TECHNO-ECONOMIC FEASIBILITY ASSEMEMNT OF INTEGRATING FLOATING SOLAR WITH HYDRO: A CASE STUDY FOR VICTORIA POWER STATION SRI LANKA

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Thesis/ Dissertation was submitted to the Department of Electrical Engineering of the University of Moratuwa in partial fulfillment of the requirements for the Degree of Master of Science in Electrical Installation

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Supervisors : Prof. L N W Arachchige
: Dr. Upuli Jayatunga

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ABSTRACT

The addition of floating solar photovoltaic (FSPV) to existing hydropower facilities is a potential game-changer in the incorporation of renewable power sources while maximizing resource allocation. This study explores the potential deployment of an FSPV system configuration at the Victoria hydropower station in Sri Lanka from a technical, as well as a financial perspective. It explores the possibility of approximately 93 MWp of solar capacity being placed on the surface of the reservoir, which would result in the generation of 133.5 GWh of energy per year. By utilizing the existing grid structure at Victoria, this method serves as a cheaper solution than ground-mounted and independent floating solar plants. The analyzed comparative levelized cost of electricity (LCOE) data is suggestive of a hybrid model in comparison to the standard solar PV design in the country.

Dynamic simulations were carried out on the proposed system with the aid of Power System Simulator for Engineering (PSS/E) and a dynamic model received from the Ceylon Electricity Board (CEB) Transmission Division. The outcome suggests that the complementary operation of FSPV and hydropower does not put system stability at risks, since the frequency response and bus voltage profiles of the system are within allowed limits under all system disturbances. Furthermore, the existing arrangement for power sharing between solar and hydro resources offers additional energy security in that it permits dominance of solar over daylight hours while allowing hydro resources to be stored for generation during the night.

The results of this study elaborate that the complimentary use of floating solar PV (FSPV) and hydropower has the potential in making the country's energy transition economically sustainable. Even though there may be some boundaries, the analysis does set up a strong case for the future large-scale implementation of hybrid FSPV-hydro systems.

Keywords: Complementary Operation, Financial feasibility, Floating Solar Photovoltaic (FSPV), Frequency stability, Hybrid Energy Systems (HESs), Power system stability, Solar energy penetration.

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LIST OF ABBREVIATIONS

Abbreviation	Description
CEB	Ceylon Electricity Board
LTGEP	Long Term Generation Expansion Plan
RE	Renewable Energy
NCRE	Non-Conventional Renewable Energy
ORE	Other Renewable Energy
FSPV	Floating Solar Photovoltaic
HES	Hybrid Energy Sources
LCOE	Levelized Cost of Electricity
PUCSL	Public Utilities Commission of Sri Lanka

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CHAPTER 1
INTRODUCTION

1.1 Present Sri Lankan Power System

At present Ceylon Electricity Board (CEB) has hydro, thermal, biomass, wind and solar PV power plants connected to the transmission system, which operates at 132 kV and 220 kV voltage levels. As of 31st December 2022, the total installed capacity of all hydro power stations owned and operated by CEB is 1,413 MW and the total installed capacity of all thermal power plants owned and operated by CEB is 1,717 MW [1]. In addition, 270 MW of private thermal power plants are connected to the system. As of 31st December 2022, approximately 1,382 MW of Other Renewable Energy (ORE) plants are connected to the national grid, which consists of 414 MW of mini hydropower plants, 252 MW of wind power plants, 50 MW of wood fuel/ dendro/ waste to energy power plants, 130 MW grid connected solar power plants and 536 MW solar roof top. The peak power demand of the country in the year 2022 was 2,708 MW while total installed generation capacity of the system was 4,246 MW at the end of 2022 [1].

However, when the most recent data is evaluated based on the report published by Public Utilities Commission of Sri Lanka (PUCSL), according to Figure 1, the installed capacity of roof top solar PV has reached up to 716.1 MW which is almost 180 MW of additional generation integrated to the system within a span of two years when compared with the data outlined above based on the transmission planning report [2]. Figure 2 illustrates that the energy generation from both roof top solar and ground mounted solar has contributed around 14% of the total renewable energy generation in the first quarter of 2024. Therefore, it can be clearly seen that solar PV integration has a rapid increase in the Sri Lankan context.

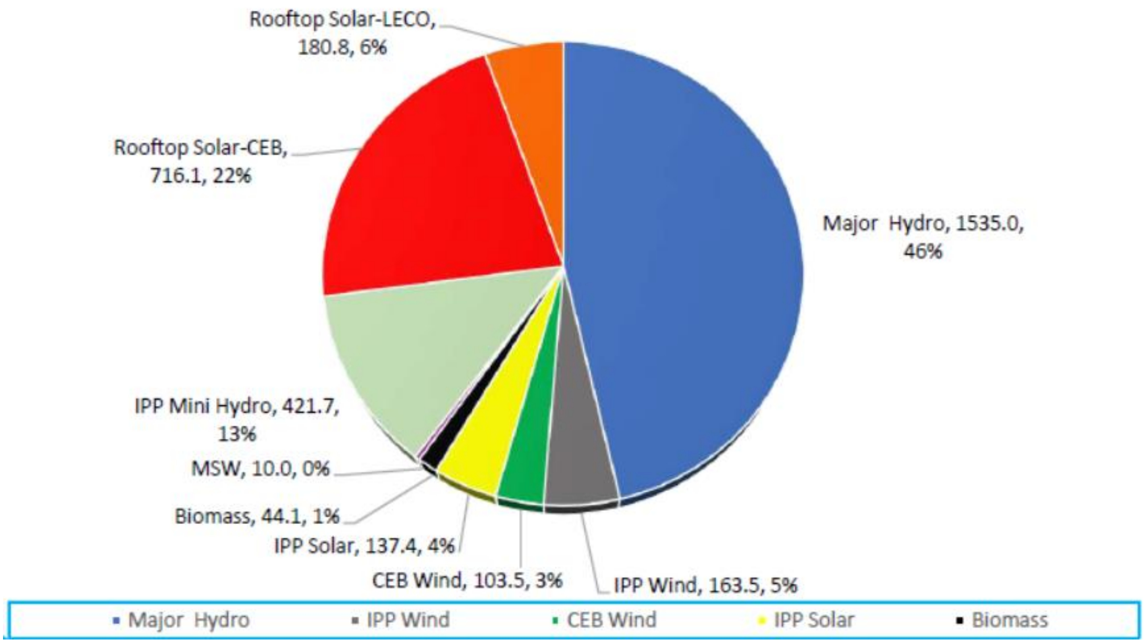

Figure 1: Renewable Energy (RE) capacity (MW) as at 31.03.2024 [2]

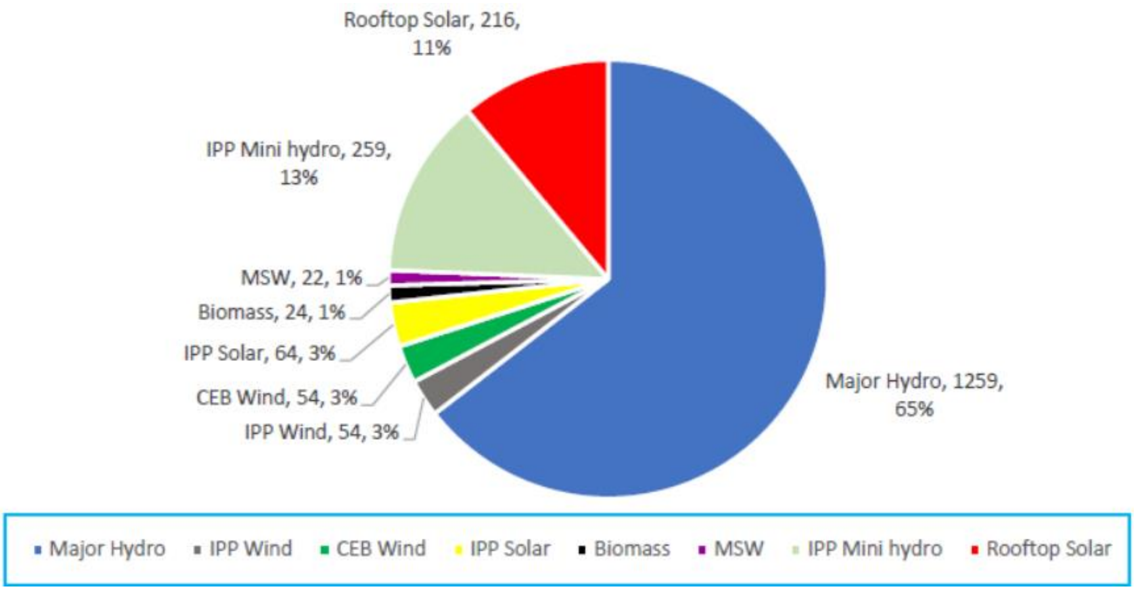

Figure 2: Renewable generation mix (GWh)- 1st Quarter 2024 [2]

1.1.1 Sri Lanka's Energy Supply

At the end of the year 2020, petroleum emerged as the key supply of energy consumption with a share of 40% [3]. In Sri Lanka, biomass, petroleum, coal, major hydro and other renewable energy sources are the primary sources of energy supply. It is dominated by biomass and petroleum. Biomass or fuel wood, which is mainly non-commercial fuel, provided approximately 34% of the country's total energy supply due to its abundant availability, while coal accounted for 14% of the primary energy supply in the year 2020.

According to Long Term Generation Expansion Plan (LTGEP) published by CEB for the period 2023 -2042, the country's electricity demand has grown at an average rate of 3.2% during the last five years. The maximum value of recorded peak demand was 2802 MW in April 2021. Whereas the total generation was recorded to be 16,716 GWh. By the end of 2021, Sri Lanka had a total installed generating capacity, including rooftop solar, of (approximately) 4,600 MW, while 2,613 MW out this 4600 MW came from renewable energy based generating capacity and 1,987 MW from thermal capacity.

1.1.2 Sri Lanka's Electricity Demand

The peak power demand for electricity in Sri Lanka has been growing at an average rate of 2.6% per year over the last two decades [3]. Based on this pattern, it is subjected to grow in the upcoming years. Electricity demand profile can be classified into three parts based on the time of use (TOU) as night peak, day peak and off peak. Presently, the night peak records the highest electricity demand, however the daytime demand is expected to dominate in years to come [3]. Figure 3 illustrates the installed capacity and demand growth over a period of 20 years from 2002 to 2021 as published by the long-term generation expansion plan report. As per Figure 3, it can be concluded that, despite the significant increase in peak demand over a period of 24 years, the total installed capacity has not increased proportionately.

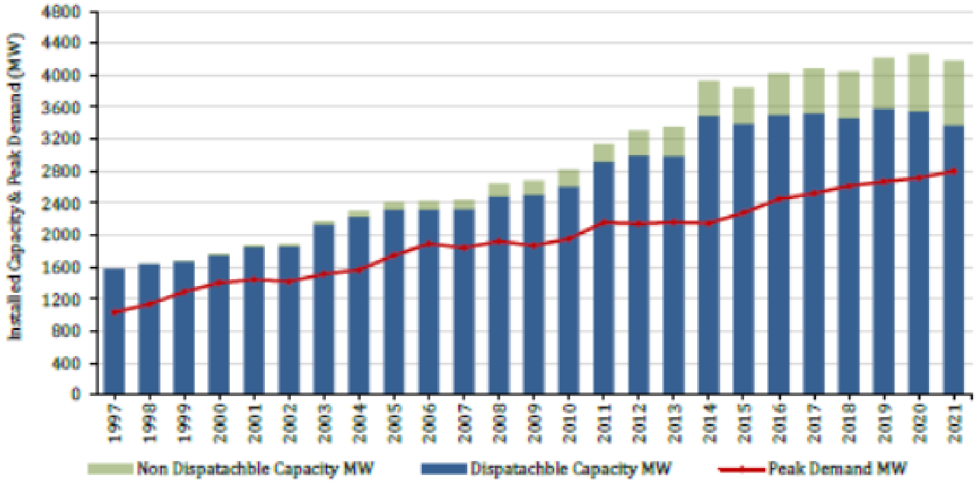

Figure 3: Total installed capacity and peak demand variation [3]

1.2 Problem Statement

The Ceylon Electricity Board (CEB), through its Long-Term Generation Expansion Plan (LTGEP), has announced ambitious targets to increase Sri Lanka's solar power capacity over the next 20 years. Solar PV capacity is planned to be increased up to 4,659 MW by end of 2030. And based on CEB data, the total capacity of solar by 2021 was only 615MW which include both roof-top and ground mounted systems. And as a long term plan, the goal is to reach solar capacity to 10,739 MW by the end of 2042. Solar PV is expected to retain its dominant share throughout the 20-year planning period [3]

While traditional solar photovoltaic (PV) systems are being encouraged, several challenges must be discussed in order to ensure their effective integration into the national grid. One of the primary concerns is the intermittent nature of solar energy, which can create grid stability issues without adequate balancing mechanisms. Additionally, ground-mounted solar PV plants, despite their growing adoption, have limitations in terms of land requirements and efficiency. The typical plant factor for ground-mounted solar in Sri Lanka is approximately 18–20%[3], and developing large-scale solar farms requires significant land resources—typically around 3.5 to 4 acres per megawatt peak (MWp) of installed capacity. Given the issue of available land and competing land-use priorities, alternative solar deployment strategies must be explored to meet Sri Lanka's renewable energy targets effectively.

Floating Solar Photovoltaic (FSPV) systems have emerged as a promising alternative due to their ability to utilize water surfaces rather than land, thereby reducing space constraints. Furthermore, FSPV installations benefit from the natural cooling effect of water, which enhances energy generation efficiency compared to traditional ground-mounted systems. Presently, Sri Lanka's Ministry of Irrigation has allocated around 0.99 hectares of water surface area and 0.1 hectares of land area from the Chandrika Wewa and Kiriibban Wewa reservoirs for two floating solar power generation pilot projects, where the 1MWp floating solar PV pilot project at Kiriibban Wewa was recently commissioned [4]. Despite these early-stage developments, the full potential of large-scale FSPV deployment remains unexplored, particularly concerning its integration with the country's existing hydropower infrastructure.

To ensure both technical feasibility and financial viability, it is crucial to evaluate FSPV deployment in reservoirs where hydropower projects are already in operation. Large hydropower reservoirs provide an ideal setting for complementary FSPV-hydro operation, enabling optimized energy generation while utilizing the existing grid infrastructure.

By integrating FSPV with hydropower plants, it is possible to enhance grid stability and mitigate solar intermittency through coordinated power generation strategies. Based on literature reviews and past feasibility assessments for Sri Lanka, the Victoria Reservoir has been identified as one of the most practical locations for implementing an FSPV system in conjunction with the Victoria hydropower station [5]. Hybrid FSPV-hydro systems are expected to maintain and improve grid stability while compensating for seasonal variations, such as solar intermittency and dry periods.

Therefore, this research focuses on assessing the technical and financial feasibility of integrating an FSPV plant with the Victoria Hydropower Station, aiming to provide insights into the potential benefits and challenges of large-scale FSPV deployment in Sri Lanka.

1.3 Research Objectives

The main objective of this project is to assess the technical and financial feasibility of integrating a floating solar photovoltaic system at Victoria hydropower station for their complementary operation towards effective resource usage. The specific objectives are:

- To develop and validate a reduced transient model of the transmission system of Sri Lanka.
- To design the FSPV based on the resource availability and perform a financial analysis.
- To analyze the frequency response of Sri Lankan power system under complementary operation with FSPV and Victoria hydropower station for different scenarios.

1.4 Thesis Outline

- Perform detailed literature survey on available renewable energy and FSPV infrastructure in Sri Lanka along with the global concepts.
- Design the floating solar photovoltaic power plant for Victoria reservoir.
- Develop and modify the model of the transmission system of Sri Lanka for year using PSS/E version 36.1
- Validation of developed reduced model of the transmission system of Sri Lanka by simulating it with actual data.
- Study of stability of the present Sri Lankan power system with contingency situations
- Identify and study the system stability once the complementary operation between the FSPV proposed for Victoria reservoir and Victoria hydropower station.

CHAPTER 2
LITERATURE REVIEW

2.1 Solar Energy and Hydropower Potential in Sri Lanka

2.1.1 Solar Energy Potential

Sri Lanka has substantial potential in harnessing solar as it is being located closer to equator, and it receives significant amounts of solar radiation across all geographical regions. The Global Horizontal Irradiance (GHI) varies between 1,247 kWh/m^2 to 2,106 kWh/m^2. The solar PV technology is becoming increasingly competitive while the growth of this technology is expected to continue [3]

The country's solar potential could be classified into three main categories based on its technology and configuration patterns as below.

a) Grid connected fully facilitated Solar Park (Medium to large scale, 10-100 MW) [3]
    i. Ground Mounted Solar
    ii. Floating Solar
b) Grid connected partially facilitated Solar Park (less than 10 MW) [3]
    i. Ground Mounted Solar
    ii. Floating Solar
c) Distribution network connected Embedded Solar [3]
    i. Rooftop (Net Metering, Net Accounting, Net Plus)
    ii. Ground Mounted

Sustainable Energy Authority (SEA) has identified potential locations to develop medium-long-term solar PV plants around the island.

