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Effectiveness of the Hybrid System Combining Hydropower and Floating Solar in the Lao PDR

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Preface

The Lao People's Democratic Republic (Lao PDR) is rich in hydropower resources. But during the dry season, the country faces an electricity supply shortage from hydropower plants due to less water flow. Consequently, the Lao PDR must import electricity from Thailand in that season. Thus, it has two options to avoid this electricity shortage: (i) construct a coal power plant using domestic coal such as lignite, and (ii) install a solar photovoltaic (PV) system, which works well during the dry season. Considering climate change and energy supply sustainability, a solar PV system is better than a coal power plant. On the other hand, solar PV is intermittent and has a small capacity factor (less than 20%), a relatively higher generation cost, and seasonality. Thus, assessment of solar PV installation should be indispensable, applying a power generation simulation approach based on the hourly basis solar irradiation data. In this regard, the Ministry of Energy and Mines, Lao PDR, requested the Economic Research Institute for ASEAN and East Asia to conduct this assessment and evaluate the effectiveness of solar PV, which can be a complementary power source to hydropower power plants.

This assessment analyses a hybrid system combining hydropower power and a floating solar PV system, which will be set on the surface of the hydropower dam. This hybrid system does not need an additional transmission line to a national grid because a transmission line is already facilitated to the existing hydropower station from the grid. But the installation capacity of a floating solar PV system is restricted to the capacity of a current transmission line.

This report suggests the effectiveness of the hybrid system for the Lao PDR. However, suppose the capacity of the solar PV system to be connected to the grid will be significant. Due to its unstable electricity supply, the national grid's operation stability will be interfered with. Thus, a solar PV system will be a very important power source for the Lao PDR and will be maximised. However, the country will also have to pay attention to stable national grid operation by installing storage batteries with smart-grid, resilience of cross-border transmission lines with neighbouring countries, and a back-up power system to apply hydrogen to be produced by rich renewable energy, such as hydropower and solar/PV.

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Acknowledgement

This report was developed by a joint working group comprising teams from the Ministry of Energy and Mines (MEM), Lao PDR, and the Economic Research Institute of ASEAN and East Asia (ERIA). The Department of Energy Policy and Planning, MEM, was the main department of the Lao PDR team. Associate Professor Keeley of Kyusyu University joined the ERIA team to conduct a simulation study of power generation by solar PV on an hourly basis.

Special acknowledgement is also given to Khammun Sorpaseth, Deputy Director General, Institute of Renewable Energy Promotion, MEM, Lao PDR, for his very helpful comments and suggestions as head of the Lao PDR team.

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List of Abbreviations and Acronyms

BAU	business-as-usual scenario
CO_2	carbon dioxide
EDL	Electricité du Laos
ERIA	Economic Research Institute for ASEAN and East Asia
FSPV	floating solar photovoltaic
GWh	gigawatt hour
IAM	array incidence losses
IPP	independent power producer
IRR	internal rate of return
IRROE	IRR on the IPP entity
IRROI	IRR on the FSPV project
kWac	kilowatt alternating current
kWh	kilowatt-hour
Lao PDR	Lao People's Democratic Republic
MEM	Ministry of Energy and Mines
MW	megawatt
MWh	megawatt-hour
PV	photovoltaic
RE	renewable energy
TWh	terawatt-hour
US	United States
Wp	watt peak

Executive Summary

The energy demand of the Lao People's Democratic Republic (Lao PDR) is increasing yearly due to population growth and sustained economic growth. The country has great potential for hydropower generation, and hydropower generates much of its electricity supply. Therefore, in the rainy season, the output of existing hydropower plants and hydropower plants under construction is sufficient to meet the demand. On the other hand, during the dry season, electricity is imported from thermal power plants in Thailand because of insufficient supply from hydropower plants due to the lack of water flow. Given this trend, supply capacity during the dry season is one of the challenges for the Lao PDR, where energy demand is expected to increase. To solve these challenges, a solar photovoltaic (solar PV) system that generates electricity well during the dry season is an option to meet future electricity demand and transition to sustainable energy development. Thus, this study analyses the effectiveness of a solar PV system in complementing hydropower generation during the dry season in the Lao PDR. This project focuses on floating solar PV (FSPV) and hybrid systems, combining an existing hydropower plant and a new FSPV on the surface of the hydropower dam. In this regard, Nam Mang 3 was selected as an existing hydropower plant.

A simulation study estimated the power generation of the new FSPV near the Nam Mang 3 plant site based on hourly solar irradiation data. The study revealed that a 40 megawatt (MW) FSPV installed in the Nam Mang 3 reservoir would generate a monthly average of 5.43 gigawatt-hours (GWh) during the dry season and 4.20 GWh during the rainy season. The FSPV generates more power in the dry season, which is the opposite of the trend for hydropower plants. Thus, a complementary relation between FSPV and hydropower plant was suggested.

How about the appropriate size or capacity of FSPV? First, to increase the amount of FSPV installed, adjusting the output of hydropower generation to match that of the FSPV is effective. In addition, it is important to determine the capacity of the FSPV to reduce the volatility and curtailment as much as possible in terms of cost-effectiveness and stable power supply. In this study, assuming 40 MW of demand and 100 MW of existing transmission line capacity, a maximum of 60 MW of FSPV was recommended to be installed on the surface of the Nam Mang 3 dam by trial-and-error approach, which reviews the volatility and curtailment when it changes the FSPV capacity from 40 MW to 100 MW. Conversely, if a huge FSPV capacity is installed relative to the capacity of the hydropower plant, it would exceed the control capability of the hydropower plant, resulting in increased fluctuations that may interfere with grid operations. Therefore, if demand increases in the future and more power supply is needed, it is necessary to improve the control ability of the hybrid power system, such as by installing storage batteries and increasing the capacity of hydroelectric power in terms of stable power supply.

A coal power plant, Hongsa, exports 100% of generated electricity to Thailand. However, this power plant's carbon dioxide (CO_2) emissions are accounted for on the Lao PDR, and coal power plants are important to export electricity to neighbouring countries. But if the Lao PDR utilises a hybrid system to combine hydropower and floating solar FSPV, it can export electricity like coal power plants. Thus, RE hybrid power system based on hydropower could decarbonise its power sector but needs to pay attention to applying new energy technologies, such as storage batteries and smart-grid systems. The

RE hybrid system can improve the energy demand–supply situation and reduce CO_2 emissions in the whole Lao PDR.

An independent power producer (IPP) will engage this FSPV business, as economic feasibility is essential for the IPP.According to this project study, the selling price of electricity to the Electricité du Laos (EDL) is crucial. Assuming the price is 5 cents, the economic feasibility is low due to the less attractive internal rate of return (IRR) and financial statements. But if we change the price to 6 cents, the IRR and financial statements will largely improve and be economically feasible. The economic feasibility analysis has many parameters besides the selling price: the unit cost of solar panel, the capacity factor of solar PV system, operation cost, financing conditions such as equity ratio, and borrowed money conditions. Thus, if we can review the parameters, such as the unit cost of solar panels, 6 cents can decrease. In this regard, if this feasibility stage will move up to the implementation stage, a sensitivity analysis is recommended to identify sensitive parameters of the FSPV system for seeking lower selling prices to the EDL.

Finally, using the solar PV system, especially for the hybrid system combined with hydropower, could be an appropriate option for the Lao PDR to promote a decarbonised energy mix in terms of total final energy consumption and total primary energy supply, mitigation of CO_2 emissions by shifting from coal power plants to RE, and reasonable electricity price. But when the Lao PDR invites IPPs to develop hydropower and solar PV system, the government must formulate appropriate environmental regulations to manage the IPPs.

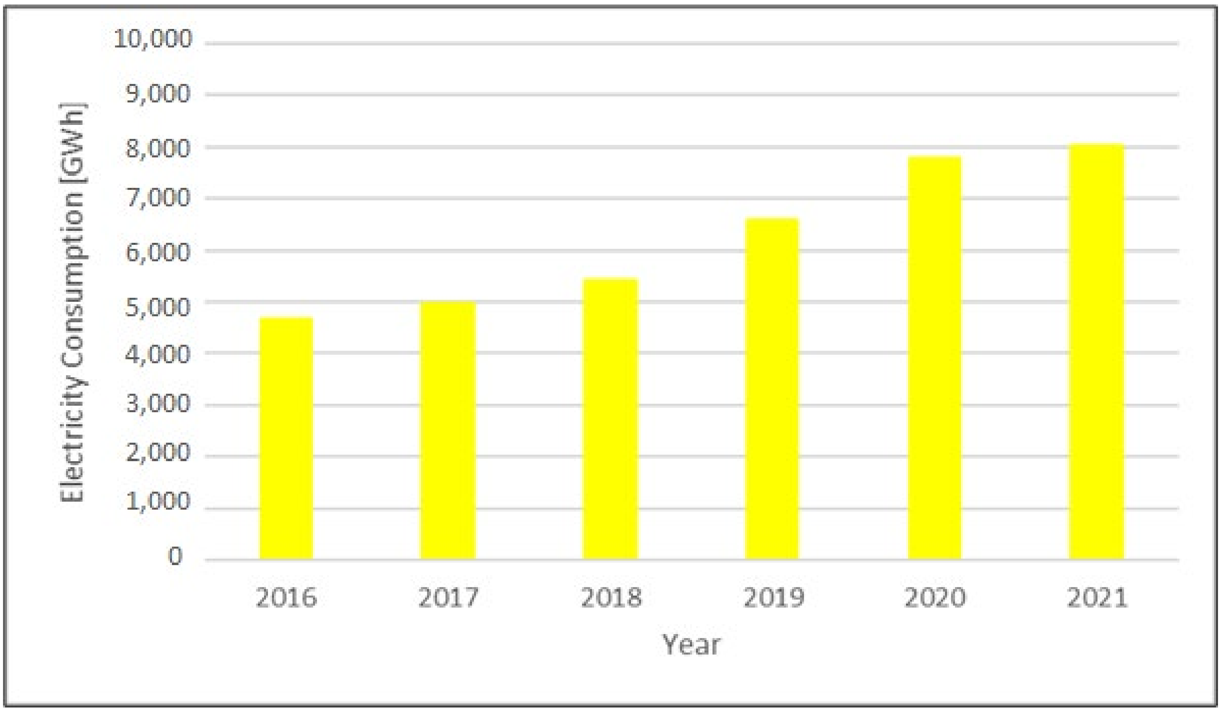
Chapter 1

Introduction

1. Background

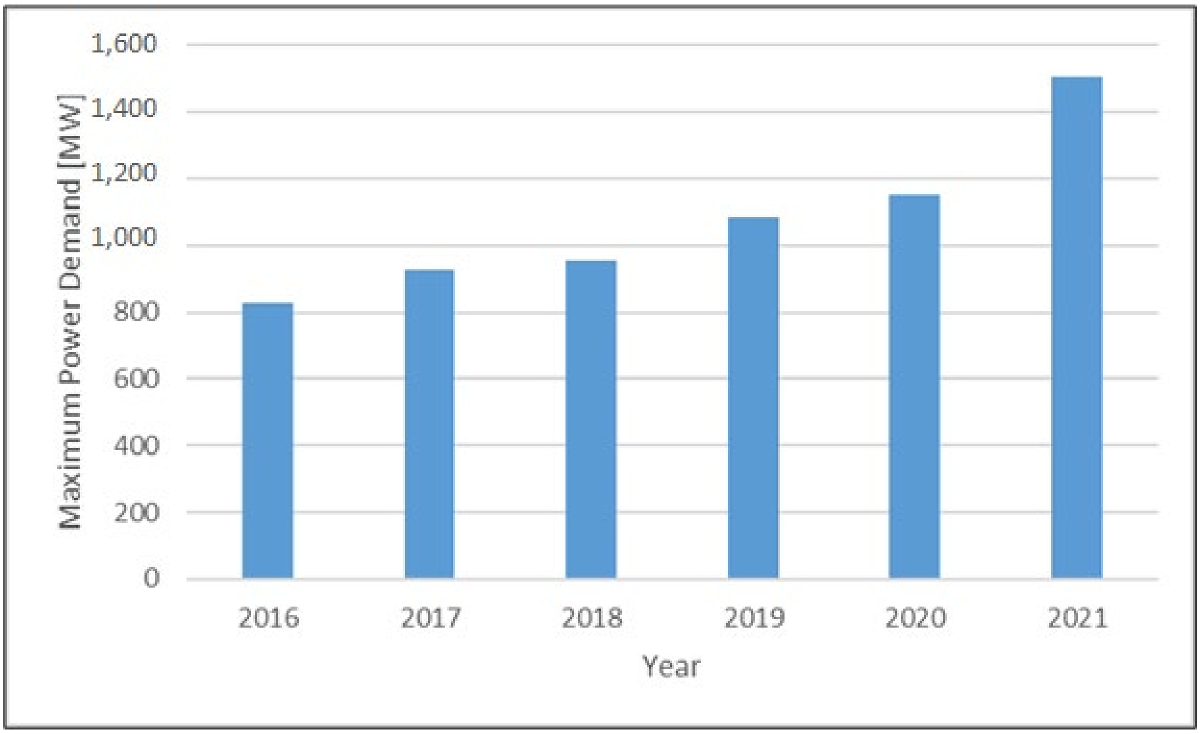
The energy demand of the Lao People's Democratic Republic (Lao PDR) is increasing yearly due to population growth and sustained economic growth. In addition, the increasing development of electricity grids in remote areas has also contributed to the increase in energy demand. Figures 1.1 and 1.2 show the Lao PDR's annual electricity consumption and maximum power demand. Between 2016 and 2021, electricity consumption and maximum power demand increased by an average of 11.7% and 13.1% per year, respectively, and energy demand is expected to continue to grow with economic growth in the future.

Figure 1.1. Electricity Consumption



Source: Lao Ministry of Energy and Mines (MEM) data, modified by the author.

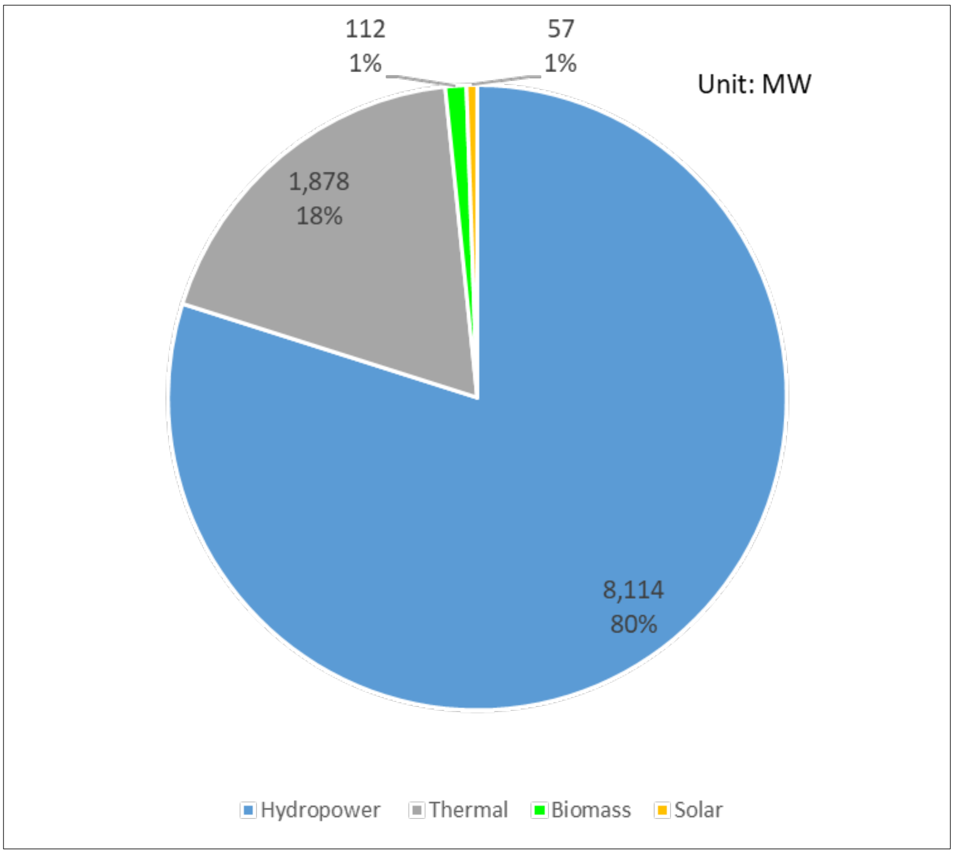
Figure 1.2. Maximum Power Demand



Source: MEM data, modified by the author.

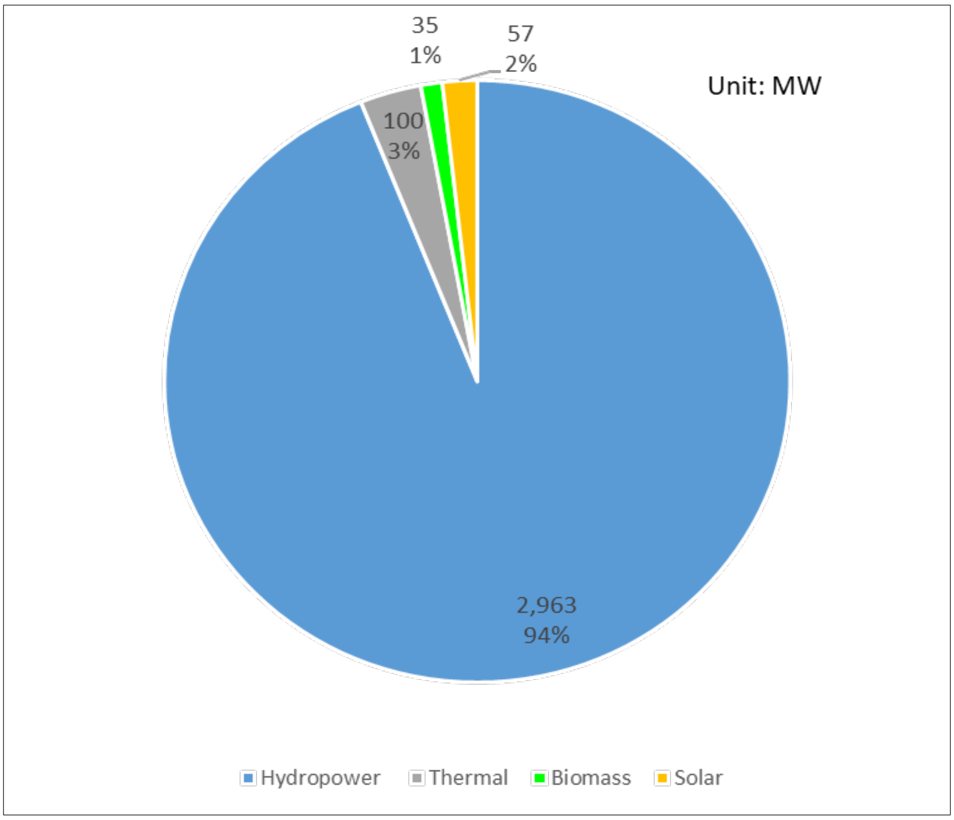
The Lao PDR has a large potential for hydropower generation. As of 2020, the total installed capacity in the country was 10,161 MW, of which 3,155 MW was for domestic use. The total installed capacity portfolio and the total installed capacity portfolio for domestic use are shown in Figures 1.3 and 1.4, respectively. These figures are referenced from the report 'Assessment of Electric Vehicle Penetration in the Lao People's Democratic Republic' prepared by ERIA in 2022 (Kimura et al., 2022). The primary generation in the Lao PDR relied on hydropower. For the whole country, the installed capacity of hydropower accounted for 80%. Next to hydropower was thermal power, which accounted for 18%. On the other hand, for domestic use, the installed capacity of hydropower accounted for 94%. The installed capacity for domestic use depends mostly on hydropower. The installed capacity of other power generation types, such as biomass and solar, is still very low.

