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Technoeconomic analysis of floating solar field for 1 GWh of electricity generation

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Abstract. This paper presents a technoeconomic evaluation of 1 GWh electricity generation using a floating solar PV (FSPV) system implemented on the Bakun Lake. Five PV brands are evaluated for 2×2, 3×3, 4×4 and 5×5 layout designs. The major factors used for the evaluations: total capital cost, total platform area, stability or percentage weight distribution, product warranty and PV efficiency. In total, 20 design scenarios are evaluated using a heuristic-based optimization approach to determine the best design. An optimization considering the total cost, coverage area and stability suggests that the 3x3 layout using Astronergy brand is the best design for the FSPV. However, a long-term analysis considering product warranty and efficiency reveals that the Panasonic brand is the most cost-effective after 40 years of operation.

1. Introduction

Energy is one of the most crucial aspects in the development of a country since it is needed in various sectors, from industries, commercial, residential, transport to agriculture. From 2010 to 2030, the global energy consumption has been projected to increase by 33% [1]. This represents an average increment of 1.6% per annum. Such a percentage increment can be considered high for the period of 20 years. Hence, it raises a critical question among researchers, i.e., how to increase the energy production to accommodate future energy demand. Various alternative energy production technologies have been extensively explored over the last few decades, such as hydrogen production, biofuels, wind, and solar. All of these energy sources have been found one way or another to be promising to meet the future energy demand. For example, the hydrogen production route via a membrane reactor technology has recently been reported to be viable at a large-scale [2]. However, it has been recognized that for sustainable mega-scale power generation, solar energy provides the most abundant energy source available in nature, i.e., earth daily receives about 2×10^{11} MW from the sun. Solar energy is regarded as a clean renewable energy which does not release any greenhouse gases [3]. The global electricity production based on solar photovoltaic (PV) makes up only 15% of the energy capacity derived from renewable sources [4]. The low power conversion efficiency and high installation costs remain the major factors limiting the application of solar PV. Detailed reviews on the progress of solar PV technologies can be found in [5]- [6].

In recent years, several studies have been reported on the implementation of floating solar PV (FSPV) plants on the open lakes and irrigations. Based on the study of the FSPV plants in Australia, two advantages were identified: (1) increased energy production due to the evaporative cooling effect, and (2) reduced evaporation rate leading to water saving [7]. A study was also reported on the



implementation of FSPV system which acts to cover irrigation reservoirs while producing electricity [8]. In addition to increasing power efficiency of the PV cells, the implementation of FSPV plants can also save a lot of land. A comprehensive analysis based on the finite element model showed that the FSPV system can improve energy efficiency by 1.5 – 2.0% compared with the traditional on land PV systems [9]. One of the important components for a FSPV plant is the supporting structure of the system. In this regard, the glass fiber reinforced polymer plastic (FRP) has been found to be a promising material for the supporting structure [10]. Note that, a few design solutions to improve FSPV systems are reported in [11]. A feasibility study on the implementation of 2 MW FSPV system as part of a smart city program is reported in [12].

The goal of the present work is to perform a technoeconomic evaluation of 1 GWh daily of a floating solar PV system, to be proposed for implementation on the Bakun dam reservoir in Sarawak, Malaysia. The analysis consider several different brands of commercial PV panels and design layouts of the panel complex. To the best of our knowledge, presently there has been no report about technoeconomic study of FSPV capable of producing electricity at the capacity of 1 GWh and above.

2. Methodology

2.1. Selection of site

The Bakun dam in Sarawak, Malaysia is selected as a potential location to implement the proposed FSPV owing to its large open area. The approximate height of the Bakun dam is 204 m and its depth is estimated to be between 100 m and 200 m. The lake surface covers about 700 km², which is sufficient to accommodate a huge number of solar PV panels. The peak solar irradiation in Malaysia is estimated to be in the range of 1,400 and 1,900 kWh/m². The major steps involved in the analysis are presented in the following sections.

2.2. Determination of number of solar PV panels

For the targeted power generation (P), the total number of solar panels (N_{PV}) required is calculated as follows

$$N_{PV} = P/R \quad (1)$$

where R is the maximum capacity of the given PV panel.

Five different brands of PV panels are considered in this study: (1) SolarWorld, (2) Astronergy, (3) LG, (4) Panasonic, and (5) Canadian Solar. The maximum or nominal capacity (W_p) of each brand is determined at the Standard Test Condition (STC). A nominal capacity of 3 kWp would produce 3 kW of output power when exposed to solar irradiation for 1 hour.

Note that, the maximum capacity used in this research project is the amount of energy generated when the FSPV system has been operated for a period of 8 hours (during daytime). Hence, the parameter R in (1) is given by

$$R = \varphi_0 t_s \quad (2)$$

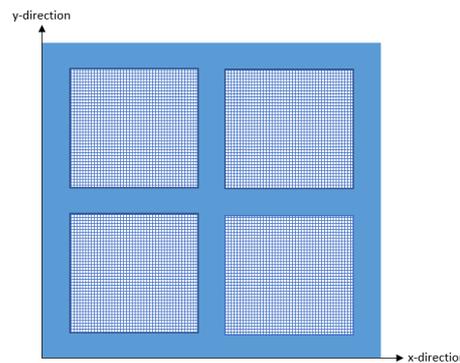
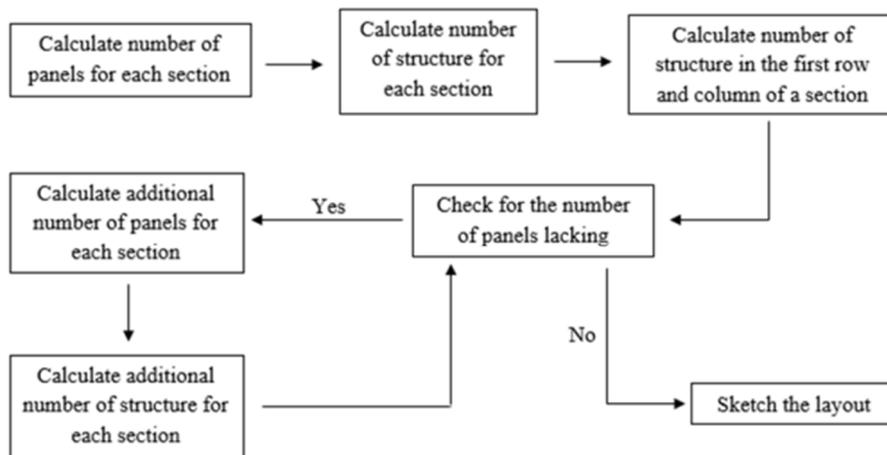
where φ_0 denotes the nominal capacity of a single PV panel and t_s the length of time over which solar irradiation is significant within 24 hours (a day). In this work, it is assumed $t_s = 8$, i.e., solar radiation is significant for 8 hours within a day.