2.1.2 Hydropower potential in Sri Lanka

Hydropower is the main renewable source of generation in the Sri Lankan power system where it is mainly owned and operated by CEB. In 2021 approximately 33.7% of the total energy demand was met by CEB owned major hydropower plants. In Sri Lanka, major hydropower schemes are mainly associated based on Kelani and

Mahaweli basins, where 59% of the total hydro capacity is based under seven major hydropower stations in the Mahaweli basin, while 26% of total hydropower schemes are based in two main tributaries of Kelani River, Kehelgamu Oya and Maskeli Oya [3]

The Mahaweli scheme is operated as a multi-purpose system unlike the Laxapana complex system. Therefore, Mahaweli scheme power stations are dependent on the down-stream irrigation requirements. The schematic diagrams of the hydro reservoir networks are shown in Appendix A

According to the data published by the PUCSL, out of all the renewable energy (RE) generation, during the 4th quarter in 2023 and in the 1st quarter in 2024, major hydro has contributed mostly to Sri Lanka's energy demand. Figure 4 shows the comparison between the RE generation for the 4th quarter in 2023 against the 1st quarter in 2024 [2]Despite the dry season in the first quarter of the year major hydro has contributed over 1000 GWh which presents the dominance of hydro power generation in Sri Lanka

Figure 4: Comparison of RE generation between Q4 2023 and Q1 2024 [2]

2.2 Floating Solar PV Systems (FSPV)

Floating Solar PV (FSPV) systems can offer effective solutions for energy generation without having substantial demand for land resources. Floating Solar PV is a new mechanism of installing PV modules on water surfaces using floating structures and is a substitute for the land-based (ground-mounted) solar PV systems.

2.2.1 Concept of Floating Solar PV Systems

The difference between traditional land based solar systems and FSPVs is the installation location of PV modules and its unique structural arrangement [6]. In addition to the common components available in a land based solar PV system such as PV modules, inverters, mounting structures, cables etc., a FSPV system requires additional structural arrangements for mounting and foundation work. Figure 5 as shown in [6] illustrates the typical layout of an FSPV system along with its basic components.

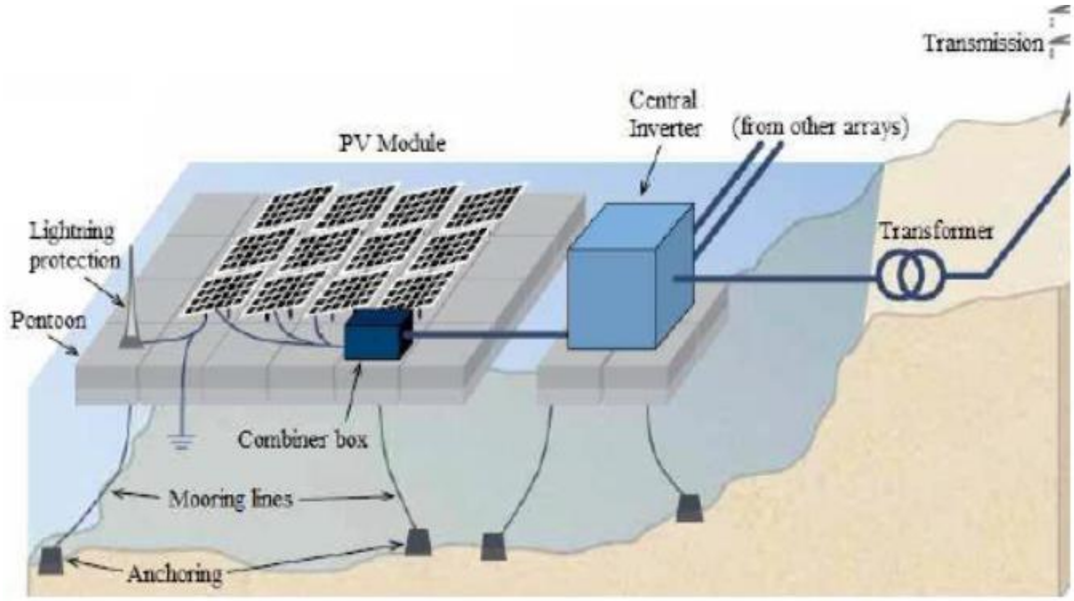

Figure 5: Typical layout of a FSPV plant [6]

Major Components of FSPV

- Floats and Pontoon – Generally floats are made of high-density polyethylene (HDPE) plastic device which has got the capability to float by itself while being able to carry weight. Pontoon is a large platform formed by joining several hollow floats
- Mooring and anchoring system – Mooring system is used to keep the pontoon in a stable position by using cables and anchors. Typically, these mooring and anchoring are done using nylon cables.

2.2.2 Benefits of Floating Solar PV Systems

The following are some key direct advantages of integrating floating solar [3]

a) Greater energy production advantages because of the low temperature
b) Less land needed than with ground-mounted solar PV
c) A decrease in the reservoirs' water evaporation
d) The potential for sharing the current electrical infrastructure

A study has identified several reservoirs with the potential to develop large scale floating solar in Sri Lanka [7] as shown in the following Table 1. According to Table 1, the study presents that Victoria reservoir has the potential to accommodate 381 MWp while contributing 602 GWh to the grid annually. However, a proper floating solar PV sizing methodology has not been discussed in detail as this study has considered 15% of the water surface area to match the solar modules which is not realistic.

Table 1: Potential reservoirs to develop large scale floating solar [7]

No.	Reservoir	Surface Area (ha)	District	% Area Covered	Area for Solar (ha)	Solar Capacity (MWp)	Annual Output (GWh)
1	Senanayake Samudraya	7680	Ampara	15	1047	1571	2488
2	Maduru Oya	6390	Polonnaruwa	15	959	1307	2100
3	Moragahakanda	4050	Matale	15	608	931	1312
4	Udawalawe	3362	Matara	15	504	772	1088
5	Lunugamwehera	3023	Hambantota	15	453	618	879
6	Kala Wewa	2861	Anuradhapura	15	429	585	833
7	Randenigala Reservoir	2583	Kandy	15	387	527	752
8	Minneriya	2550	Polonnaruwa	15	383	522	836
9	Kudutlg	2500	Polonnaruwa	15	375	511	818
10	Padaviya	2370	Anuradhapura	15	356	484	764
11	Iranamadu	2270	Kilinochchi	15	341	464	735
12	Ulhitiya-Rathkinda	2060	Badulla	15	310	422	668
13	Victoria Reservoir	1860	Kandy	15	279	381	602
14	Parakrama Samudraya	2602	Polonnaruwa	15	390	533	843
15	Huruluwewa	2100	Anuradhapura	15	315	430	680
16	Inginiyagala	1900	Puttalam	15	285	389	615
17	Nachchaduwa	1457	Anuradhapura	15	219	299	472
18	Mahakanadarawa	1425	Anuradhapura	15	214	293	463
19	Weheragala	1416	Monaragala	15	212	289	457
20	Kotmale Reservoir	1414	Kandy	15	212	289	457
21	Deduru Oya Reservoir	1280	Kurunegala	15	192	262	414
22	Kantale	1183	Trincomalee	15	177	241	382
23	Navakiri Aru	1010	Batticaloa	15	151	205	325
24	Nuwara Wewa	1004	Anuradhapura	15	151	203	337
Total		62498			8523	12784	20520

However, further studies have been carried out by the World Bank group to identify specific sites/locations for development of large scale floating solar PV systems in Sri Lanka. Predominantly they have given preference to the sites where the FSPV can be co-located and operated conjunctively with existing hydropower plants, as this will facilitate integration of the FSPV into the electricity system [5].

This study has been carried out in two phases where, in the phase A, the potential and the need for FSPV in Sri Lanka has been evaluated, while in Phase B a detailed pre-feasibility study has been carried out. Based on these studies, it has been recorded that the following FSPV capacities mentioned in Table 2 could be installed in the identified reservoirs, which is completely different to the capacities published by [7] Therefore, it is essential to consider all the reservoir parameters such as the reservoir surface area when it is fully drawn down and the operating range of the reservoir, prior to the floating solar design stage.

Table 2: Proposed floating solar capacities presented in [5]

ID	Name	Rated Capacity (MWp)
1	Bowatenna	18.8
2	Castlereigh	100.7
3	Chandrika Lake	64.1
4	Gregory Lake	20
5	Iranamadu	104.1
6	Kalawewa	12.2
7	Kalu Ganga	99.1
8	Kantale	9.9
9	Kaudulla	105.8
11	Maduru Oya	110
12	Minneriya	85.7
13	Moragahakanda	99.5
14	Moussakale	97.6
15	Parakrama	102.6
16	Rajangana	102.5
17	Randenigala	110
19	Samanalawewa	98.2
20	Senanayake	100.4
21	Uda Walawe	99.6
22	Ulhitiya	110
23	Victoria	66.9

2.3 Hydro – PV Systems

Hybrid Energy Systems (HESs) can play an important role in providing greater balance in energy supply while increasing the system's efficiency [8]. Hydro-PV could be considered as one of the commonly used HESs presently around the globe [9], [10].

Hydropower can quickly offset highly variable renewable energy sources (RESs) since large hydropower plants are dispatchable and flexible in their ability to increase and decrease power output. Despite being abundant in nature, solar photovoltaic power output is unpredictable. The complementarity between hydropower and photovoltaic can be stated as follows based on their respective attributes [11]

- Hydropower's quickly changeable output makes up for PV's intermittency. [11]
- When it comes to mid- to long-term scheduling and meeting peak load, PV makes up for hydropower's energy deficit [11]

Compensation for PV by hydropower can be classified as a two-stage process [11]:

i. First Stage – Through the small movement of guide vanes, hydropower units are utilized to smooth the sawtooth-shaped output curve of PV, as shown in Figure 6

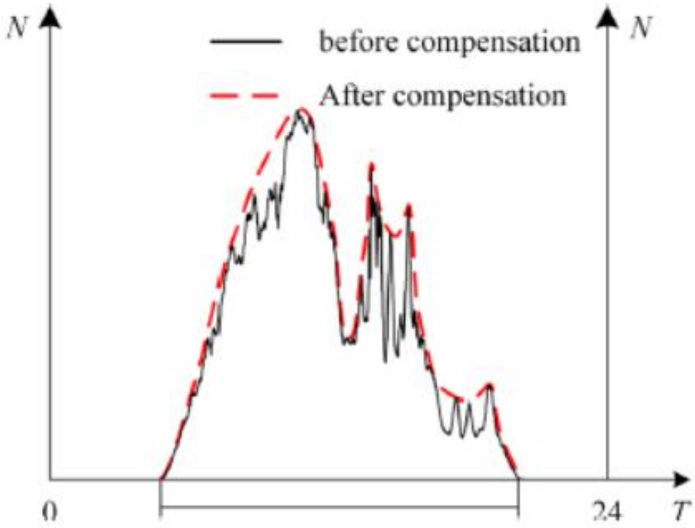

Figure 6: First stage compensation of PV through hydropower[11]

ii. Second Stage - As stated in Figure 7 and 8, reservoirs with a greater volume of stored hydro energy can allow for faster output changes from hydropower units. These factors can mitigate PV fluctuations and ensure total output is consistent.

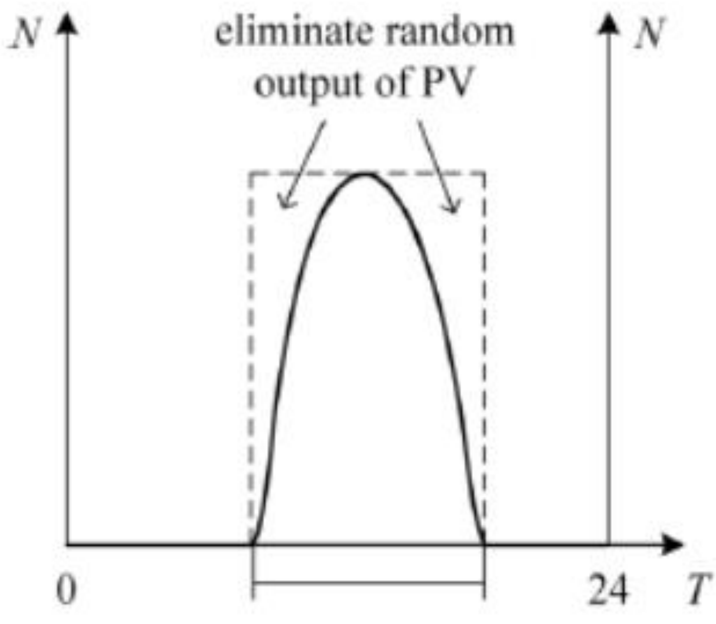

Figure 7: Stage Two Process – eliminate random output of PV [11]

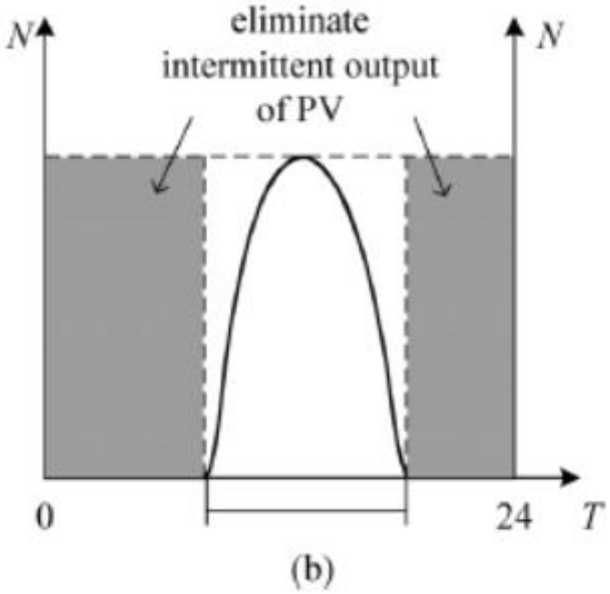

Figure 8: Stage Two Process- eliminate intermittent output of PV [11]

Thus, the integration of utility-scale PV into the power system is furthered because it is possible to improve the power quality and moderation of the highly variable output of PV is obtained through this two stage complementary process [11]

Likewise, the compensation of hydropower through PV can be performed considering the seasonal and inter-annual changes of the water storage reservoirs. As such, PV can make up for the deficit in energy supplied by hydropower during dry seasons, whereas, in wet season, hydropower can increase its output and cover the energy generated from PV, thus providing seasonal complementarity. During the day, when PV is generating electricity, hydropower reduces its generation and stores more water in the reservoir to be used later, when there is high electricity consumption at night [11]

The integration of hydro with FSPV can also offer the following advantages apart from those identified on the coupling hydropower with FSPV [12]

i. Reduction of power fluctuation - To guarantee that power is generated to match demand without the need for batteries or other storage equipment frequently associated with PV plants, an active control system could be used, where hydropower generation is reduced during the day when the PV plant is operating and increased during the night [12]

ii. Installation and decommissioning - Because floating PV plants are set up in a flush mounted system, they experience reduced inter-row shading. Unlike the foundations used for land-based PV plants, the mooring of floating systems can be placed and removed completely reversibly [12]

iii. Water saving and water quality – Additional advantages include a decrease in water evaporation when PV modules cover the water's surface. The issue of algae growth can also be resolved by partially covering the reservoirs and reducing the amount of light that is present just below the surface [12]

Generally, a PV plant working in combination with a hydropower plant serves as a hybrid power source to feed electricity into the system. A case study carried out in [13] analyses a novel operation mode by identifying three practical scenarios to satisfy different demand scenarios as discussed below.

1. All-day lifting scenario (ADL)

In this case, the solar PV plant's power output acts as the base load, and the mean daily PV output, as shown in Figure 9, simultaneously raises the hydropower's daily output curve. [13].

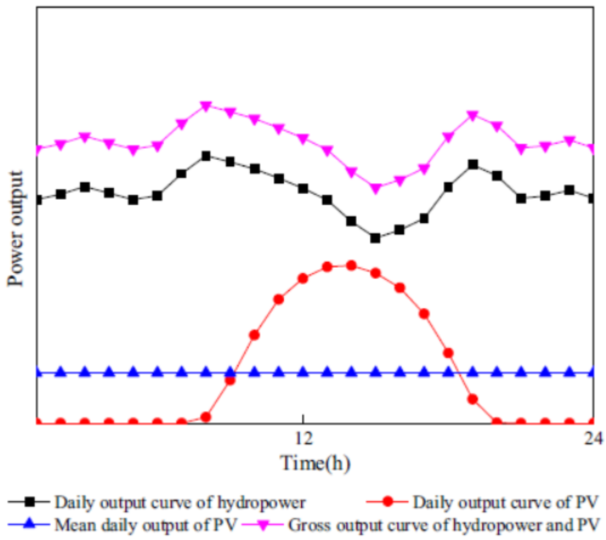

Figure 9: ADL scenario output pattern [13]

The primary benefit of the ADL scenario is that, when integrating into the system, PV production takes precedence over hydropower because it is the base load. This encourages PV's electricity to be fully utilized and boosts profitability. Furthermore, the hydro-PV plant can handle the same percentage of peak load as the standalone hydropower plant since the peak-to-valley difference of the hydro-PV plant's gross output curve does not alter when compared to standalone hydropower systems. [13]. Due to parallel lifting that happens in ADL, the daily generation of hydropower remains unchanged. Thereby, it does not affect the revenue generated from hydropower energy generation.

2. Daytime lifting scenario (DTL)

In this case, the hydro-PV plant's output curve is obtained by dividing the daily energy production of PV by 12 hours, which is equivalent to the mean hydropower output during the day (8:00–19:00). The power system will be better equipped to meet the needs of a daytime-load dominated system thanks to the raising of the output curve during the day. The DTL scenario's behavior is depicted in Figure 10.