Figure 1.3. Total Installed Capacity Portfolio



Source: Kimura et al. (2022).

Figure 1.4. Total Installed Capacity Portfolio for Domestic Use



Source: Kimura et al. (2022).

During the rainy season, the supply will be sufficient solely from the output of existing and under-construction hydropower plants. On the other hand, during the dry season, the supply from hydropower plants is inadequate due to insufficient rainfall, so the Lao PDR relies on imports from thermal power plants in Thailand. Therefore, supply capacity during the dry season is a challenge for the country, whose energy demand will continue to increase. We think an FSPV system that works well in the dry season is an option to transition to sustainable energy development while ensuring that the country has the supply capacity to meet its growing energy needs. The relationship between hydropower and solar power is complementary, and their hybrid system will be appropriate for the country.

2. Objectives

The project aims to investigate the effectiveness of a hybrid system consisting of a hydropower plant and FSPV. Regarding the study methods, firstly, targeting an existing hydropower plant in the Lao PDR, we research how much electricity would be generated if an FSPV were installed, using solar resource data from satellite data. The target is the Nam Mang 3 reservoir. Then, based on the obtained FSPV power generation data, the effectiveness of an FSPV is discussed from the following perspectives:

- the complementary relationship between a hydropower plant and an FSPV
- the appropriate FSPV capacity regarding the amount of electricity generated, volatility, and cost-effectiveness
- the impact of hybrid system installation on energy, CO_2 emissions, and economic situation in the Lao PDR.

Chapter 2

Effectiveness of the FSPV System

An FSPV is typically installed in enclosed freshwater areas such as reservoirs and hydropower dams. In 2015, the first large-scale plant was installed in Japan (Boersma et al., 2019). In 2018, a 150 MW plant was installed in China (SERIS, World Bank, and IFC, 2018). Existing studies indicate synergies between FSPV and hydropower plants (Oliveira-Pinto and Stokkermans, 2020).

Floats and pontoons used in an FSPV face ecological problems in harsh riparian environments, such as flooding during the rainy season and high waves during strong winds. Therefore, floats and pontoons need stability, strength, and long-term reliability. Installing windshields to prevent strong winds from blowing into the back of PV panels should also be considered.

The main advantages of installing FSPVs are compared to ground-mounted PV and their complementarity with hydropower plants. The first advantage is that ground-mounted solar power generation requires new land to be developed, leased, and maintained, whereas the FSPV can eliminate these requirements. Also, installing FSPVs on hydropower plant reservoirs can easily be connected to the grid because they can be close to existing transmission lines. In addition, studies have reported that the cooling effect of the temperature difference between water and air and the reflectivity (albedo) of the water increases the amount of electricity generated by the FSPVs compared to ground-mounted PV.

As a second advantage, the FSPV complements hydropower plants, which generate more power during the rainy season. But during the dry season, their generation decreases due to reduced rainfall. On the other hand, the FSPV is expected to have a higher output in the dry season because of higher solar irradiation. Therefore, FSPVs would be useful as an alternative power source to hydropower plants during the dry season. The Lao PDR is rich in hydropower resources and relies on hydropower for much of its domestic power generation. Installing FSPVs would be a good option for securing power sources during the dry season.

On the other hand, the disadvantage of FSPV is that it is a relatively new technology, so clear data and standards have not been established. For example, detailed verification based on more samples is needed for environmental impact and equipment life under various conditions. Clarification of government regulations and guidelines also requires more time.

Tables 2.1 and 2.2 summarises the advantages and disadvantages of FSPVs, which should be considered when designing local implementation.

Table 2.1. Advantages of FSPV

Advantages
Developers can utilise unused space.
Developers do not need to rent or maintain the land.
Power plants are close to existing infrastructure and easily connect to the grid (Rosa-Clot, Tina, and Nizetic, 2017).
Complementary to hydropower (the dry season usually corresponds to months with high solar irradiation (Liu et al., 2018).
They are installed in open spaces, thus, minimising the impact of barriers such as buildings.
The cooling effect of the temperature difference between water and air increases the electricity generated (Choi, Choi, and Lee, 2016).
The amount of electricity generated increases due to the reflectance (albedo) of the water (Rosa-Clot, Tina, and Nizetic, 2017).
PV modules reduce evaporation at the surface of water bodies (Cazzaniga et al., 2018). Water evaporation is reduced by about 33% in freshwater areas and up to 50% in populated facilities (Choi, 2014).
PV modules reduce algae growth.
No need to customise modules.
Water for cleaning the modules is readily available (Trapani and Millar, 2013).
The installation process is simple (floating structures can be constructed on-site without heavy machinery (Rosa-Clot and Tina, 2018).

Table 2.2. Disadvantages of FSPV

Disadvantages
Environmental impacts need to be better proven. Criteria for testing and certification have yet to be developed.
The FSPV is a new technology with few clear government regulations.
Guidelines are limited.
Concerns exist over a lifetime under humid and corrosive conditions (Liu et al., 2018).
It may need to be designed to withstand extreme wind loads, transitional fluctuations, and waves to hold at a fixed point.
Wind and wave loading may cause micro-cracks (leading to reduced power generation and durability problems) (Sahu, Yadav, and Sudhakar, 2016).
It may affect fishing and other traffic activities.
It may occur biofouling on floating structures (Liu et al., 2018).

Chapter 3

Simulation Study on the Generation of Solar PV System

1. Simulation Approach and Data

1.1. Simulation Site Information

The Nam Mang 3 Hydropower project is in the Phou Khao Khouay area, Vientiane Province, about 60 km to Vientiane capital.

The water from the Nam Yong River at 750 metres above sea level is channelled down to the power plant and reservoir at 200 metres above sea level. This 550-metre height difference allows the project to generate 40 MW of power with an annual energy capacity of 137 GWh.

1.2. Data and Method

The analysis was designed with a comprehensive meteorological database and essential parameters. This section discusses the most relevant computational simulation parameters.

The simulation parameters include site location, solar irradiation, tilt and azimuth angle, albedo, and detailed losses.

Solar irradiation

Solar PV uses solar irradiation as an energy source to generate electricity. The amount of energy obtained from solar irradiation influences the electricity generated. The component that is neither reflected nor scattered and reaches the earth's surface directly is called direct radiation, which is the component that produces shadows. The component scattered by the atmosphere and reaches the ground surface is called diffuse radiation. The small fraction of radiation reflected by the ground surface and reaches the inclined plane is called reflected radiation.

Direct normal irradiation/irradiance involves thermal (concentrating solar power) and PV concentration technology (concentrated PV).[1]

Global horizontal irradiation/irradiance (GHI) is the sum of direct and diffuse radiation received on a horizontal plane. The GHI is a reference radiation for comparing climatic zones and an essential parameter for calculating radiation on a tilted plane.[2]

It is obtained from the Solargis satellite database[3] that estimates solar radiation (past, current, and future levels) without installing ground sensors. The calculation of solar radiation with Solargis is divided into three steps.

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[1] SOLARGIS, https://solargis.com (accessed 23 December 2022).
[2] Ibid.
[3] Ibid.

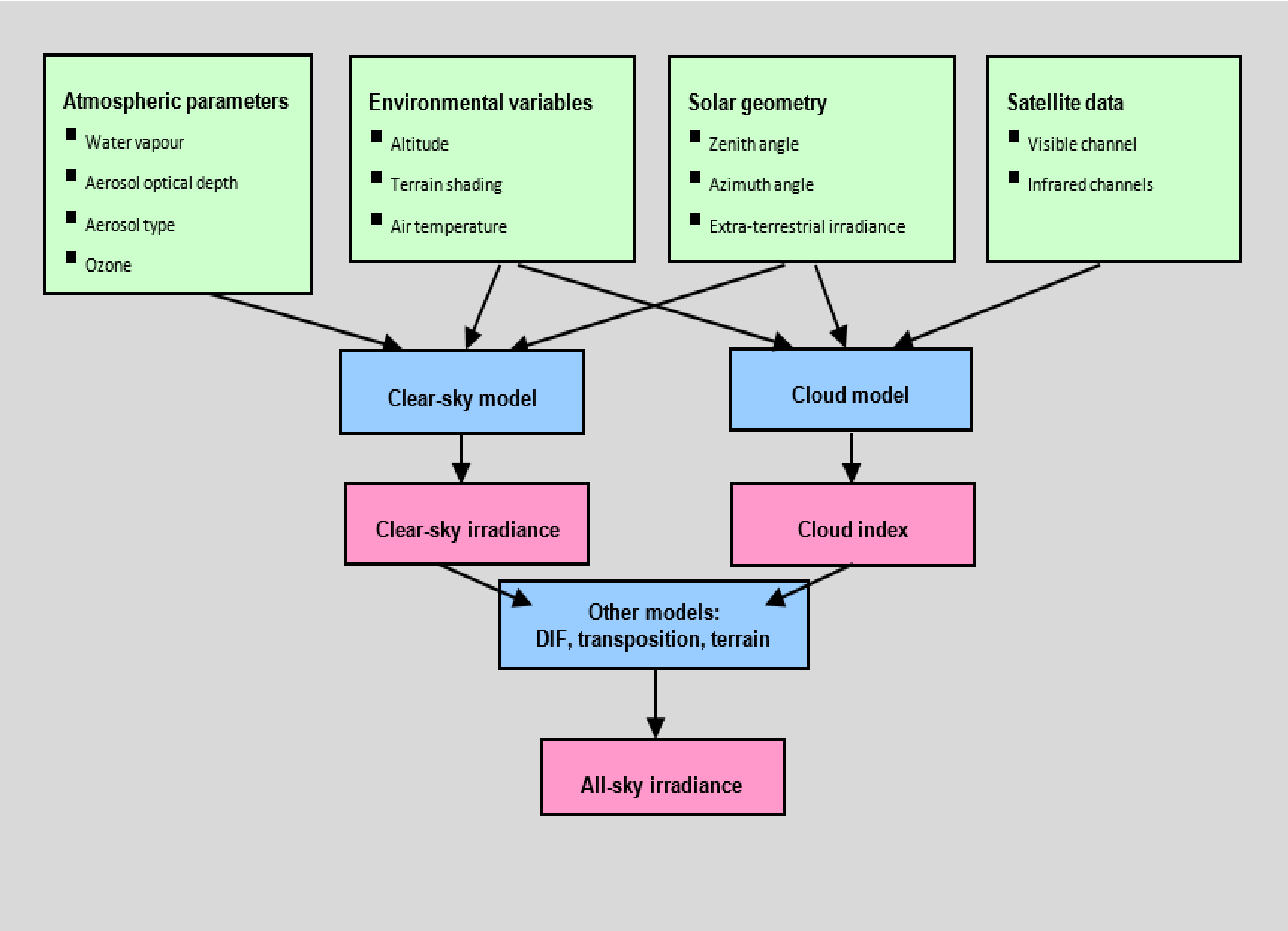
First, the clear-sky irradiance (the irradiance reaching the ground, assuming the absence of clouds) is calculated using the clear-sky model.

Second, satellite data (information from several geostationary satellites) is used to quantify the attenuation effect of clouds through cloud index calculation. Finally, the clear-sky irradiance is coupled with the cloud index to retrieve all-sky irradiance. The outcome of the procedure is direct normal and global horizontal irradiance.

Third, direct normal and global horizontal irradiance is used for computing diffuse and global tilted irradiance (irradiance in plane of the array, on tilted, or tracking surfaces) and/or irradiance corrected for shading effects from surrounding terrain or objects.

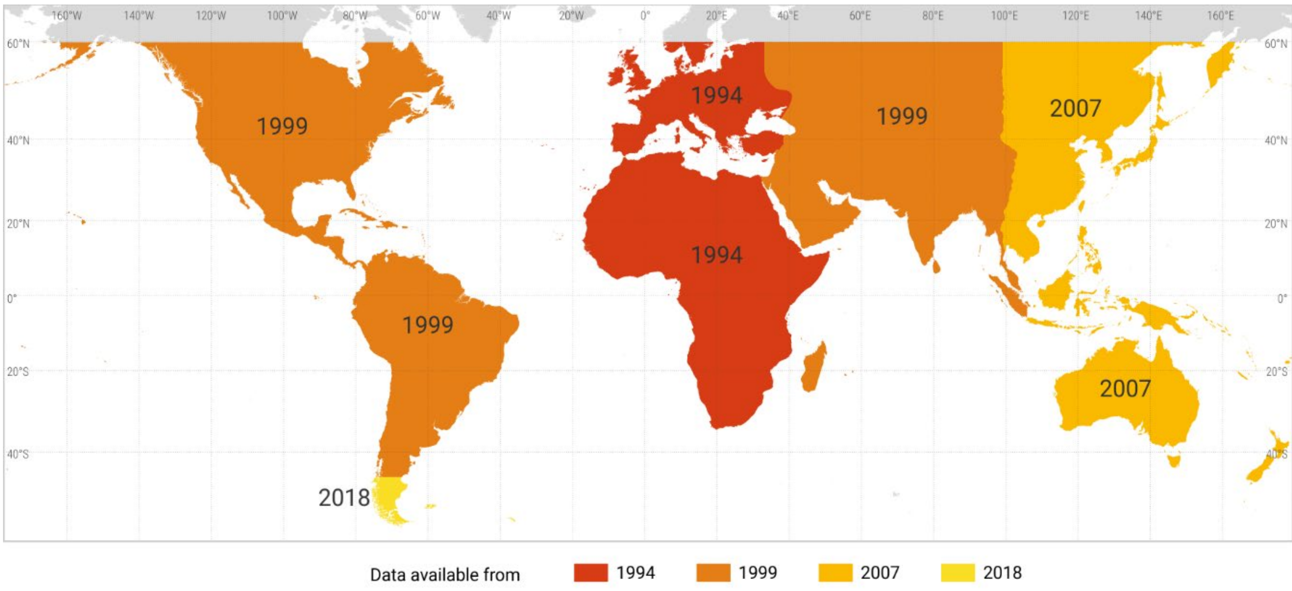
The Solargis algorithm uses the most up-to-date input data. As a result, the satellite data ensures more than 99% coverage for most regions. For time series data, the algorithm fills all gaps.

Figure 3.1. Solargis Algorithms



Source: Retrieved from Solargis Methodology Documentation, https://solargis.com/es/docs/methodology/solar-radiation-modeling.

Figure 3.2. Coverage of the Solargis Irradiation Data



Source: Developed by the authors based on Solargis data.

Tilt angle

The PV module's tilt angle strongly influences the PV system's electricity production. The tilt angle depends mainly on the distribution of solar radiation, latitude, geographical characteristics, and climatic conditions (Yadav and Chandel, 2013). Although the latitude angle is expected to be optimal (Babatunde, Abbasoglu, and Senol, 2018), dirt and shading may influence the choice of tilt angle. Furthermore, a larger tilt angle reduces dirt but increases self-shading (IFC, 2015; Mejia and Kleissl, 2013). To avoid self-shading, sufficient distance between module rows should be ensured (Saint-Drenan and Barbier, 2019). In this analysis, we compared 5 degrees above and below latitude, choosing the optimum tilt angle, the distance between rows, and coverage.

Azimuth angle

The azimuth angle of the PV modules strongly influences electricity production by PV systems. The ideal azimuth for PV systems installed in the northern hemisphere is south.

Albedo

The fraction of solar radiation is reflected off the ground or water surface and received by the PV module (IFC, 2015; Trapani, 2014). The albedo of a water body is estimated by characterising the water body by its colour, roughness, and solar height (Dvoracek and Hannabas, 1990).

Cooling effects

Solar PV is usually less efficient at generating electricity due to excessive heat. On the other hand, FSPV is introduced on the water surface and thus improves power generation efficiency due to the natural cooling effect provided by its proximity to water. Some studies have quantified the cooling effect of FSPV (Liu et al., 2018). One study found that compared to land-based solar PV, an efficiency improvement of more than 10% has been expected (Choi, Choi, and Lee, 2016; Ueda et al., 2012). As the Lao PDR is a region with high temperatures, introducing the free-standing format with a high cooling effect is considered. According to previous studies, this analysis adjusted the heat loss coefficient, which expresses the heat transfer between the solar module and the surroundings (Liu et al. 2018).

Mismatch losses

When the sunlight reaching the modules in a system is non-uniform, a mismatch occurs due to voltage and field order differences between the connected modules. Such losses are caused by shading parts of the system (Lappalainen and Valkealahti, 2017; Lorente et al., 2014). Nam Mang 3 is unlikely to be shaded in freshwater areas on land, so this effect will likely be small.

Soiling losses

The accumulation of soil (e.g. dust and bird droppings) on the surface of solar cells affects their irradiation absorption. Soil-covered cells become shaded and, in some cases, hot spots occur, rapidly accelerating the degradation of the module. This loss factor can exceed 15% in deserts but is exceptional in places where snow accumulates on the modules over a long period, usually less than 4% (IFC, 2015). Birds and other organisms are expected to be attracted to the FSPV system and the modules. The droppings they produce will affect the maintenance activities of the FSPV system and significantly reduce the energy production from the system (Liu et al., 2018). If the area is heavily populated with birds and other animals, conservatively estimating a more considerable soil loss is advisable.

Performance ratio

This indicates how effectively a PV plant produces energy (Moraitis et al., 2018; Reich et al., 2012). This measure quantifies the impact of losses due to temperature, reduced resistive efficiency, shading, and so on (Reich et al., 2012). As some of these factors are weather dependent, weather affects the performance ratio most significantly, affecting module temperature. This means that other parameters being equal, the performance ratio is lower in warmer regions, implying lower power generation.

2. Simulation Results

2.1. Generation Potential of FSPV

This sub-section presents the results of the simulations of the FSPV system on Nam Mang 3 hydropower plant employing Solargis's measured satellite-based solar irradiance data of the project site between 1 January 2019 and 31 December 2020.

