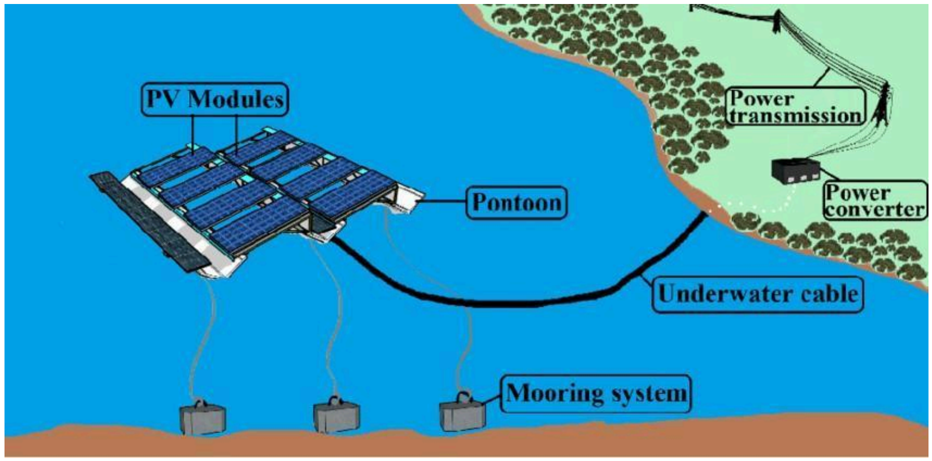

FIGURE 1. Setup of FPVs (Rodrigues et al., 2020)

Floating photovoltaics (FPVs), a novel technology introduced in 2007, have garnered significant attention in recent years. The cost-effective deployment of FPVs would not only preserve valuable onshore space, but also facilitate transitioning to green energy sources. Figure 1 illustrates the setup of FPVs: the systems are moored to limit movement, and their V-shaped reflectors are oriented toward solar radiation. The generated energy is transmitted via an underwater DC cable to an onshore array, where it is stored or converted to AC using an inverter for further transmission.

Singapore presents an ideal environment for FPV adoption due to both technical and environmental conditions. Its abundant solar irradiance has been identified by the National Market Authority as the "most viable renewable energy source" (EMA, 2017, p.12). Additionally, Singapore’s reservoir’s benign water conditions, with wave heights typically below 1 meter, minimise construction and maintenance costs that are otherwise elevated in offshore environments, which often suffer from low technical readiness levels. As a result, FPV deployment on inland water bodies can “substantially reduce the design requirements” and are considered “extraordinarily attractive” for energy generation (Zhang, 2023, p.2).

In-depth research conducted by the National University of Singapore, encompassing static analysis and hydroelastic analysis, revealed that FPVs deployed in the Tengeh Reservoir exhibit exceptional resistance to high levels of stress (Dai et al., 2019). Consequently, the likelihood of system failures is significantly reduced, further enhancing their cost-effectiveness.

FPVs offer several notable advantages over LPVs. Benefiting from lower ambient temperatures, FPVs capitalize on module cooling, resulting in reduced operational temperatures and improved conversion efficiency. Studies indicate that FPVs possess a significantly lower calculated heat loss coefficient of 30 compared to 56 for LPVs, further enhancing their performance (Micheli, 2021). Moreover, FPVs exhibit an 11% higher performance ratio than LPVs (Da Silva & Branco, 2018). However, it should be noted that previous research has reported an albedo of 13% for LPVs, whereas FPVs exhibit an albedo ranging from 5% to 7% (Muzzillo et al., 2018). The lower albedo of FPVs indicates that less light is reflected from the water surface compared to land, resulting in a marginally inferior bifacial performance.

This research paper aims to assess whether the net benefits of FPVs outweigh their associated drawbacks, contextualised to their deployment in Tengeh Reservoir. The literature review comprehensively examines prior studies on FPVs while also exploring various methods for analysing the economic viability of solar farms. The data section establishes a foundation for economic analysis through the integration of on-site data and conventional values. The methodology section identifies relevant equations and discusses approaches for analysing the variability in solar irradiance, acknowledging the inherent limitations of the selected methods. In the results section, collected data is inputted in equations and software tools to derive key values crucial for comparative assessments. Finally, the conclusion summarises the key findings, followed by a broad discussion on the overall implementation prospects of FPVs.