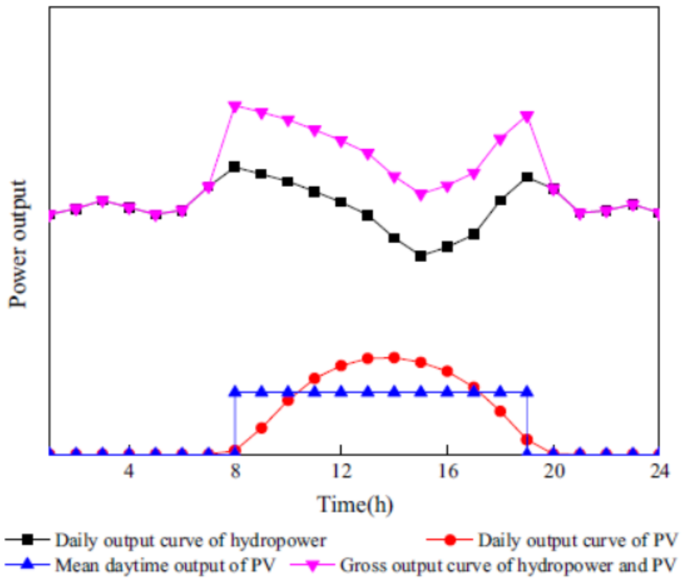

Figure 10: Daytime lifting scenario [13]

More importantly, a larger maximum output and a constant or widening peak-to-valley difference of the output curve provide the power system with more resources to meet the variable load demand, by enhancing the stability of the system [13]

3. Peak –load period lifting scenario (PPL)

- The daily energy generation of PV is split based on the ratios of morning load peak and evening peak.
- These two parts of electric energy are utilized to lift the hydropower output during morning and evening peak periods.

The output curve of PPL scenario can be depicted as shown in Figure 11.

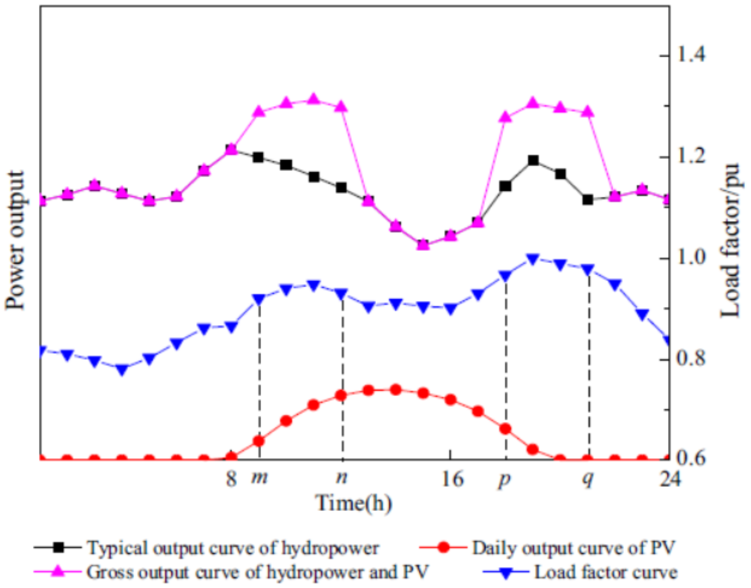

Figure 11: PPL scenario [13]

The discharged water that corresponds to the daily energy production of PV can be decreased and detained in the reservoir since hydropower in a PPL scenario provides the same quantity of electric energy that was initially planned for hydropower. [13]. Furthermore, an increase in energy output during peak periods will be economically advantageous to the hydropower producer upon implementation of the time-of-use (TOU) tariff at the generation side. The base-load electricity requirement can be met by hydropower in conjunction with PV's sporadic and unpredictable output.

2.4 Global Implementations of Floating Solar Photovoltaic (FSPV) Systems Integrated with Hydropower Plants

The case studies that have been carried out globally underscore the technical and economic viability of hybrid FSPV-hydropower systems, offering valuable insights for similar projects worldwide.

Table 3 shows the generation before and after implementation of complementary operation of FSPV and hydro power which are built in past decades globally and currently in operation along with some future planned operations.

Table 3: Present FSPV and hydro complementary power plants built globally

Name	Location	Solar Capacity	Hydro Capacity	Total Annual Generation Before (GWh)	Total Annual Generation After (GWh)
Longyangxia Dam Solar-Hydro Power Station	Qinghai Province, China	850 MW	1,280 MW	2500	3500
Sobradinho Solar-Hydro Hybrid Project	Sobradinho Dam, Bahia, Brazil	5 MW	175 MW	950	1000
Ruzizi III Solar-Hydro Hybrid Project	Ruzizi River (Rwanda, DR Congo, Burundi)	Planned	147 MW	700	800
Banja Solar-Hydro Project	Banja Lake, Albania	72 MW	72 MW	255	280

2.5 Effects of Renewable Energy Penetration on Power System Stability

The development of large-scale solar PV power plants has both advantages in economies and challenges in technical side. The increased penetration of intermittent solar power generation introduces more power output variations into the power system starting from finer time scale [3]. The geographical distribution of solar PV installations is one of the strategies to minimize the effect of inherent power output variation of solar PV systems as there is a greater diversity in intermittent characteristics in smaller time scales.

Effects of Solar PV systems on power systems have been discussed in reported research including [14]. According to standards, conventional power generation that is fossil fuel based is being replaced with renewable sources of energy to curb the environmental pollution from greenhouse equal to a clean, renewable energy system. Moreover, this paper suggests that the precise impact of higher levels of solar photovoltaic penetration is yet to be fully understood. Their impacts rest on systems that are not conventional as well as their impacts on steady-state and transient stability. Large scale conventional generation will be replaced by the distributed generation of photovoltaic systems that include utility scale and building integrated solar PV systems.

Power system collapses due to high penetration of solar and wind energy and failures of traditional UFLS methods are analyzed in [15]. According to [15] the grid connected solar PV and wind, which has no rotational inertia, is effectively displacing the rotating systems of the conventional generators. This reduces environmental effects and the cost of generation. However, frequency dynamics become faster with low inertia, and it affects the frequency stability of the power system. Maintaining frequency stability becomes a challenge due to this because frequency control becomes complex and difficult.

By 2015, the total generation capacity of the Lakvijaya coal power station is 900 MW. Even though the full load running of the plant provides high efficiency in energy generation, the plant is sometimes partly loaded, as it is operated in compliance with the recommended standards to maintain system stability. Considering the stability under ***n-1*** contingency, the running capacity of the largest generator is limited to 20-30 % of the demand at any given time [16]. Therefore, it is important to conduct detailed stability studies for verifying such capacity limitations.

2.6 Research Gap

While efforts have been made to evaluate the technical and economic aspects of integrating hydropower with FSPV systems, which are mostly focused on energy use, water use, and economic analysis. However, there is a notable gap in the existing literature regarding the operation of FSPV-hydro systems and their effects on grid inertia, specifically in their frequency response behavior.

On the other hand, my research will utilize the Victoria hydropower station and examine the frequency response characteristics to fill that gap. Considering that the stability of frequency determines reliability of power systems, it is important to see how the complementary operation shifts frequency deviations and the response time.

Additionally, contrary to the literature outlined above, many have attempted and analyzed the overall emerging market in terms of investment opportunities and possibilities. However, this study will focus mainly on evaluating the system response and grid stability simulations once the FSPV is integrated as a complementary mode while assessing the financial viability.

CHAPTER 3
SYSTEM MODELING

3.1 Present Sri Lankan Transmission System

The Present Sri Lankan network comprises with 220 kV and 132 kV transmission lines connected to power generating plants across the island and to loads through 220/ 33 kV, 132/ 33 kV or 132/ 11 kV grid substations. The map of the present transmission network is shown in Appendix B. Generally, all the daily power network operations and controls of the transmission system are carried out at the National System Control Centre (NSCC). Presently, the largest unit in operation in the network is 300 MW at Lakvijaya power plant at Norochcholai [1].

Bulk power from Mahaweli hydro complex, Puttalam coal power station, Kerawalapitiya combined cycle power plant, and Mannar wind power are mostly transmitted via the 220 kV transmission network to major load centers via Biyagama, Pannipitiya, and New Chilaw, Padukka, Veyangoda and Kotugoda, New Polpitiya, New Habarana, Colombo Port grid substations (220 kV/132kV). Furthermore, the Kotmale power station's 220 kV transmission line Power transfer is facilitated by Mannar, Nadukuda, New Anuradhapura grid substations, which feed power to the Northern and Eastern parts of the country [1]

The 132kV transmission network acts mainly as an interconnection network in grid substations. In Sri Lanka, presently 220/ 132/ 33 kV grid substations are located at Biyagama, Kotugoda, Veyangoda, New Chilaw, New Anuradhapura, Pannipitiya, Kelanitissa New Habarana, Padukka, New Polpitiya and Colombo Port [1]

Table 4 illustrates the summary of Grid Substations (GSS) in present transmission network, while Table 5 shows the transmission-route lengths of the present transmission network in Sri Lanka according to the data published by [1]

Table 4: Summary of grid substations (GSS) present in the network [1]

Description	Number of GSS	Total Capacity (MVA)
132/33 kV (No./ Capacity [MVA])	62	4,883.50
220/132/33 kV (No./ Capacity [MVA])	4	1,600/380
220/33 kV (No./ Capacity [MVA])	6	624
132/11 kV (No./ Capacity [MVA])	8	792
220/132 kV (No./ Capacity [MVA])	9	4,010

Table 5: Transmission network line lengths [1]

Transmission Lines (Route length)	Length (km)
220 kV, Double circuit	807
220 kV, Single Circuit	20
220 kV, UG cable	22
132 kV, 4 Circuit	4
132 kV, Double Circuit	1,964
132 kV, Single Circuit	382
132 kV UG cable	54.8

3.2 System Modeling

Power system modeling could be considered as the preliminary step for all power system studies as it involves conducting power system performance assessments, calculation of operating limits, power system planning studies, and all the other power system studies. A power system model is generally an approximate mathematical representation of the generation, transmission, and loads along with a set of models detailing each part's characteristics of the power system.

Presently, there are several simulation software tools that can be used for transient simulations such as, Power System Simulator for Engineering (PSS/E), Power System Computer Aided Design (PSCAD), Digital Simulation and Electrical Network Calculation Program (DigSILENT) and Electrical Transient Analyzer Program (ETAP).

In this research, Sri Lankan power system was modeled using PSS/E Version 36 software. It was modelled as a reduced system, but with the consideration of real system based on the planning models used by the CEB Transmission and Planning branch.

3.2.1 Overview of PSS/E Software

PSS/E (Power System Simulator for Engineering) is a widely used software developed by Siemens PTI for power system analysis and planning, which facilitates load flow analysis, dynamic simulations, short circuit calculations, and stability assessments.

3.2.2 Steady State and Dynamic Analysis

In CEB, long-term transmission planning primarily relies on static and dynamic state analyses. Both steady-state and dynamic behavior assessments are critical for evaluating the impact of renewable energy integration on frequency stability. By conducting these analyses, it becomes possible to ensure that system stability is maintained under various disturbances and contingencies. Static analysis, also known as steady-state analysis, involves power flow studies that assess transformer loading, transmission line performance, and voltage profiles at bus bars when the power system is in equilibrium. In this state, power generation is equal to the sum of total load demand and system losses, ensuring a balanced operation.

However, to gain deeper insights into the power system's behavior under varying conditions, it is essential to conduct dynamic simulations. Dynamic stability analysis is performed in the time domain to evaluate the system’s response to sudden disturbances, such as the unexpected disconnection of critical generator units or multiple large power plants. Unlike static models, which assume steady-state conditions, dynamic models account for transient responses and control mechanisms within the power system. For instance, when a significant generation unit is tripped, dynamic analysis helps in understanding the subsequent frequency fluctuations and system recovery mechanisms.

In steady state modeling, all system components including transmission lines, shunt capacitors/reactors, transformers, generators, and loads—are represented using steady-state parameters. Transmission network elements are modeled based on accurately calculated ratings, impedances, and other electrical characteristics. Generators in steady-state models are defined by their active and reactive power capabilities, as well as voltage control characteristics. Load models can be represented as constant current, constant impedance, or constant power models (both active and reactive). These individual component models are integrated to develop a comprehensive representation of the Sri Lankan power system network.

Dynamic models are used to simulate the transient behavior of power plants and their associated control mechanisms. These models are crucial for assessing grid stability in response to disturbances and ensuring appropriate frequency and voltage regulation strategies. To maintain consistency between static and dynamic assessments, the parameters used in steady-state models must be compatible with those in their corresponding dynamic models. This integrated modeling approach allows for a more accurate and reliable evaluation of the power system's performance, particularly in the context of increasing renewable energy penetration.

3.3 Modeling of 2023 Reduced Sri Lankan Power System

Based on the data presented in Chapter 4 of the Long-Term Transmission Planning study, the reduced network model primarily focuses on the 220 kV transmission network. As illustrated in Figure 12, the single-line diagram provides a comprehensive representation of the key generation sources and their interconnections. The model incorporates three generating units from the Victoria Hydropower Station, along with two operational units from the Lakvijaya Power Plant at Norochcholai. Additionally, the system includes the barge-mounted power plant with a generation capacity of 60 MW.

The primary 220 kV transmission network considered in this model extends from Victoria to the Biyagama substation via the Kotmale and Upper Kothmale substations. From the Kothmale grid substation (GSS) it further extends towards New Anuradhapura through New Habarana and reaches Vavuniya and Mannar GSS, ensuring a realistic depiction of the country's major high-voltage corridors. Furthermore, the Kelanitissa, Kotugoda along with Pannipitiya and other Colombo related 220 kV networks have been incorporated to provide a holistic representation of Sri Lanka's transmission system. This comprehensive network model ensures that the study accurately reflects the operational characteristics and interconnections of the national grid, facilitating an effective analysis of the system stability.

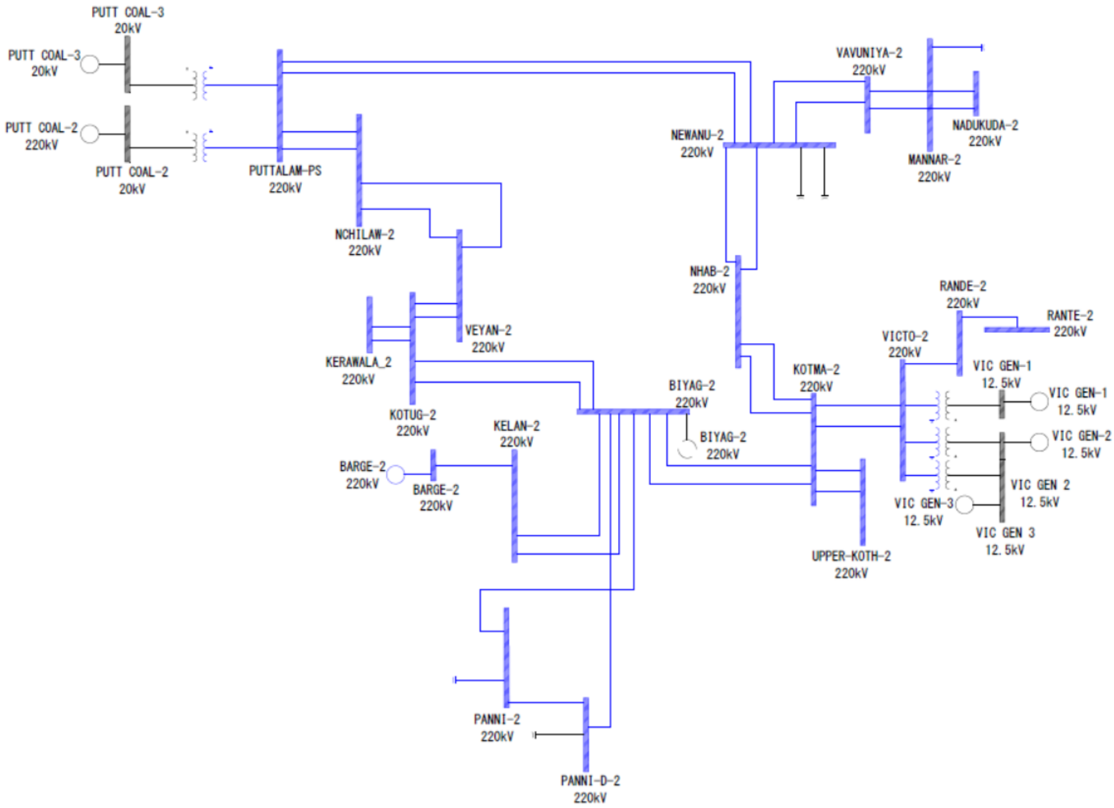

Figure 12: Single Line Diagram (SLD) of the reduced network model used in PSS/E

3.3.1 PSS/E Model Used for Simulations

According to the long-term transmission development plan report published by CEB for the year 2023 – 2032 period [1], the system studies were performed under ten generation and demand scenarios as illustrated in Table 6 and these options have been selected by considering the worst-case scenarios from the generation dispatch simulations carried out by transmission planning unit of CEB. The studies have been carried out under six generation scenarios and two demand scenarios. Under each of these scenarios, they have observed how the overall network responds to different contingencies and disturbances.

Table 6: Generation and loading scenarios [1]

Scenario	Load	Generation	2023	2025	2026	2028	2030	2032
Max RE	Day Peak (WE/WD)	RE	69	82	90	86	93	96
Max RE	Night Peak (WD)	RE	62	71	77	82	75	83
Max Solar	Day Peak (WE)	Solar	36	60	61	78	68	75
Max Wind	Off Peak (WE/WD)	Wind	17	21	46	56	59	68
Max Hydro	Night Peak (WE/WD)	Hydro	58	51	50	48	24	45
Max Hydro	Off Peak (WE/WD)	Hydro	33	51	57	51	44	58
Max Thermal	Off Peak (WE/WD)	Thermal	80	87	84	81	77	80
Max Demand	Day and Night Peak (WD)	MW	3006	3283	3428	4132	4343	4088
Min Demand	Off Peak (WE)	MW	1095	1137	1155	1265	1371	1506
Max Curtailment	Day Peak (WE)	MW		516	1005	2258	2900	3709

3.4 Model Validation

The simulation of future power system models is based on the validation of the existing power system for a critical failure event occurred recently. Therefore, modeling of 2019 power system was carried out for a more precise representation of actual system events. The information on operation records of generation power plants in 2019 Sri Lankan power system was obtained from the System Control Branch in CEB. These details were maintained by individual power generation stations and the Generation Planning Branch of CEB.