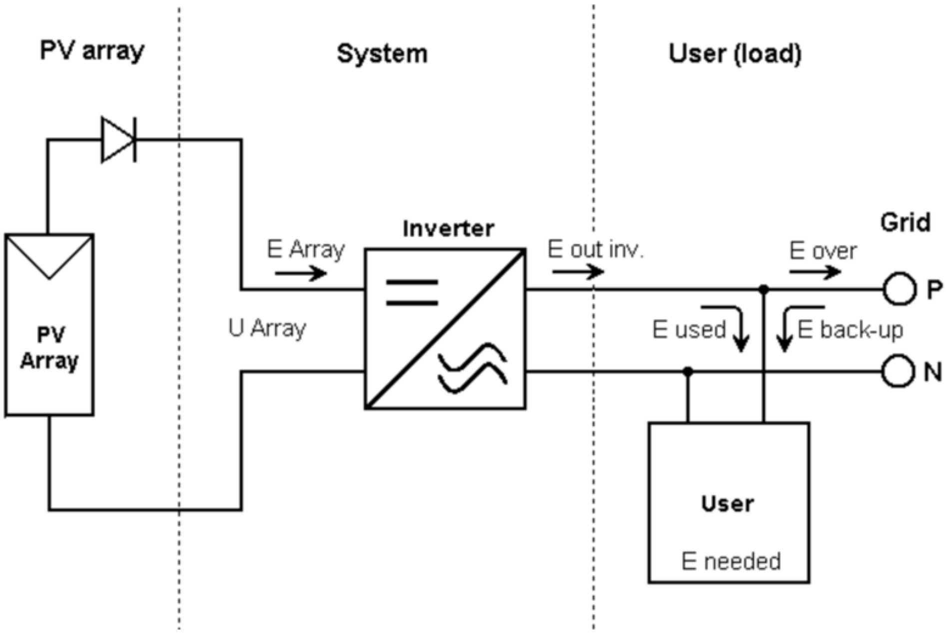
The 400 Watt peak (Wp) generic, mono-crystalline 72 cells module were chosen for this simulation. The description of the selected module is listed in Table 3.1, along with that of the 40-kilowatt alternating current (kWac) string inverter chosen for the simulation. Considering Nam Mang 3 hydropower plant's generation capacity of 40 MW power with an annual energy capacity of 137 GWh and that of the hydropower plant, the FSPV's generation capacity is 40 MW for the simulation. Figure 3.3 illustrates the system diagram of the FSPV system.

Table 3.1. Specifications of the PV Module and Inverter

Specifications	Parameters
PV Module	
Manufacture	Generic, Mono 400 Wp 72 cells
Technology used	Mono-crystalline
Rated power	400 Wp
Inverter	
Manufacture	Generic 40 kWac Inverter
Model	SE40K-EU-APAC/AUS

Source: Original PVsyst database (https://www.pvsyst.com/help/pvmodule_database.htm)

Figure 3.3. System Diagram of the FSPV System

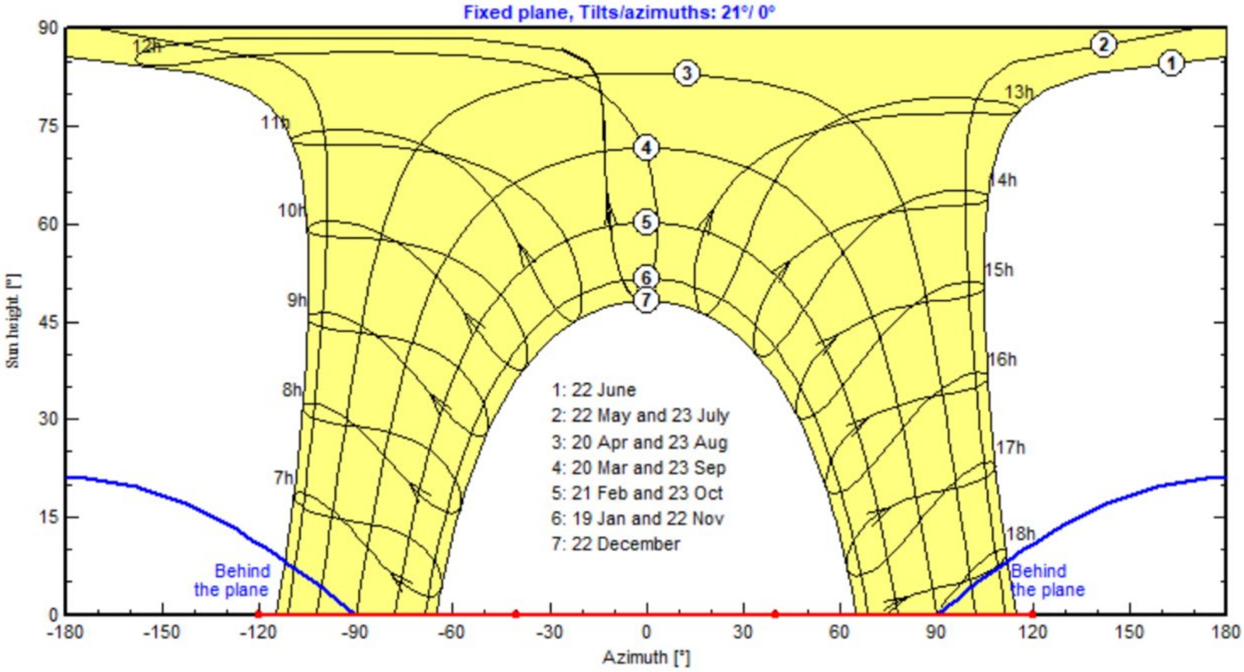


Source: Authors.

With the employed 400 Wp PV module and 40 kWac string inverter, 99,996 units and 962 units are required to develop the 40 MW FSPV system, making the size of the simulated FSPV system around 0.224 km^2. The simulated FSPV system (0.224 km^2) fits well in the upstream area even when the water level is low.

The tilt and azimuth angles must be adjusted correctly to achieve maximum efficiency. For maximum solar exposure, the panel must be positioned at an angle corresponding to the altitude of the site location. The panel is tilted at a 21-degree angle for the simulation. Solar data are some of the major inputs for an energy yield simulation. Analysis based on weather records, including temperature and humidity at the selected location, was carried out. Figure 3.4 illustrates the path of the sun over the simulated period.

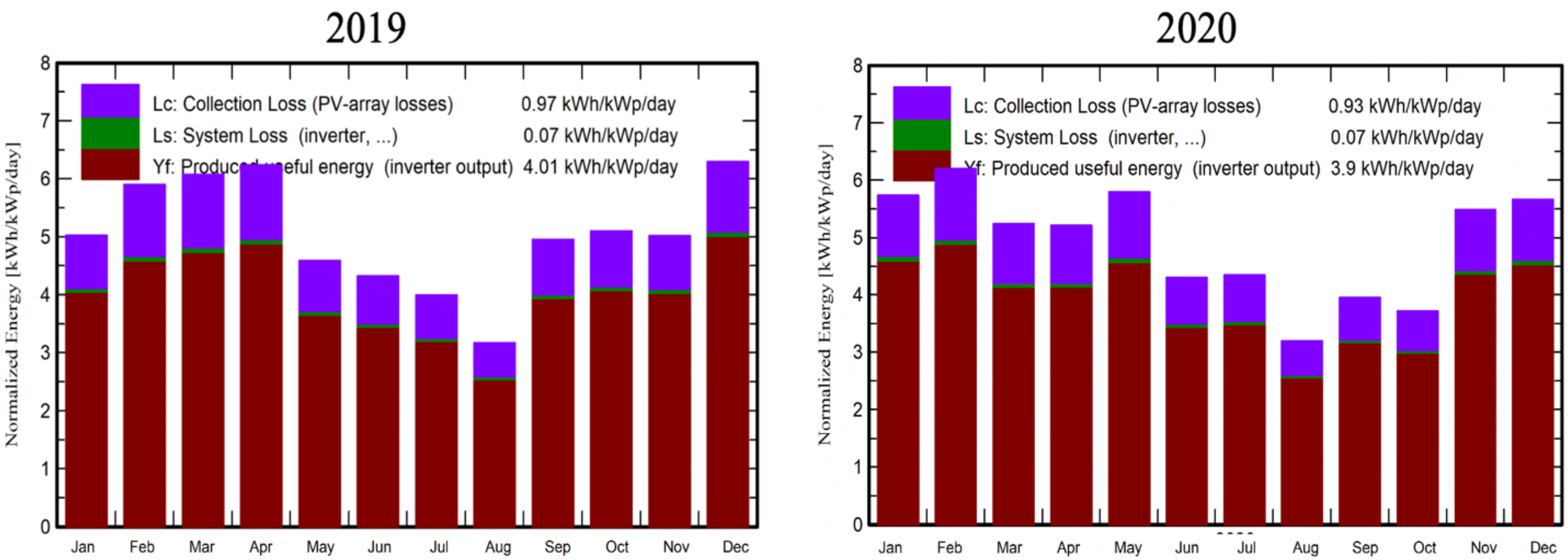
Figure 3.4. Path of the Sun over the Simulated Years



Source: Authors based on Solargis data.

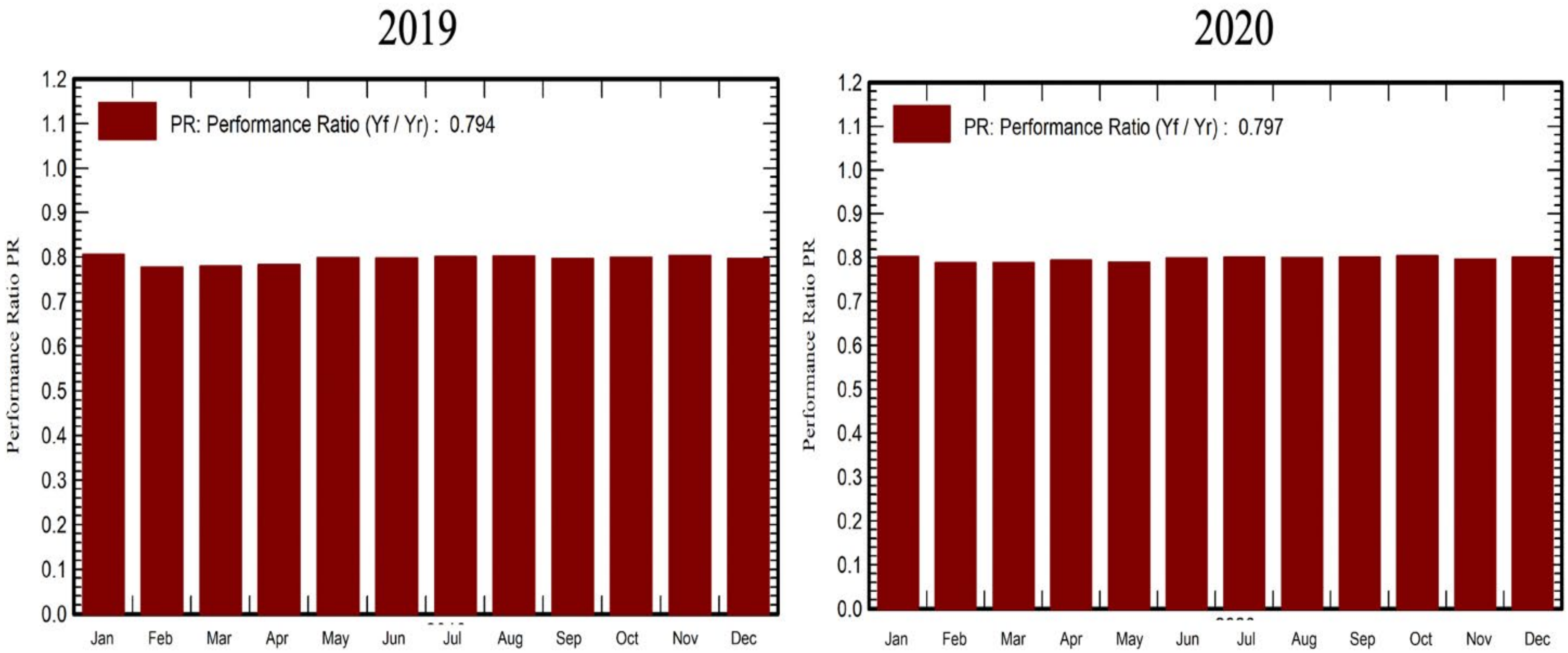
Figures 3.5 and 3.6 show the normalised energy and performance ratio for the simulated years 2019 and 2020. Figure 3.5 gives three important parameters: collection loss (0.97 kWh/kWp/day and 0.93 kWh/kWp/day), system loss (0.07 kWh/kWp/day in both years), and produced useful energy (4.01 kWh/kWp/day and 3.9 kWh/kWp/day). The simulation result shows that the FSPV system is working in good condition with a performance ratio of 79.6% on average during the simulated years (Figure 3.6).

Figure 3.5. Normalised Productions (per installed kWh/kWp/day) for 2019 and 2020



Source: Author's calculations.

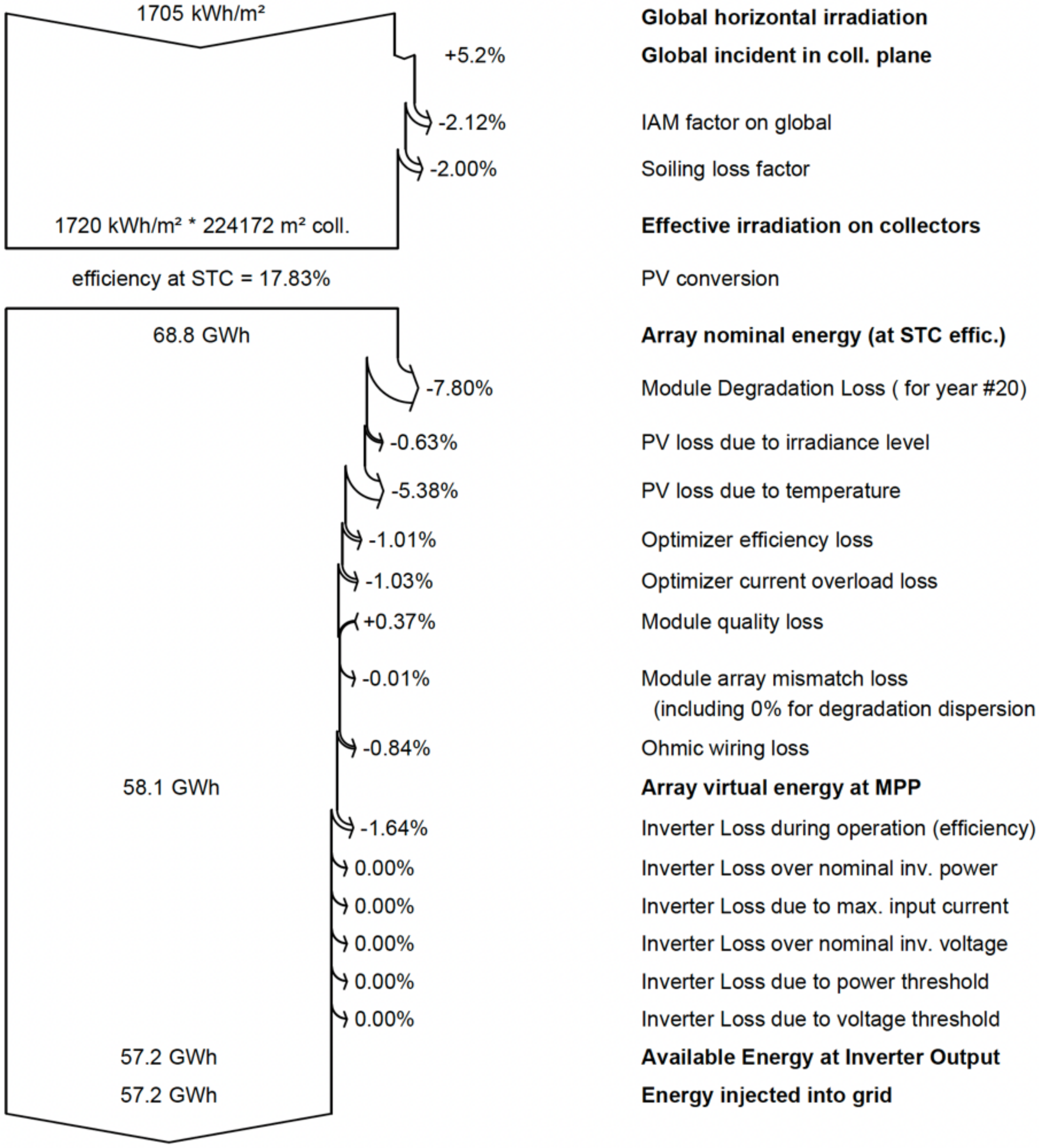
Figure 3.6. Performance Ratio for 2019 and 2020



Source: Author's calculations.

Figure 3.7 illustrates all the losses in the system step by step, with 1,705 kWh/m^2 falling in the project site to the FSPV system. Due to array incidence losses (IAM) and soiling losses, the total energy generated in this system is 66.8 GWh. Finally, energy loss – including light-induced degradation, mismatch loss, inverter loss during operation, and ohmic loss – makes the final energy injected into the grid at 57.2 GWh in the case of the 2020 simulation.

Figure 3.7. Loss Diagram (Based on 2020 Simulation)



Source: Developed by the authors.

Table 3.2 presents the overview of the solar irradiation data and generation results for 2019 and 2020. The table shows the FSPV system can produce 57.86 GWh on average (58.55 GWh in 2019 and 57.17 GWh in 2020). The result of electricity injected into the grid implies that the FSPV system produces considerably more electricity during the dry season (November to April) than the rainy season (May to October) at the project site. Based on the simulations, the FSPV system produces 5.43 GWh (monthly average) of electricity during the dry season. During the rainy season, the system produces less electricity, with a monthly average of 4.20 GWh.

