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Overview and Feasibility of Floating Solar Photovoltaic System in Nepal

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Abstract:
As a next generation technology, Floating Solar Photovoltaic (FSPV) System has had a remarkable growth in the field of Renewable Energy since 2014 with an installed capacity of more than 200 MWp as of 2017. Interest in FSPV system is on the rise compared to its land-based counterpart due to significant benefits like an increased efficiency of the panel, omission of land-related cost and cost of the mounting structure along with environmental benefits like water conservation of the reservoir through a reduced rate of evaporation and containment of algae boom. In this paper, the overall benefit of exploiting FSPV system in case of Nepal has been explored and the techno-economic feasibility of such system in Nepalese scenario has been analyzed. Improvement in efficiency of the panel has been calculated mathematically which also seems to support results from previous works. After analyzing the techno-economic benefits, it was found that FSPVs, even though having a marginal financial profit at current PPA rate of Rs. 7.3/kWh, can still prove beneficial if used concomitantly with storage type hydropower plants.

Keywords: Floating Solar Photovoltaic System (FSPV), PV Cell Efficiency, Solar Feasibility, Techno-Economic Analysis

1 Introduction

As one of the leading technologies of renewable energy, Solar Photovoltaics is on the rise throughout the world. However, one of the major issues with the Solar PV is requirement of large landscape near the load center [1-8]. Since Floating Solar Photovoltaic system can be installed over water surfaces, they have emerged as an effective solution to mitigate the issue of huge land requirement for PV system along with other additional advantages such as prevention of evaporation of water from the reservoirs. Recently many floating systems have been constructed throughout the world with varying degree of utilizations [1]. The cumulative installed capacity of FSPV plants is 225MWp by the first quarter of 2018; out of which 96 MWp alone was installed in 2017, with China being home to a 40 MWp and a 20MWp FSPV plants, the two biggest plants as of now in this technology [1]. The installed capacity, however, is higher in Japan with about 66% and rest of the Asian Nations share 20% of the total installed capacity throughout the world. Similarly, USA boasts 3% and Europe boasts 11% of the total installed capacity respectively [1]. It is further estimated that the total installed capacity of FSPV system will be approximately 1GW within few years [1].

An FSPV plant can use standard PV modules which are installed over floats at 10-12º angles on water bodies like hydropower reservoir, drinking water reservoir, lakes and so on [2]. The floating system is easy to install and dismantle, configure, is fully recyclable and cost effective as well [3]. The greatest benefit an FSPV system offers is the elimination of land requirement. As FSPV systems are installed on water, the land they would have required otherwise, can be utilized for other purposes like agriculture or other commercial ventures. One of the added benefits of employing FSPV system is improvement in cooling of the solar modules due to which the efficiency of the system as a whole increase and the rate of evaporation of water is also reduced concomitantly [2-4].

With land-based solar installations increasing rapidly, use of land resources by such systems is ever-rising. Furthermore, PV systems that employ solar tracking mechanisms of some sort will only require additional land to avoid obstruction and shading [5]. Since the efficiency of a typical PV panel degrades at high operating temperature, the necessity to search for design solutions that will maintain the operating temperature of the PV system at a constant lower value is paramount [5] and this is where an FSPV system emerges as an effective solution. FSPV system can accommodate easier and inexpensive tracking mechanism as compared to a land-based PV system with no land-related cost whatsoever [2].

Nepal, being endowed with numerous water resources, is heavily dependent on hydropower and the development of other renewable power projects is still in a rudimentary stage. Due to rugged land structures, land-based solar projects are difficult to install in hilly regions which occupy almost 70% of the total area of the country. With the Terai region serving as the bread basket of the country, utilization of its flat arable lands for agriculture is preponderant amongst all the possible uses. Therefore, development of FSPV system in Nepal is justified owing to the fact that FSPV plants could be used in conjunction with irrigation and drinking reservoirs to prevent the evaporation of water and also in conjunction with hydropower reservoirs to provide an auxiliary means of power generation or for local distribution. This paper, along with the pertinent details, assesses the techno-economic viability of FSPV system used on a hydropower reservoir in Nepal and also evaluates the increased efficiency of the panel over its land-based counterpart.