It is important to validate a power system model prior to performing steady state and dynamic power system analysis. By validating, it ensures that the developed model is up to date, accurate and does not have any mismatches with the actual network parameters. The model validation process could be explained as follows.

a) Data Collection
   - Gather field measurements (SCADA systems, disturbance recordings).

- Obtain generator excitation system, governor, and protection system parameters from the real system
- Collect system operating conditions data.

b) Base Case Development

- Develop a steady-state power flow case that matches system conditions during a disturbance.
- Ensure accurate load and generation dispatch.

c) Dynamic Simulation Setup

d) Simulation vs actual data comparison

- Simulate with known disturbances such as recreating a failure that happened in the network recently and compare the system behavior in real scenario with the simulated version (e.g., transmission line trip, generator outages).

In this research, since the 2023 reduced model of 220 kV network has been considered, it was a perfect platform to validate the model based on the total failure occurred around 17:00hrs on 09th December 2023 which involved all transmission lines, power stations and grid substations (GSS) in the Sri Lankan network. All this data was obtained by the preliminary report published by the Control and Protection branch of the transmission division, CEB [17]. Figure 13 illustrates the general overview of the tripped circuits. The two tripping events are as follows.

- Tripping of Biyagama – Kothmale line 1 & 2
- Tripping of Kothmale – New Habarana 1 followed by line 2

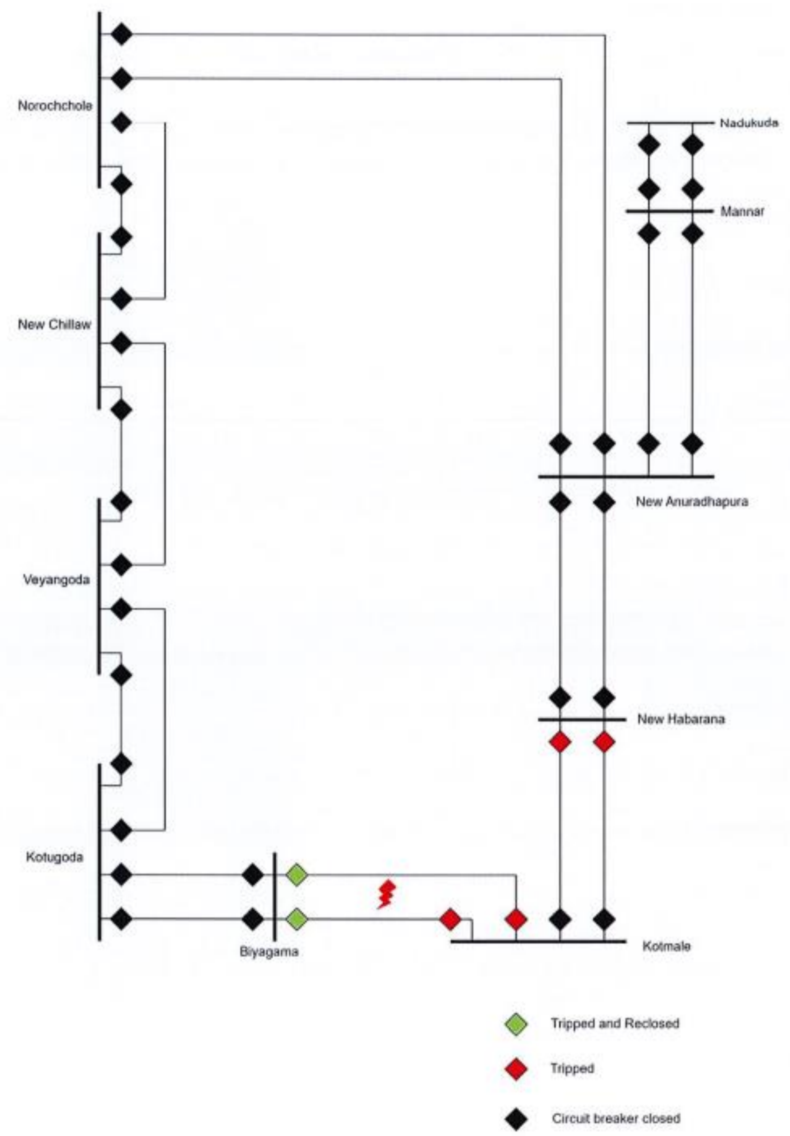

Figure 13: Overview of the tripped circuits during the failure [17].

Figure 14 shows how the frequency changed over time at the Biyagama 220kV system. It occurred after a number of transmission line trippings. The x- axis depicts the seconds lapsed from a fault initiation event, while the y- axis depicts system frequency in Hz.

Key observations

The start frequency of around 50Hz indicates that the system was stable before any disturbances occurred.

- First Event (Tripping Of Biyagama-Kothmale Lines 1 and 2, 17:02:48):
    - There are minor fluctuations to the frequency but the system manages to remain stable, fluctuating around the 50 Hz mark.
- Second Event (Tripping of Kothmale-New Habarana Lines 1 and 2 17:03:49-17:03:50):
    - The first line trips at 17:03:49 and the second line trips at 17:03:50.
    - After this sequence of occurrences, the system frequency experiences minor, yet noticeable, drops before hitting a constant low level.
- Final Collapse:
    - Around sixty seconds after the fault initiation, the system frequency drops deeming system collapse or islanding scenario

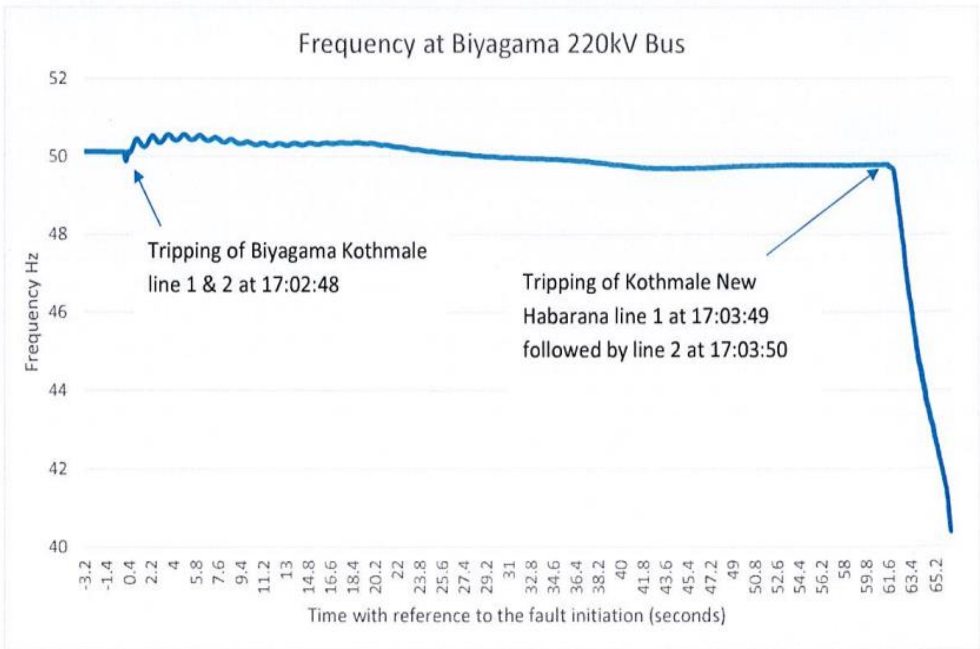

Figure 14: Frequency variation at Biyagama GSS during the failure [17]

When the similar two incidents were recreated in the reduced 2023 network model in PSS/E simulation software, the graph shown in Figure 15 was obtained.

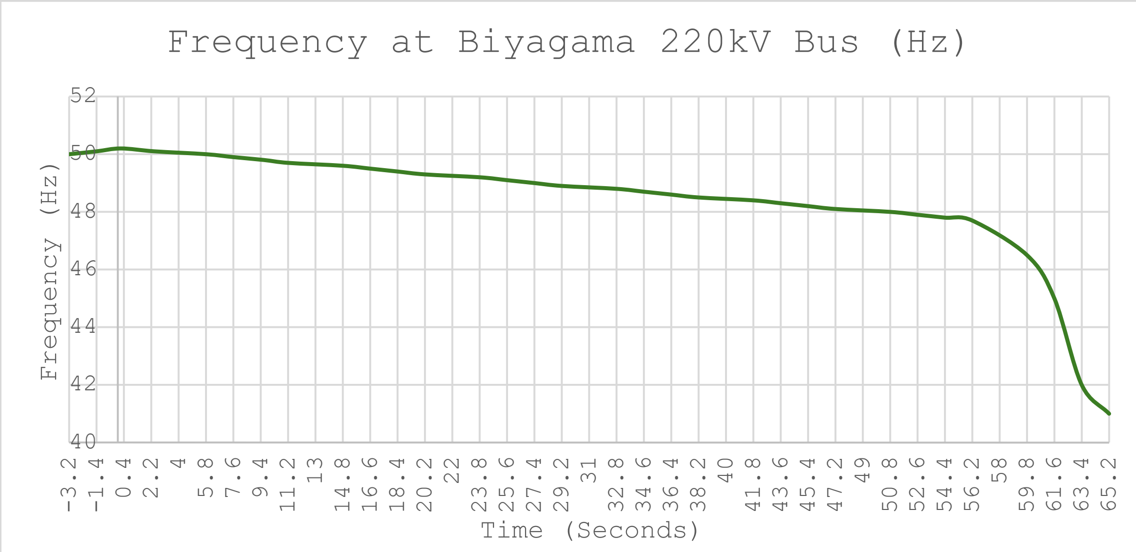

Figure 15: The Frequency of the fault recreated in PSS/E

Figure 14 and Figure 15 verify that the PSS/E simulation results and actual scenario are almost similar within a small margin of tolerance and follow the same frequency response patterns. Therefore, by considering all these tolerances, it can be concluded that the reduced network of Sri Lankan power system, which was modeled in PSS/E software is validated, and could be used to perform future system studies by modeling forecasted system data on the validated model.

Moreover, Table 7 summarizes the load flow calculations carried out for this reduced network used in this research study. It was identified that as per the allowable voltage variations announced by CEB in [1], all the values calculated in the load flow analysis fall within the allowable ranges by confirming its accuracy.

Table 7: Load flow data

Bus Name	Volt (PU)	Volt (KV)	Angle (Deg)	Gen (MW)	Gen (MVAR)	Load (MW)	Load (MVAR)
2220 KOTMA-2 220.00	1.015	223.000	-5.259	0.000	0.000	-292.863	-16.607
2222 BARGE-2 220.00	0.973	213.924	-10.966	58.913	37.000	0.000	0.000
2225 UPPER-KOTH-2 220.00	1.019	224.111	-4.677	0.000	0.000	-150.000	-38.026
2230 VICTO-2 220.00	1.019	224.086	-3.907	0.000	0.000	0.000	0.000
2240 RANDE-2 220.00	1.019	224.230	-3.465	0.000	0.000	-118.180	-1.944
2245 VAVUNIYA-2 220.00	1.005	220.982	-8.714	0.000	0.000	0.000	0.000
2250 RANTE-2 220.00	1.019	224.180	-3.509	0.000	0.000	41.382	7.035
2280 MANNAR-2 220.00	0.997	219.301	-8.839	0.000	0.000	12.630	1.699
2281 NADUKUDA-2 220.00	0.997	219.423	-8.843	0.000	0.000	0.000	0.000
2300 KELAN-2 220.00	0.972	213.863	-10.987	0.000	0.000	-28.613	33.578
2305 KERAWALA_2 220.00	0.974	214.227	-11.265	0.000	0.000	40.104	7.828
2560 PANNI-2 220.00	0.963	211.751	-12.031	0.000	0.000	213.959	76.676
2561 PANNI-D-2 220.00	0.963	211.751	-12.031	0.000	0.000	104.698	51.857
2570 BIYAG-2 220.00	0.969	213.221	-11.147	0.000	0.000	215.714	120.276
2580 KOTUG-2 220.00	0.972	213.837	-11.337	0.000	0.000	196.419	31.655
2691 NHAB-2 220.00	1.008	221.689	-8.243	0.000	0.000	75.645	4.191
2705 NEWANU-2 220.00	1.005	221.191	-8.594	0.000	0.000	194.487	17.537
2810 PUTTALAM-PS 220.00	1.010	222.200	-5.332	0.000	0.000	-13.642	6.517
2815 NCHILAW-2 220.00	0.984	216.563	-9.766	0.000	0.000	203.816	44.257
2830 VEYAN-2 220.00	0.975	214.433	-10.990	0.000	0.000	45.307	20.514
4230 VIC GEN-1 12.500	0.990	12.250	0.000	42.382	-5.953	0.000	0.000
4231 VIC GEN 2 12.500	1.020	12.750	2.300	70.000	22.207	0.000	0.000
4232 VIC GEN 3 12.500	1.020	12.750	2.259	70.000	22.305	0.000	0.000
4811 PUTT COAL-2 20.000	1.022	20.430	0.316	260.000	57.977	0.000	0.000
4812 PUTT COAL-3 20.000	0.996	19.922	0.583	260.000	57.977	0.000	0.000

3.5 Power Flow Data Entry in PSS/E

Before carrying out the simulations, it is important to identify each of the parameters, model specifications and data used in the simulations to ensure its accuracy with the actual system.

1. Case Identification data: consists of system MVA base, Units of transformer ratings, Units of ratings of non-transformer branches, System base frequency in Hertz
2. Bus data: In PSS/E, each network bus is represented with Bus number, Bus Name, base Voltage data, Bus type
3. Load data: In PSS/E, each load is represented with Bus number, Load Identifier, Load status, and the machine data. Load bus, generator bus swing bus are the types of buses used to model the power system.
4. Fixed Bus Shunt data: Each fixed shunt bus in PSS/E is represented with Bus number, Identifier, Shunt status.
5. Generator data: Each generator in PSS/E is represented as a generating unit or plant bus with Bus number, Identifier and the machine data.
6. Non-Transformer Branch data: Branches in the network which are modeled without transformers are specified in this data category. Branch from bus number, Branch to bus number, Branch resistance, Branch reactance, Rating data, complex admittance, branch status, line length are the details to be included for this category.
7. Transformer data: Each ac transformer is represented with bus number, winding data, impedance data, magnetizing admittance data, transformer status.

3.6 Power System Dynamic Modeling in PSS/E

Dynamic models in the PSS/E library can be categorized as per the information provided in [18]

1. Device Models: These models are attached with corresponding equipment in power flow models such as generator models, excitation models, turbine governor models, load characteristic models, etc.
2. Protection Models: Load relay models which are used to model LSS are categorized as protection models. Machine and wind machine protection models are also included in this model category.
3. Miscellaneous Other Models: Under voltage or over voltage generator bus disconnection or trip relays, under frequency or over frequency generator bus disconnection or trip relays, transformer saturation models, switched capacitor bank models are categorized into this type.
4. Data Models: CONS, VARS, ICONS, channels are categorized into this type.

The power system dynamic modeling of the Sri Lanka power system for the year 2023 was carried out under three main categories: Hydro power plant modeling, thermal power plant modeling and solar power plant modeling.

3.6.1 Hydropower Plant Modeling

All large hydro and mini hydro power plants considered in the reduced network were modeled as discussed in this section. Mainly, a hydro power plant consists of Generator model, Turbine-Governor model and Excitation System model in PSS/E [18] power system dynamic modeling.

Generator Model – GENSAL

PSS/E model library includes a family of generator models [18], which allows to model different levels of generator effects based on the requirement. In this research, synchronous generators were used to model hydro power stations. Therefore, GENSAL model in PSS/E was used.

Turbine-Governor model – HYGOV, PIDGOV

Generally, for modelling the hydro turbine governors there exists two types in PSS/E namely, HYGOV and PIDGOV models. The PIDGOV was selected for this study considering the existing governor type at the Victoria power plant, which supports the frequency control.

Excitation System model – SEXS, SCRX, ESAC1A and ESST1A

PSS/E dynamic model library provides standard IEEE excitation models to match the requirement of the user to model the power network dynamic characteristics. Victoria, power plant should be represented by a simple excitation system model. Simplified Excitation System model in PSS/E dynamic model library provides to represent typical conservative response characteristics for this purpose. The following could be considered as the key components of a simplified excitation system

- Voltage Reference (V_{ref})
- Voltage Comparator (Error Signal Calculation)
- Automatic Voltage Regulator (AVR)
- Exciter
- Generator Field Winding

3.6.2 Thermal Power Plant Modeling

All thermal power plants modelling was done as discussed below. Similar to hydro power plants, thermal power plants also consist of the Generator model, Turbine-Governor model, and Excitation System model in PSS/E power system dynamic modeling.

Generator model - GENSROU

The GENROU (Round Rotor Generator Model) in PSS/E represents a detailed sixth-order synchronous generator model, specifically for round rotor (cylindrical rotor) synchronous machines, commonly used in thermal power plant. And the similar model has been adopted in modelling the Norocholoai power plant.

Steam Turbine - Governor Model – TGOV1

TGOV1 model in PSS/E dynamic model library is used for modeling coal fired power plant in Norochcholai coal power plant.

3.6.3 Solar Power Plant Modeling

The solar power plant designed in Chapter 4 of this research study is modeled as discussed in this section. Solar power plants consist of a power converter or a generator model (PVGU) and an electrical control model (PVEU). Other two models are introduced specifically for solar power plants. They are a linearized model of a panel's output curve module (PANEL) and a linearized solar irradiance profile (IRRAD). [18].