2.3. Selection of floating solar system layout

There are four layouts to be evaluated in this project. Each layout consists of a different number of sections as shown in Table 1. Each section is separated by a walking area of 1 m width. As an illustration, Figures 1 shows the sketch for a 2×2 layout arrangement. Figure 2 represents the steps used to evaluate a given FSPV system layout. Brief descriptions of the steps are described in the next sections.

Table 1. Type of layout and its corresponding number of sections.

Layout	Number of Sections
2 x 2	4
3 x 3	9
4 x 4	16
5 x 5	25

**Figure 1.** Sketch of 2x2 layout.**Figure 2.** Steps used to analyse a floating solar PV system layouts.

2.4. Number of structures for each section

The number of solar PV panels for each section (N_A) is calculated as follows

$$N_A = N_{PV}/N_B \quad (3)$$

where N_B is the number of sections.

The structures are used to hold the solar PV panels on the surface of the lake, which are based on the FSPV system implemented in South Korea [13]. Each structure is fabricated with fiber reinforced polymer (FRP) members and consists of three parts where each part is connected to each other with bolts. This feature enables the structure to be segregated into three equal parts where each part can accommodate 11 panels. Therefore, a single-unit structure can hold a maximum of 33 solar PV panels.

The structure has a length of 12.6 and width of 11.5 m, and the weight of a single unit is about 1,148 kg. Table 2 shows the properties of the FRP based structural system.

Table 2. Properties of structural system.

Material	FRP members
Length	12.6 m
Width	11.5 m
Number of panels in the first row	11
Number of panels in the first column	3
Total number of panels in a single-unit complete structure	33
Weight of a single unit structure	1,148 kg
Unit cost of member	0.044 USD/kg

By using the above data (Table 2), the number of structures (N_C) for each section is

$$N_C = N_A/N_D \quad (4)$$

where N_A is the number of solar PV panels for each section and N_D is the maximum number of panels in a single unit structure, i.e., $N_D = 33$.

2.5. Number of panels in the first row and column of a section

It is assumed that all the layouts investigated in this project follow a square shape. Therefore, by computing the square root of the number of structure in a given section, the number of panels in the first row or column in a section (N_E) is

$$N_E = \sqrt{N_C} \quad (5)$$

The number of panels is fixed according to a given PV brand. Since the equation (5) might lead to a decimal value, it is best to round the value to an integer number. For instance, if the number of structures in a section is 21,345.67, it is recorded as 21,345. This principle is applied to all calculations involved in this work. Nevertheless, this approach might lead to the possibility of having a lower number of solar panels than that is actually needed. Hence, it is important to calculate the number of panels lacking (N_L) as follows:

$$N_L = N_{PV} - N_E^2 N_D N_B \quad (6)$$

where N_E is the number of structures in the first row or column for each section. The number of panels lacking calculated in (6) is divided equally among the number of sections available. This step is carried out only if the number of panels lacking is greater than the number of sections available. If the number of panels lacking is smaller than the number of sections available, the panels are distributed accordingly by considering the stability of the whole floating platform.

The additional number of panels for each section (N_G) is estimated by

$$N_G = N_L/N_B \quad (7)$$

Meanwhile, the additional number of structures for each section (N_H) is obtained via

$$N_H = N_G/N_D \quad (8)$$

Note that, the calculation using (8) is only valid if $N_G > N_D$. Otherwise, the structure is segregated into three equal parts, thus the rules in Table 3 are applied. It is important that all the additional structures

must be added to a new row. Thus, the number of structures in x-direction of any section is kept constant throughout the calculation.

Table 3. Rules for the number of additional panels in each section less than 33.

Rules	Number of additional structure
$N_G \leq 11$	1/3 structure
$11 < N_G \leq 22$	2/3 structure
$22 < N_G \leq 33$	1 structure

2.6. Area of the floating solar field

2.6.1. Length and width of single section

The length of a single section (L_I) is given by

$$L_I = N_J/W_K \quad (9)$$

where N_J is the number of structures in the first row of a single section, and W_K is the width of a single unit structure.

Here, the width of a single section is given by

$$W_L = N_M/W_N \quad (10)$$

where W_M is the updated number of structures in the first column of a single section, and W_N is the length of a single unit structure.

2.6.2. Length and width of the whole floating platform

The length of the whole floating platform (L_V) is

$$L_V = L_I N_Y + W_Z \quad (11)$$

where N_Y is the number of section in x- or y-direction, and W_Z is the total width of walking area in x or y direction.

The width of the whole floating platform (W_U) is

$$W_U = W_L N_Y + W_Z \quad (12)$$

The values of N_Y and W_Z are different for different layouts as shown in Table 4. The higher the number of sections, the larger are the values of N_Y and W_Z .

Table 4. Values of Y and Z for each layout.