2 Classification of Floating PV System and major Components

FSPV system is the fusion of PV system and floating system. This system, developed as an alternative to land-based PV systems due to decreasing land availability, has seen massive growth alone in last year due to the efforts from countries like China and Japan [1].

2.1 Classification of FSPV System

2.1.1 Based on PV Module Tracking

a) Fixed Type Floating PV System: As the name suggests, in this configuration PV modules are fixed over floats at a certain optimum angle (usually 10-15°) and fixed securely using a mooring system. The benefit of this type of system is saving in cost since fewer mechanical structures are needed and the design is also simple [4,5].

b) FSPV system with Tracking: A tracking mechanism is incorporated in such design so as to track the azimuth angle of the sun thereby increasing the energy generation by 60-70% as compared to Fixed Type design [4]. A Fiber Reinforced Plastic (FRP) structure that uses active and passive systems is normally used as a round rotary component for tracking [4,6]. In [2], the author has proposed to use low-power propellers in any two diagonally opposite edges with the floating system anchored in the center as an axis of rotation to match the optimum azimuth angle of the sun.

2.1.2 Based on types of floating mechanism

a) Pontoon Based: Widely used floating mechanism for the FSPV system are pontoons made of HDPE or MDPE which has sufficient buoyancy to support the load of PV system [1,4].

b) Thin Film Flexible FPV modules: Designed by Trapani et al, the PV modules, in this type of system, are flexible and customizable and can easily deform as per the water waves [7,8]. Such modules are reported to be 5% more efficient than other system. Lesser structures are required since the floating system and PV system are incorporated into single unit. Also, the cooling effect of water is also more administered.

c) Submerged FSPV: The PV modules are submerged in shallow water in this type of system. The advantages of this system are (i) decreased operating temperature of the PV modules due to ample cooling effect of water, and (ii) decreased light reflection in submerged state. The efficiency of the module increases with the depth of water and there is an optimum depth at which the efficiency is maximum. It is estimated that the increase in efficiency lies in the range of 10-20% [4,5].

2.2 Components of Floating PV

FSPV system is composed of floating system, mooring system, PV system, cables and connectors.

a) Floating system: The floating system consists of a floating body (floater and structure) over which PV system is mounted. It provides the buoyancy required so that the whole system can remain afloat. Floaters are typically made of High-Density Polyethylene (HDPE) or Medium Density Polyethylene (MDPE) [1,4,5].

b) Mooring System: The mooring system keeps the floating system secured with the help of anchors and cables. It can further adjust to the perturbations caused by water level fluctuations while maintaining its position in southward direction [9] thereby preventing the modules from floating away or turning.

c) PV system: PV system is composed of PV modules and other power conditioning equipment that convert solar energy into electrical energy. Standard PV modules used in land-based PV system can be used but researches for developing specific PV modules for floating application are being carried out [4].

d) Cables and Connectors: Underground cables are normally used to transfer the electricity generated from the PV system to the substation. These cables could be run underwater or through the floaters but floating cables could also be used. [5].

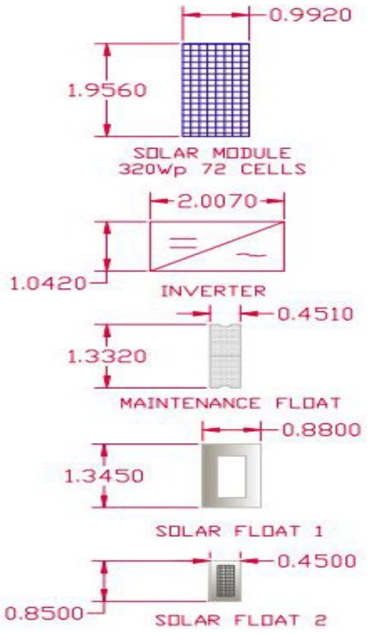


Figure 1: Dimension of components used in FSPV system

3 Techno-Economic Analysis of FSPV System in Nepalese Scenario

As a reference, Indrasarovar Lake of Kulekhani-I Hydropower Project was selected for the techno-economic analysis of the proposed FSPV system. Since it is a man-made lake, the ecological effects on the natural aquatic ecosystem is not much of a concern. Furthermore, since it is a reservoir-type hydropower, power evacuation could be done easily and water conservation due to FSPV system could increase the hydropower production as well.