Table 3.2. Overview of Solar Irradiation Data and Generation Results for 2019 (upper table) and 2020 (lower table)

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	GWh	GWh	ratio
January	130.0	63.02	21.63	155.8	149.8	5.106	5.023	0.806
February	144.0	62.53	23.95	165.3	159.2	5.227	5.143	0.778
March	177.9	92.11	25.94	188.2	181.2	5.973	5.876	0.780
April	190.5	91.34	28.19	187.2	179.8	5.959	5.863	0.783
May	151.9	91.27	26.60	142.2	135.8	4.614	4.537	0.798
June	143.3	79.68	26.82	129.7	123.3	4.205	4.136	0.797
July	134.1	83.95	26.16	123.8	117.9	4.039	3.971	0.802
August	102.9	73.18	25.27	98.3	93.7	3.213	3.157	0.803
September	144.8	77.44	26.03	148.7	142.4	4.813	4.735	0.796
October	142.7	74.88	25.68	158.2	151.6	5.140	5.057	0.799
November	126.0	59.36	23.12	150.6	144.7	4.919	4.838	0.803
December	152.9	49.27	20.01	195.2	188.3	6.315	6.213	0.796
Year	1741.1	898.03	24.95	1843.2	1767.7	59.522	58.548	0.794

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	GWh	GWh	ratio
January	145.2	62.12	21.81	177.9	171.3	5.805	5.712	0.803
February	157.9	72.82	22.57	179.9	173.2	5.767	5.674	0.788
March	156.1	90.18	25.28	162.6	156.2	5.216	5.131	0.789
April	159.8	92.47	26.22	156.4	149.9	5.052	4.969	0.794
May	193.5	83.42	28.23	179.7	172.3	5.771	5.677	0.790
June	142.8	77.32	26.24	129.1	122.9	4.199	4.129	0.799
July	146.1	83.37	26.37	134.8	128.7	4.395	4.322	0.802
August	102.9	70.92	25.35	99.1	94.5	3.228	3.172	0.800
September	117.3	76.45	26.02	118.5	113.2	3.863	3.799	0.802
October	108.1	71.42	24.35	115.2	110.4	3.772	3.708	0.805
November	136.0	55.01	23.73	164.5	158.4	5.330	5.243	0.797
December	139.5	51.49	20.23	175.7	169.3	5.723	5.630	0.801
Year	1705.1	886.98	24.70	1793.5	1720.3	58.120	57.166	0.797

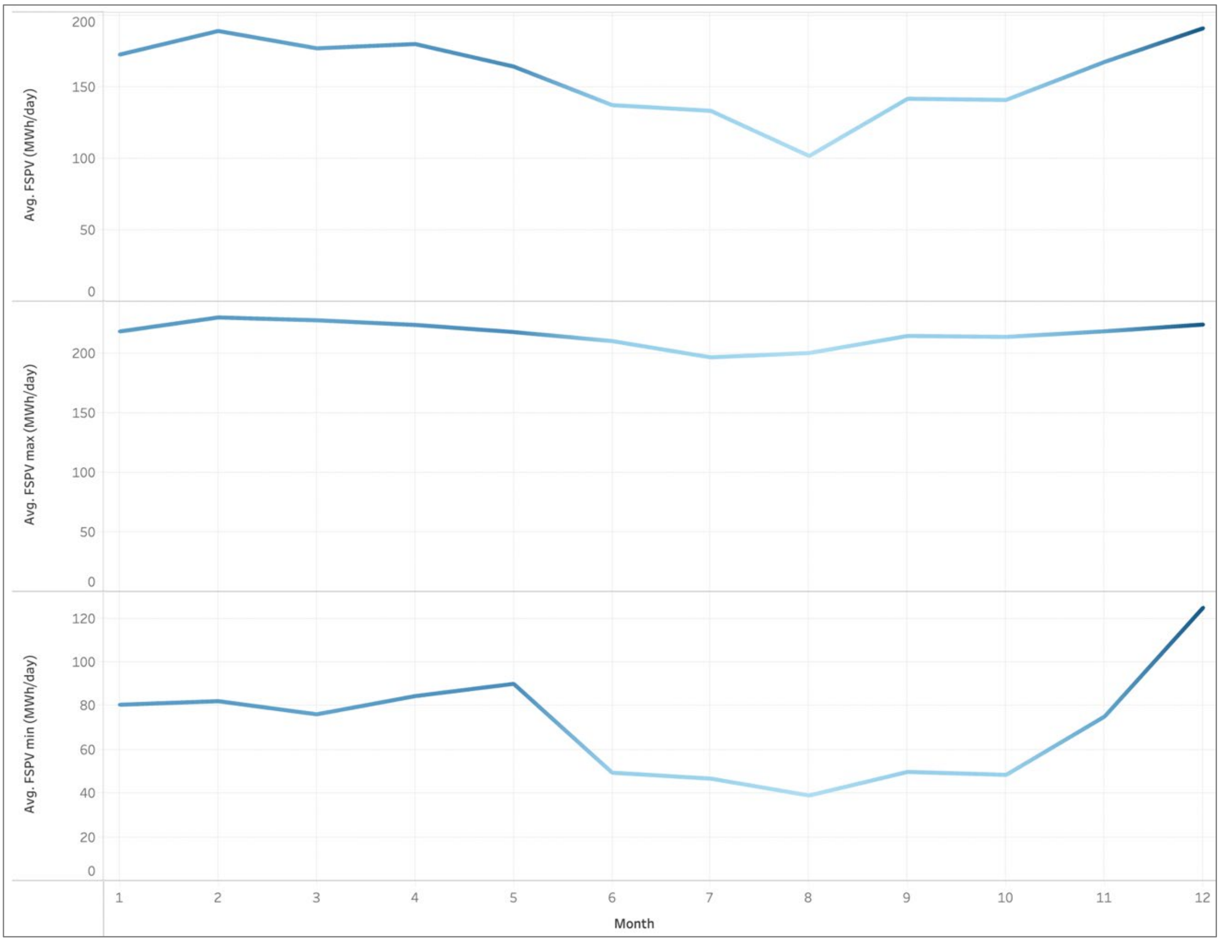
Legend

GlobHor Global Horizontal Irradiation
DiffHor Horizontal Diffuse Irradiation
T_Amb Ambient Temperature
GlobInc Global Incident in Coll. Plane
GlobEff Effective Global Corr. For IAM and Shadings
Earray Effective Energy at the Output of the Array
E_Grid Energy Injected into Grid
PR Performance Ratio

Source: Author's calculations.

Figure 3.8 shows the daily average electricity production of the FSPV system from January to December based on the average electricity production in the simulated years (2019 and 2020). Table 3.3 describes the daily average electricity production results in detail. The figure and table show that the FSPV system produces more electricity during the dry season. The daily average production in each month ranges between 102 megawatt-hour per day (MWh)/day and 200 MWh/day. The maximum and minimum daily average production is 232 MWh/day and 30 MWh/day.

Figure 3.8. Daily Average Electricity Production of FSPV (2019 and 2020 average)



Source: Author's calculations.

Table 3.3. Daily Average, Maximum, and Minimum Electricity Production of FSPV in 2019 and 2020

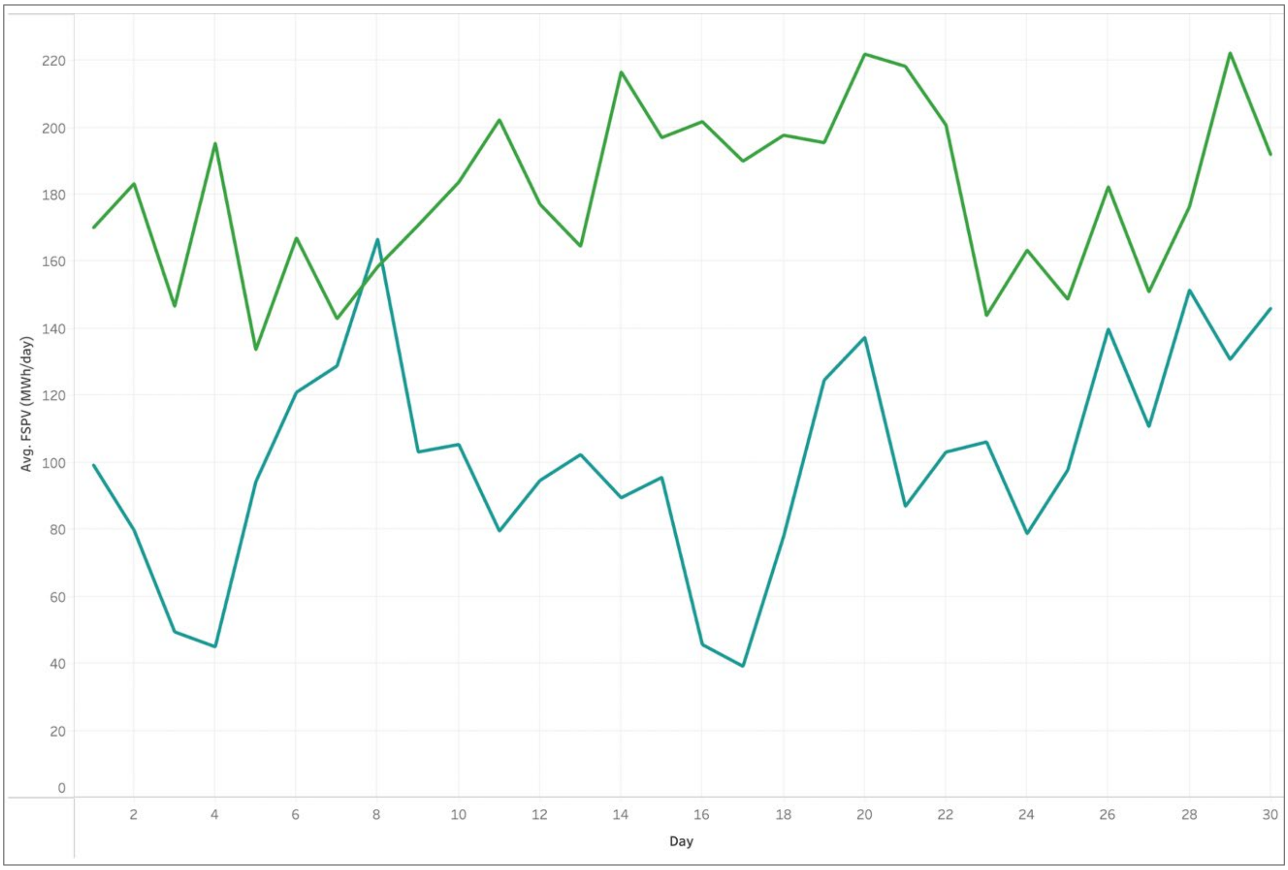
Year	Month	FSPV_average (MWh/day)	FSPV_max (MWh/day)	FSPV_min (MWh/day)
2019	1	162	218	37
2019	2	184	232	51
2019	3	190	225	107
2019	4	195	226	89
2019	5	146	222	65
2019	6	138	215	69
2019	7	128	198	35
2019	8	102	189	47
2019	9	158	229	52
2019	10	163	220	54
2019	11	161	219	74
2019	12	200	225	148
2020	1	184	220	124
2020	2	196	230	114
2020	3	166	231	46
2020	4	166	223	80
2020	5	183	215	115
2020	6	138	206	30
2020	7	139	196	58
2020	8	102	213	31
2020	9	127	201	48
2020	10	120	209	43
2020	11	175	219	76
2020	12	183	224	102

Source: Author's calculations.

To take a closer look at the differences in daily average electricity production of FSPV in dry and rainy seasons, Figure 3.9 presents the daily average production in April and August based on the results of simulated years (2019 and 2020). The figure shows that the FSPV system produces significantly more electricity in April than in August, with only a day in August yielding higher electricity generation.

Figure 3.10 shows the hourly average electricity production of FSPV in April and August. In both months, the peak comes around noon, with 24 MWh/hour in April and 14.5 MWh/hour in August on average. Although the maximum electricity production is mostly the same in both months, the minimum electricity generation has a slightly different pattern during the dry and rainy seasons, represented by the results of April and August.

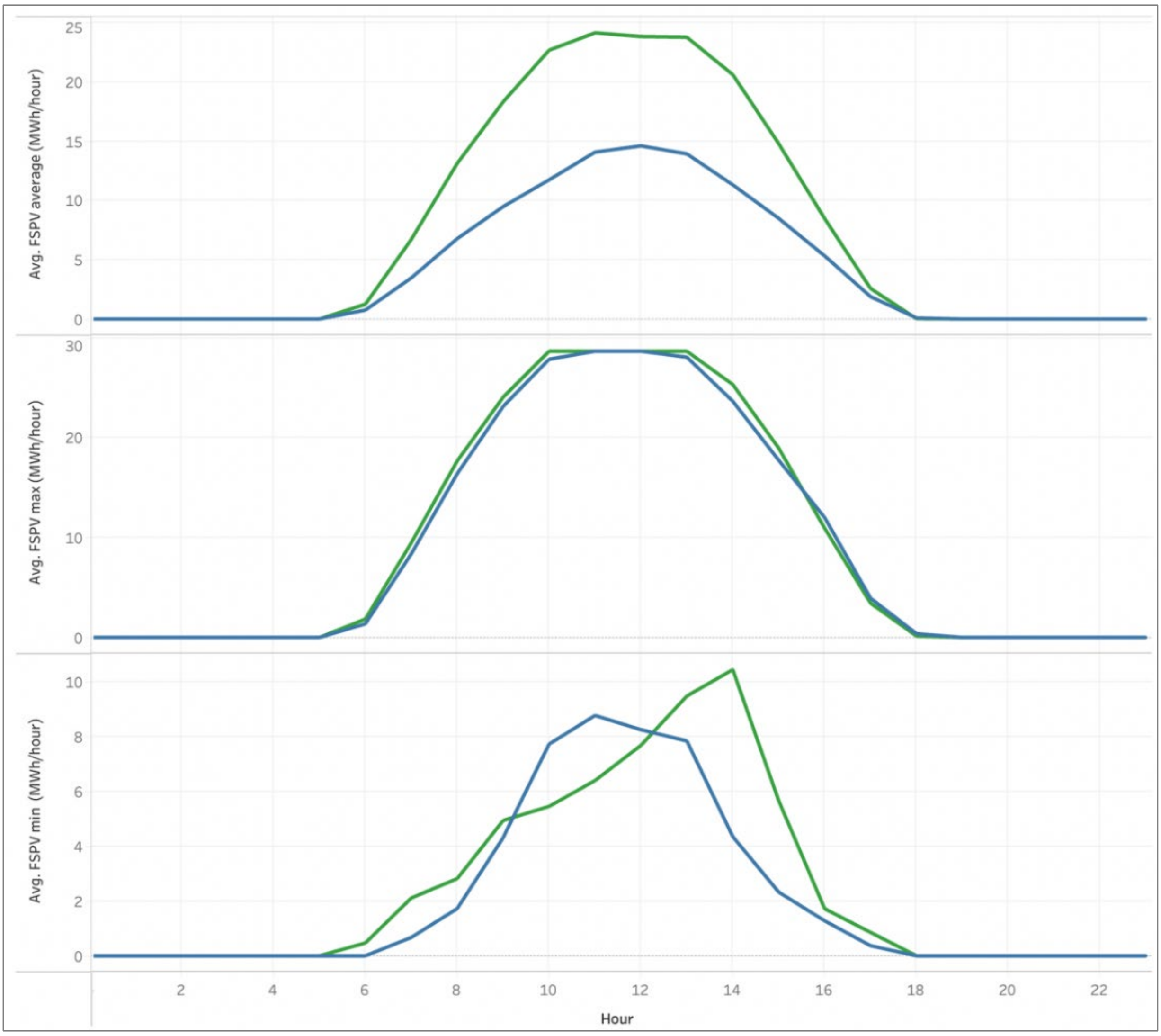
Figure 3.9. Daily Average Electricity Production of FSPV in April (green line) and August (blue line) (2019 and 2020 average)



Source: Author’s calculations.

Note: 31 August is excluded from the figure for comparison purposes.

Figure 3.10. Hourly Average Electricity Production of FSPV in April (green line) and August (blue line) (2019 and 2020 average)



Source: Author’s calculations.

2.2. Complementarity with Hydropower Plant

Based on the simulation results of the FSPV system and the ex-post generation data of the Nam Mang 3 hydropower plant for 2019 and 2020, this sub-section examines how the generation of the 40-MW FSPV system complements that of the hydropower plant, which significantly differs among different seasons.

Table 3.4 presents the overview of the electricity generation by the FSPV, the hydropower plant, and the hybrid system composed of the FSPV and the hydropower plant by showing the daily average, maximum, and minimum generation amount of each system.

Table 3.4. Daily Average, Maximum, and Minimum Electricity Production of FSPV, Hydropower Plant (Hydro), and Hybrid System in 2019 and 2020

Year	Month	FSPV_average (MWh/day)	Hydro_average (MWh/day)	Hybrid_average (MWh/day)	FSPV_max (MWh/day)	Hydro_max (MWh/day)	Hybrid_max (MWh/day)	FSPV_min (MWh/day)	Hydro_min (MWh/day)	Hybrid_min (MWh/day)
2019	1	162	467	629	218	513	729	37	164	310
2019	2	184	445	628	232	494	724	51	0	204
2019	3	190	486	676	225	523	741	107	329	529
2019	4	195	422	617	226	493	716	89	0	164
2019	5	146	134	280	222	289	509	65	0	113
2019	6	138	526	663	215	960	1095	69	0	122
2019	7	128	368	496	198	960	1112	35	0	96
2019	8	102	633	735	189	970	1099	47	0	47
2019	9	158	545	703	229	973	1163	52	0	195
2019	10	163	157	320	220	329	467	54	0	102
2019	11	161	124	285	219	330	540	74	0	84
2019	12	200	199	399	225	390	608	148	21	226
2020	1	184	146	330	220	328	507	124	0	173
2020	2	196	143	339	230	304	529	114	0	114
2020	3	166	226	391	231	587	740	46	0	191
2020	4	166	523	688	223	937	1115	80	287	450
2020	5	183	244	427	215	411	584	115	0	115
2020	6	138	750	888	206	961	1168	30	0	64
2020	7	139	928	1068	196	972	1164	58	493	672
2020	8	102	955	1057	213	985	1188	31	687	778
2020	9	127	951	1078	201	985	1186	48	596	695
2020	10	120	898	1018	209	983	1173	43	492	536
2020	11	175	218	392	219	492	660	76	0	128
2020	12	183	45	228	224	287	510	102	0	102

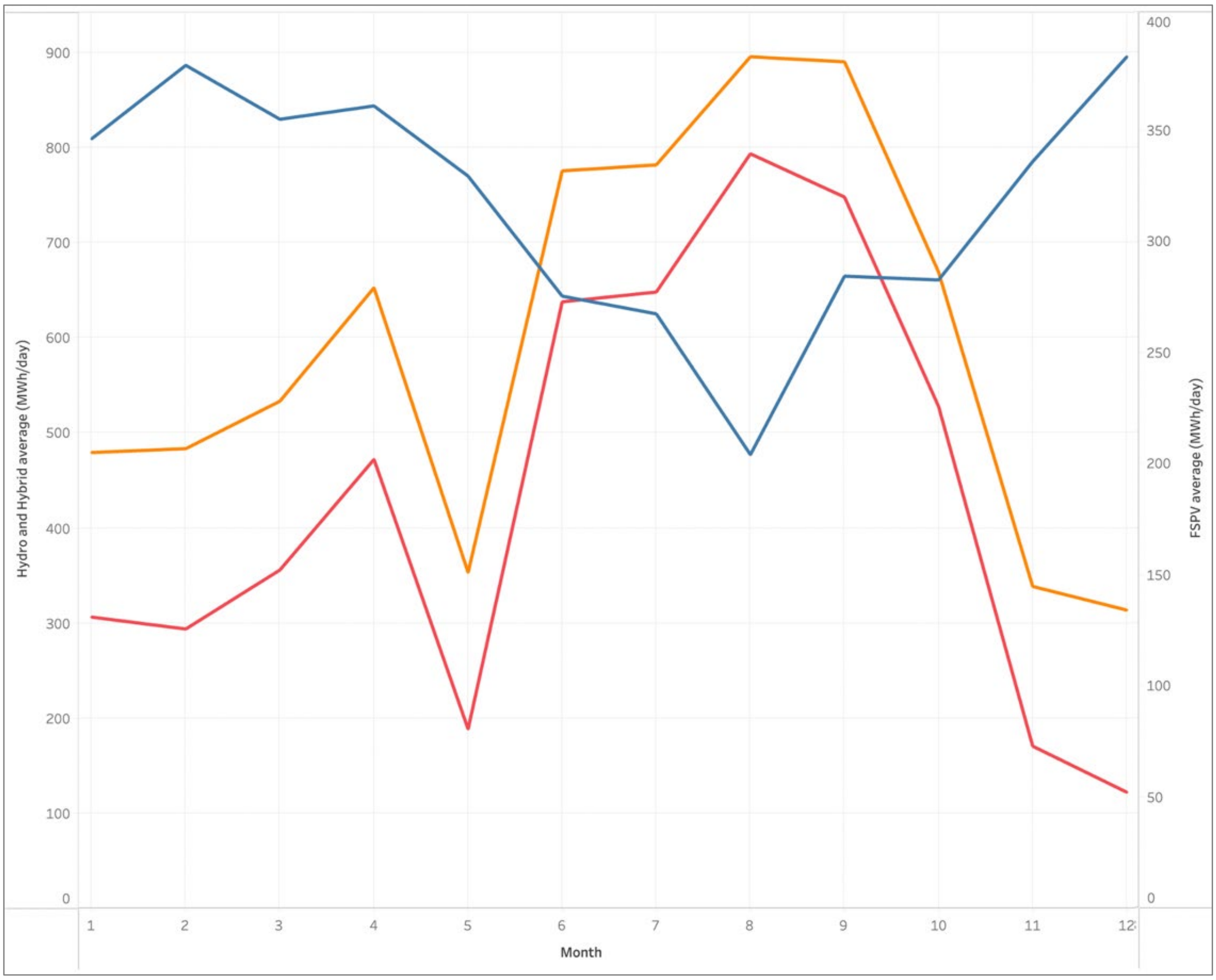
Source: Author’s calculations.