These modules are under Photovoltaic (PV) Generic Model category in PSS/E power system dynamic modeling for solar power plants. The PV model connectivity diagram is illustrated in Figure 16.

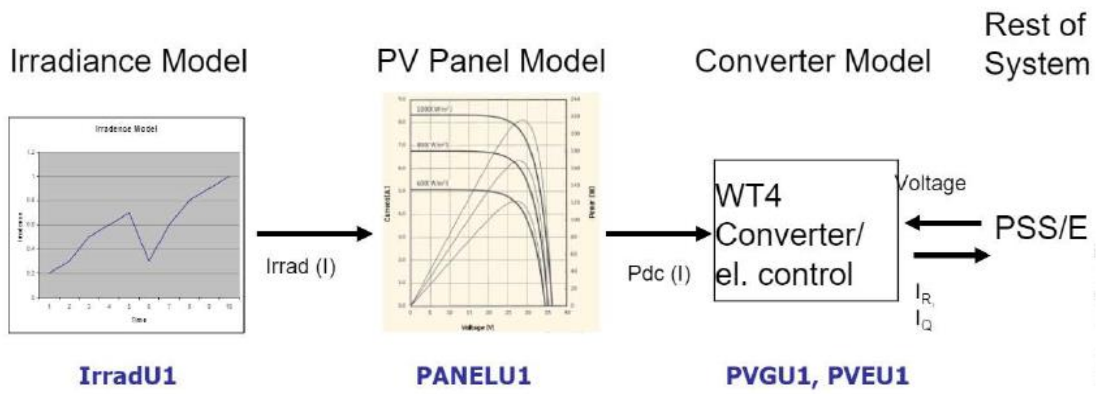

Figure 16: PV connectivity diagram for solar dynamic modeling [18]

Power Converter or Generator Model – PVGU1 (PV Converter)

The parameters of PVGU1 model are similar to the parameters of WT4G1 wind generator model [18]. The block diagram in Figure 17 represents a voltage and reactive power control system for a wind turbine generator (WTG) or a similar renewable energy system. Below is an explanation of the key components and their functions:

Key Components and flow

- WIQCMD: This represents the reactive power command received from a higher-level control system (e.g., grid or turbine model).
- WIPCMD: This represents the active power command from the grid/turbine model.

- Both WIQCMD and WIPCMD pass through first-order transfer function.
- Voltage Compensation (VCOMP)
- The Low Voltage Power Logic (LVPL) block ensures that power is adjusted based on terminal voltage.
- It uses voltage levels (V1, V2, and V3) and corresponding power levels (P1, P2, P3) to determine how much power should be reduced when voltage drops.

Final Output

This is the final reactive current output of the system, which is injected into the grid to stabilize voltage.

The system maintains proper reactive power support based on grid voltage conditions.

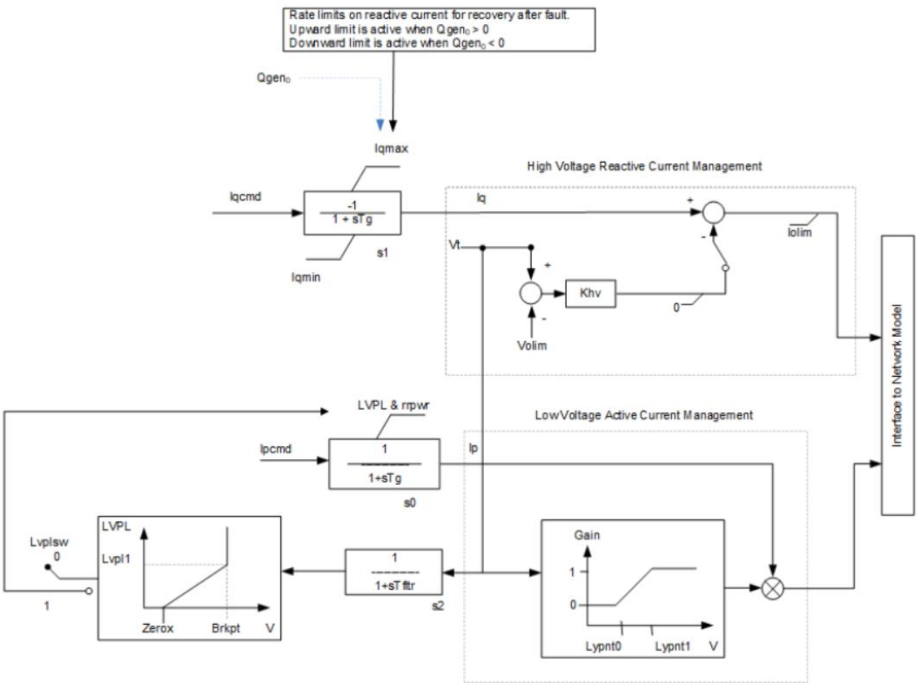

Figure 17: Generator block diagram of PV converter [18]

Electrical Control Model – PVEU1 (Electrical Control model for converter)

The PVEU1 model in Figure 18 in PSS/E is used to simulate the electrical control dynamics of a grid-connected photovoltaic (PV) This model represents the voltage and reactive power control functions of a PV system, focusing on how the inverter responds to voltage deviations and grid conditions.

Key Functions of PVEU1 Model:

- Voltage Regulation:
    - Controls the reactive power (Q) output of the inverter to maintain voltage stability at the point of interconnection (POI).
- Reactive Power Control:
    - Reactive power support is based on system conditions and grid voltage variations.
- Low Voltage Ride-Through (LVRT):
    - Ensures the inverter remains connected and provides reactive power support during voltage dips (fault conditions).

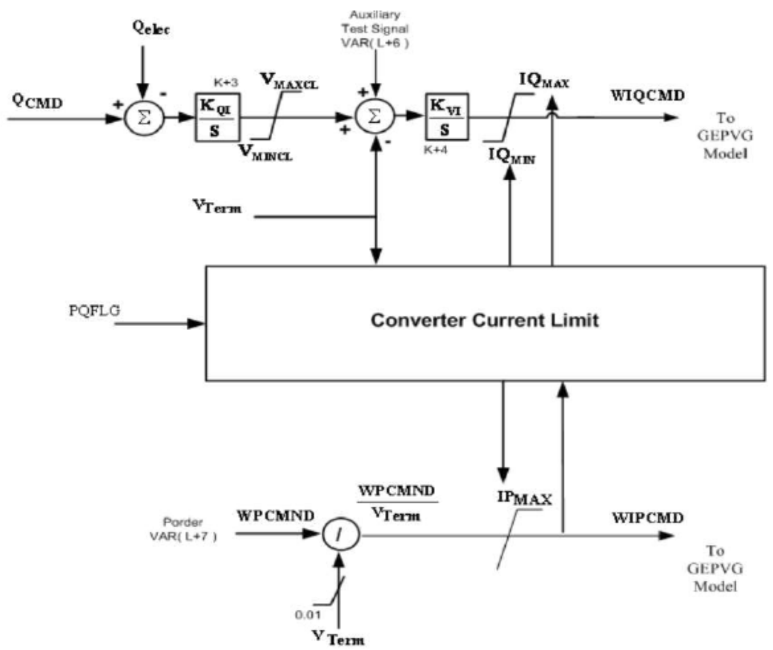

Figure 18: Electrical control model block diagram [18]

Linearized Model of a Panel's Output Curve – PANELU1

The parameters of the Linearized Model of a Panel's Output Curve and PV Irradiance profile are provided in Table 8 and 9 respectively.

Table 8: Panel output curve parameters [18]

Parameter	Description
PDCMAX200	Maximum Power of Solar Panel at an Irradiance Level of 200 W/m^2 (pu on PDCMAX1000 base)
PDCMAX400	Maximum Power of Solar Panel at an Irradiance Level of 400 W/m^2 (pu on PDCMAX1000 base)
PDCMAX600	Maximum Power of Solar Panel at an Irradiance Level of 600 W/m^2 (pu on PDCMAX1000 base)
PDCMAX800	Maximum Power of Solar Panel at an Irradiance Level of 800 W/m^2 (pu on PDCMAX1000 base)
PDCMAX1000	Maximum Power of Solar Panel at an Irradiance Level of 1000 W/m^2 (pu on PDCMAX1000 base)

Linearized Solar Irradiance Profile – IRRADU1 (PV Irradiance profile)

Table 9: Irradiance parameters [18]

Parameter	Description
Time1	Time of Data Point 1 (sec)
Irradiance1	Irradiance Level at Data Point 1 (W/m^2)
Time2	Time of Data Point 2 (sec)
Irradiance2	Irradiance Level at Data Point 2 (W/m^2)
Time3	Time of Data Point 3 (sec)
Irradiance3	Irradiance Level at Data Point 3 (W/m^2)
Time4	Time of Data Point 4 (sec)
Irradiance4	Irradiance Level at Data Point 4 (W/m^2)
Time5	Time of Data Point 5 (sec)
Irradiance5	Irradiance Level at Data Point 5 (W/m^2)
Time6	Time of Data Point 6 (sec)
Irradiance6	Irradiance Level at Data Point 6 (W/m^2)
Time7	Time of Data Point 7 (sec)
Irradiance7	Irradiance Level at Data Point 7 (W/m^2)
Time8	Time of Data Point 8 (sec)
Irradiance8	Irradiance Level at Data Point 8 (W/m^2)
Time9	Time of Data Point 9 (sec)
Irradiance9	Irradiance Level at Data Point 9 (W/m^2)
Time10	Time of data point 10 (sec)
Irradiance10	Irradiance level at data point 10 (w/m^2)

CHAPTER 4

FLOATING SOLAR PV DESIGN FOR VICTORIA RESERVOIR

In Sri Lanka, electricity demand will grow from around 17,000 GWh to 42,000 GWh, and peak power demand from 3,000 MW to just over 7,000 MW from 2020 to 2039 [5]. Around 11,000 MW of new generation is planned to be added to the system by 2039 while replacing the aging plants by that time. Therefore, it is necessary to analyze the potential of moving to Floating Solar PV plants (FSPV) since it has some significant advantages. Sri Lanka has over 2,900 km^2 of large inland water bodies. By using only 10% of this surface area for FSPV would provide enough energy to meet the total forecasted national electricity demand in 2039.

Table 10 : Reservoirs with FSPV development potential [5]

ID	Name	Primary function	ID	Name	Primary function
A.1	Upper Kotmale	Irrigation	A.23	Nachchaduwa	Irrigation
A.2	Kotmale	Irrigation	A.24	Nuwarawewa	Irrigation
A.3	Morogolla Pond	Irrigation	A.25	Tissawewa	Irrigation
A.4	Polgolla Barrage	Irrigation	A.26	Huruluwewa	Irrigation
A.5	Victoria	Irrigation	A.27	Giritale	Irrigation
A.6	Randenigala	Irrigation	A.28	Minneriya	Irrigation
A.7	Rantambe	Irrigation	A.29	Kantale	Irrigation
A.8	Bowatenna	Irrigation	A.30	Venderasan	Irrigation
A.9	Moragahakanda	Irrigation	A.31	Chandrika Lake	Irrigation
A.10	Castlereigh	Power	A.32	Kaudulla	Irrigation
A.11	Mousakele	Power	A.33	Parakrama Samudraya	Irrigation
A.12	Canyon Pond	Power	A.34	Nialmbe	Power
A.13	Norton Pond	Power	A.35	Senanayake Samudraya	Irrigation
A.14	Laxapana Pond	Power	A.36	Ulhitiya/Ratkinda	Irrigation
A.15	Kehelgamu Weir	Power	A.37	Kukule	Power
A.16	Main Dam	Power	A.38	Maduru Oya	Irrigation
A.17	Samanalawewa	Power	A.39	Uma Oya	Power
A.18	Uda Walawe	Irrigation	A.40	Gregory Lake	Leisure
A.19	Dambulu Oya	Irrigation	A.41	Iranamadu	Irrigation
A.20	Kandalama	Irrigation	A.42	Kalu Ganga	Irrigation
A.21	Kalawewa	Irrigation			
A.22	Rajanagana	Irrigation			

Along with CEB and other authorities such as PUCSL, the government of Sri Lanka (GOSL), have identified around 40 reservoirs that might contain the potential for FSPV installation. Table 10 presents a long list of identified reservoirs for FSPV, and their primary functions.

The targeted installed capacity of around 100 MWp is considered appropriate to achieve economies of scale and make a significant contribution to the generation expansion plan. This indicates that the reservoirs should have a surface of at least 100 ha, based on the assumption/ approximation that 1 ha can accommodate 1 MWp of FSPV [5] Among the candidate reservoirs, 23 were identified to match with this criterion. Figure 19 illustrates the map of the finally selected water body locations, which has got the potential to install FSPV plants with at least 100 MWp capacity.

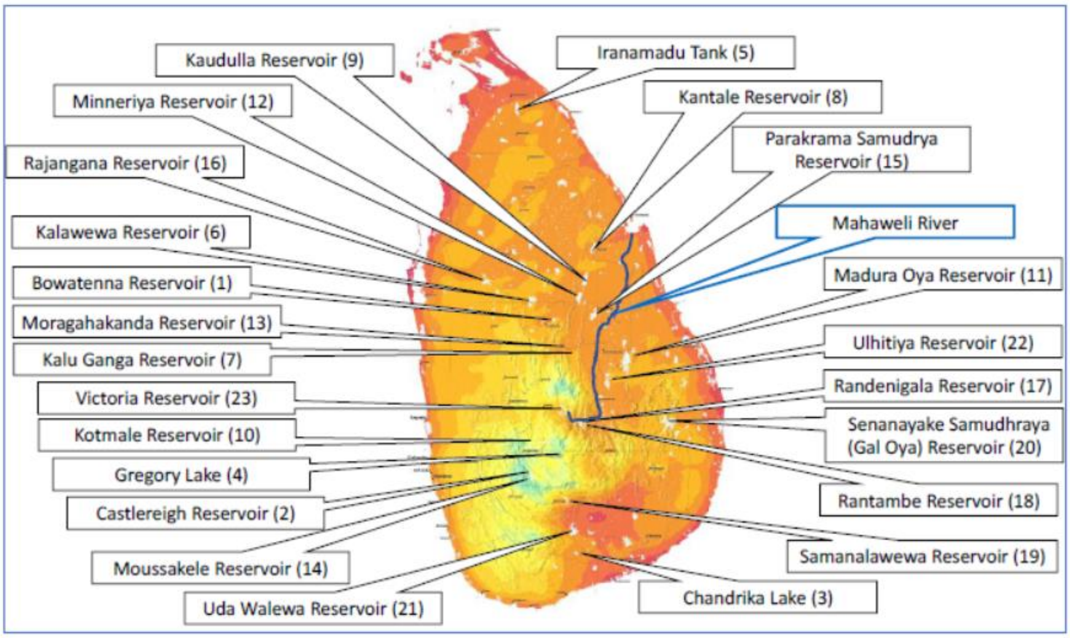

Figure 19: Map of selected water body locations [5]

4.1 Data Acquisition

It is essential to acquire important data related to the reservoir prior to the designing of the FSPV. Since this research work is a case study carried out for Victoria reservoir, the data was captured mainly from the following sources and authorities.

- Mahaweli Authority of Sri Lanka (MASL)
- Ceylon Electricity Board (CEB)
- Irrigation Department, Ministry of Irrigation, Sri Lanka (IDSL)

Most of the reservoirs in Sri Lanka are used primarily for irrigation purposes and has the ability to be drawn down until almost empty to supply irrigation water in very dry seasons. Some of the reservoirs that belong to Mahaweli Authority, generates hydropower with the released water, but the minimum level for hydropower generation is typically higher than for irrigation release. Hence, the surface area at the minimum level for irrigation is the parameter that governs how much FSPV can be installed.

Another important parameter that should be considered when developing a FSPV is the range of water levels. For all these reservoirs it is the difference between full supply levels by maintaining an allowance of 2.0 m for flood surcharge while the minimum drawdown level for irrigation is also should be maintained. Based on these factors, Table 11 depicts the reservoirs, which have the potential for FSPV development along with the possibility to operate in conjunction with existing hydropower plant. In addition, it shows the key electrical characteristics of the selected plants too. Whereas Table 12 illustrates the key reservoir characteristics identified by the floating solar energy analysis study carried out by the World Bank Group (WBG). Therefore, it is essential to consider these important parameters when sizing the floating solar plant at the Victoria power station.