Layout	N_Y	W_Z (m)
2 x 2	2	3
3 x 3	3	4
4 x 4	4	5
5 x 5	5	6

The total area covered by the floating platform (A_T) is given by

$$A_T = L_V \times W_U \quad (13)$$

where L_V and W_U are as given by (11) and (12) respectively.

2.7. Cost analysis of the FSPV system

Recall in this work, there are five categories of costs used in the analysis for a given FSPV system. The costs include: (1) solar panels, (2) structural system, (3) power storage system, (4) floating system, and (5) mooring system.

2.7.1. Cost of solar panels

The total cost of solar panels (C_{PV}) is calculated as follows

$$C_{PV} = N_{PV} \times b_{pv} \quad (14)$$

where b_{pv} is the unit price (in USD) of the solar panel and N_{PV} as given in (1).

2.7.2. Cost of structural system

The cost of the structural system depends on the total weight of the entire structures for a given layout. The total weight of structures is estimated in the following manner

$$M_c = (N_d + N_e)m_f \quad (15)$$

where N_d is the total number of complete structures used in the whole layout, N_e the total number of additional segregated structures used in the whole layout, and m_f the weight of a single unit of the complete structure.

After the total weight of structures for the whole layout is known, then the cost of structural system (C_S) is determined as follows

$$C_S = M_c b_s \quad (16)$$

where b_s is the unit cost of a single unit of complete structure (in USD/kg).

2.7.3. Cost of power storage system

There are three types of power storage systems evaluated in this work, which are the Absorbent Glass Mat (AGM) battery, Lithium Ferro Phosphate (LFP) battery, and Tesla Powerpack. The properties of each technology are quite different as shown in Table 5.

Table 5. Power storage system candidates for the 1 GWh FSPV system.

LFP	Battery Capacity	130 Ah
	Voltage	48 V
	Unit Price	6,875 USD
AGM	Battery Capacity	250 Ah
	Voltage	12 V
	Unit Price	517 USD
Tesla Powerpack	Unit Price	398,000 USD/MWh

For the LFP and AGM, the power storage capacity in MWh is calculated as the capacity given by the manufacturers in Amp hour (Ah). The power storage capacity (P_S) in Watt hour (Wh) is given by

$$P_S = \Omega_b \times V_b \quad (17)$$

where Ω_b is the battery capacity (Ah) and V_b the battery voltage (V).

2.7.4. Cost of mooring system

There are four major components that make up a mooring system adopted in this work, which are heavy chain, light chain, mooring buoy, and pyramid anchor. The design of the mooring system of a floating facility is highly dependent on the depth of water [14], in addition to other related factors such as the wind speed and fluctuation of water level [13]. The impoundment area of Bakun dam has its full capacity at 228 m above sea level [15] with the average depth estimated at about 200 m [16]. The fluctuation of water level in the reservoir is less severe than that of an ocean or sea. The average daily gust and wind speed at the Belaga District in which Bakun dam is located, is 9 mph and 6 mph respectively. Considering this data, a ground-mounted mooring system is chosen to moor the FSPV platform as shown in Figure 3.

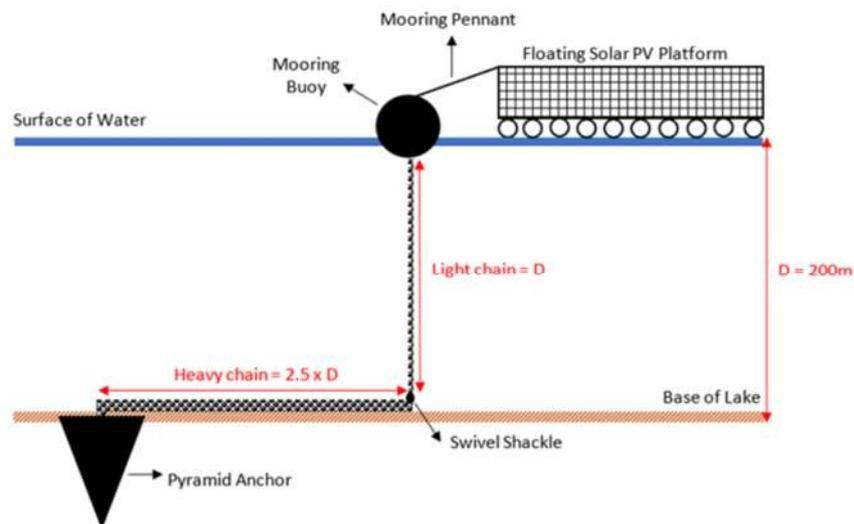


Figure 3. Illustration of ground-mounted mooring system.

As in a usual practice, the length of mooring line is set to be 3 times as long as the depth of water by equalizing the length of light chain to the water depth [17]. Note that, the mooring system is not included in the optimization study (the cost is fixed for all design schenarios). The basic components of mooring system are shown in Table 6.

Table 6. Components of mooring system and their values.

Components	Parameter	Value
Pyramid Anchor	Weight of a single-unit	25,000 kg
	Unit Price	3.86 USD/kg
Heavy Chain	Weight per length of a single-unit chain	574.74 kg/m
	Unit Price	0.77 USD/kg
Light chain	Weight per length of a single-unit chain	219 kg/m
	Unit Price	0.77 USD/kg
Mooring Buoy	Diameter	0.762 m
	Unit Price	577.8 USD

The total cost of the mooring system is calculated as in the steps below:

Step 1: Cost of a single unit mooring line (q)

$$q = r + s + t + u \quad (18)$$

where r the cost of a single unit anchor, s the cost of heavy chain in a single unit mooring line, t the cost of light chain in a single unit mooring line, and u the cost of a single unit mooring buoy.