Based on the simulation results and the ex-post generation data in 2019 and 2020, Figure 3.11 depicts the daily average electricity production of FSPV, hydropower plant, and hybrid system from January to December. The figure shows that FSPV generates more electricity during the months the generation by hydropower plant is relatively low, while when hydropower generates higher electricity (during the rainy season), FSPV generates relatively less electricity. The figure illustrates how FSPV can effectively complement hydropower plants and increase the hybrid system's generation amount while making the generation less volatile. Using the hourly generation data and monthly generation data of the FSPV, hydropower plant, and the hybrid system in 2019 and 2020, the hourly and monthly volatility of the generation is calculated following the equation below to confirm the reduction of volatility:

$$\text{Volatility} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (1)$$

where n is the number of data, x_i is the generation data, and $\bar{x}$ is the average of data. Table 3.5 presents the results and shows that while hourly volatility increases when installing the FSPV system at the hydropower plant (from 15.63 to 18.12), monthly volatility decreases from 9,116.84 to 8532.56.

Figure 3.11. Daily Average Electricity Production of FSPV (blue line), Hydro (red line), and Hybrid (orange line) (2019 and 2020 average)



Source: Author's calculations.

Table 3.5. Hourly and Monthly Volatility of FSPV System, Hydropower Plant, and Hybrid System

	FSPV	Hydro	Hybrid
Volatility (Hourly)	9.33	15.63	18.12
Volatility (Monthly)	849.40	9,116.84	8,532.56

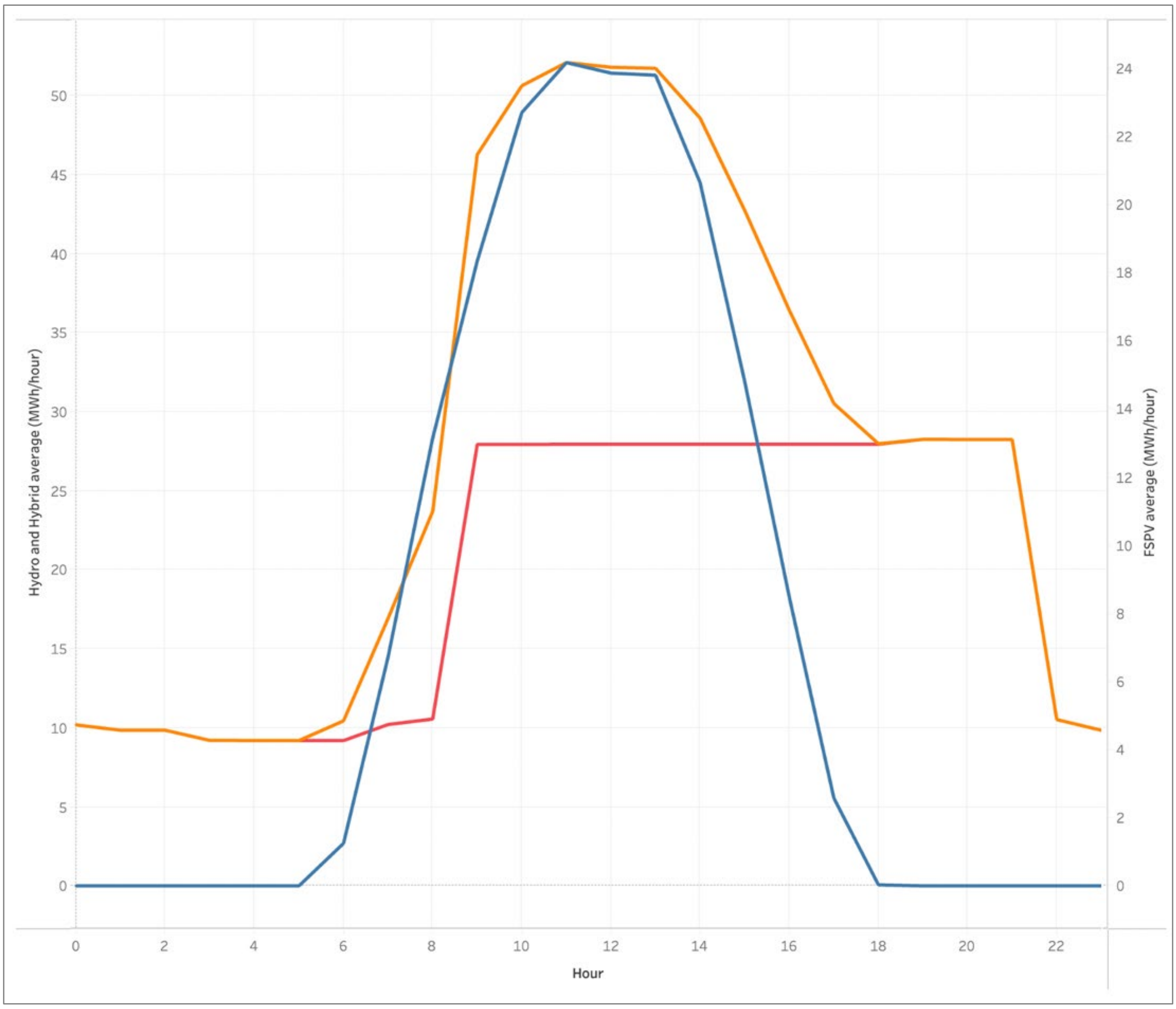
Source: Author's calculations.

Finally, to take a closer look at the hourly average generation amount and differences in the pattern between the dry and rainy seasons, Figures 3.12 and 3.13 depict the hourly average electricity generation of the FSPV system, the hydropower plant, and the hybrid system using the simulation results of the FSPV system and the ex-post data of the hydropower plant in 2019 and 2020.

The figures show that hydropower generates less electricity during the dry season (represented by April), ranging from around 10 MWh/day to 27 MWh/day, compared to the rainy season (represented by August), which generates more than 30 MWh/day constantly. However, the FSPV system complements the change in hydropower generation due to the opposite generation pattern during the dry and rainy seasons, making the peak generation of the hybrid system around the same in April and August.

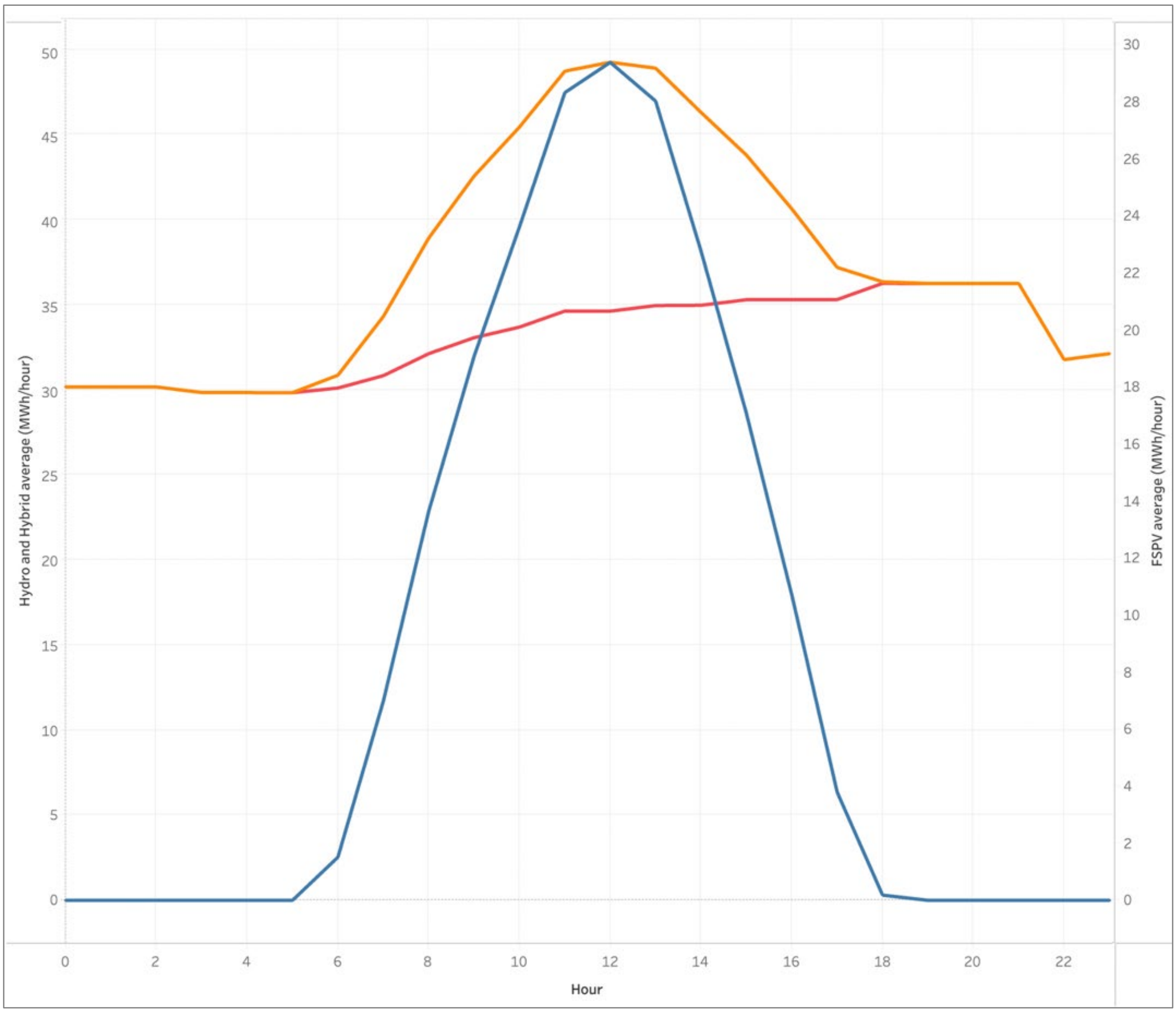
The simulation results and ex-post data show that the hybrid system composed of FSPV and hydropower can effectively increase electricity production while lowering the long-term volatility. Although the short-term volatility increases with the introduction of FSPV if no measure is taken, operating the hydropower plant coordinately with the generation pattern of FSPV, the short-term volatility can be significantly reduced, contributing to a more stable electricity supply.

Figure 3.12. Hourly Average Electricity Production of FSPV (blue line), Hydro (red line), and Hybrid (orange line) in April (2019 and 2020 average)



Source: Author's calculations.

Figure 3.13. Hourly Average Electricity Production of FSPV (blue line), Hydro (red line), and Hybrid (orange line) in August (2019 and 2020 average)



Source: Author’s calculations.

Chapter 4

Analysis of Appropriate FSPV Capacity with Hydropower Plant

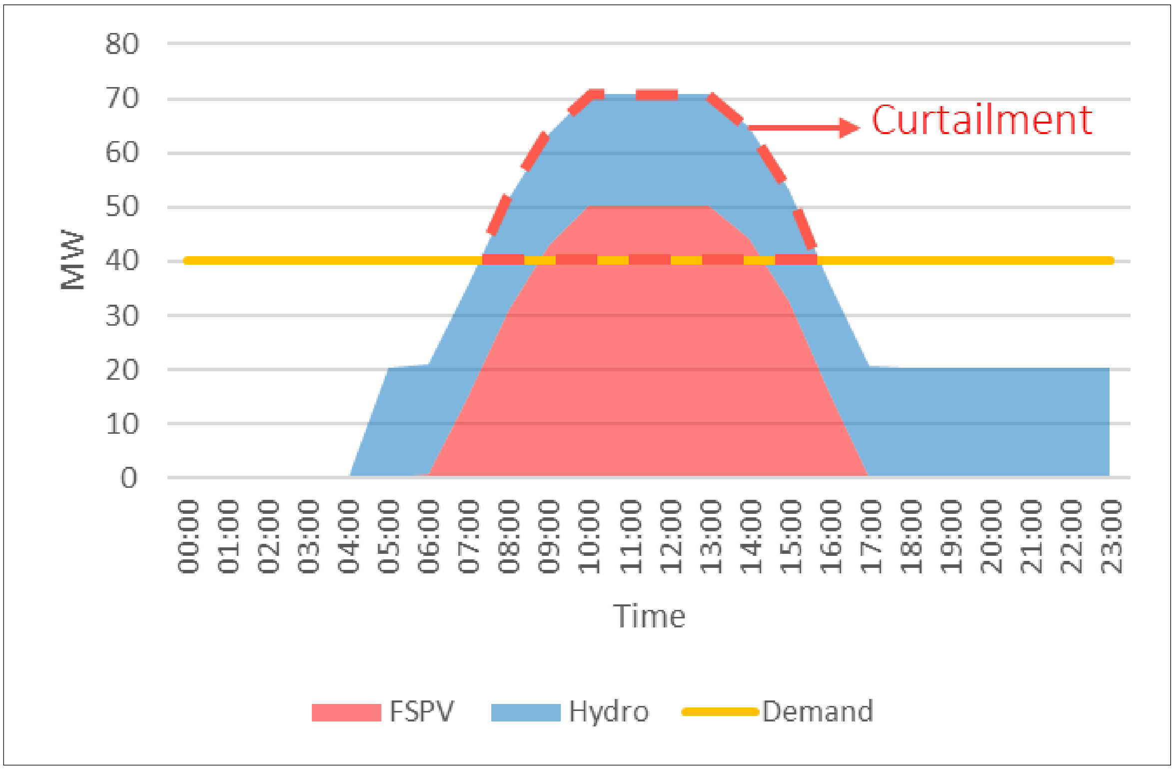
1. Method

This chapter shows the appropriate FSPV capacity for cost and volatility when combined with a hydropower plant. Specifically, when the FSPV capacity is varied, the hybrid system output is evaluated using the following indicators.

1) Output curtailment

Figure 4.1 shows an example of the first indicator, output curtailment. In a power grid system, supply and demand must always match. The difference cannot flow to the grid if power output exceeds the demand or transmission line capacity. In other words, even if power is generated, it will be wasted. Therefore, the amount of curtailment should be low. To reduce curtailment, it is necessary to properly determine the capacity of FSPVs to match demand and transmission line capacity and to adjust the output of hydropower generation to consider the output characteristics of FSPVs.

Figure 4.1. Example of Output Curtailment



MW = megawatts.
Source: Authors.

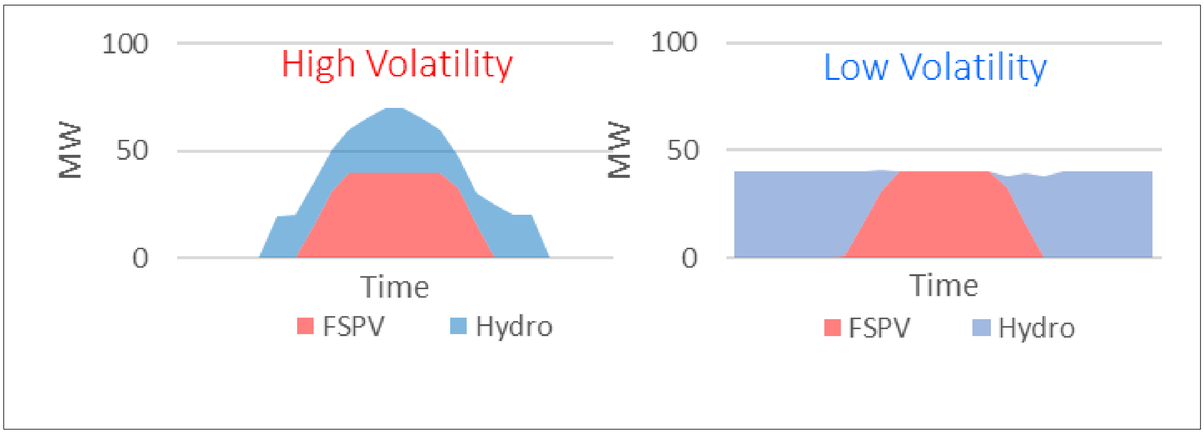
2) Volatility

A stable output is desirable for grid operation when power plants are used as baseload power sources. Since the output of RE sources such as solar and wind power depends on climatic conditions, the daily and hourly outputs fluctuate. It is difficult to adjust the output by itself unless combined with storage batteries. However, a hybrid system combined with a hydropower plant, which is the focus of this project, is expected to reduce the fluctuation of its output and approach a stable power source by adjusting the hydropower plant's output to the RE output. As a measure of a power plant's output fluctuation, volatility is calculated by the following formula.

$$\text{Volatility} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (1)$$

where n is the number of data, x_i is the hourly hybrid generation data, and $\bar{x}$ is the average of data. Figure 4.2 shows the image of volatility. High volatility means the output of a hybrid system is not stable. As the capacity of FSPV increases, its output increases, but volatility also increases. Therefore, it is necessary to determine the appropriate FSPV capacity by balancing it with the capacity of a hydropower plant.

Figure 4.2. Image of Volatility



MW = megawatts.
Source: Authors.

2. Conditions

Table 4.1 shows the study conditions of the generation and demand. As in chapter 3, Nam Mang 3 reservoir is the simulation site. The rated output of the hydropower plant is 40 MW and its hourly generation data is based on actual data received from MEM from 1 January 2019 to 29 December 2020. FSPV generation capacity is changed from 40 MW to 100 MW in 10 MW steps. Hourly generation data of FSPV is based on the result of chapter 3. Hourly FSPV generation data for each capacity is prepared by calculating FSPV generation per MW from the results in chapter 3. Since estimating the demand for a power plant connected to grids is difficult, in this study, the demand curve for a day in 2019–2020 when hydropower plant output is at its maximum is applied to the demand of the hybrid system.

As a result, the demand for the hybrid system is assumed to be constant at 40 MW. Incidentally, according to the Lao PDR, the transmission line capacity from the Nam Mang 3 reservoir to the nearest substation is approximately 100 MW, so no restrictions due to transmission line capacity are considered. Regarding the control method of the hydropower plant output, two patterns – independent control and coordinated control – are assumed in this study. Figure 4.3 shows an image of the two control methods. Independent control means the hydropower output is not adjusted to match the FSPV output. Therefore, if hydropower output is also large during the daytime when the FSPV output is high, supply may exceed demand, resulting in curtailment and increased volatility.