2. Literature Review

This section begins with an examination of existing data, categorising countries based on their respective stages of solar energy adoption. Subsequently, consideration is given to specific technical parameters employed for assessing the viability of solar energy implementation. These will later be compared to precise calculations derived from the FPV farm situated at Tengeh Reservoir.

Typically, the costs of a photovoltaic plant encompass eight essential components: solar modules (i), land (ii), inverters (iii), installation costs (iv), maintenance expenditures (v), DC and AC cables (vi), racking and mounting expenses (vii) and financial costs (viii). The installation costs for FPVs are typically $0.26 per watt-direct current, which is 25% higher than their land-based counterparts. This disparity can be attributed to the 300% greater structural costs associated with the floating and mooring system (Ramasamy et al., 2021). Although the fixed costs of FPVs presently surpass those of LPVs, research conducted indicates that operational expenses can be minimised due to reduced major site works (Micheli, 2022). Moreover, in Singapore specifically, the utilisation of drones has effectively reduced maintenance costs by 30%, thus enhancing the economic viability of FPVs as a means of electricity generation (IES, 2021).

To assess the long-term sustainability and efficiency of FPVs and LPVs, it is crucial to compare their respective annual degradation rates and system losses. Previous research indicates that LPVs exhibit an average degradation rate of 1.07% per year (Goswami & Sadhu, 2021). In the Tengeh Reservoir FPV, the projected annual degradation rate is estimated to be 3% for the first year, followed by 0.5% for subsequent years (EDB, 2021). Mathematically, this implies that from the fifth year onwards, FPVs surpass the structural performance of the average LPV. Both photovoltaic systems exhibit typical system losses of 14%, further highlighting the systemic promise of FPVs (PVGIS, 2017).

The cost disparity among PV plants in various countries will be examined by using the weighted average cost of capital (WACC) computed by the International Renewable Energy Agency (IRENA). The WACC determines the proportionate expenditure required to generate an additional $1 in revenue. It is an important metric that directly influences the level of financing a project can attract based on its hurdle rate, and can simultaneously be used to judge cost disparities across countries in their stage of solar energy implementation.

Country	WACC
Brazil	6.1%
India	4.4%
United States of America	4.2%
United Kingdom	2.8%
China	2.7%
Germany	1.8%

TABLE 1. Differences in WACC across countries (IRENA, 2021)

As seen in Table 1, countries with substantial investments in solar energy, such as Germany and China, have a lower WACC. This can be attributed to the economies of scale associated with their extensive adoption and construction of FPVs. In this study, the WACC will be computed for the solar farm located at Tengeh Reservoir and compared against global benchmarks to evaluate the current status of solar energy implementation in Singapore.

Overall, while LPV systems are well-studied, research on FPVs is limited and can benefit from economic analysis contextualised to specific farms to hypothesise general findings.

3. Methodology

3.1. Parameters

Table 2 presents an overview of the parameters utilised in the computation of key economic and environmental values for the FPV farm in Tengeh Reservoir:

Parameter	Definition
Total capital investment for the project (Ci)	The capital expenditure required to acquire the necessary physical assets essential for the establishment of the FPV plant
Rated capacity (Pr)	The maximum total power generated by the FPV plant under optimal sunlight conditions and minimal degradation
Expected project life (n)	The projected duration for which the FPV is expected to operate without system failures
Capacity factor (Cf)	The ratio of the annual average energy production of the FPV plant to the theoretical maximum annual energy production at peak rated capacity
Annual operation and maintenance (m)	The fraction of the initial capital expenditure required for annual maintenance and operational activities of the FPV plant
Real rate of discount (I)	The nominal interest rate adjusted for expected inflation, used to discount future cash flows
Annual benefit (Ba)	The monetary inflow resulting from the supply of electricity generated by the FPV plant
Depreciation period (Nd)	The period over which the FPV plant experiences a decline in quality and yield
Discount rate (d)	The interest rate charged by the central bank when lending to commercial banks
Linear system degradation (Rd)	The gradual decline in the performance of the photovoltaic cells due to sustained wear and degradation over time
Years of operation (T)	The projected number of years the FPV farm is expected to remain operational

TABLE 2. Parameters and their Definitions

3.2. Variation in Solar Irradiance

Singapore, located in the equatorial region, is classified as Af under the Köppen-Geiger system, indicating a tropical rainforest climate with year-round humidity - conditions that are conducive for solar energy (Vasquez, 2018).