Step 2: Number of mooring lines required

The number of mooring lines is calculated based on the ratio of total weight of the floating platform to the total weight of mooring lines. An increment factor is multiplied with the total weight of mooring lines to compensate for the buoyancy effect of material underwater.

Step 3: Cost of mooring system

The total cost of mooring system is calculated as follows

$$v = q \times w \quad (19)$$

where v is the total cost of mooring system and w the number of mooring chains required.

2.8. Percentage of weight distribution analysis

It is important to ensure that the weight of a floating platform should be equally distributed as to achieve optimum stability of the platform. In addition, it is important to ensure that the platform can float on the surface of water without significant inclination. A method to evaluate the weight distribution is proposed, via the Percentage of Weight Distribution (PWD) calculated as in (20),

$$PWD = \frac{TWSPLR}{TWSPFR} \times 100\% \quad (20)$$

where $TWSPLR$ is the total weight of structures and solar panels in the last row of a section (kg), and $TWSPFR$ is the total weight of structures and solar panels in the first row of a section (kg). If the ratio of $WSPLR$ to $TWSPFR$ is equal to 1, the value of PWD is equal to 100%. Thus, it can be deduced that the weight of the floating platform is equally distributed, and the optimum stability is achieved.

3. Optimization study

The optimization conducted in this work is based on three decision parameters summarized as follows:

- 1) Total cost of FSPV system for a given layout. These include the costs of solar panels, structural system, and floating system. The cost of power storage system and cost of mooring system are excluded from the optimization study – they are considered fixed for all designs.
- 2) Total area covered by the FSPV system for a given layout.
- 3) Percentage of Weight Distribution (PWD) for a given layout.

Table 7. Ranking and scoring system (RSS) for optimization.

Rank	Score	Rank	Score
1 st	20 points	11 th	10 points
2 nd	19 points	12 th	9 points
3 rd	18 points	13 th	8 points
4 th	17 points	14 th	7 points
5 th	16 points	15 th	6 points
6 th	15 points	16 th	5 points
7 th	14 points	17 th	4 points
8 th	13 points	18 th	3 points
9 th	12 points	19 th	2 points
10 th	11 points	20 th	1 point

The optimization is conducted by mean of a Ranking and Scoring System (RSS) approach. In this work, there are 20 case studies (design scenarios), which are ranked from the 1st rank to 20th rank as

illustrated in Table 7. The case study ranked first is given 20 points, whereas the case study ranked last (20th rank) is given 1 point. The maximum score that could be obtained is up to 60 points, whereas the minimum score is 2 points. The case study that gives the highest score is regarded as the most optimal design of the FSPV system.

4. Results and discussion

4.1. Optimization results and analysis

To meet the 1 GWh power generation, the analysis shows that the Canadian Solar PV brand requires the highest number of panels which is 462,962. The SolarWorld brand requires the lowest number of panels which is 357,142. The number of panels required is highly dependent on the nominal capacity of the panel brand. A higher nominal capacity means that the solar panel is able to generate more power within 8 hours. Thus, less number of panels is required to achieve the targeted 1 GWh power generation. Figure 4 shows the numbers of panels required for the five panel brands with different nominal capacities.

Table 8 summarizes the cost of solar panels associated with the five different brands. The LG brand requires the highest cost which is USD 183,955,062 while the Astronergy brand offers the lowest cost, i.e., USD 123,076,800. As can be observed from Table 8, the cost of solar panels is highly dependent on the number of panels required and the panel unit price.

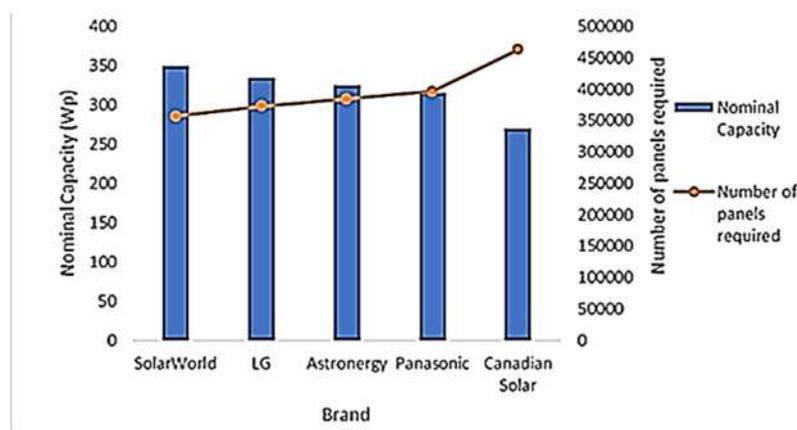


Figure 4. Relationship between nominal capacity and number of panels required for 5 different PV brands.

Table 8. Total cost of solar panels for each brand.

Brand	Number of solar panels required	Unit Price (USD)	Total cost (USD)
SolarWorld	357,142	400	142,856,800
Astronergy	384,615	320	123,076,800
LG	373,134	493	183,955,062
Panasonic	396,825	420	166,666,500
Canadian Solar	462,962	275	127,314,550

Note that, it is found that by increasing the number of panels, it does not necessarily lead to a higher total cost of solar panel. As can be observed from Figure 5, the highest cost of solar panels is given by the LG brand, at USD 183,955,062 although it is ranked as the second lowest in term of the number of panels required. On the other hand, the Canadian Solar brand which requires the highest number of panels is ranked as the second lowest in term of the total cost of solar panels, i.e., at USD 127,314,550.

Based on Figure 6 it can be concluded that the unit price of a solar panel is not proportionally related to its nominal capacity for the different brands. For instance, the Panasonic brand which is ranked as the

second lowest in term of nominal capacity (at 315 Wp) is the second highest in term of unit price. This is because there are other factors that contribute to the unit price of a solar panel besides its nominal capacity. These other factors are the product warranty, material of construction, and cell efficiency.