Table 11: Proposed FSPV capacities and key electrical parameters [5]

ID	Name	Hydro Plant Name	Installed Capacity (MW)	Average Energy (GWh pa)	Plant Factor (%)
1	Bowatenna	Bowatenna	40	48	14%
2	Castlereigh	Wimalasurendra	50	112	26%
3	Chandrika Lake	Blackpool	0	0	0%
4	Gregory Lake	N/A	0	0	
5	Iranamadu	N/A	0	0	
6	Kalawewa	N/A	0	0	
7	Kalu Ganga	N/A	0	0	
8	Kantale	N/A	0	0	
9	Kaudulla	N/A	0	0	
10	Kotmale	Kotmale	201	498	28%
11	Maduru Oya	Moya Left Bank	5	15.5	35%
12	Minneriya	N/A	0	0	
13	Moragahakanda	Moragahakanda	25	70	32%
14	Moussakele	Canyon	60	160	30%
15	Parakrama Samudra	N/A	0	0	
16	Rajangana	N/A	0	0	
17	Randenigala	Randenigala	122.6	454	42%
18	Rantambe	Rantambe	50	239	55%
19	Samanalawewa	Samanalawewa	120	344	33%
20	Senanayake Samudra	Inginiyagala	11	38	39%
21	Uda Walawe	Uda Walawe	6	21	40%
22	Ulhitiya	N/A	0	0	
23	Victoria	Victoria	210	865	47%

Table 12: Key reservoir characteristics [5]

ID	Name	Surface Area at Full Supply Level (ha)	Surface Area at Min. Operating Level (ha)	Water Level Range (m)
1	Bowatenna	470	20	13.9
2	Castlereigh	368	294	21.2
3	Chandrika Lake	357	68	10.6
4	Gregory Lake	40	40	6
5	Iranamadu	2000	500	17
6	Kalawewa	2480	13	12.4
7	Kalu Ganga	840	400	29.5
8	Kantale	2430	10	13.8
9	Kaudulla	2700	970	9.7
10	Kotmale	635	1	75
11	Maduru Oya	6390	2219	13.5
12	Minneriya	2550	91	13.6
13	Moragahakanda	2926	669	32
14	Moussakele	724	169	23.9
15	Parakrama Samudra	2500	647	10.3
16	Rajangana	1600	323	12.7
17	Randenigala	2350	740	55.8
18	Rantambe	117	1	20
19	Samanalawewa	975	314	38
20	Senanayake Samudra	7790	135	20.3
21	Uda Walawe	3413	670	15.4
22	Ulhitiya	2220	1110	8.1
23	Victoria	2370	75	55.5

4.2 FSPV System Design for Victoria Reservoir

As outlined above, the design process assesses the smallest surface area of these reservoirs when they are drawn down to their minimum operating level during extremely dry periods. Most of the reservoirs that belong to the Mahaweli area, the minimum level is generally governed by the irrigation outlet, which is typically lower than the hydropower outlet.

Based on these crucial factors and with the use of Google Earth facility, the Victoria reservoir, which is having 75 ha of pond area at Minimum Operating Level (MOL), which is the worst-case water level is a potential location to develop a FSPV system. The critical reservoir factors that should be considered are discussed below, and Table 13 and 14 presents the corresponding values for the identified reservoirs.

Reservoir operating range – Since the priority of most of the reservoirs is to regulate the water flows. The operating range for irrigation is typically greater than that for hydropower. It is therefore the operating range for irrigation that needs to be considered when designing the floating solar facility.

Reservoir Depth – For the typical anchoring mechanisms used presently the maximum water depth is around 90 m. One of the challenges FSPV development at Victoria reservoir is the depth. However, it might be possible to locate the floating solar facility to avoid the deepest parts of the reservoir.

Area at Minimum Operating Level (MOL) – Minimum Operating Level (MOL) is known as the surface area remaining when the reservoir is drawn down to its lowest level.

Table 13: Minimum Operating Level (MOL) data [5]

Rank	Name	Area at MOL irrigation (ha)
1	Maduru Oya	2219
2	Ulhitiya	1110
3	Kaudulla	970
4	Randenigala	740
5	Uda Walawe	670
6	Moragahakanda	669
7	Parakrama Samudra	647
8	Iranamadu	500
9	Kalu Ganga	400
10	Rajangana	323
11	Samanalawewa	314
12	Castlereigh	294
13	Moussakele	169
14	Senanayake Samudra	135
15	Minneriya	91
16	Victoria	75
17	Chandrika Lake	68
18	Gregory Lake	40
19	Bowatenna	20
20	Kalawewa	13
21	Kantale	10
22	Kotmale	1
23	Rantambe	1

Table 14: Reservoir range data [5]

Rank	Name	Range (m)
1	Gregory Lake	6
2	Ulhitiya	8.1
3	Kaudulla	9.7
4	Parakrama Samudra	10.3
5	Chandrika Lake	10.6
6	Kalawewa	12.4
7	Rajanagna	12.7
8	Maduru Oya	13
9	Minneriya	13.6
10	Kantale	13.8
11	Bowatenna	13.9

12	Uda Walawe	14
13	Iranamadu	17
14	Rantambe	20
15	Samanayake Samudra	20.3
16	Castlereigh	21.2
17	Moussakale	23.9
18	Kalu Ganga	29.5
19	Moragahakanda	30
20	Samanalawewa	38
21	Victoria	55.5
22	Randenigala	55.5
23	Kotmale	75

4.2.1 FSPV Sizing Methodology

It is important to determine the area that is potentially available for the FSPV development, the area of the floats, and net area of the panels. Table 15 gives the reasonable margins that should be allowed within the designated area for arrangement of FSPV facility, and the spacing on the floats for walkways, inverters and other components.

Table 15: Percentage allocations [5]

Description	Value
Percentage of facility occupied by floats	68%
Percentage of float area occupied by panels	82%
Net area of panels as % of FSE area	56%

For this research the PV module datasheet given in Appendix C has been adopted, which is taken from one of the reputed solar PV module manufacturers known as Trina Solar. The 620Wp module with an efficiency of 22.7% was selected. It comprises a dimension of 2.384 m × 1.134 m with a power output of 620 Wp. Table 16 and 17 presents the key electrical and mechanical characteristics of the selected PV module under Standard Test Conditions (STC).

Table 16 : Trina Solar PV module electrical characteristics

Pmax (Wp)	**Vmp (V)**	**Imp (A)**	**Voc (V)**	**Isc (A)**	**Module Efficiency (%)**
595	40	14.89	48.1	15.75	22
600	40.3	14.91	48.4	15.8	22.2
605	40.5	14.94	48.7	15.83	22.4
610	40.8	14.96	49	15.86	22.6
615	41.1	14.98	49.3	15.89	22.8
620	41.4	14.99	49.6	15.91	23

Table 17: Trina Solar PV module mechanical characteristics

Rear Power Gain	**Pmax (Wp)**	**Vmp (V)**	**Imp (A)**	**Voc (V)**	**Isc (A)**
5%	620	39.7	15.6	47.8	16.51
10%	649	39.7	16.35	47.8	17.29
5%	625	40	15.63	48.1	16.55
10%	655	40	16.32	48.1	17.34
5%	630	40.3	15.66	48.4	16.59
10%	661	40.3	16.4	48.4	17.38
5%	635	40.5	15.69	48.7	16.62
10%	667	40.5	16.43	48.7	17.41
5%	640	40.8	15.71	49	16.65
10%	673	40.8	16.45	49	17.45
5%	645	41.1	15.73	49.3	16.68
10%	677	41.1	16.48	49.3	17.48

In addition to the above outlined design criteria, the feasibility study carried out in [5], it further elaborates the overall design steps in a flow chart which is shown in Figure 20. The basic design criteria related to my research is based on this design steps that has been discussed in [5].

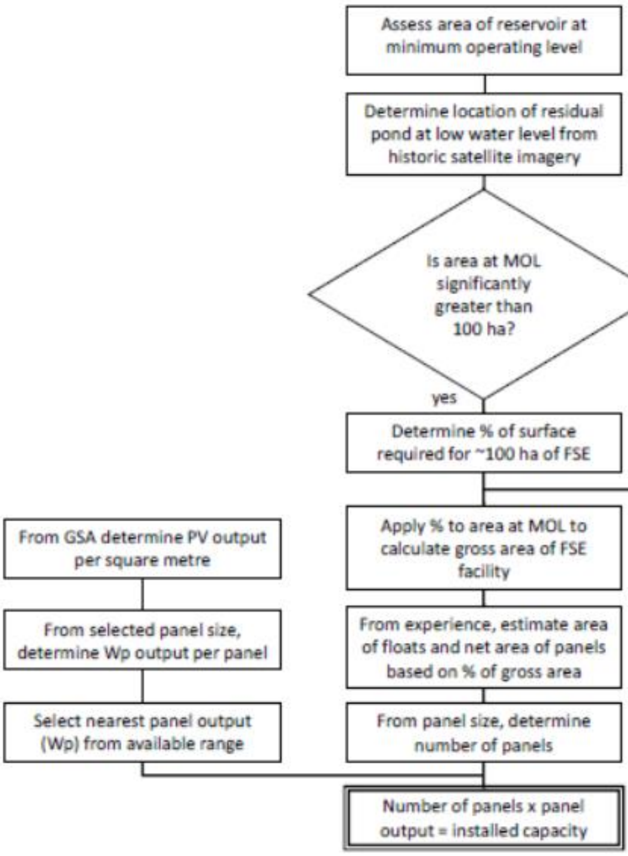

Figure 20: FSPV sizing methodology [5]

Based on the feasibility study carried out by the World Bank Group in assessing the FSPV development for Sri Lanka, the area available for the FSPV plant, the area occupied by floats and the net area of the PV panels is summarized, along with the number of panels proposed in Table 18. However, the World Bank Group report has considered a low efficient PV module for the study, it is crucial to re-calculate the values to arrive at accurate PV plant sizing figures. According to Table 18, Kothmale and Rantambe reservoirs do not possess a potential area for the deployment of a FSPV plant as both these reservoirs comprise with a surface area of 1 hectare at the minimum operating level (MOL). Hence, developing a FSPV plant at these two locations is not a feasible option.

Table 18: PV modules that can be accommodated at each location [5]

ID	Name	Area at MOL (ha)	% for PV	Area of Facility (ha)	Area of Floats (ha)	Net Area of Panels (ha)	No of panels
1	Bowatenna	20	0.95	19	12.92	10.59	54599
2	Castlereigh	294.4	0.35	103.04	70.07	57.46	296099
3	Chandrika Lake	68.1	0.95	64.7	43.99	36.07	185910
4	Gregory Lake	40	0.52	20.8	14.14	11.6	59772
5	Iranamadu	500	0.21	105	71.4	58.55	301732
6	Kalawewa	13	0.95	12.35	8.4	6.89	35489
7	Kalu Ganga	400	0.25	100	68	55.76	287363
8	Kantale	10	1	10	6.8	5.58	28736
9	Kaudulla	970	0.11	106.7	72.56	59.5	306617
10	Kotmale	1.3	Not enough space for FSPV development				
11	Maduru Oya	2219	0.05	110.95	75.45	61.87	318830
12	Minneriya	91	0.95	86.45	58.79	48.2	248426
13	Moragahakanda	669	0.15	100.35	68.24	55.96	288369
14	Moussakale	169	0.6	101.4	68.95	56.54	291387
15	Parakrama Samudra	647	0.16	103.52	70.39	57.72	297479
16	Rajanagna	323	0.32	103.36	70.28	57.63	297019
17	Randenigala	740	0.15	111	75.48	61.89	318973
18	Rantambe	1	Not enough space for FSPV development				
19	Samanalawewa	314	0.32	100.48	68.33	56.03	288743
20	Senanayake Samudra	175	0.75	101.25	68.85	56.46	290955
21	Uda Walawe	670	0.15	100.5	68.34	56.04	288880
22	Ulhitiya	1110	0.1	111	75.48	61.89	318973
23	Victoria	75	0.9	67.5	45.9	37.64	193970

Therefore, based on all these values outlined according to [5]and its design steps, a similar approach was considered to size the FSPV proposed for Victoria reservoir.

Area at MOL – i.e 75 ha [5]

From Table 16 the net area available for FSPV modules is 56% = 67.5 ha x 0.56 = 42 ha

Based on the mechanical parameters given in the datasheet attached in Appendix C**.** The 620 Wp **Trina solar Vertex N series (TSM-NEG19RC.20)**, has a dimension of 2384×1134×30 mm which indicates that each module has an effective area of 2.8 m^2.

Based on this, Total number of modules that could be placed on the Victoria reservoir will be, **150,000 nos. of 620 Wp modules**

Therefore, the total FSPV capacity that could be installed at the Victoria Reservoir is,

93 MWp

4.2.2 Energy Calculation for the Proposed FSPV at Victoria Reservoir

The PVSyst version 6.8.8 simulation software tool was used to determine the energy generation for the proposed FSPV facility development at Victoria reservoir. PVSyst is a comprehensive software tool designed for sizing, simulation, and analysis of photovoltaic (PV) systems. Widely used by researchers, engineers, and solar energy professionals, it offers detailed modeling capabilities for grid-connected, standalone, and hybrid PV systems. The software provides an interface for designing system layouts, performing energy yield assessments, and analyzing various losses affecting system performance.

PVSyst includes a robust database featuring meteorological data, PV module and inverter specifications, as well as user-defined parameters for detailed simulations. Its tools support shading analysis, financial evaluations, and system optimization, allowing users to predict energy output under different conditions. With its advanced modeling and reporting features, PVSyst plays a crucial role in optimizing solar power projects for both feasibility studies and operational efficiency assessments.

Based on the capacity calculation outlined above, all the required data was given as an input to the PVSyst software.

The PVsyst report provides a detailed analysis of the Floating Solar Photovoltaic (FSPV) Plant Sizing for a grid-connected system in Teldeniya, Sri Lanka area, which is the weather data captured for Victoria reservoir. The report presents the technical parameters, simulation results, system performance, and loss analysis for the designed FSPV system over a 20-year operational period. Below is a summary of the key findings from the report.

1. System Specifications & Configuration
    - Project Location: Teldeniya, Sri Lanka
    - System Type: Grid-connected FSPV (No shading or 3D scene defined)
    - PV Module Model: Trina Solar TSM-620NEG19RC.20 (Mono-Si, 620 Wp)
    - Total Number of PV Modules: 150,000
    - Total Installed Capacity: 93,000 kWp (at STC), with an operational power of 86,431 kWp at 50°C
    - Tilt & Orientation: Tilt angle 7°, Azimuth 180°
    - Inverter Model: Sungrow SG3000HV
    - Number of Inverters: 27 units
    - Total Inverter Capacity: 81,000 kW AC
2. Energy Generation & Performance
    - Annual Energy Production: 133,520 MWh/year
    - Specific Yield: 1,436 kWh/kWp/year
    - Performance Ratio (PR): 80.8%, indicating efficient system performance
    - Monthly Production: Ranges from 9,789 MWh (December) to 13,400 MWh (March)
3. Loss Analysis & Efficiency Factors

The report details various loss factors that impact system performance, including,

- PV Array Losses
- Thermal Loss: 7.80% (Degradation over 20 years)
- Ohmic Wiring Loss: 1.04%
- Mismatch Loss: 3.56% (due to degradation dispersion)
- Module Degradation Loss: 7.80% (Over 20 years)

Inverter Losses

- Operational Efficiency Loss: 1.23%

External Transformer Loss: 1.10%

4. System Balances & Grid Injection
   - Total Global Horizontal Irradiation (GHI): 1,802 kWh/m²
   - Effective Global Irradiation on PV Modules: 1,754 kWh/m²
   - Annual Energy Injected into the Grid: 133,520 MWh
   - Energy Output Distribution: A daily production pattern is provided, with peak energy injection into the grid occurring during midday hours.

Appendix E and Appendix F indicate the key results generated from the PVSyst report.

Key Observations & Implications

High Performance Ratio (80.8%) indicates that the system is optimized for energy production. The use of a FSPV system on a reservoir reduces land usage and benefits from the cooling effect of water, leading to improved efficiency.

Complementary Operation with Hydro Power - Since the system is designed for grid injections, it could effectively work in conjunction with the existing hydropower infrastructure, ensuring stable energy supply even during fluctuating solar conditions.

The PVSyst energy calculation report serves as a comprehensive feasibility study for integrating floating solar PV with Sri Lanka's energy grid and provides key technical insights into system efficiency

4.3 System Integration

It has been identified that in practical scenario, only Victoria hydropower can be operated complementarily with the FSPV, since it has a large re-regulating reservoir downstream [5]. At all the other hydropower stations, the need to release irrigation water may require the hydro plant to operate simultaneously with the FSPV. The ability of the FSPV to integrate efficiently into the grid network, and to operate in complementary mode will be a viable option only if it has a strong connection to the grid with a shortest distance. This is most likely to be achieved if the proposed FSPV is connected directly to the 220 kV grid or connected to a 132kV grid substation that has a direct link to the 220 kV grid. Table 19 shows the hydro power plants, which have a strong link to the 220 kV network.

Table 19: Hydropower plants with strong links to 220kV network [5]

ID	Name	Conjunctive with Hydro	Conjunctive Hydro	Strong link to 220kV
1	Bowatenna	No	No	No
2	Castlereigh	No	Yes	Yes
3	Chandrika Lake	No	No	Yes
4	Gregory Lake	No	No	No
5	Iranamadu	No	No	No
6	Kalawewa	No	No	No
7	Kalu Ganga	No	No	No
8	Kantale	No	No	No
9	Kaudulla	No	No	No
10	Kotmale	Yes	No	No
11	Maduru Oya	No	No	No
12	Minneriya	No	No	No
13	Moragahakanda	No	No	No
14	Moussakale	Yes	Yes	Yes
15	P' Samudra	No	No	Yes
16	Rajanagna	No	No	No
17	Randenigala	Yes	Yes	Yes
18	Rantambe	Yes	No	Yes
19	Samanalawewa	No	No	No
20	Senanayake Samudra	No	No	No
21	Uda Walawe	No	No	No
22	Ulhitiya	No	No	No
23	Victoria	Yes	No	Yes

It is considered that FSPVs with installed capacity of less than 20 MWp are connected to the 33 kV while with the larger schemes connected at 132kV and 220kV level[5].

Existing transformer capacity utilization can also be considered. This is possible where the FSPV can operate complementarily with a co-located hydro scheme, or where the grid substation has transformers of adequate capacity. Table 20 illustrates some key transmission line parameters for the identified FSPV plants with potential for FSPV and hydropower complementary operation.