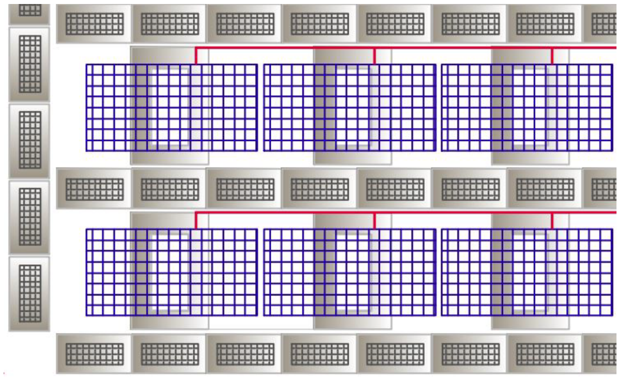


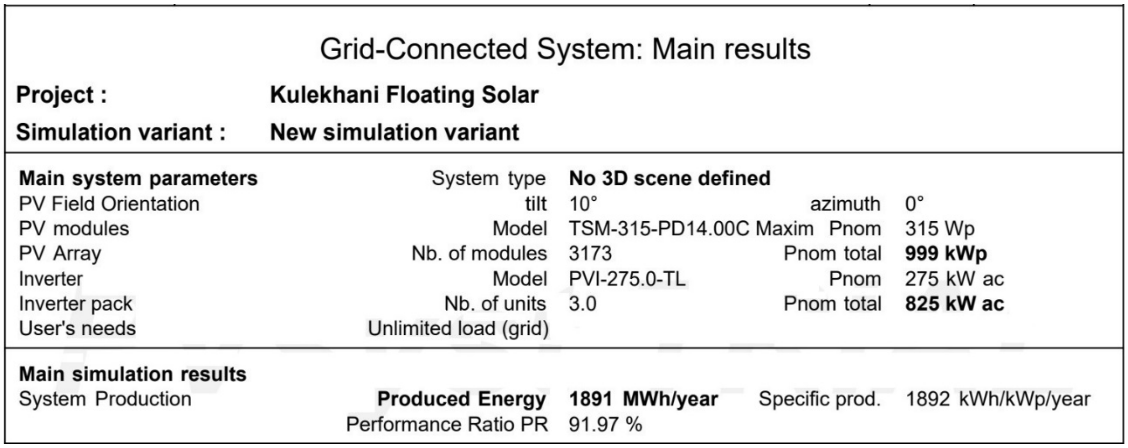
Figure 2: Arrangement for FSPV system components

3.1 Technical Analysis

3.1.1 Preliminary Design of FSPV System

One of the main reasons for decreased efficiency of PV system is an increased temperature of the PV cells. Since the FSPV system is in constant contact with water, the PV cells are cooled which increases the efficiency of the system. Basic approach of an FSPV system is to install PV system over floaters oriented to the south with a fixed azimuth angle (0°) and a fixed tilt angle (10-15°) [2]. Tracking the azimuth angle will result in an

Figure 3: Layout of FSPV system in Kulekhani Reservoir and Evacuation Point



Grid-Connected System: Main results

Project : **Kulekhani Floating Solar**
Simulation variant : **New simulation variant**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	TSM-315-PD14.00C Maxim	Pnom	315 Wp
PV Array	Nb. of modules	3173	Pnom total	**999 kWp**
Inverter	Model	PVI-275.0-TL	Pnom	275 kW ac
Inverter pack	Nb. of units	3.0	Pnom total	**825 kW ac**
User's needs	Unlimited load (grid)			
Main simulation results				
System Production	**Produced Energy**	**1891 MWh/year**	Specific prod.	1892 kWh/kWp/year
	Performance Ratio PR	91.97 %		

Figure 4: FSPV System Main Results

increased efficiency with less sophisticated mechanism and lower cost [2,4,5] but that design is not considered in this paper since numerous papers on tracking PV system have been published previously. In this paper, 1 MWp plant is considered with 3 arrays, each of 275KWp STC power and 3 inverters with the output of 400V 3-phase connected by approximately 1 km long cables to the substation on land.