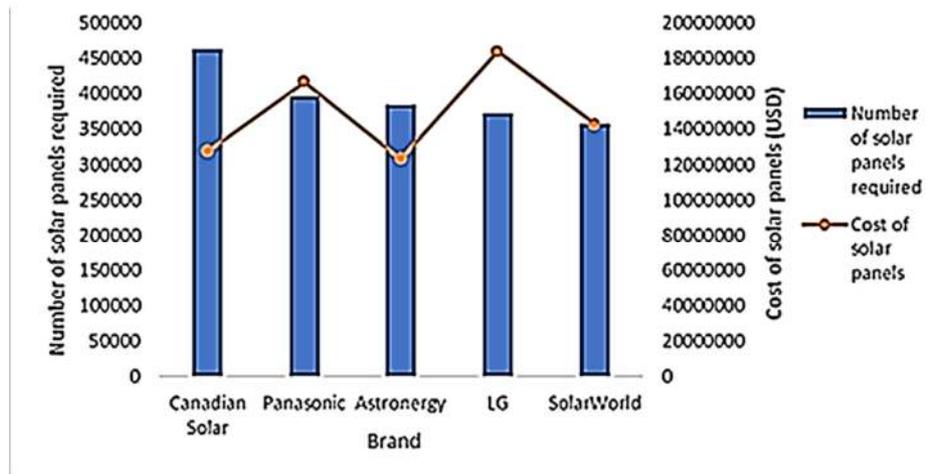


Figure 5. Relationship between the solar panel cost and the number of panels required for the 5 different PV brands.

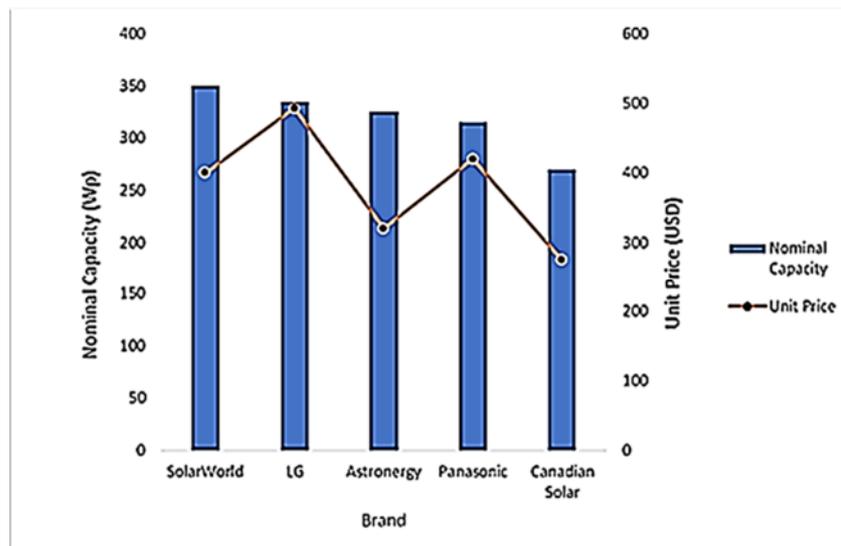


Figure 6. Nominal capacities and unit prices of five different brands.

Table 9 shows the optimization results based on the RSS approach. The most optimal FSPV system design in term of total panel cost is the 3x3 layout structure using the Astronergy brand. The optimal panel cost for generating 1 GWh is USD 211.8 million. Meanwhile, based on the total area covered by the FSPV platform, it is found that the 2x2 layout structure using the SolarWorld brand requires the least area (see Table 10). The 3x3 layout structure using the Astronergy (which gives the most optimal design in term of panel cost) is ranked in the middle, which requires a total area of 1.7 km². Since Bakun Lake has a surface area of about 720 km², the space is not an issue as far as the project implementation is concerned. Based on the PWD criterion, again the 3x3 layout using the Astronergy brand is the best, i.e., with 100% score, thus leading to the most stable system design. Note that, the 4x4 layout using the Astronergy brand gives the lowest PWD score, i.e., 2.6 %. The optimization result based on the PWD criterion is given in Table 11. Table 12 shows the overall optimization results considering the total cost,

area covered and stability. The FSPV with 3x3 layout of Astronergy brand gives the best result with total score of 52 out of maximum score of 60. The top five designs are based on the Astronergy and SolarWorld brands. Please note that, the optimization results shown in Table 12 do not include other factors such the warranty and panel efficiency. These two factors will be considered in the long term analysis in the next section.

Table 9. Optimization based on total panel cost for the 1 GWh FSPV system.

Brand	Layout	Total Cost (USD)	Score
Astronergy	3 x 3	211,843,611	20
Astronergy	2 x 2	211,851,227	19
Astronergy	4 x 4	211,871,537	18
Astronergy	5 x 5	211,932,467	17
SolarWorld	2 x 2	225,284,394	16
SolarWorld	3 x 3	225,294,549	15
SolarWorld	5 x 5	225,302,165	14
SolarWorld	4 x 4	225,314,859	13
Canadian Solar	2 x 2	234,164,759	12
Canadian Solar	3 x 3	234,177,452	11
Canadian Solar	4 x 4	234,185,068	10
Canadian Solar	5 x 5	234,195,223	9
Panasonic	5 x 5	258,251,305	8
Panasonic	2 x 2	258,253,844	7
Panasonic	4 x 4	258,263,999	6
Panasonic	3 x 3	258,266,537	5
LG	2 x 2	270,079,052	4
LG	5 x 5	270,081,590	3
LG	3 x 3	270,094,284	2
LG	4 x 4	270,109,516	1

Table 10. Optimization based on the total area covered by the 1 GWh FSPV platform.