Despite its lack of seasonality, it is crucial to examine the variations in solar potential to assess their impact on solar module energy output. To investigate this, the PVGIS-ERA5 dataset will be utilised to extract national-scale solar data, which will then be integrated into the System Advisory Model (SAM) software for visualisation purposes. Furthermore, specific geographic information system (GIS) data pertaining to Tengeh Reservoir will be analysed and compared to global FPV sites to determine if the levels of solar irradiance are consistent for wide scale implementation.

3.3. Economic Analysis

The economic feasibility of FPVs warrants careful analysis. While specific data for the FPV at Tengeh Reservoir is not publicly accessible, it is possible to assess the projected metrics by using the present worth approach. This methodology involves converting expected future costs and revenues into present-day monetary values. Financial indicators that elucidate the cost-effectiveness of the project include the net present value (NPV), payback period, and internal rate of return (IRR). These metrics provide insight into the project's creation over time, how quickly costs can be recovered and the expected return rate respectively, which is crucial for assessing its viability and profitability. The equations for these indicators are derived from a research paper proposing the establishment of a LPV farm in Brunei Darussalam (Satyajith et al., 2013).

The NPV measures the total expected value of future cash flows generated by the FPV farm, disregarding changes in the monetary gain resulting from inflation.

$$(1)\ NPV = B(A)\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right] - \left\{C(I)\left[1 + m\left(\frac{(1+I)^n - 1}{I(1+I)^n}\right)\right]\right\}$$

EQUATION 1. Net Present Value

Equation 1 relies upon two fundamental assumptions: the reinvestment rate assumption, which posits that cash inflows will be reinvested into the project, and the assumption that both cash inflows and outflows occur at specific time intervals, namely at the conclusion of each period. This metric is highly effective in assessing the value trajectory of the FPV farm across different time horizons, as it discounts future cash flows. However, it is important to acknowledge that future cash flow projections are estimations and are susceptible to fluctuations. Thus, the NPV should be regarded as a guiding tool rather than definitive.

The next value to be computed is the payback period, which denotes the expected duration necessary for Sembcorp to recoup their initial investment outlay. Examining this metric enables a deeper comprehension of the long-term implications of an FPV project and the anticipated arrival of returns. This will be deduced using Equation 2:

$$(2)\ PBP = -\frac{ln(1-\frac{IC(I)}{B(A)-mC(I)})}{ln(1+I)}$$

EQUATION 2. Payback Period

When calculating the payback period, it is assumed that timings and magnitude of the cash inflows are accurately forecasted. However, this metric does not incorporate the time value of money or account for the financial risks associated with lengthier projects. Nonetheless, this value is valuable in assessing the project's feasibility and can be compared against its counterparts, namely the NPV and IRR.

The IRR will be calculated using the Newton-Raphson method, which leverages the intermediate value theorem to determine the roots of an equation. The IRR represents the discount rate needed to nullify the NPV, thus signifying the annual compounded rate of return earned from a project. If the IRR surpasses the hurdle rate established for solar farms, which denotes the minimum acceptable rate of return, then the project is deemed viable for continuation. A pivotal assumption underlying the calculation of the IRR is that all positive cash flows are assumed to be reinvested into the project at a constant rate rather than at the company's cost of capital. While the IRR is a more robust measure than the payback period, its underlying assumption can be unrealistic in practical scenarios. The IRR will be derived by equating the following equations:

$$(3)\ B(A) = \left[\frac{(1+IRR)^n-1}{IRR(1+IRR)^n}\right] = C(I)\left\{1 + m\left(\frac{(1+IRR)^n-1}{IRR(1+IRR)^n}\right)\right\}$$