Each array is securely anchored at four corners, thus preventing them from floating away or turning. The tilt angle of PV system is normally taken to be 10-15° only, unlike its land-based counterpart where the optimum tilt angle is selected to be equal to the latitude of the location. The reason for lowering the tilt angle is to reduce the effect of wind pressure so that the PV system can remain stable over the water surface [2]. Also, the increased efficiency due to decrease in temperature counteracts the effect of optimum tilt angle.

3.1.2 Energy Production and Overall Efficiency

Energy generated by the PV system is determined by the following expression:

$$W = I_{avg} \times A \times \eta \quad (1)$$

Where, I_{avg} is the mean hourly insolation, A is the effective area of the PV modules and η refers to the overall efficiency of the system.

The efficiency of the overall Grid-Connected PV System directly affects the amount of energy that can be produced from the plant. The efficiency of the equipment of PV system other than PV modules is given by

$$\eta_e = \eta_i \times \eta_{tr} \times \eta_c \quad (2)$$

η_e = efficiency of the equipment,
η_i = efficiency of inverter,
η_{tr} = efficiency of transformer,
η_c = efficiency of the cable

The efficiency of the PV arrays is dependent on the temperature of the module cells. The data of the PV modules is measured at standard temperature of 25°C. The actual temperature of the cell is approximately 20°C higher than the surrounding temperature, called Nominal Operating Temperature of PV cell, which is given by following expression [10]:

$$\Delta T = T_p - T_a = \frac{NOCT - 20°}{0.8} \times I$$

$$V_{ocv'} = V_{ocv} - \Delta T \times 0.0842$$

$$I_{scc'} = I_{scc} - \Delta T \times 0.0086 \quad (3)$$

Where T_p = Panel temperature (˚C),
T_a = Ambient temperature (˚C),
V_{ocv} = Open-circuit voltage (V),
I_{scc} = Short circuit current (A)

The efficiency of photovoltaic array (η_{PV}) can be determined by following equation:

$$\eta_{PV} = \frac{V_{ocv'} \times I_{scc'}}{V_{ocv} \times I_{scc}} \quad (4)$$

Considering standard Silicon PV cells, the change in efficiency of PV panels due to change in temperature is significant. It is found that the efficiency of the PV panels decreases by approximately 0.5% /°C increase in temperature [2,10].

$$\eta_{(PV)} = \eta_{(STC)} \times (1 - 0.005 \times (Tp - 25)) \quad (5)$$

Since the PV arrays are kept at certain optimum angle (in this case 10°) and solar radiation falls on the array at different angles, the efficiency of the system further decreases which gives rise to following expression for the total efficiency of the PV system

$$\eta_{te} = \eta_{tilt} \times \eta_{PV} \times \eta_e \quad (6)$$

Where, η_{te} = Total efficiency of the PV System

η_{tilt} = Efficiency of inclination angle

The efficiency of the PV Arrays further decreases due to shading and soiling on the panels. Therefore, the location must be free of shading and to prevent reduction in efficiency due to soiling, the PV arrays must be cleaned regularly. Shading and soiling can result into 3% loss on the output of the PV system [10].

Simulation of the Floating PV system at Kulekhani was carried out in the PVSyst software. The solar irradiance and meteorological data were taken from NASA-SSE. In order to adapt the system for simulation in PVSyst, the operating temperature of PV modules was reduced by increasing the thermal loss factor due to the cooling effect of water and also the Albedo factor was also decreased. For land-based PV cells, the thermal loss factor is generally taken to be about 20 W/m^{2}K. But for water, the thermal loss factor could be as high as 250-300 W/m2/K. However, in this scenario, the thermal loss factor assumed to be 100 W/m^{2}K only. However, the Albedo factor for water surface was reduced to 0.1 from 0.2 (for general land-based PV installation) but its effect was insignificant as per PVSyst simulation, which might require a newer model for floating installation.