Brand	Layout	Total Area Consumed (km ²)	Score
SolarWorld	2 x 2	1.60497	20
SolarWorld	3 x 3	1.60634	19
SolarWorld	5 x 5	1.60909	18
SolarWorld	4 x 4	1.62013	17
LG	3 x 3	1.65344	16
LG	2 x 2	1.66656	15
LG	5 x 5	1.68916	14
Astronergy	2 x 2	1.69734	13
Astronergy	3 x 3	1.69922	12
LG	4 x 4	1.70081	11
Astronergy	4 x 4	1.74115	10
Panasonic	2 x 2	1.76067	9
Astronergy	5 x 5	1.76558	8
Panasonic	5 x 5	1.76558	7
Panasonic	4 x 4	1.76598	6
Panasonic	3 x 3	1.79471	5
Canadian Solar	3 x 3	2.04582	4
Canadian Solar	2 x 2	2.06039	3
Canadian Solar	4 x 4	2.09870	2
Canadian Solar	5 x 5	2.10029	1

Table 11. Optimization based on the percentage of weight distribution for 1 GWh FSPV system.

Brand	Layout	PWD (%)	Score
Astronergy	3 x 3	100.0	20
Astronergy	2 x 2	98.1	19
Canadian Solar	3 x 3	97.4	18
Panasonic	5 x 5	90.5	17
LG	3 x 3	90.5	16
Panasonic	4 x 4	83.9	15
SolarWorld	5 x 5	65.0	14
LG	5 x 5	53.9	13
Canadian Solar	2 x 2	44.6	12
Canadian Solar	5 x 5	40.6	11
SolarWorld	3 x 3	37.2	10
LG	2 x 2	33.9	9
Panasonic	2 x 2	33.9	8
Canadian Solar	4 x 4	24.1	7
Astronergy	5 x 5	20.6	6
LG	4 x 4	19.2	5
Panasonic	3 x 3	12.0	4
SolarWorld	2 x 2	3.2	3
SolarWorld	4 x 4	2.6	2
Astronergy	4 x 4	2.6	1

4.2. Long-term cost analysis

The product warranty is one of the long-term parameters that affects the cost-effectiveness of a solar panel. Generally, the product warranty is determined by manufacturer which reflects confidence in the products. Table 13 shows the product warranty and module efficiency for each solar brand used in this project. By taking the product warranty into consideration, it is appropriate to revisit the total cost of solar panels over a long-term analysis.

The cost projection of solar panels for the period of 10 years to 50 years can be estimated based on two assumptions listed below:

- 1) The unit price of a solar panel is constant within 50 years.
- 2) All solar panels need to be replaced at the end of warranty period.

In Figure 7, SolarWorld and Panasonic are proven to be more cost-effective compared to other brands after as early as 20 years of the FSPV operation. At the initial stage, the Astronergy brand offers the lowest cost of solar panels among the other brands. However, after 50 years of operation, it is found that the cost is projected to exceed USD 700 million for the Astronergy brand. This is approximately 122% higher than the cost of solar panels offered by the Panasonic brand over the same operating period. It is interesting though to note that, both SolarWorld and Panasonic brands maintain their panel cost to remain below USD 500 million after 50 years of FSPV operation. This is due to their long warranty period (Table 13). Given 25 years of warranty period, the Panasonic brand is found to be the most cost-effective brand after 40 years of the FSPV operation. Therefore, the outcome of this long term analysis needs to be integrated with the optimization study conducted earlier. As the Astronergy, LG, and Canadian Solar brands are found to be not economically viable in a long run, therefore, the choice is only left with the Panasonic and SolarWorld brands.

By taking the module efficiency as showed in Table 13, as another basis of comparison, it is shown that the Panasonic brand has a slight advantage over the SolarWorld brand. The Panasonic brand has 18.8% efficiency, which is 1.3% higher than the efficiency of the SolarWorld brand. The installation of a high efficiency solar panels can be more cost-effective and beneficial in a long run for electricity

generation. Considering all factors, based on both short-term optimization and long-term analysis, it is recommended that the Panasonic brand should be used in the project. The second best choice should be the SolarWorld brand. For the Panasonic brand, the 5x5 FSPV layout system is the best design with the total score of 34/60 (Table 12). The Astronergy brand requires a higher cost than the Panasonic brand after 20 years of operation – thus, though the Astronergy ranks the first based on the RSS optimization, it is less viable for a long term operation due to its short product warranty and pane lower efficiency.

Table 12. Ultimate result of optimization study

Brand	Layout	Total Score
Astronergy	3 x 3	52
Astronergy	2 x 2	51
SolarWorld	5 x 5	46
SolarWorld	3 x 3	44
SolarWorld	2 x 2	39
LG	3 x 3	34
Canadian Solar	3 x 3	33
Panasonic	5 x 5	32
SolarWorld	4 x 4	32
Astronergy	5 x 5	31
LG	5 x 5	30
Astronergy	4 x 4	29
LG	2 x 2	28
Panasonic	4 x 4	27
Canadian Solar	2 x 2	27
Panasonic	2 x 2	24
Canadian Solar	5 x 5	21
Canadian Solar	4 x 4	19
LG	4 x 4	17
Panasonic	3 x 3	14

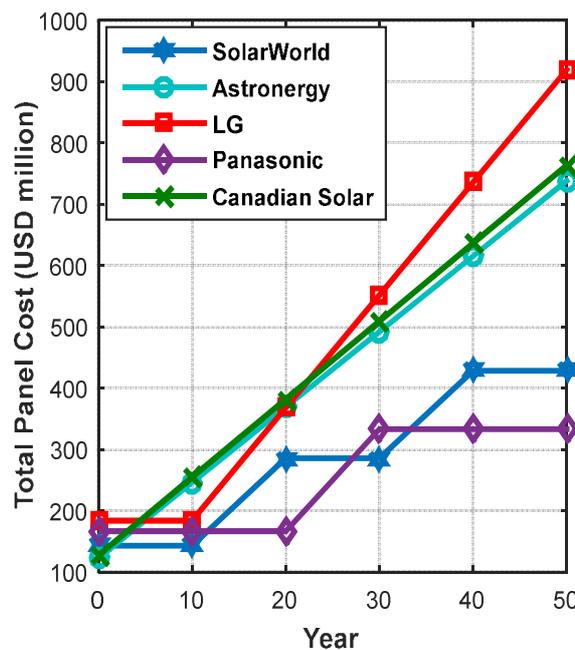


Figure 7. Cost of solar panels within the period of 10 to 50 years classified into 5 different brands.