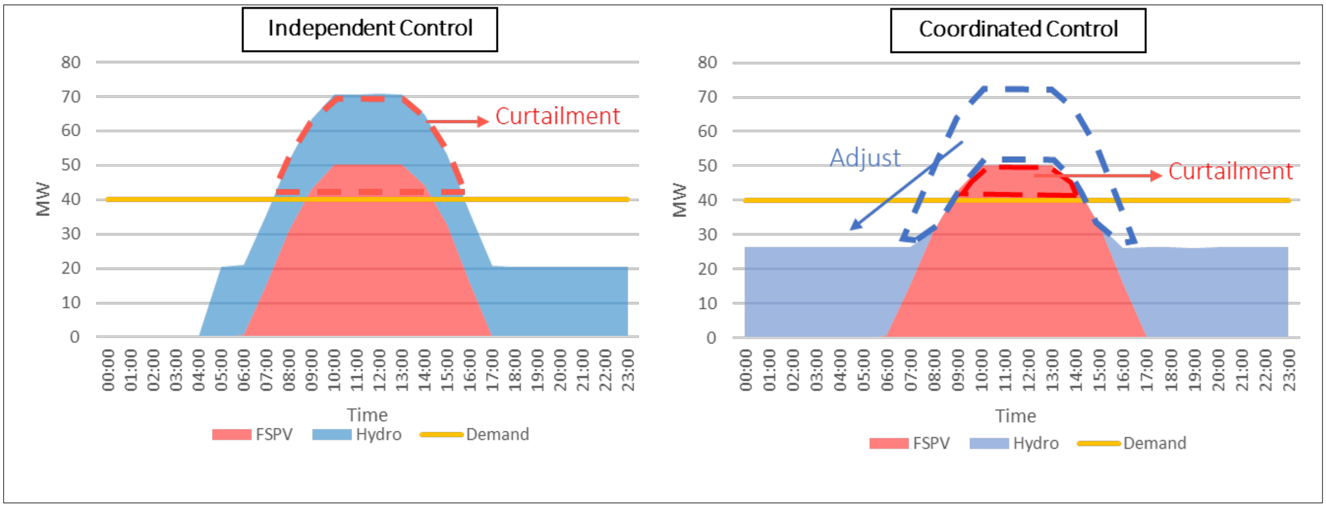
On the other hand, in the case of coordinated control, hydropower plant output is adjusted considering the FSPV output. Therefore, reduced curtailment and lower volatility can be expected compared to independent control. In this study, during coordinated control, the output allocation of hydropower generation is implemented to minimise volatility while the daily curtailment is reduced. The daily hydropower generation (kWh) is based on actual data. When the output of the hydropower plant is adjusted considering the FSPV output, any surplus can be carried over to the subsequent days. The amount of this carryover is assumed to be unlimited. (In other words, assume that the amount of water in the reservoir is not limited.)

Table 4.1. Study Conditions for the Generation and the Demand

Simulation Site		**Nam Mang 3 Reservoir**
Simulation Period		**1/1/2019～12/29/2020**
Generation Capacity	Hydro	40 MW
	FSPV	40, 50, 60, 70, 80, 90, 100 MW
Demand		40 MW
Control Method for Hydro		Independent Control
		Coordinated Control

MW = megawatts.
Source: Authors.

Figure 4.3. Image of Independent and Coordinated Controls



MW = megawatts.
Source: Authors.

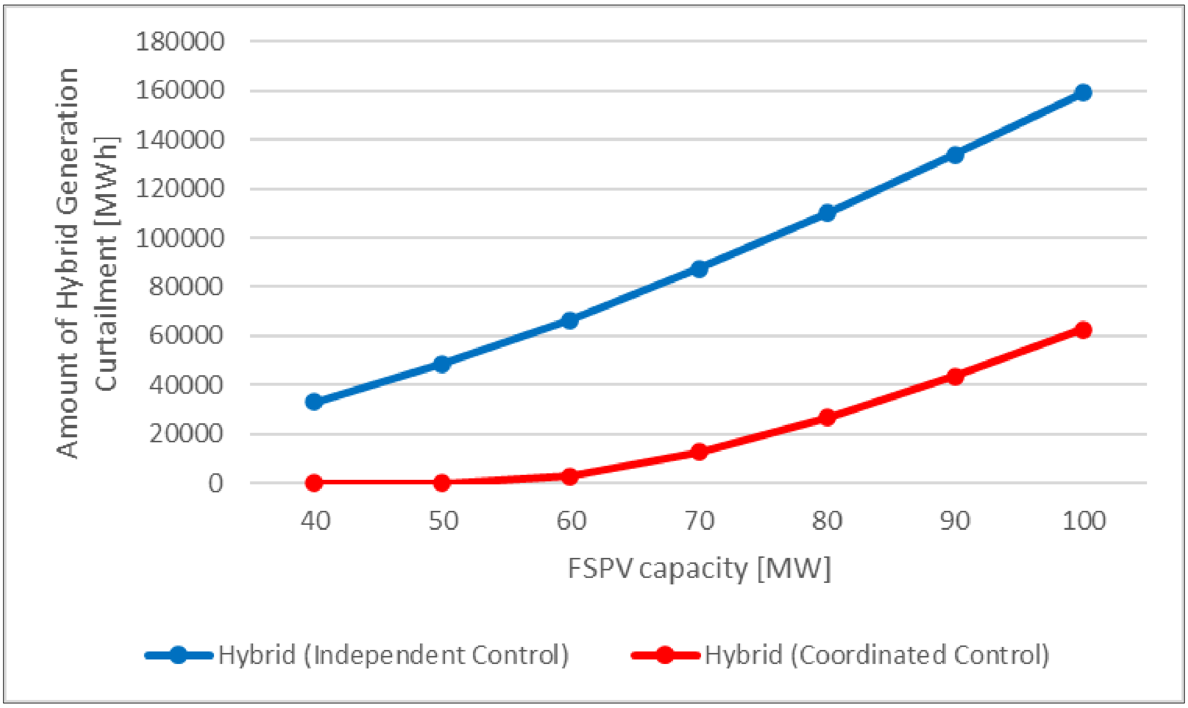
3. Results

Figure 4.4 shows the relationship between the capacity of the FSPV and the total curtailment of hybrid generation during the verification period. In the independent control, the curtailment amount increases as the capacity of the FSPV increases. On the other hand, in coordinated control, the curtailment amount is reduced by shifting the excess hydro output to another time. However, when the FSPV capacity exceeds 60 MW, FSPV output becomes too large relative to demand, resulting in curtailment. Therefore, an FSPV capacity of 40–60 MW would be appropriate.

Figure 4.5 shows the relationship between FSPV capacity and average volatility per day. The blue line shows the volatility of hybrid power generation with independent control of the hydropower plant. The red line shows the volatility of hybrid power generation with coordinated control of the hydropower plant. And the yellow line is the volatility of hydropower only without FSPV based on actual data. Since there is no standard for how low the volatility must be for a power supply to be stable, the yellow line is considered the standard for this study. In the independent control, introducing FSPV will increase volatility compared to only hydropower. This is because when hydropower and FSPV generate power simultaneously during the day, the output increases rapidly relative to the night-time when FSPV does not generate power.

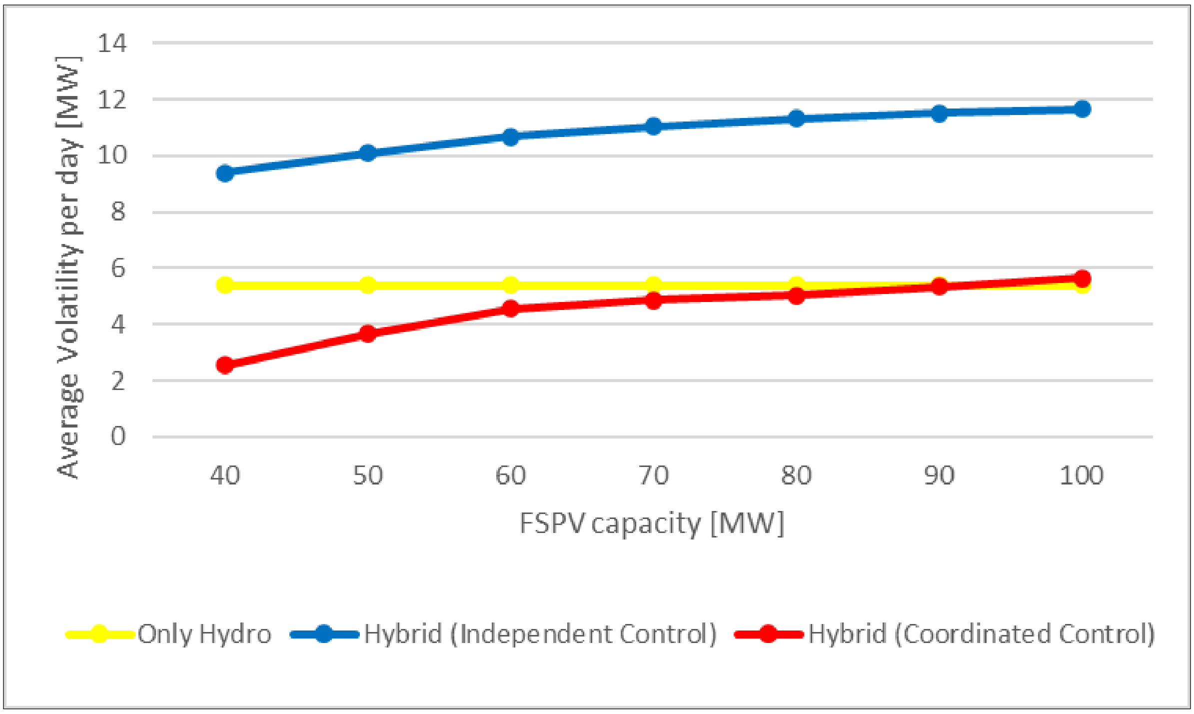
On the other hand, volatility can be greatly reduced by adjusting hydropower output. The result suggests that coordinated control of hydropower generation is preferable when introducing FSPV. As well as the result of the curtailment amount, an FSPV capacity of 40–60 MW would be appropriate since its volatility is especially low.

Figure 4.4. Amount of Hybrid Generation Curtailment



MWh = megawatt-hour, MW = megawatts.
Source: Author's calculations.

Figure 4.5. Average Volatility per Day



MW = megawatts.
Source: Author's calculations.

This study examines the appropriate FSPV capacity in Nam Mang 3 reservoir regarding hybrid generation curtailment and volatility. It concludes that an FSPV of 40–60 MW should be installed in conjunction with coordinated control. However, since it is physically possible to install more than 60 MW FSPV in the Nam Mang 3 reservoir, if a larger FSPV is recommended to be installed, it should be combined with hydrogen production equipment and storage batteries or with increased hydropower plant capacity. These will use surplus power effectively and strengthen the adjustment capabilities of the system. Although the verification is conducted for the Nam Mang 3 reservoir in this study, the results cannot apply to all upcoming hybrid systems between FSPVs and hydropower plants. The appropriate capacity will depend on the scale of the hydropower plant and demand and should be considered for each situation. In addition, if multiple PV systems, including FSPV, are to be connected to the same grid in the future, it will be necessary to verify the feasibility of the connection through a detailed grid analysis.

4. Reference Study

For reference, we also describe the case where the demand condition is changed from the abovementioned study. In the future, demand is expected to grow along with economic growth. Therefore, this reference study assumes a demand of 100 MW, which is the capacity of the transmission line connected to Nam Mang 3. Table 4.2 shows the conditions of this reference study. Conditions other than demand remain the same as in Table 4.1.

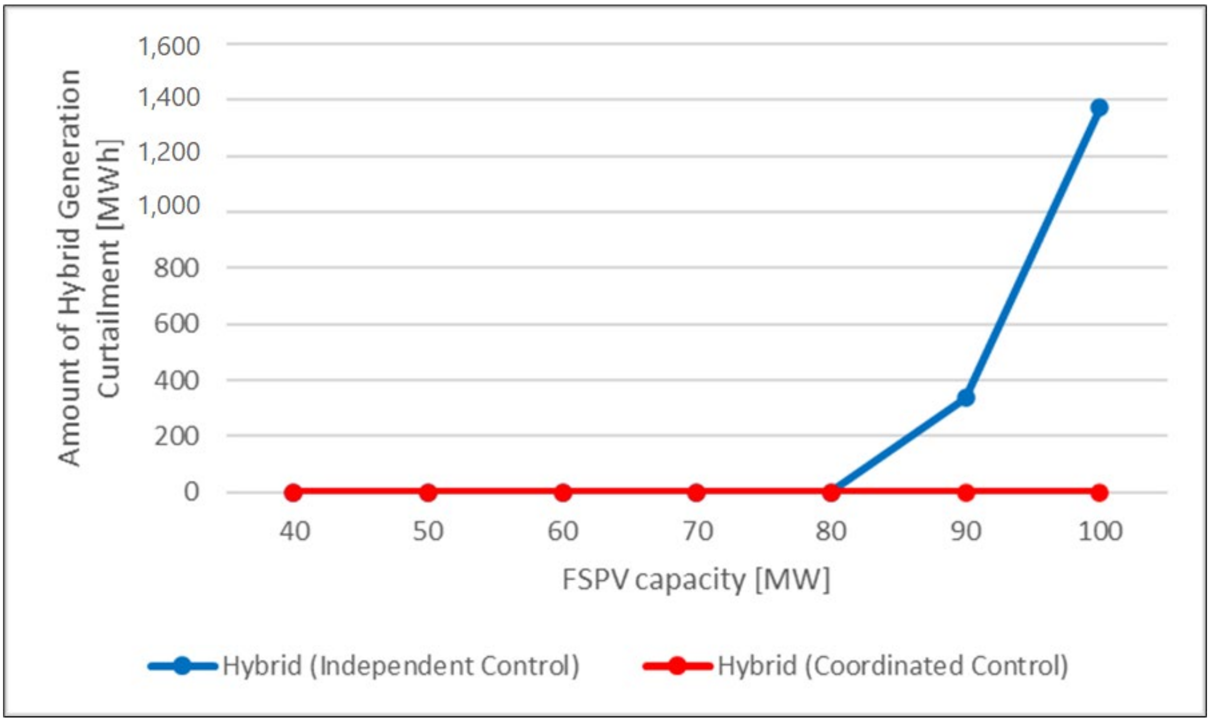
Table 4.2. Conditions of the Reference Study

Simulation Site		**Nam Mang 3 Reservoir**
Simulation Period		**1/1/2019～12/29/2020**
Generation Capacity	Hydro	40 MW
	FSPV	40, 50, 60, 70, 80, 90, 100 MW
Demand		100 MW
Control Method for Hydro		Independent Control
		Coordinated Control

MW = megawatts.
Source: Authors.

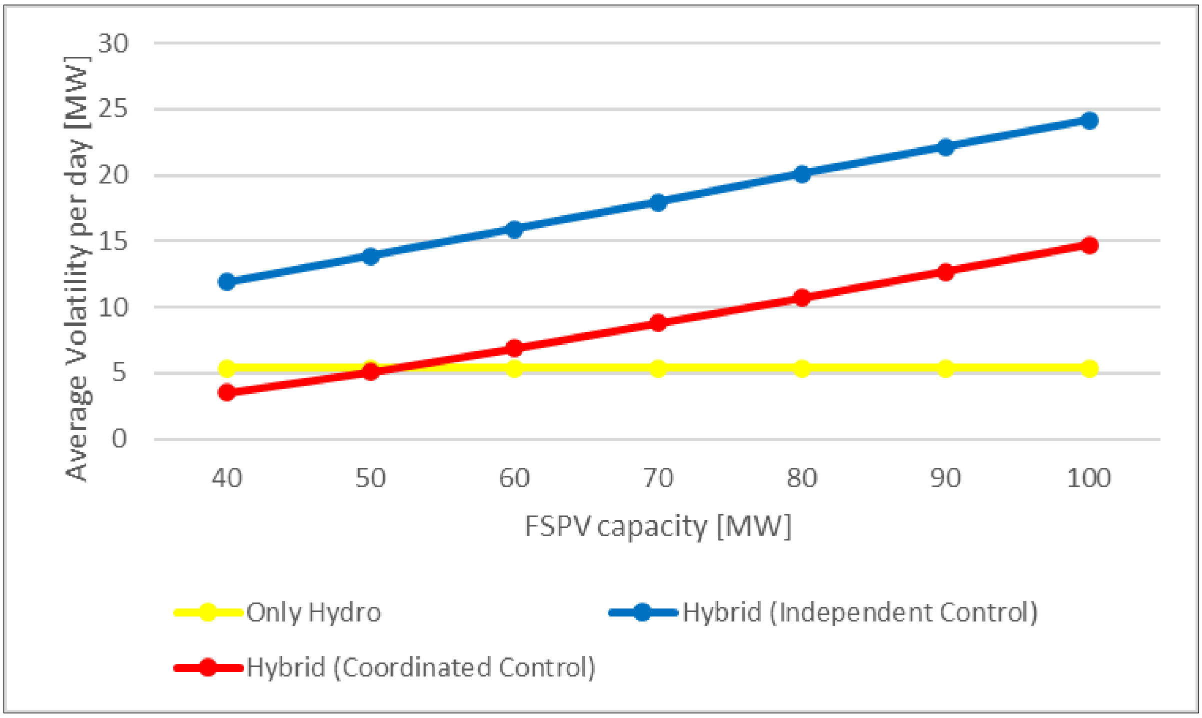
Figure 4.6 shows the relationship between the FSPV capacity and the total curtailment of hybrid generation during the verification period. Figure 4.7 shows the relationship between the capacity of the FSPV and the average daily volatility. The growth in demand has increased the amount of electricity that can flow into the grid. As a result, no curtailment occurs even if the FSPV capacity is 80 MW. However, volatility increases as the capacity of the FSPV is increased. Although a certain volatility reduction effect can be achieved through coordinated control of hydropower generation, if the FSPV capacity is too large relative to the hydropower capacity (e.g. FSPV: 100 MW, hydropower: 40 MW), the output of the FSPV fluctuates too much, and volatility remains high due to the poor adjustment capability of hydropower. Therefore, when introducing a larger FSPV in the future, it is necessary to improve the control ability of hybrid generation by introducing storage batteries or increasing hydropower capacity.

Figure 4.6. Amount of Hybrid Generation Curtailment (For Reference)



MWh = megawatt hour, MW = megawatts.
Source: Author's calculations.

Figure 4.7. Average Daily Volatility (For Reference)



MW = megawatts.
Source: Author's calculations.