Table 20: Key transmission line parameters of the selected hybrid plants [5]

ID	Name	Rated Capacity (MWp)	Voltage (kV)	GSS	TL Length (km)
1	Bowatenna	18.8	33 kV	Naula	4.2
2	Castlereigh	100.7	132 kV	New Polpitiya	20
3	Chandrika Lake	64.1	132 kV	Embilipitiya	1.2
4	Gregory Lake	20	132 kV	Nuwara Eliya	2.4
5	Iranamadu	104.1	132 kV	Kilinochchi	5.3
6	Kalawewa	12.2	33 kV	O'Anuradhapura	33.4
7	Kalu Ganga	99.1	132 kV	Naula	24.3
8	Kantale	9.9	33 kV	N' Kappalthurai	27
9	Kaudulla	105.8	132 kV	Old Habarana	27
10	Kotmale	N/A			
11	Maduru Oya	110	132 kV	Polonnaruwa	43.5
12	Minneriya	85.7	132 kV	Polonnaruwa	13
13	Moragahakanda	99.5	132 kV	Naula	11
14	Moussakale	97.6	132 kV	New Polpitiya	21
15	Parakrama Samudra	102.6	132 kV	Polonnaruwa	12.5
16	Rajanagna	102.5	132 kV	New Habarana	31
17	Randenigala	110	220 kV	Randenigala HEP S/s	0.2
18	Rantambe	N/A			
19	Samanalawewa	98.2	132 kV	Samanalawewa HEP S/s	10.3
20	Senanayake Samudra	100.4	132 kV	Ampara	19
21	Uda Walawe	99.6	132 kV	Embilipitiya	21.2
22	Ulhitiya	110	132 kV	Mahiyangane	15.2
23	Victoria	66.9	220 kV	Victoria HEP S/s	1.2

Based on the practical scenarios discussed above and as stipulated in [5] it can be concluded that Victoria has a strong link to the existing 220kV network, and the transmission line length is 1.2km which indicates that the distance is significantly low when compared with the rest of the FSPV-hydro potential plants.

CHAPTER 5

ANALYSIS OF SYSTEM STABILIT UNDER COMPLEMENTARY OPERATION

To observe the system behavior when FSPV is operated complementarily with Victoria hydropower station, it is essential to analyze the system stability under different operating scenarios along with various system disturbances.

5.1 Generation Scenarios

Two generation dispatch scenarios were used to perform simulations by considering the various generation dispatch patterns in Sri Lankan power system. These generation scenarios are mainly categorized according to the seasonal and weather variations during certain periods. The CEB defines these generation scenarios for every week of the year. There are mainly two generation dispatch scenarios identified as Hydro maximum (HM), and thermal maximum (TM). The System Control Center of CEB has identified a new dispatch scenario, Maximum Wind and Solar scenario, which is considered as the worst case hydro maximum scenario with high solar and wind penetrations.

The generation dispatch scenarios used to perform detailed system analysis as explained in [1] are as follows,

1. **Hydro Maximum (HM) Scenario -**
   This scenario is identified for rainy seasons or very wet conditions when most of the hydro reservoirs' water levels are high. With the high inflows to run of river plants, they too generate maximum power output. A larger number of hydro power plants are used to contribute to the system generation to match the system demand. The frequency control swing machine is a hydro generator.

2. **Renewable Maximum (RM) Scenario -**

   This typically refers to a scenario where the deployment of renewable energy sources (such as solar, wind, hydro, and biomass) is maximized to the fullest feasible extent.

Key Characteristics of a "Renewable Maximum" Scenario could be illustrated as follows.

- High Renewable Penetration – Prioritization of renewable energy sources over fossil fuels and nuclear power.
- Grid Integration of Renewables – Increased investment in energy storage, grid upgrades, and smart technologies to accommodate variable renewable energy generation.
- Minimal Fossil Fuel Dependence – Reduction or elimination of coal, oil, and natural gas-based generation.
- Policy and Market Support – Implementation of strong regulatory and financial incentives to drive renewable energy growth.
- Sustainability and Emission Reduction Goals – Focus on meeting climate targets by reducing greenhouse gas emissions to near-zero levels.

3. Solar Maximum (S) Scenario-

This generation scenario refers to a case where the deployment of solar energy (photovoltaic) is maximized to its highest feasible potential.

Key Characteristics of a "Solar Max" Scenario:

- Maximum Solar Energy Deployment – Prioritization of solar power (utility-scale and rooftop) as the dominant energy source.
- High Investment in Storage – Large-scale battery storage (e.g., lithium-ion, flow batteries) and other energy storage solutions (e.g., pumped hydro) to handle solar intermittency.
- Grid Modernization – Upgrades to transmission and distribution infrastructure to efficiently integrate high solar penetration.
- Demand-Side Management & Electrification – Encouragement of demand response programs, smart grids, and electrification of transport & industry to optimize solar utilization.

- Minimal Fossil Fuel Use – Reduction of coal, oil, and natural gas reliance, with backup generation from hydro, nuclear, or other renewables.
- Favorable Policies & Incentives – Strong government support through subsidies, tax credits, and regulations to accelerate solar deployment.

5.2 Demand Scenarios

The demand scenarios are mainly considered according to the peak values in the daily load curve as a maximum or a minimum of the consumer demand considering a single typical day. Hence, three different scenarios have been identified by the CEB transmission planning engineers according to [1].

1. **Day Peak Demand Period** –
   The maximum demand during the daytime occurs around 11:00 hours.
   Typical average day peak demand would be around 2815 MW in the selected simulations

2. **Night Peak Demand Period –**
   The maximum demand during the nighttime occurs generally around 18:30hrs to 19:30 hrs. Typical average night peak demand considered for this research simulation is 3000 MW

3. **Off Peak Demand Period -**
   Typically, the minimum demand during the daytime occurs around 03:00 hours.

For this case study, the Renewable Maximum Day Peak (Max REDP) scenario was considered, and its model was used.

Appendix G illustrates the key simulation parameters considered for the simulations in PSS/E software tool.

5.3 Simulation Results

5.3.1 Traditional Mode (FSPV is not Integrated at Victoria Reservoir)

The reduced 220 kV network model, which was developed in PSS/E was simulated and analyzed for the system behavior under contingencies and various system disturbances. The disturbances considered are as follows.

- At time = 25s – Three phase temporary, solid fault at bus number 2810 (Puttlam)

  At time = 100 s – Victoria Machine 03 tripped.

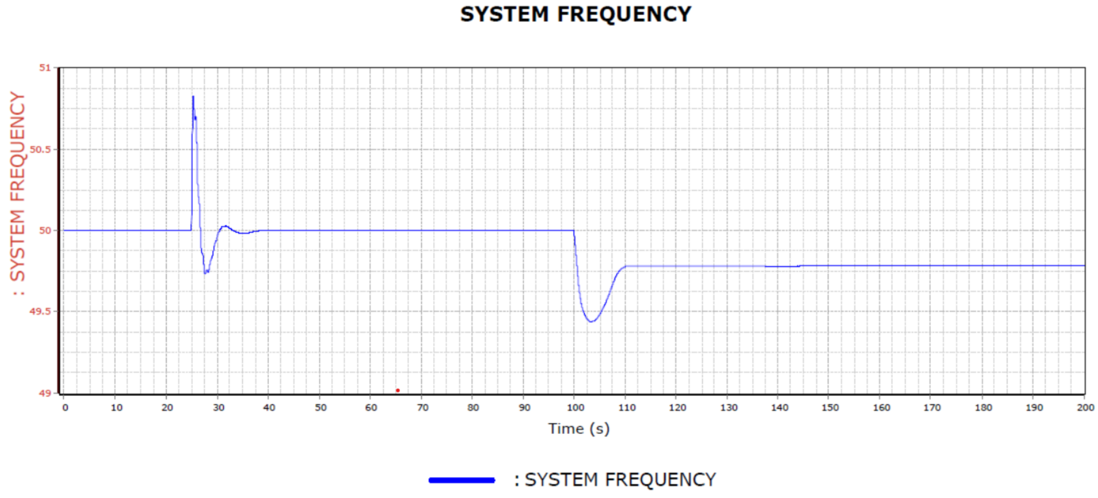

Figure 21: Frequency response– non-hybrid mode

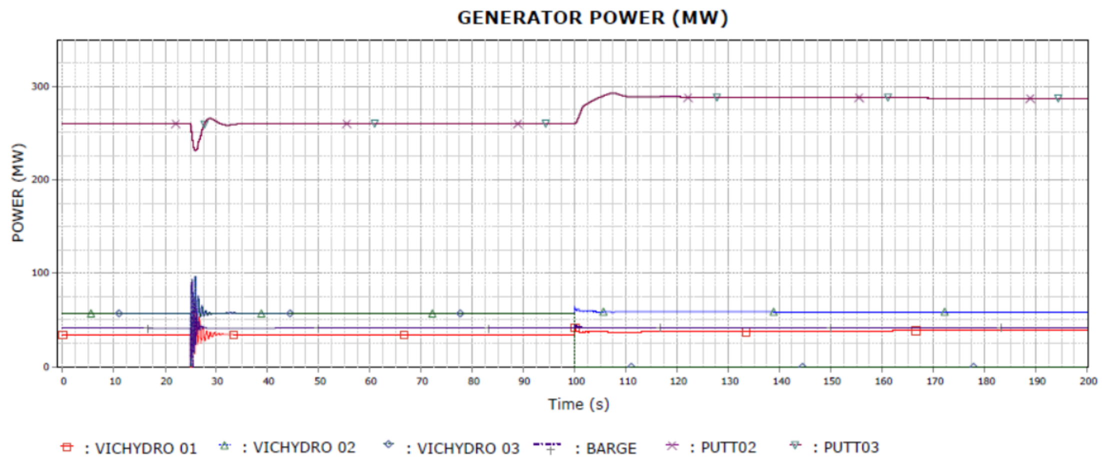

Figure 22: Generator power – non-hybrid mode

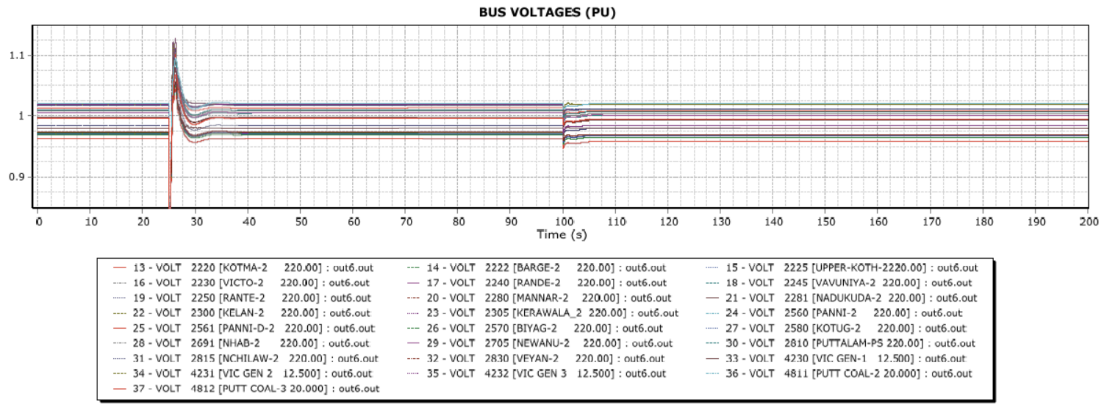

Figure 23- Bus Voltages – non-hybrid mode

Figures 21, 22 and 23 depict the system frequency variation, the power generated by the generators considered in the reduced network and the associated voltages at each of the buses respectively during the system disturbances outlined above. Although system frequency fluctuates, it does not go beyond the specified limits stipulated in Table 21 as per [1] and hence does not affect a total system failure.

Table 21: Allowable voltage variations [1]

Bus Bar Voltage	Allowable Voltage Variation (%)	
	Normal Operating	**Single Contingency**
400 V	± 5%	+5% to -10%
220 kV	± 5%	± 10%
132 kV	± 10%	± 10%

According to Figure 23, the bus voltages are subjected to some significant fluctuations at 25 s period due to the bus fault occurred at the Puttlam bus bar but, it recovers within 4 seconds – 5 seconds. However, the voltage variation observed during the generator trip at Victoria hydropower station (VIC 03 machine) is comparatively lower than that for fault at the Puttalam bus bar.

In addition, Victoria hydropower unit 01 is generating power around 42 MW while Victoria hydropower unit 02 and 03 generate around 70 MW of power each. However, when the system loses 70 MW of power once the Victoria machine 03 is tripped, the Lakvijaya power plant at Norocholai has ramped up to compensate for that loss.

5.3.2 Complementary Mode (FSPV + Hydro)

As per the calculations carried out in Chapter 4, the 93 MWp FSPV is integrated into the system at the Victoria hydropower Bus to assess the behavior of system stability under the same disturbances studied earlier. The solar plant and its specific dynamics were modelled as discussed in Chapter 4. Figure 24 illustrates the parameters used in modelling the dynamic file for the FSPV plant.

```
// PV models - PSSe
// Pmax=90 MW - Irradiance model
/ PV Converter
4230 'USRMDL' 2 'PVGU1' 101 1 0 9 3 3      0.020 0.020 0.40 0.90 1.11 1.20 2.0 2.0 0.020 /
/ Electrical Control Model for PV Converter Pmax=100 MW = last CON
4230 'USRMDL' 2 'PVEU1' 102 0 4 24 10 4     0 0 1 0
      0.15 18.0 5.0 0.05 0.10 0 0.08 0.47 -0.47 1.1  0 0.5 -0.5 0.05 0.1 0.9 1.1 120.00 0.05 0.05 1.70 1.11 1.11 100.0 /
/ PV I-P Characteristics
4230 'USRMDL' 2 'PANELU1' 103 0 0 5 0 1    0.16 0.38 0.59 0.85 1 /
/ PV Irradiance Profile [0=set to off,line 12]
4230 'USRMDL' 2 'IRRADU1' 104 0 1 20 0 1
      0
      5 1000 10 900 15 850 20 800 25 700  30 600 35 700 0 0 0 0 0 0 /
// end of PSSe PV models
```

Figure 24: Dynamic modeling of FSPV at Victoria reservoir in PSS/E

Similar disturbances considered for the analysis under traditional mode operation in Section 5.3.1 (i.e. without the FSPV), were repeated for the case with complementary operation as follows,

- At time = 25 s – Three phase temporary, solid fault at bus number 2810 (Puttlam)
- At time = 100 s – Victoria Machine 03 tripped.

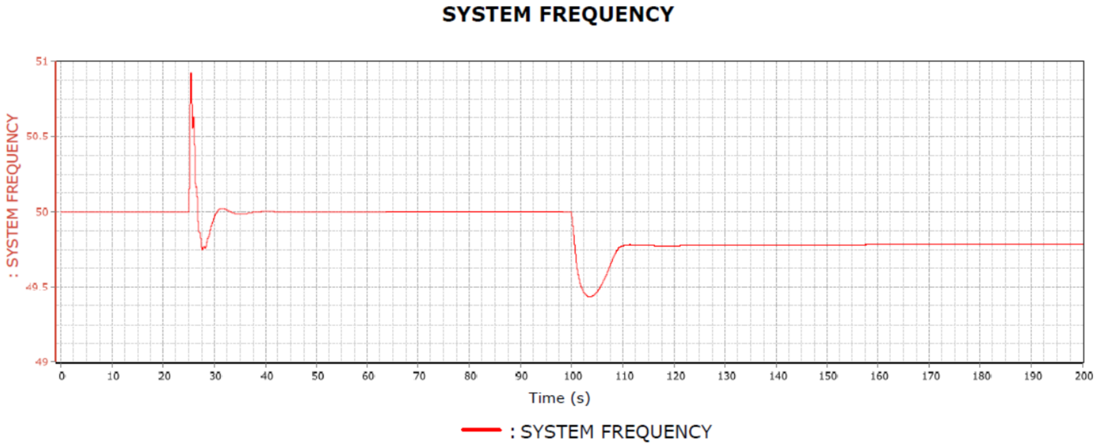

Figure 25: Frequency response – complementary mode

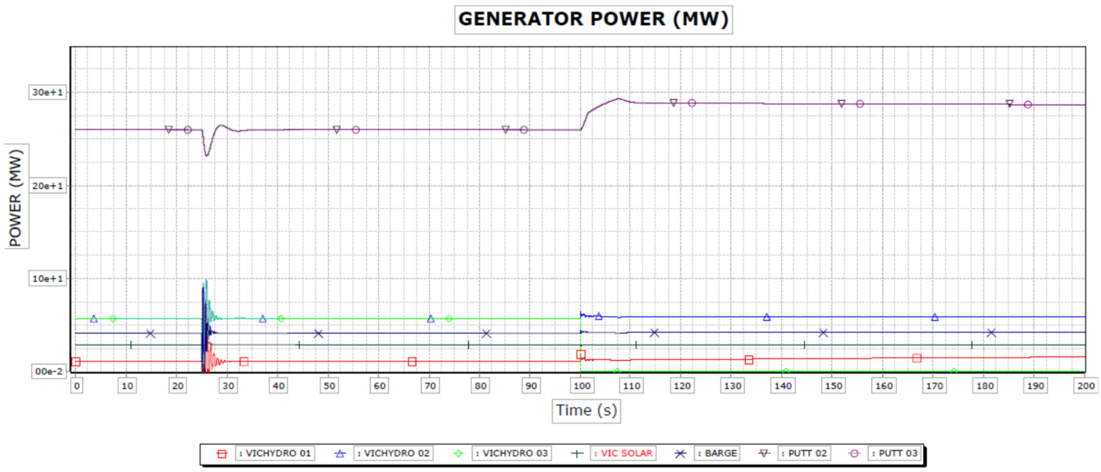

Figure 26: Generator power- complementary mode

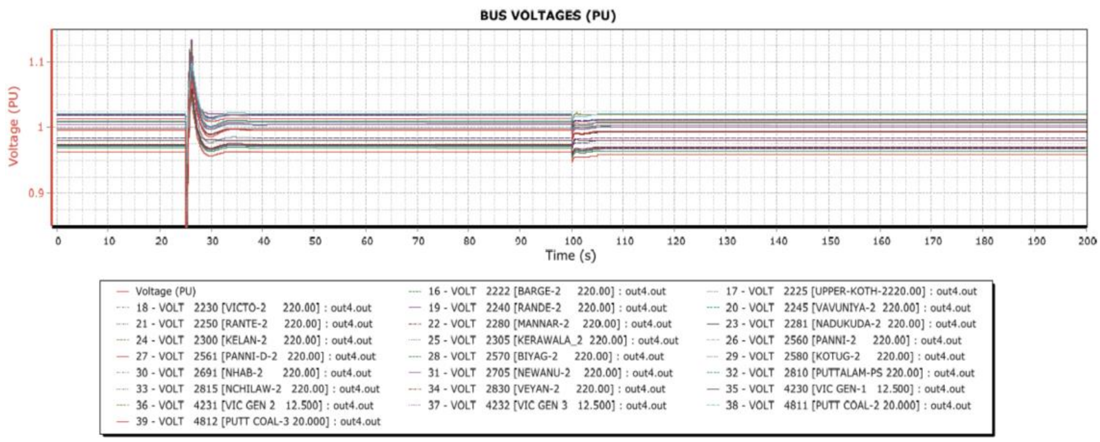

Figure 27: Bus Voltages – complementary mode

Figure 25 illustrates system frequency variations over a total simulation period of 200 s, with critical events occurring at 25 s and 100 s. Similar to the traditional mode, under complementary mode too, a slight deviation in system frequency could be observed. However, the system quickly stabilizes, maintaining overall operational integrity. Similarly, at 100 seconds, when Victoria Machine 03 is tripped, the system undergoes a frequency deviation but follows a stabilization process similar to that observed in the typical mode outlined in section 5.3.1. These responses demonstrate the system's inherent resilience to disturbances under normal operating conditions.