The result from PVSyst simulation is shown below:

Annual electricity generation for proposed FSPV system amounts to 1892 MWh/year with Performance ratio of 92% with Average Solar Irradiation of 5.45 kWh/m^2/day which is significantly better result for a Solar PV system. This corroborates the feasibility and benefits of an FSPV system from technical perspective.

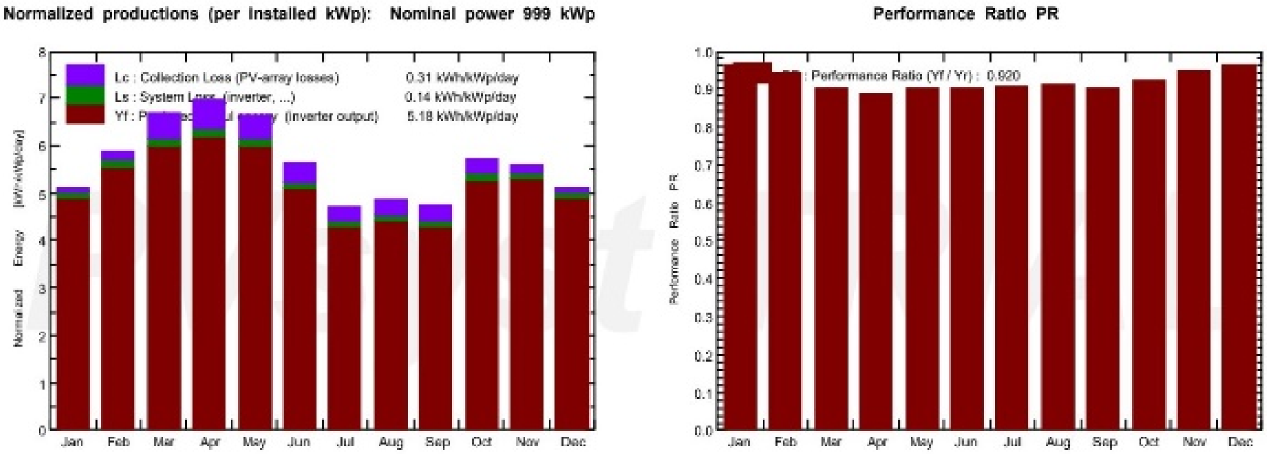
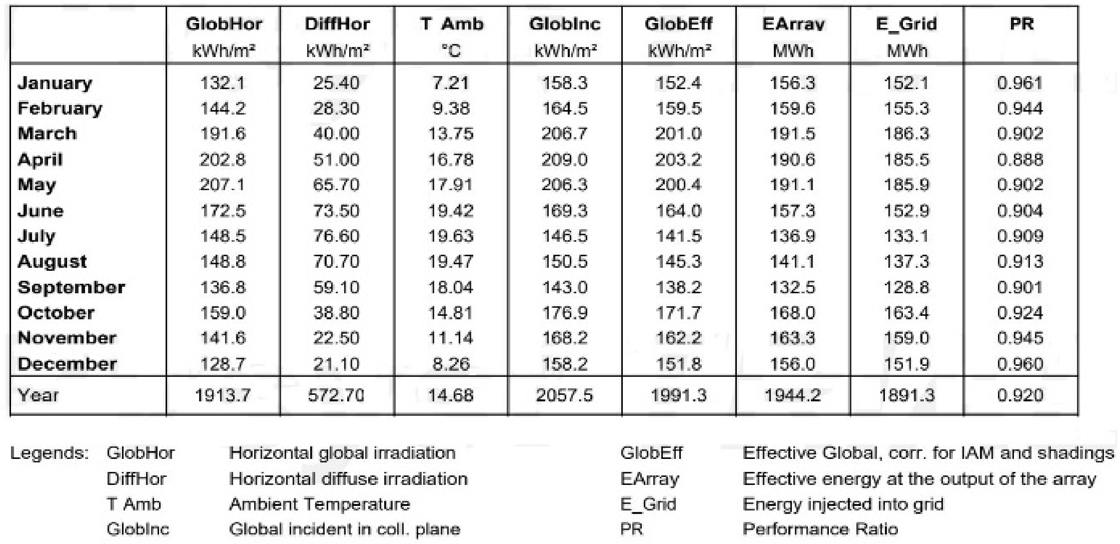