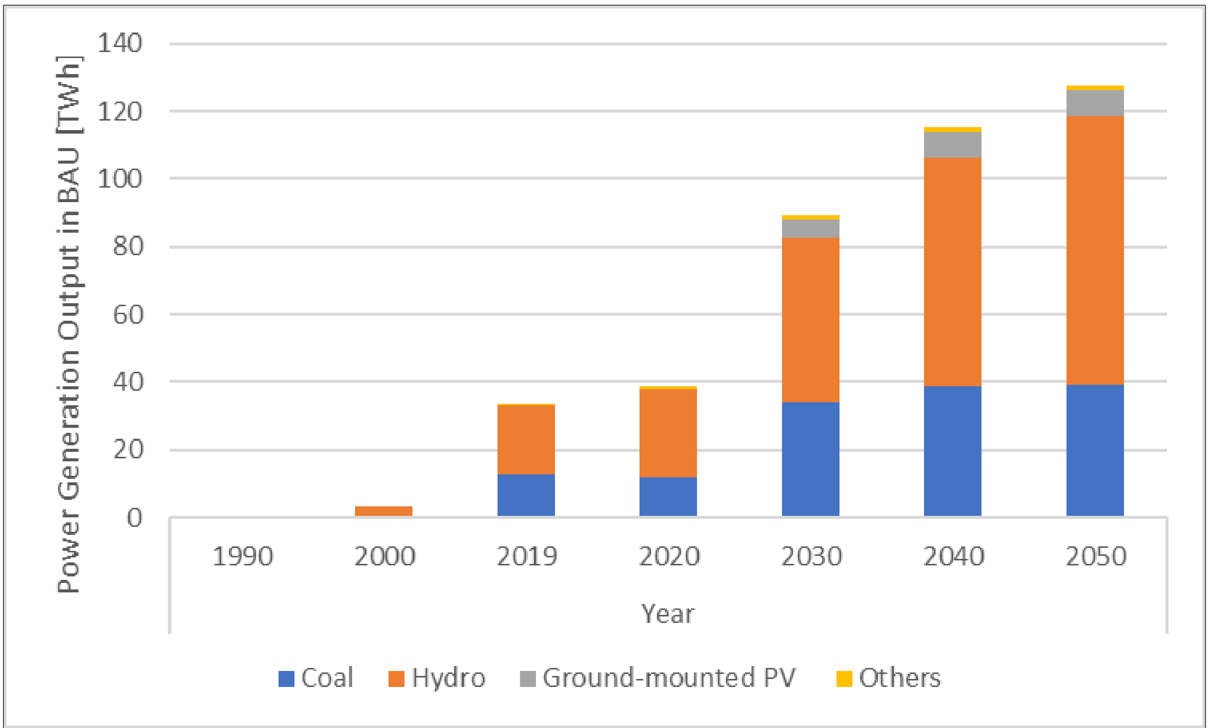
Chapter 5

Impact on Energy Composition and CO_2 Emissions

Figure 5.1 shows the projected power generation output in the business-as-usual scenario (BAU) for the Lao PDR, as prepared by ERIA. BAU is developed based on the assumptions that the Lao PDR's demand for energy will continue to increase per historical trend and future growth in gross domestic product, population, and oil price in the conventional energy efficiency and conservation policies and RE promotion.

Based on BAU, if 40 MW of FSPV were installed in the Nam Mang 3 reservoir, FSPV would account for about 0.06 terawatt-hours (TWh), or 0.06%, of the total power output of 89.16 TWh in the country in 2030. In addition, when the FSPV power output is compared to the power output of coal power plants, it is equivalent to about 0.17%.

Figure 5.1. Power Generation Output of BAU



TWh = terawatt hours.
Source: Author's calculations.

The major sources of CO_2 emissions from fuel combustion in the Lao PDR are solid fossil fuel (coal) and liquid fossil fuel (oil). In 2030, CO_2 emissions from coal and oil are expected to be 11.80 million tonnes of carbon (Mc-t) and 1.20 Mc-t, respectively. Assuming that 40 MW of FSPVs is used to supply a part of the electricity generated by a coal-fired power plant, installing an FSPV can reduce about 0.5% of the total CO_2 emissions of the Lao PDR. Since there are several hydropower plants in the Lao PDR other than the Nam Mang 3 hydropower plant targeted in this study, CO_2 emissions could be further reduced by installing FSPVs in the reservoirs of these hydropower plants in the future. Currently, the Lao PDR exports more than 70% of its electricity to neighbouring countries, including coal power, through the Hongsa Coal Power Plant. This trend will continue until 2030, and coal power plants will be an important option for exporting electricity to Cambodia, Thailand, and Viet Nam. However, if the Lao PDR would shift from coal power plants to solar PV systems, including the floating type, it could minimise coal power generation for internal and export uses. Thus, the power sector could achieve net-zero emissions if a hybrid system combining hydropower and FSPV will deliver electricity stably during wet and dry seasons by applying large-scale battery storage and smart-grid system. However, it needs to pay attention to multilateral interconnection during an emergency. In addition, if the transport sector, especially the road sector, shifts from internal combustion engines to electric vehicles, the Lao PDR can minimise the import of petroleum products, such as gasoline and diesel oil, and significantly reduce CO_2 emissions by vehicles. The country will be fully electrified using RE, which is hydropower, solar PV, and wind power. Thus, RE, such as solar PV and FSPV, will surely contribute to securing an appropriate energy mix and achieving a carbon-neutral society by 2050.

Chapter 6

Economic Feasibility Analysis

This chapter analyses the economic feasibility of the FSPV business using the following assumptions.

1. Assumptions for the Economic Feasibility Analysis

1.1. Type of Business

An independent power producer (IPP) facilitates the FSPV system on the surface of the Nam Mang 3 dam and sells electricity generated by the FSPV system to the EDL through an existing transmission line between the Nam Mang 3 hydropower station and the nearest national grid. The EDL purchases the electricity unconditionally.

1.2. Capacity of the FSPV System and its Capital Cost

The IPP installs a 40 MW FSPV system. Referring to existing publications, we assume $730/kWp for the unit capital cost of the FSPV system. Then the necessary investment is estimated at $29.2 million. The investment comprises a module (solar panel), inverter, mounting system, balance of system, basic design, and construction. In addition, this system covers 0.224 km^2 of the dam's surface.

1.3. Operation Cost

The operation cost comprises regular solar panel cleaning and maintenance of the whole FSPV system. Then we assume 2% of the capital cost mentioned at 2) for the annual operation cost, which is $0.584 million annually. If we assume $1,000 for the employee's average monthly salary, the IPP can hire 48 employees to maintain the FSPV system at 40 MW.

1.4. Depreciation

Since we assume that the FSPV system is usable for 20 years, we select 20 years for the depreciation period with a straight-line method (same amount per year during the depreciation period). We also assume zero salvage value, accounting for $1.46 million in years 1–20 as capital cost depreciation.

1.5. Financing

The IPP finances the capital costs: shared capital ratio at 30% (internal money) and borrowed money ratio at 70% (external money). Then, we assume the following conditions of external money:

- Repayment method: straight-line (same repayment amount during the repayment period)
- Repayment period: 10 years
- interest rate: 5% annually

1.6. Electricity Generation by FSPV System and its Selling Price

We assume 16.5% for the capacity factor of the FSPV system. Thus, the annual power generation amount is estimated as 57.816 GWh. We also assume the selling price of electricity to the EDL is 5 cents. Then the IPP's annual revenue is estimated at $2.89 million.

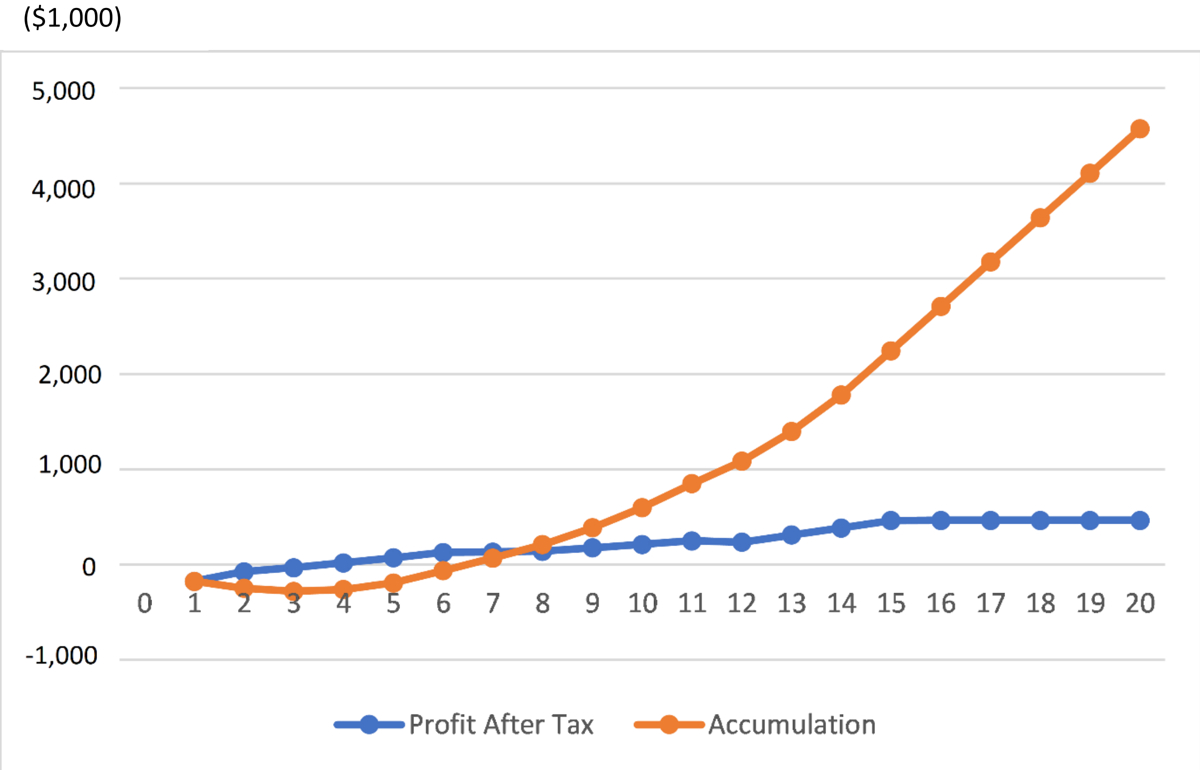
1.7. Income Tax Rate

We assume 45% for the income tax ratio. When the IPP makes a profit, the IPP pays 45% x profit before tax to the Lao PDR's tax office as income tax.

2. Financial Analysis

Table 6.1 shows an income statement of the IPP entity. Its profit after tax reflects a deficit in the first 3 years, but registers a surplus from the 4th year. Its accumulation becomes a surplus from the 7th year. Consequently, the IPP's profit-loss situation looks good. Income tax on the 4th to 6th years is zero even though profit before tax is positive. The profit is negative because it can be carried over the next 5 years due to the usual taxation. (Refer to Figure 6.1.)

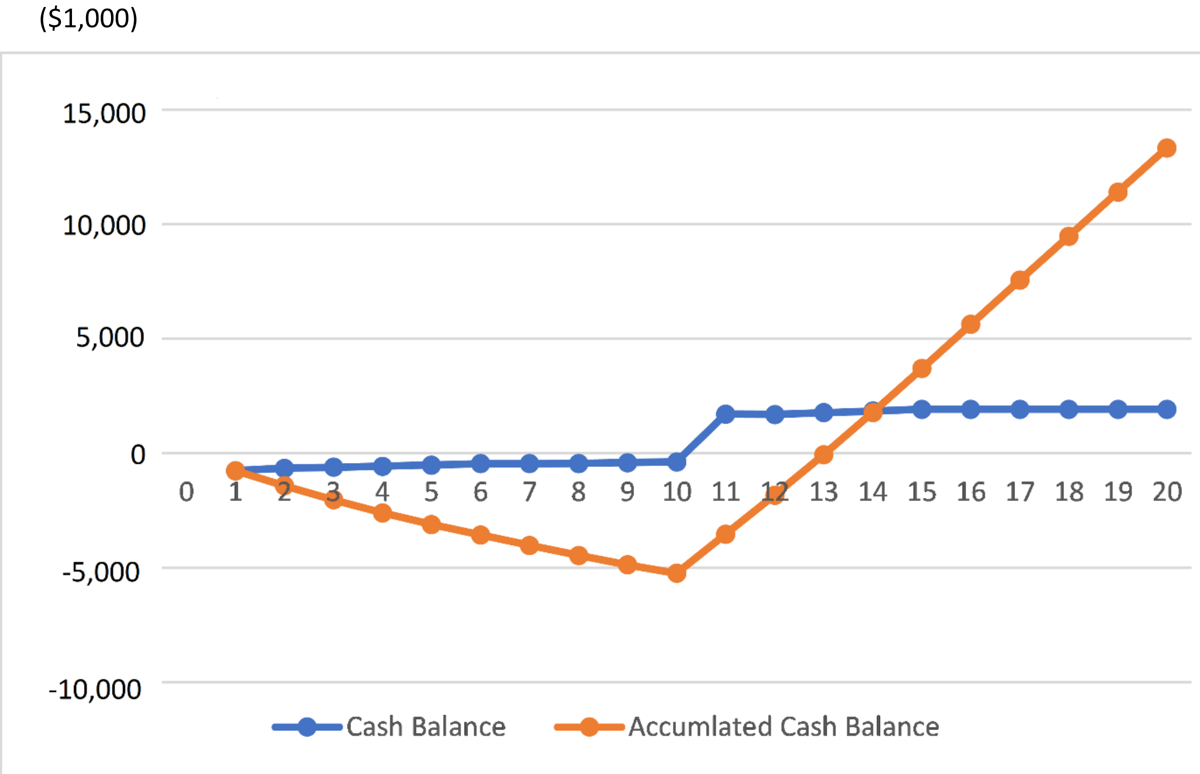
Figure 6.1. Transition of Profit after Tax



Source: Author.

Table 6.2 shows the cash flow statement of the IPP.Due to a large repayment amount in the first 10 years, the cash balance becomes positive just after the 11th year. An accumulated cash balance changes positively from the 14th year. The maximum cash shortage is $5.5 million in the 10th year. However, $13.2 million of cash remains in the IPP by the 20th year. (Refer to Figure 6.2.)

Figure 6.2. Cash Balance



Source: Author.

Table 6.1. Income Statement (Unit: $1,000)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Revenue		2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8	2890.8
Operating cost		584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584
Depreciation		1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460
Interest (long)		1022	919.8	817.6	715.4	613.2	511	408.8	306.6	204.4	102.2										
Interest (short)			60.736	118.1549	171.9913	221.9586	267.7473	309.023	337.1517	374.9376	409.8892	441.8819	307.2655	166.726	20.00277	0	0	0	0	0	0
Profit Before Tax		-175.2	-133.736	-88.9549	-40.5913	11.64143	68.05274	128.977	203.0483	267.4624	334.7108	404.9181	539.5345	680.074	826.7972	846.8	846.8	846.8	846.8	846.8	846.8
Income Tax								-103.415	91.37174	120.3581	150.6199	182.2131	242.7905	306.0333	372.0588	381.06	381.06	381.06	381.06	381.06	381.06
Profit After Tax		-175.2	-133.736	-88.9549	-40.5913	11.64143	68.05274	232.3919	111.6766	147.1043	184.0909	222.7049	296.744	374.0407	454.7385	465.74	465.74	465.74	465.74	465.74	465.74
Accumulation		-175.2	-308.936	-397.891	-438.482	-426.841	-358.788	-126.396	-14.7195	132.3849	316.4758	539.1807	835.9247	1209.965	1664.704	2130.444	2596.184	3061.924	3527.664	3993.404	4459.144

Source: Author.

Table 6.2. Cash Flow Statement (Unit: $1,000)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cash in-flow																					
Shared capital	8760																				
Borrowed money (long)	20440																				
Borrowed money (short)		759.2	1476.936	2149.891	2774.482	3346.841	3862.788	4214.396	4686.719	5123.615	5523.524	3840.819	2084.075	250.0346							
Depreciation		1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460
Profit after tax		-175.2	-133.736	-88.9549	-40.5913	11.64143	68.05274	232.3919	111.6766	147.1043	184.0909	222.7049	296.744	374.0407	454.7385	465.74	465.74	465.74	465.74	465.74	465.74
Total Cash in-flow	29200	2044	2803.2	3520.936	4193.891	4818.482	5390.841	5906.788	6258.396	6730.719	7167.615	5523.524	3840.819	2084.075	1914.738	1925.74	1925.74	1925.74	1925.74	1925.74	1925.74
Cash out-flow																					
Capital cost	29200																				
Repayment (long)		2044	2044	2044	2044	2044	2044	2044	2044	2044	2044										
Repayment (short)			759.2	1476.936	2149.891	2774.482	3346.841	3862.788	4214.396	4686.719	5123.615	5523.524	3840.819	2084.075	250.0346						
Total Cash out-flow	29200	2044	2803.2	3520.936	4193.891	4818.482	5390.841	5906.788	6258.396	6730.719	7167.615	5523.524	3840.819	2084.075	250.0346	0	0	0	0	0	0
Cash Position	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1664.704	1925.74	1925.74	1925.74	1925.74	1925.74	1925.74
Accumulated Cash Position	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1664.704	3590.444	5516.184	7441.924	9367.664	11293.4	13219.14

Source: Author.