EQUATION 3. Internal Rate of Return

The Benefit-Cost Ratio (BCR) is a ratio that measures the magnitude of benefits derived from the FPV relative to its associated costs, thereby providing insights into whether the solar farm is anticipated to yield a net positive return for investors. While the BCR shares underlying assumptions with the NPV, which may impede its applicability, it nevertheless contributes to understanding the inherent risk profile of a project. The BCR will be calculated as per Equation 4:

$$(4)\ BCR = \frac{B(A)\left[\frac{(1+I)^{n}-1}{I(1+I)^{n}}\right]}{C(I)\left[1+m\left(\frac{(1+I)^{n}-1}{I(1+I)^{n}}\right)\right]}$$

EQUATION 4. BCR

The Profitability Index (PI) is a measure of an investment's monetary attractiveness by calculating its expected profit. By quantifying the generated value in relation to the input, the PI directly assesses the efficiency with which capital has been deployed. It will be computed using the following formula in Equation 5:

$$(5)\ PI = \frac{\sum_{n=1}^{N}\frac{NCF(n)}{(1+r)^{n}}}{\sum_{n=1}^{N}\frac{I(n)}{(1+r)^{n}}} = \frac{NPV}{I_{o}}$$

EQUATION 5. PI

An additional parameter essential for evaluating the cost-effectiveness of the solar farm at Tengeh Reservoir is the unit cost of generation. The unit cost of generation denotes the expenditure incurred in generating 1 kilowatt of energy once the installation costs have been accounted for. As it falls under the present worth approach, the unit cost of generation shares the same underlying assumptions, advantages and disadvantages as the NPV. It will be calculated using the following formula in Equation 6:

$$(6)\ c = \frac{NPV(Ca)}{E(I)} = \frac{C(I)}{8760n}\left(\frac{1}{P(R)C(F)}\right)\left\{1 + m\left(\frac{(1+I)^{n}-1}{I(1+I)^{n}}\right)\right\}$$

EQUATION 6. Unit Cost of Generation

3.4. Cost Analysis

The WACC will be determined using the NREL SAM Software after incorporating the requisite data inputs. The WACC serves a dual purpose: firstly, it allows for the comparison of Singapore's FPV adoption against that of other countries and secondly, it acts as a hurdle rate to evaluate whether the Internal Rate of Return (IRR) surpasses it, thereby meeting the expectations of the project's stakeholders and lowering the levelised cost of energy (Ondraczek, 2014).

3.5. Environmental Analysis

The quantification of CO2 mitigation, CO2 emissions, and net CO2 reduction will be accomplished by applying the equations outlined in the study by Kumar et al. (2017). These calculations will enable a comprehensive comparison between FPVs, LPVs and other green technologies, thereby providing valuable insights from a sustainable and societal perspective. Additionally, we can consider the expenditure required amongst different renewable energy sources to achieve the same CO2 reduction and thus determine their economic feasibility.

(7) *CO_2 Mitigation by PV Plant = Annual Energy Generation * Emission Factor*
EQUATION 7. CO_2 Mitigation by PV Plant

(8) *CO_2 Emission by PV Plant = Annual Energy Generation * (7) CO_2 per KWh*
EQUATION 8. CO_2 Emission by PV Plant

(9) *Net CO_2 Reduction = CO_2 Mitigation by PV Plant-CO_2 Emission from PV Plant*
EQUATION 9. Net CO_2 Reduction

3.6. Limitations of Methodology

The limitations of using each equation for economic and environmental analysis have been recognised. However, employing a range of such economic indicators provides a more holistic understanding of the FPV farm while mitigating the shortcomings of each specific equation. Due to the unavailability of specific data regarding expected annual energy generation, approximations have been utilised. This introduces uncertainty into the results, thereby impacting the accuracy of the calculated economic and environmental parameters. Moreover, as the FPV farm at Tengeh Reservoir commenced operations only in July 2021, there is a lack of on-site data. Consequently, the actual performance ratio of the FPV farm cannot be accurately determined, thus hindering the assessment of its operational success compared to the projected parameters.