Figure 5: Monthly Normalized Production and Performance Ratio Chart

Table 1: Solar Irradiation, Effective Solar Irradiation and Generated Energy Table



	GlobHor kWh/m²	DiffHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	132.1	25.40	7.21	158.3	152.4	156.3	152.1	0.961
February	144.2	28.30	9.38	164.5	159.5	159.6	155.3	0.944
March	191.6	40.00	13.75	206.7	201.0	191.5	186.3	0.902
April	202.8	51.00	16.78	209.0	203.2	190.6	185.5	0.888
May	207.1	65.70	17.91	206.3	200.4	191.1	185.9	0.902
June	172.5	73.50	19.42	169.3	164.0	157.3	152.9	0.904
July	148.5	76.60	19.63	146.5	141.5	136.9	133.1	0.909
August	148.8	70.70	19.47	150.5	145.3	141.1	137.3	0.913
September	136.8	59.10	18.04	143.0	138.2	132.5	128.8	0.901
October	159.0	38.80	14.81	176.9	171.7	168.0	163.4	0.924
November	141.6	22.50	11.14	168.2	162.2	163.3	159.0	0.945
December	128.7	21.10	8.26	158.2	151.8	156.0	151.9	0.960
Year	1913.7	572.70	14.68	2057.5	1991.3	1944.2	1891.3	0.920

Legends:			
GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
T Amb	Ambient Temperature	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	PR	Performance Ratio

3.1.3 Comparison of Land-based PV System and FSPV System

Electricity generation in a land based and an FSPV system needs to be compared to highlight the benefit of the FSPV system. Therefore, a land-based PV system at Bhorleni, Makwanpur near Kulekhani has been selected as reference, which was installed by Alternative Energy Promotion Centre (AEPC) on 2016 for Rural Electrification. As per the AEPC, the plant is operating at 18% Capacity Factor with 5.4 kWh/m2/day of average solar irradiation. A ground PV plant with fixed optimal azimuth angle (0°) and fixed tilt angle (28°) and a base FSPV plant with fixed azimuth angle (0°) and fixed tilt angle (10°) are considered.

The comparison result is presented in table (2):

Table 2: Comparison of Land-based and Floating Solar

	Specific Production (kWh/kWp/year)	Average Irradiation (kWh/m^2/day)
Ground PV Plant	1600	5.40
FSPV Plant	1892	5.45

The percentage increase in energy generation in floating solar is 18.25% higher than the Ground-mounted PV, based on the table (2). This result is in line with our discussion that the PV cells efficiency increases in FSPV system due to the cooling effect of water.

3.1.4 Conservation of Water in the Reservoir

As per the Global Evaporation Map by EU WATer and global Change (WATCH) project, average monthly evaporation in Nepal is around 60 mm/month [11].

So, the annual evaporation rate could be taken as = 60×12 mm/year = 0.72 m/year

The overall area of Kulekhani reservoir to be covered by FSPV system = 6157 m^2

Therefore, estimated volume of water prevented from evaporation in Kulekhani reservoir = 0.72×6157 = 4433 m^3/year. By installing a 1MWp FSPV system, approximately 4433 m^3 volume of water could be conserved annually and if wind effect (as low as 0.5 m/s wind speed) is also included, the volume of water that could be conserved ranges from 8,000-10,000 m^3.

3.2 Economic Analysis

For economic analysis, the project parameters were used in creating a financial model in Microsoft Excel to determine the output results of the model which are Net Present Value (NPV), Internal Rate of Return (IRR), Benefit/Cost Ratio (BCR), and Debt Service Coverage Ratio (DSCR). Input Parameters for the modeling are:

Table 3: Economical Analysis Input Parameters

System Design	
System Cost ($/watt DC)	$0.91
System Size (DC) (MW)	1
Initial debt service reserve funding	$83,749
Total System Cost	$993,749
Performance Inputs	
DC Capacity Factor	21.60%
Annual Output for Year 1 (MWh)	1,892
Degradation Factor	0.60%
System lifetime	25 years
Other	
O&M Costs ($/kW)	$5.00
O&M Costs Escalator (%/yr)	2.00%
Inverter replacement cost ($/W)	$0.06
10yr inverter replacement cost	$60,000
Annual inverter amount to reserve	$6,000
Inverter replacement time (in Years)	10
Insurance Expense ($/kW)	$5.00
Insurance Escalator (%/yr)	2.00%
Feed in Tariff Value/MW	$0
Land Lease/Year	$0
Wholesale Price of Electricity	$0.07
Electricity Escalator	0.00%
Custom/Excise Duty Tariff	15.00%
Financing	
% Financed w/ equity	30%
% Financed w/ debt	70%
Debt Interest rate	10.00%
Debt period in years	12
Discount Rate	10.00%
Interest Rate on DSRF	5.00%
Equity Amount	$301,046
Debt Amount	$702,442
Effective Tax Rate: 100% exempt for first 10 years, 50% rebate after 10th year	

The economic measures with reference to given conditions showcase the marginal profitability of the project. The Internal Rate of Return is just above the discount rate of 10 %. The B/C Ratio of the project is

1.003 and Debt Service Coverage Ratio is 1.09 which reflects that cash flow available is just sufficient to repay current debt obligations. Cash flow until 12 years is less because of loan repayment and low electricity tariff. The cash flow then increases after complete repayment of the debt in 12 years. This analysis clearly shows that the wholesale price of Electricity (NPR 7.30) [12] set by Ministry of Energy for Solar or other alternative energy sources is less for such project to be profitable.

Table 4: Output of Economic Analysis

Output	
Net Present Value	$885
Internal Rate of Return	10.025%
Debt Service Coverage Ratio	1.09
Benefit/Cost Ratio	1.003

4 Conclusion

With annual production of 1892 MWh and performance ratio of 92%, FSPV project is technically better than land-based PV project even with smaller tilt angle. The primary reason for increased energy production is the increased efficiency of PV cells due to reduced operating temperature resulting from the cooling effect of water. Furthermore, the proposed FSPV project prevents water evaporation in the reservoir by 4433m^3 annually; thus, making such projects suitable even for irrigation reservoirs in Terai region and drinking water reservoirs throughout the country where water conservation could also result in financial benefit of such projects.

Even though the FSPV Project in Kulekhani is technically more beneficial than ground-mounted PV system, it can be concluded from the economic analysis that at current tariff, the FSPV system is beneficial for specific applications only. Even with the omission of land-lease cost and reduction of mechanical structures cost, the project is found to lie in the breakeven point for the current tariff of Rs. 7.3/kWh with zero tariff escalation. Therefore, in-line with techno-economic analysis presented in this paper, it can be concluded that such projects are not profitable enough for commercial purposes at current tariff but could be highly beneficial if operated in conjunction with reservoir type hydropower plants given the water conservation benefits and auxiliary power requirement for the intake side of such hydropower could be provided by the FSPV system. Similarly, for the irrigation or drinking water reservoir as well, the project could be an attractive solution to power requirement for operation and water conservation. However, the paper does not recommend installation of FSPV system in natural water bodies since it could affect the aquatic ecosystem in such water bodies. So further environmental studies and researches may be required to determine the environmental effects of such projects.

However, FSPV system has good prospects in Solar Photovoltaic sector because of higher energy generation as compared to land-based PV system. There are several issues that hinder the development of the Solar PV System in Nepal in general and also affect the growth of Floating PV system. From the analysis presented above, it can be concluded that the lower Power Purchase Agreement Rate and lack of Feed-In-Tariff mechanism will not make such projects lucrative enough to promote investment from private and foreign agencies in Nepalese Power Sector. Even though the Government of Nepal had decided Power Purchase Rate for Solar projects to be Rs. 9.61/kWh in previous studies, it was later reduced to Rs. 7.30/kWh in a recently published Grid-Connected Alternative Energy Development Procedure (2074) [12]. The Power Purchase rate of solar is extremely low in Nepalese scenario as compared to India, Japan, USA and other European countries. The government should emphasize on Feed-In-Tariff (FiT) Mechanism, which has been successfully implemented in some European Countries, Japan, USA and India, to facilitate the acceleration of the income of grid-scale solar investors. This could be helpful in attracting the potential solar investors in the near-future.

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