Next, we analyse the internal rate of return (IRR), which is of two types: IRR on the FSPV project (IRROI) and IRR on the IPP entity (IRROE). The formulas of cash flow are different:

IRROI

Cash inflow: Revenue – operating cost

Cash outflow: Capital cost

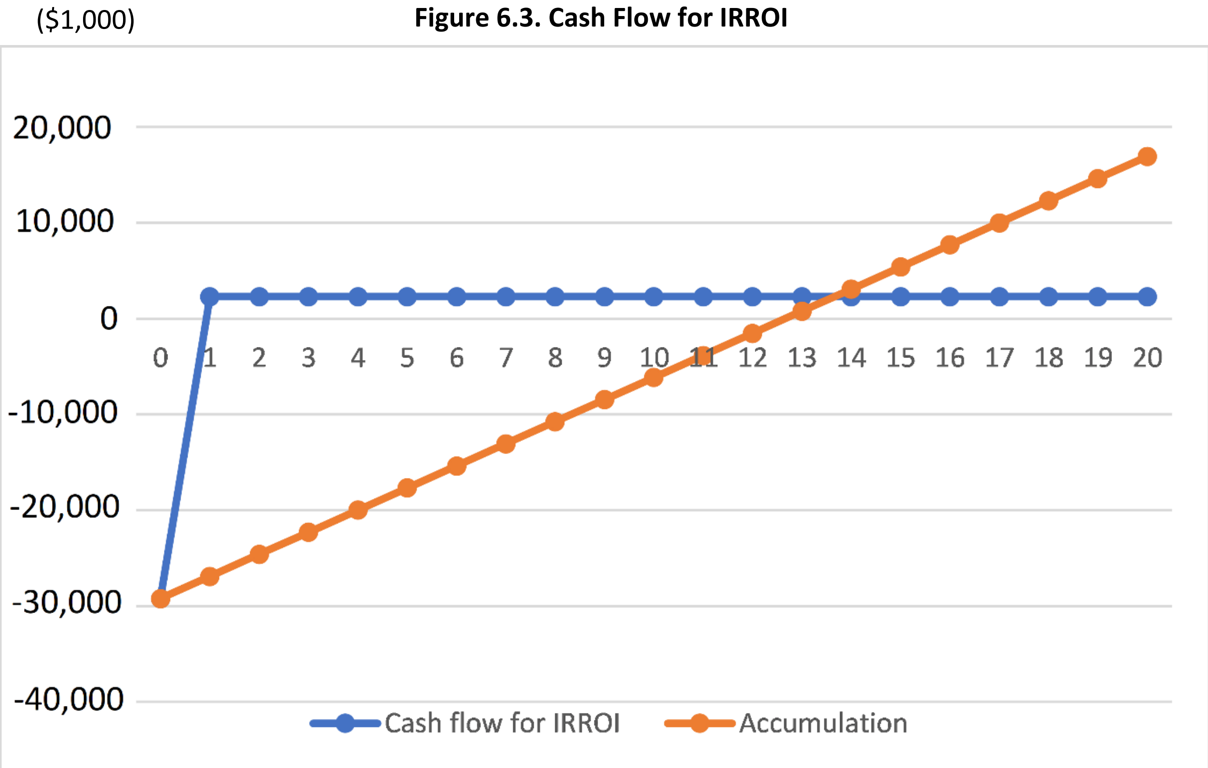
IRROE

Cash inflow: Cash position

Cash outflow: Shared capital

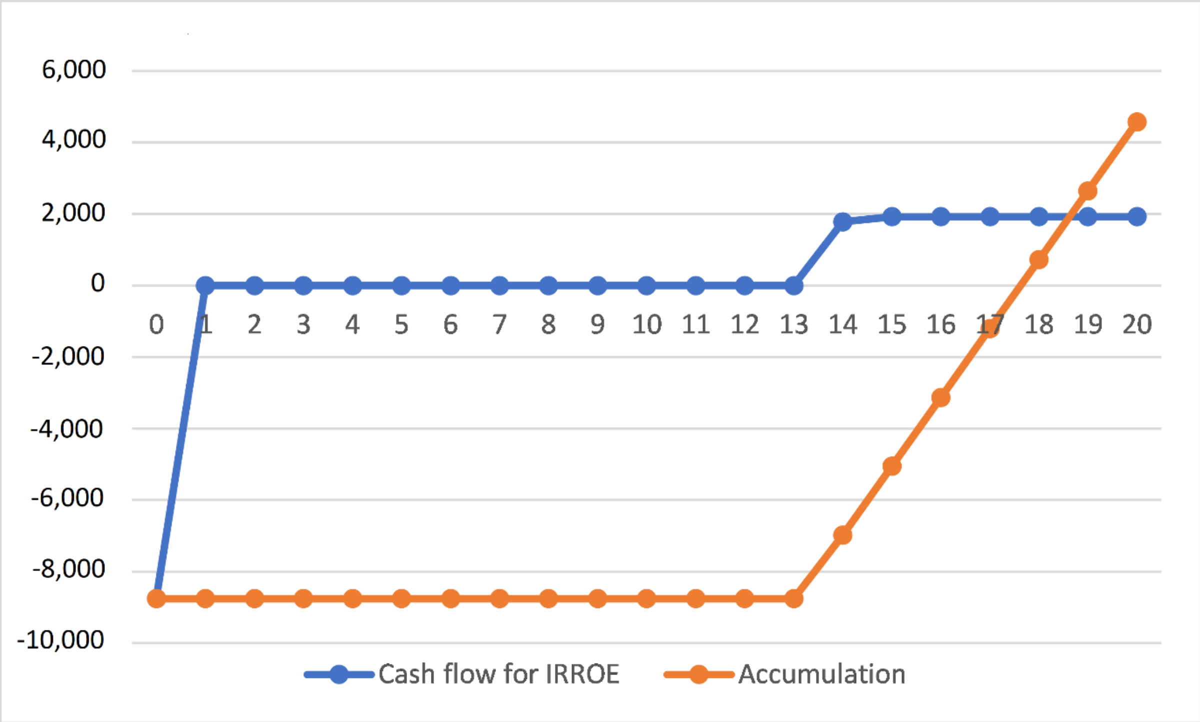
IRROI is calculated as 4.82%, while IRROE is at 2.45%. Figures 6.3 and 6.4 show the cash flow of the IRRs. Both IRRs are not attractive for the business sector because it takes the accumulated cash flow 13 years for the IRROI and 18 years for the IRROE to become positive. Thus, one way to improve both IRRs is to increase the wholesale electricity price to the EDL from 5 cents to 6 cents. In addition, we change the repayment period from 10 to 15 years to improve the cash balance from negative to positive. But total interest payment surely increases from $5.6 million to $8.2 million. Under these changes from the previous case, IRROI improves from 4.82% to 7.59%. IRROE improves from 2.45% to 6.42% due to an earlier change of positive accumulated cash flow (IRROI changes to positive in the 11th year and IRROE in the 16th year). The new IRRs (7.59% and 6.42%) are attractive for the business sector. Assuming 6 cents for the wholesale electricity price to the EDL, the IPP profits from the 1st year and never incurs a cash shortage. In this regard, the IPP can deliver dividends to its shareholders from the 1st year. Thus, 6 cents is a very important financial parameter for the IPP.(Refer to Figures 6.5 and 6.6, and Tables 6.3 and 6.4.)

Figure 6.3. Cash Flow for IRROI



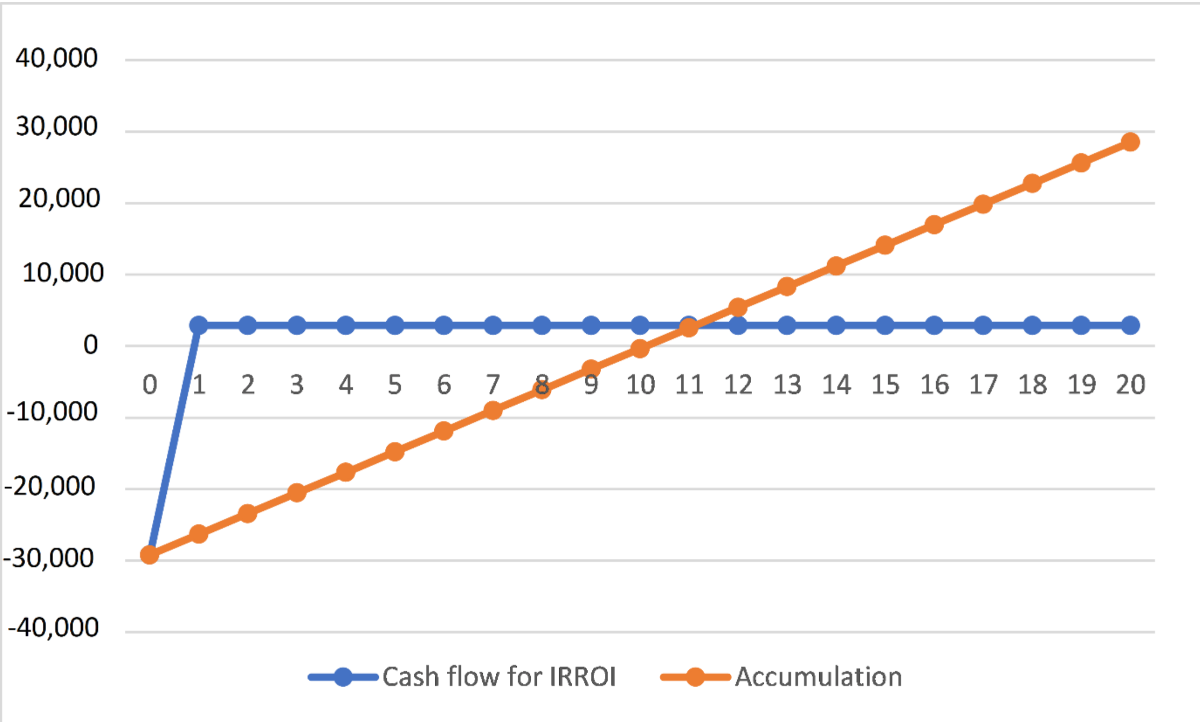
Source: Author.

($1,000) **Figure 6.4. Cash Flow for IRROE**



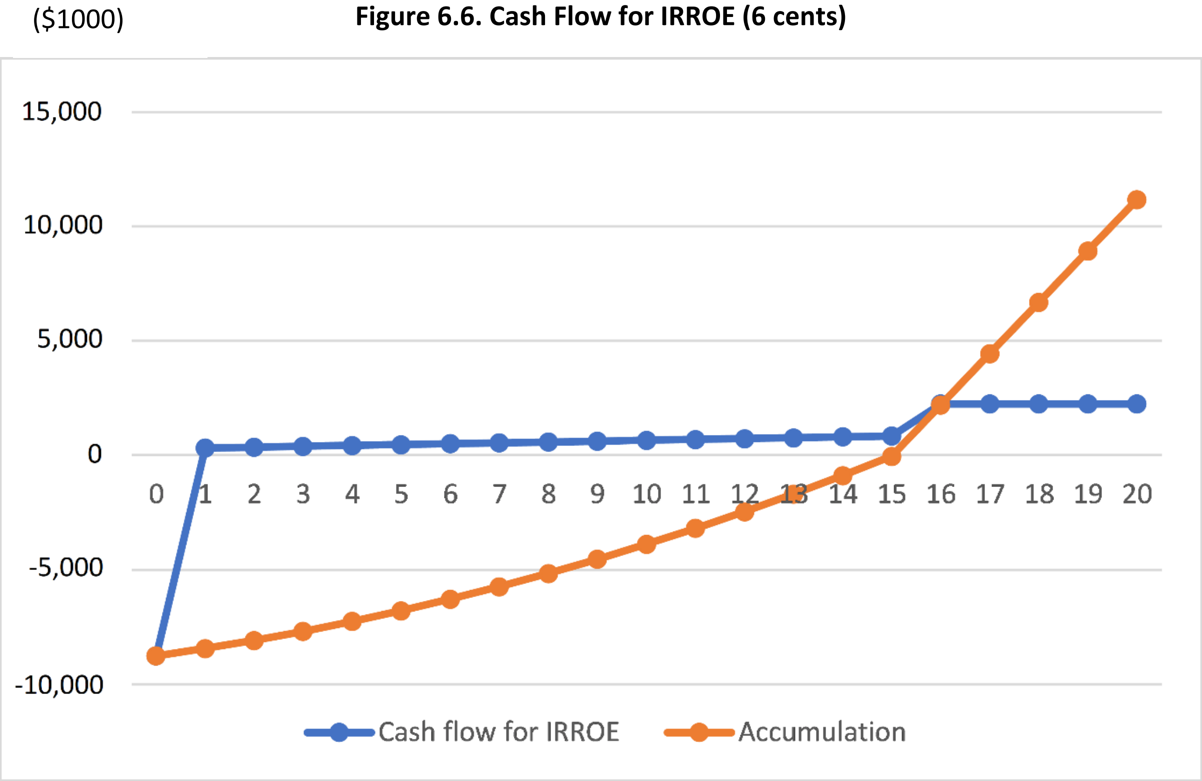
Source: Author.

($1,000) **Figure 6.5. Cash Flow for IRROI (6 cents)**



Source: Author.

Figure 6.6. Cash Flow for IRROE (6 cents)



Source: Author.

Table 6.3. Income Statement (6 cents, unit: $1,000)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Revenue		3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96	3468.96
OPEX		584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584
Depreciation		1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460
Interest (long)		1022	953.8667	885.7333	817.6	749.4667	681.3333	613.2	545.0667	476.9333	408.8	340.6667	272.5333	204.4	136.2667	68.13333					
Interest (short)			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Profit Before Tax		402.96	471.0933	539.2267	607.36	675.4933	743.6267	811.76	879.8933	948.0267	1016.16	1084.293	1152.427	1220.56	1288.693	1356.827	1424.96	1424.96	1424.96	1424.96	1424.96
Income Tax		181.332	211.992	242.652	273.312	303.972	334.632	365.292	395.952	426.612	457.272	487.932	518.592	549.252	579.912	610.572	641.232	641.232	641.232	641.232	641.232
Profit After Tax		221.628	259.1013	296.5747	334.048	371.5213	408.9947	446.468	483.9413	521.4147	558.888	596.3613	633.8347	671.308	708.7813	746.2547	783.728	783.728	783.728	783.728	783.728
Accumulation		221.628	480.7293	777.304	1111.352	1482.873	1891.868	2338.336	2822.277	3343.692	3902.58	4498.941	5132.776	5804.084	6512.865	7259.12	8042.848	8826.576	9610.304	10394.03	11177.76

Source: Author.

Table 6.4. Cash Flow Statement (6 cents, unit: $1,000)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Cash in-flow																					
Shared capital	8760																				
Borrowed money (long)	20440																				
Borrowed money (short)																					
Depreciation		1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460
Profit after tax		221.628	259.1013	296.5747	334.048	371.5213	408.9947	446.468	483.9413	521.4147	558.888	596.3613	633.8347	671.308	708.7813	746.2547	783.728	783.728	783.728	783.728	783.728
Total Cash in-flow	29200	1681.628	1719.101	1756.575	1794.048	1831.521	1868.995	1906.468	1943.941	1981.415	2018.888	2056.361	2093.835	2131.308	2168.781	2206.255	2243.728	2243.728	2243.728	2243.728	2243.728
Cash out-flow																					
Capital cost	29200																				
Repayment (long)		1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667					
Repayment (short)			0	0	0	0	0	0	0	0	0	0	0	0	0						
Total Cash out-flow	29200	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	1362.667	0	0	0	0	0
Cash Balance	0	318.9613	356.4347	393.908	431.3813	468.8547	506.328	543.8013	581.2747	618.748	656.2213	693.6947	731.168	768.6413	806.1147	843.588	2243.728	2243.728	2243.728	2243.728	2243.728
Accumulated Cash Balance	0	318.9613	675.396	1069.304	1500.685	1969.54	2475.868	3019.669	3600.944	4219.692	4875.913	5569.608	6300.776	7069.417	7875.532	8719.12	10962.85	13206.58	15450.3	17694.03	19937.76

Source: Author.

Chapter 7

Conclusions and Recommendations

1. Conclusions

This study examined the effectiveness of a hybrid system consisting of hybrid hydropower and FSPV in the Lao PDR. During the dry season, the electricity supply from hydropower plants is inadequate due to insufficient water flow, so the country imports electricity from Thailand. Therefore, electricity supply capacity during the dry season is one of the challenges for the Lao PDR. Thus, the FSPV system that works well in the dry season is an option to transition to sustainable energy development while ensuring that the country has the supply capacity to meet its growing electricity needs.

In chapter 3, we simulated how much electricity would be generated if the FSPV were installed using solar resource data from Solargis's satellite data. The study focused on the Nam Mang 3 hydropower plant as a simulation target. The simulation results show that if a 40 MW FSPV is installed in the Nam Mang 3 reservoir, the FSPV system can produce 57.86 GWh per year on average (58.55 GWh in 2019 and 57.17 GWh in 2020). The result of electricity injected into the grid implies that the FSPV system produces considerably more electricity during the dry season (November to April) than the rainy season (May to October) at the project site. Based on the simulations, the FSPV system produces a monthly average of 5.43 GWh of electricity during the dry season.

On the contrary, during the rainy season, the system has less electricity, with a monthly average of 4.20 GWh. The simulation results also show that hydropower generates less electricity during the dry season (represented by April), ranging from around 10 MWh/day to 27 MWh/day, compared to the rainy season (represented by August), which generates more than 30 MWh/day constantly. However, the FSPV system complements the change in the hydropower generation due to the opposite generation pattern in the dry and rainy seasons, making the peak generation of the hybrid system around the same in April and August. Thus, the hybrid system can effectively increase electricity production while decreasing long-term seasonal volatility.

In chapter 4, the appropriate FSPV capacity to be installed in Nam Mang 3 reservoir was simulated regarding the amount of electricity generated, volatility, and cost-effectiveness. The simulation results showed that adjusting the hourly output of the hydropower plant to the FSPV would reduce the amount of power curtailment and hourly variability of the hybrid system compared to each generating power independently. It was also suggested that 40 MW to 60 MW capacity is appropriate for the FSPV because it is superior in power curtailment, hourly volatility, and cost-effectiveness. Conversely, introducing more than 60 MW of FSPV capacity would result in excessive supply relative to demand, limiting the sales of electricity and reducing cost-effectiveness. In addition, if an excessively large FSPV capacity were installed relative to the capacity of the hydropower plant, it would exceed the control capability of the hydropower plant, resulting in increased fluctuations that may interfere with grid operations.

Chapter 5 discussed the impact of FSPV installation on power generation and CO_2 emissions in the Lao PDR. Based on BAU, if 40 MW of FSPV were installed in the Nam Mang 3 reservoir, the FSPV would account for about 0.06 TWh and 0.06% of the total power output of 89.16 TWh in 2030. In addition, when the power output of the FSPV is compared to the power output of coal power plants, it is equivalent to about 0.17%. Also, assuming that 40 MW of FSPVs is used to supply a part of the electricity generated by a coal-fired power plant, installing an FSPV can reduce about 0.5% of the total CO_2 emissions. Thus, if the country utilises RE, such as solar PV and wind power, to combine hydropower applying large-scale battery storage and smart-grid system at the national level, its power sector can be decarbonised. If the country uses clean electricity, shifting from internal combustion engines to electric vehicles, CO_2 emissions in the transport sector can be reduced. The RE hybrid system will be a key element for improving the energy situation and CO_2 emissions.

Economic feasibility is important to the solar PV business in the Lao PDR because no government policies support RE penetration. If we assume that the selling price of electricity to the EDL is at 5 cents, the economic feasibility is quite low due to the less attractive IRR, which is 4.82%. Assuming the price is 6 cents, the IRR jumps to 7.59%. In addition, income and cash flow statements improve, and this IPP company can provide dividends to its shareholders. Therefore, Just a cent difference is crucial for the IPP company.

2. Recommendations

Based on the results of the study, we recommend the following:

- FSPV is an effective option to solve the electricity supply shortage in the Lao PDR during the dry season. Thus, the hybrid system to combine hydropower and floating solar/PV will be accelerated.
- Under the current circumstances, when combining the Nam Mang 3 hydropower plant with the FSPV, the FSPV capacity should be suitable for the same size as the hydropower plant (40 MW to 60 MW).
- Since the FSPV works well during the day, hydropower producers can save water outflow from the reservoir. It means they can use enough water for hydropower generation at night to meet higher electricity demand than in daytime.
- Both solar PV and FSPV systems will be essential power sources for the Lao PDR to meet the increased electricity demand in the future and contribute to the carbon-neutral target by 2050. However, if the remarkable capacity of the solar PV system connects to the national grid, the solar PV system will interfere with grid operation. Thus, the appropriate capacity of the solar PV system in the Lao PDR should be examined through power system analysis, which uses a broader (national) grid simulation system. Another way is to prepare storage batteries or hydrogen production facilities, which store/curtail electricity from hybrid (or combined) system.
- This FSPV business is economically feasible if we assume that the selling price of electricity to the EDL is 6 cents, currently an acceptable level in the Lao PDR. If so, the legislative framework of the existing hydropower station should be reviewed, and the regulations revised, if necessary, to meet the IPP’s demand. For example, who has a right to the surface of the dam?

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