Lastly, the NREL SAM software does not distinguish between LPVs and FPVs Hence, when calculating the WACC an assumption is made that the WACC for LPVs is equal to that of FPVs. This assumption introduces the possibility of skewed results. Considering the current technological advancements, it is likely that the WACC estimate for the FPV farm at Tengeh Reservoir is a conservative estimate as FPV technology is yet to reach the level of maturity achieved by LPVs.

4. Data

4.1. Variation in Solar Irradiance

The solar irradiance variability in Singapore will be examined by analysing data obtained from the Photovoltaic Geographic Information System (PVGIS) using the System Advisory Model (SAM). In line with prior research on FPVs conducted in India, a system loss of 9.3% will be incorporated as an assumed parameter (Nagananthini et al., 2021),. Utilising the PVGIS-ERA5 dataset, the acquired data will be graphically represented to illustrate the solar irradiance patterns.

4.2. Economic Analysis

The inputs used for computing key economic formulae will be as such:

Parameter	Value
Total capital investment for the project (Ci)	$120.507 million
Rated capacity (Pr)	60 MWp
Expected project life (n)	25 years
Capacity factor (Cf)	0.149

TABLE 3. Economic Analysis Parameters (EDB)

In Table 3, out of the 7 required parameters, 3 of them—including the capital investment for the FPV plant, rated capacity and expected project life—can be sourced from publicly available data. The remaining 4 variables will be approximated based on previous research findings. To determine the capacity factor, an investigation into the efficiency of FPVs conducted at Hapcheon dam was referenced (Choi, 2014), yielding a value of 0.149. The annual operation and maintenance costs are typically estimated to be 1% of the total capital investment. However, as highlighted earlier, the utilisation of automated systems at Tengeh Reservoir has led to a 30% reduction in these costs. Consequently, the value was adjusted to approximately 0.7% of the initial capital investment. The annual benefit is computed by multiplying the total electricity generated by the revenue per kilowatt-hour of electricity, which is $0.2794 in Singapore (Tay, 2022). Although the precise total electricity generated was not available, it was mentioned that the energy produced had the potential to power 16,000 4-bedroom HDB flats. Hence, the figure of 16,000 was multiplied by the average annual power consumption per 4-bedroom HDB flat, which is 4,742.2 kilowatt-hours—as provided by data from the Singapore Energy Market Authority (EMA, 2022). The discount rate used in Singapore is notably—and favourably—low at 3%, compared to an average range of 6% to 9% in other countries.

4.3. Cost Analysis

The following table will outline the values used to compute the WACC.

Parameter	Value
Analysis period	25
Inflation rate	2.2%
Internal rate of return (nominal)	9.37%
Project term debt	33.2%
Nominal debt interest rate	4%
Effective tax rate	25%
Nominal construction interest rate	3.5%

TABLE 4. WACC Parameters

In Table 4, the nominal debt interest rate, effective tax rate and nominal construction interest rate are assumed to be 4%, 25% and 3.5% respectively as per the default values in the SAM model. The remaining values are specific to the FPV in Tengeh Reservoir.

4.4. Environmental Analysis

In Singapore, the emission factor is 0.408 and it is assumed that 0.105 CO2 is released per kWh (EMA, 2022).

Renewable Energy Type	GHG Emissions
Biomass	650
Photovoltaic	300
Geothermal	78
Tidal	50
Hydropower	50

TABLE 5. Life cycle greenhouse gas (GHG) emissions for renewable energies (Amponsah et al., 2014)

Table 5 displays the GHG emissions associated with diverse renewable energy sources, quantified in grams of carbon dioxide emitted per kilowatt of energy generated. The diverse selection of energy sources facilitates an assessment of the GHG emission profiles pertaining to FPVs and LPVs.