Table 13. Product warranty and module efficiency of each brand.

Brand	Product Warranty	Panel Efficiency
SolarWorld	20 years	17.5 %
Astronergy	10 years	16.8 %
LG	12 years	19.6 %
Panasonic	25 years	18.9 %
Canadian Solar	10 years	16.8 %

4.3. Analysis of power storage system

There are three types of power storage system evaluated in this project which are the Absorbent Glass Mat (AGM) battery, Lithium Ferro Phosphate (LFP) battery, and Tesla Powerpack. Note that, the AGM battery is the cheapest choice which offers a total cost of USD 172 million (as the initial cost). On the other hand, the total initial cost of LFP and Tesla Powerpack are USD 1.1 billion and USD 398 million respectively. However, similar to the solar panel technology, the product warranty also plays a key role in comparing the cost benefit of power storage systems in a long run. Table 14 shows the warranty period, total initial cost, and cost after 10 years of operation for both AGM and LFP battery.

After 10 years of operation, the cost of AGM battery is estimated to be around USD 1.7 billion. This calculation is done based on the worst-case scenario where it is assumed that all batteries need to be replaced at the end of warranty period, and the unit price of battery is constant within the 10 years of operation. Although the unit price of the AGM battery is cheaper (USD 517) than the LFP battery, it is still not cost effective as it has a short warranty period of only 1 year compared to 10 years for the LFP battery. This causes the cost of AGM power storage system to rise annually while the cost for LFP battery maintains at the same value over the 10 years period. In fact, from the technological point of view, the LFP battery is known to have stable properties in terms of chemical and thermal characteristics. Therefore, it is a safe technology with minimum possibility of thermal runaway. Additionally, the LFP battery is known for its high specific energy, compact size, and light weight, thus making it suitable for renewable energy storage system. In addition, the LFP battery needs less maintenance and able to endure irregular discharging pattern.

Table 14. Cost comparison of AGM and LFP battery within ten years operation

Type of battery	Warranty	Total initial cost (USD)	Cost after 10 years (USD)
AGM	1 year	172,333,161	1,723,331,610
LFP	10 years	1,101,760,000	1,101,760,000

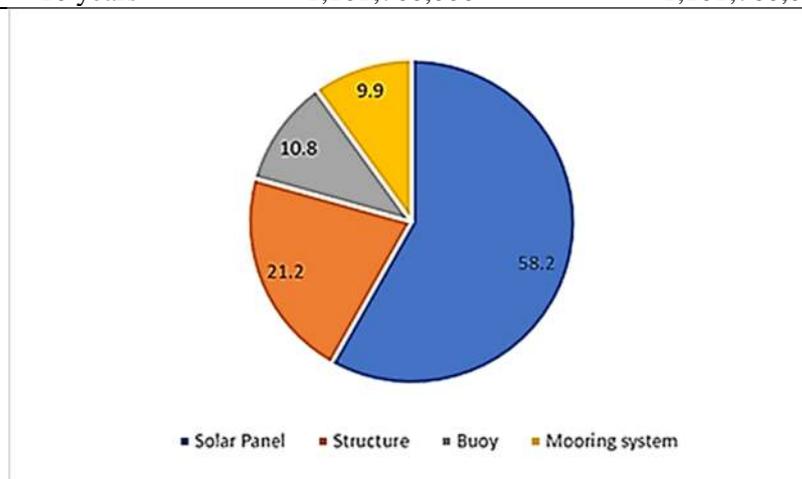


Figure 8. Cost percentage of FSPV (5x5 layout Panasonic) without power storage system.

The total cost of FSPV system without power storage system based on the Panasonic brand with 5x5 layout is estimated at USD 286,611,305. As shown in Figure 8, solar panel contributes the highest percentage (58.2%) for the case of FSPV without the storage system. This is quite an expected outcome; although solar technology price has been decreasing over time, its cost has remained stagnant since the end of 2012 [18]. This can be explained as a result of manufacturers trying to balance between the cost reduction and economic viability of the technology; they have to consider the return of investment. Furthermore, the Panasonic brand is considered as among the excellent manufacturers of solar panel technology for their ability to produce high efficiency solar cell. For instance, in 2014, Panasonic unveiled its highest efficiency solar panel at 25.6%, marking a new world record for solar panel efficiency [19]. Hence, it justifies the higher unit price of solar panel from Panasonic although it comes with a lower nominal capacity compared to other brands.

The second highest percentage is contributed by the structural system at 21.2%. In this project, fiber-reinforced polymer (FRP) structural system is used to hold the solar panels on the Bakun Lake. In most projects that involve floating systems, the structure used is generally made up of steel. One of the major drawbacks of steel material is its vulnerability to corrosion, thus causing the maintenance cost to increase and lifespan of the structure to decrease [13]. Another 10.8% of the total cost is contributed by the floating system (buoy) where multiple buoys are used to float the structures. In this project, the buoys used are made up of high density polyethylene (HDPE). HDPE is a thermoplastic material derived from petroleum. One of its notable advantages is the stability in term of thermal characteristic; its thermal properties hardly change with variation of temperatures.