5. Results and Discussion

5.1. Variation in Solar Irradiance

Using the PVGIS-ERA5 data, the following irradiance graphs were obtained for 2021:

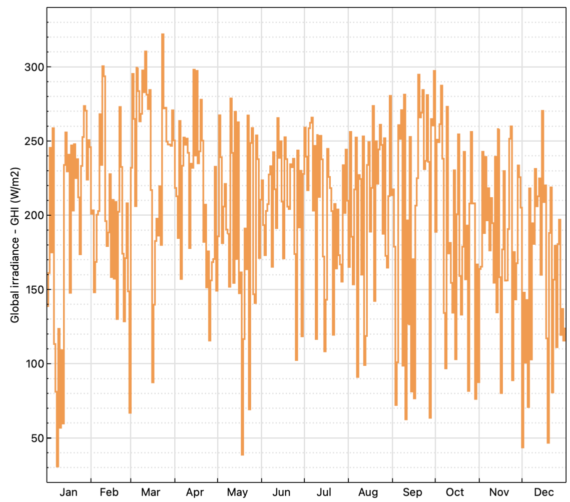

FIGURE 2.1. Daily Global Irradiance Levels Singapore

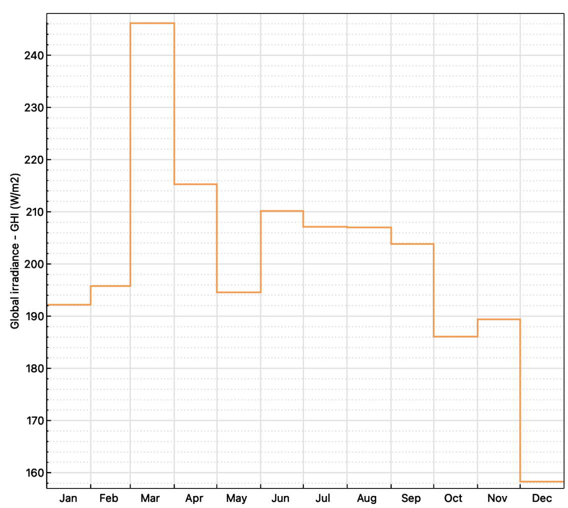

FIGURE 2.2. Monthly Global Irradiance Levels Singapore

Figure 2 illustrates the solar potential analysis based on the PVGIS-ERA5 dataset, revealing the month of March as the period of peak photovoltaic (PV) output, characterised by the highest recorded global irradiance level of 248 W/m^2. Subsequently, the solar potential throughout the remaining months exhibited a relatively consistent pattern, maintaining an average value of approximately 201 W/m^2, reinforcing the year-long viability for solar energy generation. The daily global irradiance chart offers a micro-level view of the consistency of solar irradiance on a day-to-day basis, with the visible deviations due to the small percentage of extremely rainy or overcast days.

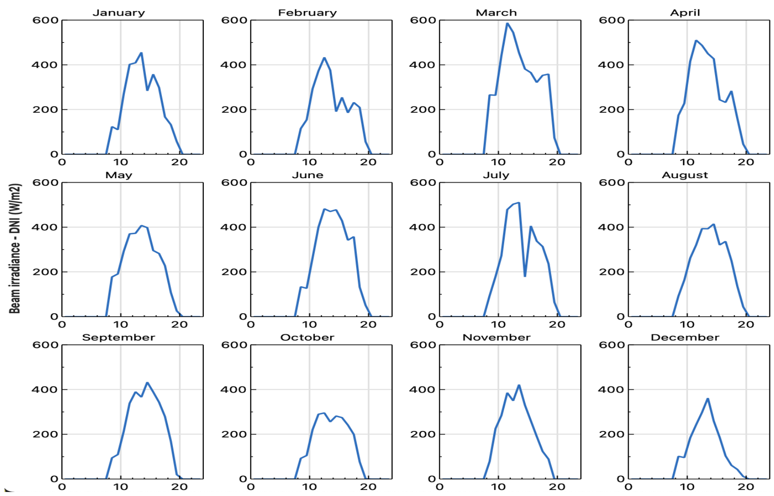

FIGURE 3. Monthly Distribution of Beam Irradiance in Singapore

Figure 3 reveals the monthly beam irradiance in Singapore, demonstrating the reduced seasonality and volatility in solar output as values exhibited are generally consistent and well exceeding the required amount for solar power generation. To ascertain whether such levels of sunlight specific to Tengeh Reservoir are comparable to other major FPV sites globally, GIS data was utilised:

Singapore (Tengeh Reservoir)	1644.5 kWh/m^2
China (Dezhou Dingzhuang)	1417.8 kWh/m^2
Thailand (Sirindhorn Dam)	1790.3 kWh/m^2
South Korea (Saemangeum)	1481.4 kWh/m^2

TABLE 6. Global Irradiance Level Comparison with World largest Floating Solar Farms

Table 6 reveals that the solar conditions in Singapore are comparable to other major FPV farms. Cumulatively, all three solar comparisons suggest that there is a favourable combination of reduced volatility in solar conditions and consistently high levels of solar irradiance in Singapore. This promising insight underscores the significant potential for widespread adoption and successful deployment of FPV systems in Singapore.

5.2. Economic Analysis

The calculated net present value (NPV) of $250 million signifies a positive difference between the anticipated cash inflows from energy generation by the FPV plant and the corresponding cash outflows associated with expenditures and overheads. This highlights the economic sustainability of the investment, substantiating its viability and potential profitability. Regular reassessment of this parameter at predetermined intervals can help ensure that the FPV farm meets performance benchmarks.

The benefit-cost ratio obtained for the FPV system is 2.85, surpassing the threshold of 1 and indicating a positive NPV for Sembcorp, the developer. This signifies the potential for significant financial and monetary benefits associated with investing in floating solar technologies. However, the FPV at Tengeh Reservoir underperforms when compared to the 4.17 BCR observed in a LPV plant in the Philippines (Farias-Rocha et al., 2019), primarily due to the higher capital costs currently associated with FPV systems. However, it is worth noting that historical benefit-cost ratios for LPVs ranged from 1.50 to 1.83 (O'Connor et al., 2010), suggesting that FPVs, being a relatively emerging technology, are expected to experience similar increases in their benefit-cost ratios over time, eventually aligning with—and perhaps even surpassing—LPVs. An examination of the United States' DOE Wind Energy program revealed a benefit-cost ratio of 3.9 at a discount rate of 3% and a benefit-cost ratio of 2.1 at a discount rate of 7%. Remarkably, the benefit-cost ratio of the FPV farm at Tengeh Reservoir falls between these two values. This further bolsters the economic attractiveness of FPVs, positioning them alongside other established renewable energy sources. This is especially true given the greater technological maturity of the compared energy sources, suggesting that even marginal improvements in FPV systems could non-linearly, significantly enhance their BCR.

The payback period for the FPV farm is 6.23 years—a highly encouraging value considering the project's duration of 25 years. This is comparable to the estimated payback period of 6 years observed for an FPV project in Iran, further reinforcing the practicality of Singapore's FPV system (Fereshtehpour et al., 2020). The IRR is 9.37%. Previous research has defined an IRR value of 8.55% as "very promising," and the slight deviation in the calculated IRR suggests that the FPV project at Tengeh Reservoir exhibits robust economic potential (Essak & Ghosh, 2022). Moreover, the IRR exceeds the hurdle rate, represented by the

WACC, of 4.9%. This indicates that the project is expected to generate a return deemed acceptable to shareholders.

The unit cost of generation is $0.0691 per kW, indicating that the revenue generated surpasses the average variable cost of energy production. As the average fixed costs related to the construction of the FPV project diminish as more energy is produced, this forecast suggests that Sembcorp can anticipate substantial profitability. Moreover, the solar farm at Tengeh Reservoir has a profitability index of 2.07, meaning that the future discounted cash inflows are expected to exceed the future discounted cash outflows.

Temasek, a state-held investment firm, has a 48.94% stake in Sembcorp (Sembcorp, 2024). Consequently, a significant portion of the project's long-term earnings is expected to be directed towards public expenditure. If the government decides to reinvest these profits into the development and widespread adoption of FPV technologies across Singapore's water bodies through contracting with private companies, it could not only reduce the setup costs of such plants, but also help Singapore move towards a more sustainable society. However, such reinvestment would come with economic and implicit costs for the government, as they could alternatively allocate profits to other green technologies or subsidise merit goods such as healthcare and education. Therefore, striking a balance is crucial. As a recommendation, reinvesting approximately 10% of the profits into the advancement of FPVs is suggested to ensure the long-term continuity and progress of this emerging technology, while considering overall sustainability objectives and diverse public expenditure priorities.

Sembcorp's strategic shift from non-renewable to renewable energy sources, exemplified by their investment in the construction of the FPV farm, showcases their environmental stewardship. This transition not only aligns with the Singaporean government's ambitious schemes and regulatory policies aimed at bolstering renewable energies, but also positions Sembcorp to leverage the associated benefits. As demonstrated in this paper, Sembcorp derives substantial financial advantages from their foray into the renewable energy sector. Motivated by the twin objectives of profitability and sustainability, Sembcorp should be encouraged to sustain this trajectory by further expanding their portfolio of FPVs.

5.3. Cost Analysis

The WACC is 4.9%. This places Singapore's level of technological advancement in PV technologies between countries like Mexico and India—both nations that receive high annual solar irradiation levels. Considering that the Tengeh Reservoir solar farm represents Singapore's first commercial-scale venture into FPVs, it is reasonable to anticipate a decreasing WACC over time if Singapore instals additional FPV projects. Furthermore, the observed hurdle rate of 4.9% is significantly lower than the established industry benchmark of 8.55% for solar farms, meaning that Singapore is en route on their journey towards adopting and scaling up FPV technologies.

5.4. Environmental Analysis

The findings reveal that the FPV farm at Tengeh Reservoir mitigates 30,989,721.6 tonnes of CO2 emissions. To provide context, this is equivalent to removing 7000 cars from the road, thus contributing to Singapore's ambitious goal of achieving net-zero emissions by 2050. Equally encouraging, the FPV farm emits 7,975,296 tonnes of CO2, which, compared to its mitigation impact, is relatively modest and far more eco-friendly than non-renewable energy sources. Consequently, the net CO2 reduction achieved amounts to 23,014,425.6 tonnes, representing a substantial decrease in carbon emissions and underscoring the potential of photovoltaic technologies in advancing environmental sustainability.

In comparison to other renewable technologies, solar technologies, including both FPVs and LPVs, tend to exhibit relatively higher GHG emissions. Specifically, photovoltaics emit 300 grams of CO2 per kW of energy generated, far surpassing tidal and hydropower technologies which serve as the primary counterparts to FPVs. However, it should be noted that FPVs demonstrate fewer adverse effects on aquatic ecosystems where they are deployed. Nonetheless, the results highlight the need for technological advancements to align FPVs and LPVs, from an environmental perspective, with other established renewable technologies.

6. Conclusion

The primary objective of this study was to evaluate the viability of the FPV farm at Tengeh Reservoir. The findings strongly indicate that the expansion of FPV projects in Singapore holds substantial economic and environmental advantages. Although certain parameters of FPVs slightly lag behind LPV technologies, continued research and investment will likely narrow such disparities. Strategic and targeted improvements in cost-reduction technologies that focus on enhancing key financial metrics like the BCR and WACC can create a positive feedback loop by accelerating technological developments and thereby inviting more investments. Nevertheless, even at its current stage, with promising financial metrics such as a low unit cost of generation, positive profitability index and substantial carbon emissions mitigation, this project carries a multitude of benefits, both for developers and society at large.

From a policy standpoint, as highlighted in the economic analysis, it is highly recommended that the Singaporean government continues to invest in FPVs. Integrating FPVs across different water bodies in Singapore would make a substantial contribution to meeting the nation's energy requirements. For future research, it would be advantageous to obtain actual, on-site data to ensure that results are aligned with the performance of an FPV. Comparative assessments of diverse FPV technologies on a global scale will inform optimal operating conditions and facilitate the development of more efficient photovoltaic plants. Regularly reviewing IRENA reports and keeping a lookout for innovative pilot projects that optimize on-site conditions, particularly recently developed plants in China, will help us track FPV growth over time (Fan et al., 2025).

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