The lowest percentage is contributed by the cost of mooring system at 9.9%. It is important to note that, the FSPV system in this project is installed on a gigantic floating platform. For the case of Panasonic brand with 5x5 layout; the length of the whole platform is 1,329 m. Meanwhile, the width of the whole floating platform is 1,328.5 m. This makes the total area of 1.77 km². The floating platform is divided into 25 equivalent sections where the dimension of each section is 264.6m x 264.5m. This layout requires 396,825 panels which are installed on the total of 12,025 structures. The combination of weight of both solar panels and structural system is 21,145,963 kg. Therefore, this enormous floating platform requires an appropriate mooring system to keep it in place on the surface of Bakun Lake.

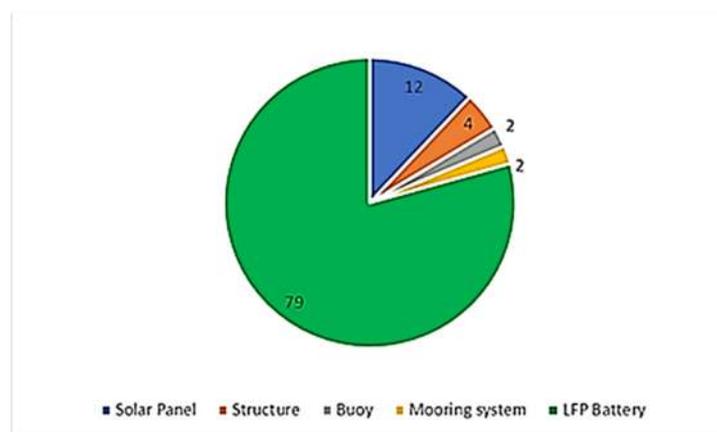


Figure 9. Cost percentage of FSPV (5x5 layout Panasonic) system equipped with LFP battery.

The FSPV with Panasonic brand (5x5 layout) can be equipped with the LFP battery, or Tesla Powerpack as a power storage system. As shown in Figure 9, the power storage system contributes the largest percentage of the total cost at 79%. The increment of total cost after including the LFP battery as the power storage system reaches 384%, rising from USD 286 million without power storage system to USD 1.4 billion. This is a huge elevation of capital cost, but it is an expected result. This is because, solar technology is often considered to be less economically viable due to high cost of power storage system [20].

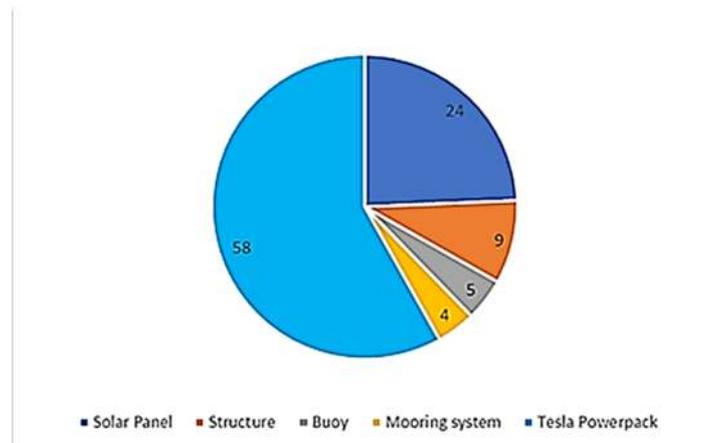


Figure 10. Cost percentage of FSPV (5x5 layout Panasonic) system equipped with Tesla Powerpack.

To reduce the high cost of power storage system, the Tesla Powerpack can be considered as the alternative power storage system. Offered at USD 398/kWh, the total cost to store 1,000 MWh of electricity by using Tesla Powerpack is estimated to be USD 398 million. Thus, the total cost of the whole FSPV system including power storage system is calculated to be USD 684,611,305. The increment of total cost after including the Tesla Powerpack is around 139% from the cost without power storage system, which is far less than that using the LFP battery. Figure 10 shows the percentage cost components of the FSPV with Tesla Powerpack system.

4.4. Comparison with real floating solar PV plant

To date, there has been no FSPV system ever built at the capacity of 1,000 MWh. Nevertheless, a qualitative comparison can still be made between the present theoretical study with that of the real mega-scale FPSV systems already built at a smaller capacity.

Presently, the FSPV plant located in Anhui province, China has an installed capacity of 150 MW. The cost to build this plant is reported at USD 151 million [21]. The plant is built on the lake used to be a coal mine subsidence area. Initially, the project started with 40 MW installed capacity, involving 165,000 solar panels in 2017, before expanded to 150 MW in May 2018. This plant is able to generate power at 150,000 MWh per year, which is equivalent to 410 MWh per day on average. In term of the return of investment, this FSPV plant can generate USD 3,897,000 annually [22], thus giving the payback period of around 39 years.

Another real project is the solar farm with a total of 51,000 solar panels and 270 W capacity, implemented on the reservoir of Yamakura dam, Japan. This plant is able to generate up to 16,170 MWh per year or 44 MWh per day approximately. All solar panels are fixed on the HDPE floating devices. The area of the whole floating platform is about 0.18 km² [23].

5. Conclusion

In this project, a rigorous economic evaluation has been carried on the proposal of 1 GWh of FSPV system, to be implemented on a large artificial lake, e.g., Bakun dam. Based on the heuristic optimization considering three factors: total cost, area covered and stability, it has been found that the 3x3 layout using Astronergy brand gives the highest score. However, based on the long-term analysis considering the product warranty and panel efficiency, the FSPV system using the Astronergy brand is less viable after 20 years of operation – the cost is staggeringly high after 50 years of operation compared to the FSPV using the Panasonic and SolarWorld brands. The Panasonic based FSPV plant requires the lowest cost after 40 years of operation. Thus, considering the long-term analysis, it is recommended to use the Panasonic brand in the FSPV plant. Based on the optimization results for the Panasonic brand, the best design is the 5x5 layout.

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