The results in Figure 25 indicate that applying complementary mode does not negatively affect the stability of the power system. During the daytime, solar energy generation provides an additional power source, thereby allowing hydro resources to be conserved for nighttime operation according to Figure 26. This approach enhances energy efficiency by optimizing resource utilization without compromising grid stability. Additionally, bus voltage profiles as shown in Figure 27 remain unaffected when the complementary mode is applied, further confirming that system stability is preserved. The ability of solar power to contribute during the day while reserving hydro resources for later use enhances the overall sustainability and reliability of the power system.

5.3.3 Other Different Contingencies Considered

Below mentioned disturbances were applied to both the traditional and complementary modes to analyze system behavior. When observing the frequency plots for both schemes, it is evident that they follow the same system response pattern. This indicates that even when Floating Solar Photovoltaic (FSPV) operates in conjunction with the Victoria Power Station, the overall system stability remains unaffected, under contingencies as well.

- At time 25sec - 3Φ Fault at New Habarana end - From 2705 [NEWANU-2 220.00] to 2691 [NHAB-2 220.00]
- At time 100sec - 3Φ Fault at Kothmale end- From 2580 [KOTUG-2 220.00] to 2220 [KOTMA-2 220.00]
- At time 150sec – Generator Trip – Barge mounted power plant

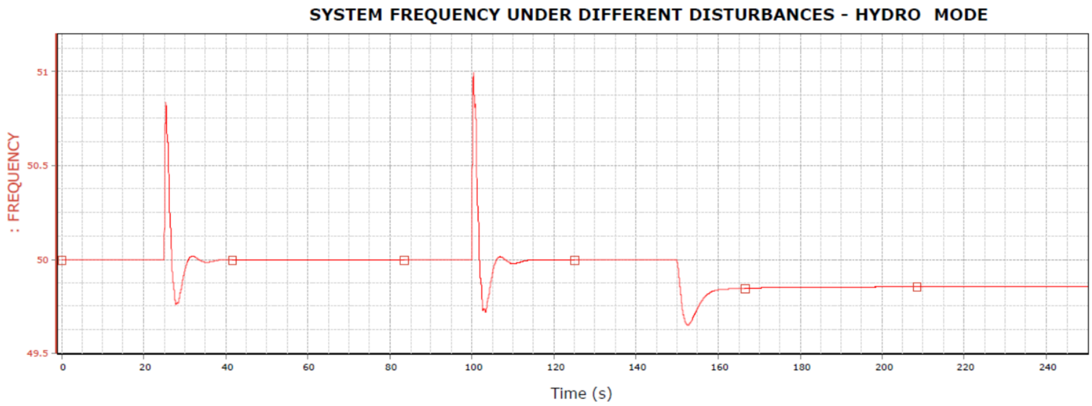

Figure 28: Frequency response – non-hybrid mode

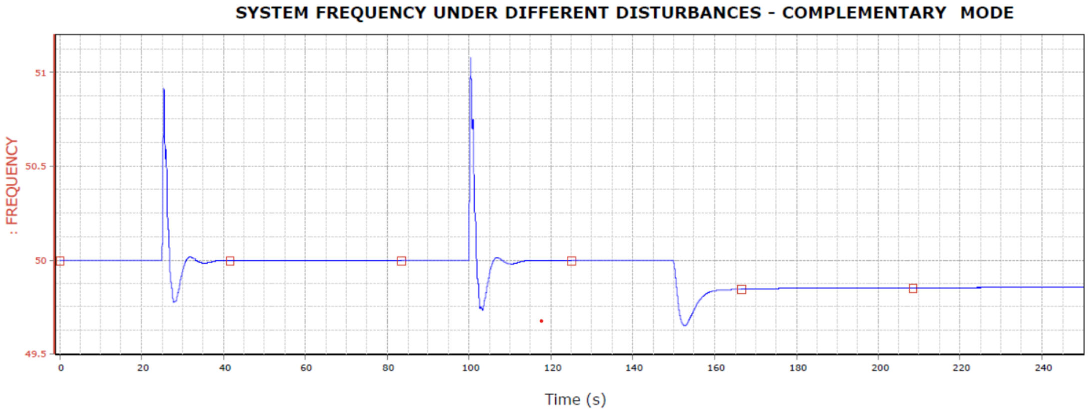

Figure 29: Frequency response – complementary mode

When observing the frequency plots for both schemes in Figure 28 and 29, it is evident that they follow the same system response pattern. This indicates that even when Floating Solar Photovoltaic (FSPV) operates in conjunction with the Victoria Power Station, the overall system stability remains unaffected, under contingencies as well.

The consistency in frequency response across both modes suggests that the integration of FSPV does not introduce additional instability or unexpected deviations.

Instead, the system continues to exhibit resilience, maintaining its operational integrity despite disturbances. This further reinforces the reliability of the complementary approach, confirming that the coordinated operation of hydro and solar resources can effectively support grid stability while maximizing energy efficiency.

CHAPTER 6

FINANCIAL ANALYSIS OF INTEGRATING FSPV VICTORIA HYDROPOWER STATION

6.1 Overview

Improvement in renewable energy generation can be achieved by integrating floating solar photovoltaic (FSPV) systems into the existing hydropower infrastructure. This hybrid model takes advantage of both solar and hydro resources while maximizing the value of current assets and infrastructure. This chapter primarily deals with the financial feasibility of installing an FPV system on the Victoria Hydropower Station in Sri Lanka and estimates the Levelized Cost of Energy (LCOE) and other financing using HOMER Pro software tool.

6.2 HOMER Pro Software

HOMER Pro is an energy modeling software that helps design, optimize and analyze a micro-grid or hybrid renewable energy system. Originally developed by HOMER Energy, and now under UL Solutions, it enables users to assess the techno economic aspects of incorporating multiple energy sources like solar PV, wind turbines, hydropower, diesel generators, batteries, and grid power. The software performs comprehensive simulations and optimizations based on user-defined requirements to minimize cost and maximize sustainability of the provided energy.

Some of the key components in the database are:

- Energy Resource Data: Solar radiation, wind speed, hydro resources, and load demand profiles from various global sources.
- Technology Base: Ready to use templates for Solar Panels, Wind Turbines, Inverters, Batteries, and Generators. Users can also add custom components when required.
- Economic Measuring Instruments: Capital expenditures, operation and maintenance expenditures, fuel costs, discount percentages, and electricity costs for effective financial reporting.

- Grid and Tariff Information: Grid availability, import and export price, and penalty demand information to evaluate the interaction of a hybrid system with the grid.

This is possible with the combination of these databases. HOMER Pro has users calculate the feasibility studies, levelized cost of energy (LCOE), and optimize hybrid energy systems, both off the grid and with on-grid applications.

6.3 Financial Analysis Methodology

The following points indicate the key steps followed in determining the financial viability of the proposed FSPV system at Victoria.

Data Collection

A variety of data sources are used in the study to guarantee precise modeling and analysis. Global horizontal irradiance (GHI) figures and other solar resource data were obtained from the National Solar Radiation Database. These figures are essential for calculating the Victoria reservoir area's potential solar energy generation. In order to comprehend the current power output and seasonal fluctuations, historical generation data from the Victoria Hydropower Station was also acquired. To evaluate the hybrid system's financial viability, economic variables were gathered, including market pricing for necessary parts such solar panels, floating structures, inverters, and operation and maintenance (O&M) expenses.

Financial Parameters

The hybrid system's financial feasibility was assessed using a number of economic factors. A discount rate of 8% was used to account for normal financial conditions in Sri Lanka, and the project was anticipated to last for 20 years. The price of FSPV modules, floating platforms, installation, and grid connectivity with pre-existing infrastructure were all included in the capital expenditure (CAPEX). In order to account for long-term operational sustainability, annual maintenance expenditures were calculated as a percentage of CAPEX and referred to as operational expenditure (OPEX).

Simulation and Optimization

The performance of the hybrid system over its operating lifetime was simulated using HOMER Pro. Through an analysis of different system sizes and operational techniques, the software's optimization tool was used to identify the most economical system design. Variable sun irradiation, the availability of hydropower, and financial limitations were all taken into consideration during the modeling process.

Results

Energy Production

- FSPV System: The 93 MWp FSPV installation is projected to generate approximately **133,520 MWh/year**.

The Levelized Cost of Electricity (LCOE) for ground-mounted solar photovoltaic (PV) systems in Sri Lanka has varied over the years due to factors such as technological advancements, policy changes, and market dynamics.

Before 5-6 years, the LCOE for solar plants was estimated to be around LKR 22 to 25 per kilowatt-hour (kWh) [19]. By November 2023, the Ceylon Electricity Board (CEB) launched a 70 MW ground-mounted solar tender with a maximum tariff set at LKR 34.93/kWh [20]. This indicates an increase in the upper limit of solar tariffs over the past six-year period.

It is important to note that the LCOE can vary based on project-specific factors such as location, scale, financing, and technological choices. Additionally, currency exchange rates and inflation can influence cost assessments over time.

As per [5] the specific cost of the FSPV typically ranges between $770 and $890 per MW excluding transmission, roads and land acquisition, and between $830 and $1230 per MW, when other infrastructure costs are considered. The projects at the higher end of this scale are small schemes with disproportionately large transmission costs.

6.4 Levelized Cost of Electricity Calculation

The levelized costs of energy (LCOE) ranges from $70 to $105 / MWh in the base case without consideration of water and carbon benefits. The range is $42 to $76 / MWh when these positive externalities are considered.

Based on [5], the LCOE for the FSPV developed ranges around 78.92 USD/MWh which indicates that it will be LKR 23.7/ kWh when the exchange rate was assumed to be at 300 LKR. But since the market is now developed and the PV module, inverter prices are getting cheaper daily, the following calculation in Table 22 was used to calculate the LCOE for the FSPV plant proposed at the Victoria reservoir.

Table 22: Levelized Cost of Electricity (LCOE) calculation for the proposed FSPV plant at Victoria

Parameter	Value
System Size (kWp)	93,000.00
Specific Plant Cost (LKR/kWp)	LKR 250,000.00
Total CapEx (LKR)	LKR 23,250,000,000.00
Module Cost (LKR)	LKR 20,000.00
Annual OpEx (1.5% of CapEx)	LKR 348,750,000.00
Project Lifetime (Years)	20
Annual Energy Generation (kWh/year)	133,500,000
Total Lifetime Energy Production (kWh)	2,670,000,000.00
Generation Considering Linear Degradation and other factors	2,136,000,000.00
Total Lifetime Cost	LKR 30,225,000,000.00
Estimated LCOE (LCOE) LKR/kWh	14.1902809

Based on the values outlined in Table 22 it is evident that LCOE for the proposed FSPV at Victoria hydropower station is LKR 14.20/ kWh. However, the LCOE will be affected when considering other practical scenarios such as structural depreciation, long-term operation and maintenance costs.

In complementary operation systems, it is essential to evaluate financial viability of the system as an integrated system rather than separate generation units to manage the LCOE. Despite higher LCOE for the hydro component when complementary operation is implemented, the overall system LCOE can be decreased by implementing a shared infrastructure strategy and optimizing dispatch based on solar availability and more importantly it enhances the reservoir management.

When taken into consideration as individual systems, the levelized cost of electricity (LCOE) for hydro increases when complementary operation between the existing hydropower plant and a floating solar PV (FSPV) system is implemented, according to the financial calculations shown in [21]. This is mostly because annual hydroelectric generation has decreased. However, because solar energy partially offsets the hydro load, this operational change also lowers the overall cost of hydro generation and enables more effective reservoir management. A study in [21] indicate that complementary operation can lower hydro's generation cost by about 15%. Consequently, the updated LCOE for hydro-only and hybrid mode operation under this complementary scheme is recalculated as given in Table 23.

- Average Annual Generation of Victoria Hydro Power Station – **760 GWh** [3]
- Average Annual Generation Cost of Victoria Hydro Power Station – **LKR 2,127,928,760.10** [22]

Table 23 : Levelized Cost of Electricity Analysis (For Each Case)

Case	Annual Generation (GWh)	Average Annual Generation Cost (LKR)	LCOE (LKR/kWh)
Hydro Only (Existing Mode)	760	2,127,928,760.10	2.80
Hydro Only (During Complementary)	626.5	1,915,135,884.09	3.06
FSPV	133.5	1,511,250,000.00	14.20
Integrated System (Complementary Operation)	760	3,426,385,884.09	4.50

According to the levelized costs calculated and published by the PUCSL [23], the average LCOE for major hydro power plants in Sri Lanka is 4.81 LKR/kWh. Therefore, once the complementary mechanism is operated by integrating the proposed FSPV to the existing Victoria hydro power plant, the LCOE is 4.50 LKR/kWh which indicates that the hybrid system is financially viable.

CHAPTER 7
CONCLUSION

As part of the Sri Lankan government's solar energy action plan, it is anticipated that over the next decade these policies and targets will lead to low carbon emissions and an increase in the share of solar energy mix. The government hopes to fulfill these intentions by harnessing and utilizing solar energy resources. The government has conducted evaluation studies about the country's solar resources and prospective solar energy projects. As per the Ceylon Electricity Board (CEB), it plans to integrate 1300 MW of solar sources of energy into the local grid by the year 2030.

To facilitate the process of increasing solar to the national, it is proposed to explore solar photovoltaic technologies. Such systems can be either mounted on rooftops or can utilize on land as ground mounted solar. In addition, the integrated system of floating solar photovoltaic (FSPV) can be installed widely on water bodies such as reservoirs and water supply intakes. Exploring new technologies related to solar PV integration will help increase the share of solar energy use and contribute toward a cleaner Sri Lanka.

This study was mainly focused on assessing the technical and financial feasibility of integrating a floating solar photovoltaic plant (FSPV) on Victoria reservoir while evaluating the system response. Based on the calculations and design assessments conducted in the study, it was determined that approximately 93 MWp of FSPV can be accommodated at the Victoria Reservoir, yielding an estimated annual energy generation of around 133.5 GWh.

When the Levelized Cost of Electricity (LCOE) was analyzed across different operational configurations, namely hydro-only, floating solar photovoltaic (FSPV) only, and the integrated hydro-FSPV hybrid system it was observed that the LCOE of the hybrid system is approximately 4.50 LKR/kWh. This value is consistent with the typical LCOE range of major hydropower plants in Sri Lanka, indicating that integrating FSPV with existing hydro infrastructure does not increase the overall generation cost significantly. In contrast, the LCOE of FSPV when considered as a standalone system was calculated to be 14.20 LKR/kWh, which is still significantly lower than the current LCOE of conventional ground-mounted solar PV plants in Sri Lanka, reported at around 25 LKR/kWh [3]. These findings suggest that both the standalone FSPV system and the integrated hybrid configuration offer financial advantages. This compelling cost ratio illustrates the practicality of implementing FSPV hydropower systems in the country, and it draws attention to the incorporation of such hybrid systems in Sri Lanka's renewable energy strategy.

In addition, studies conducted with the help of PSS/E show that incorporating FSPV into Victoria Power Station does not negatively impact the system's stability. The research involved developing a realistic reduced model of the 220kV network of Sri Lanka to validate the accurate operation of the proposed complementary FSPV and hydro system. It was observed that the system stability did not negatively impact the system behavior upon integrating the FSPV with hydro at Victoria reservoir. Furthermore, bus voltages were within the acceptable limits, and no violations were registered, which further supports the technical feasibility of the proposed strategy for complementary operation. As discussed in the results, it was observed that power sharing was available in complementary operation. During daytime, especially in dry and sunny seasons when solar generation is at its peak, solar power can take a dominant role, reducing the reliance on hydropower. This allows water in the reservoir to be conserved for use during nighttime or periods of lower solar generation.

In conclusion, this study demonstrated that the integration of FSPV with Victoria Hydropower Station is not only technically feasible but also economically advantageous. By utilizing the existing infrastructure and adopting a complementary solar-hydro operation, Sri Lanka can enhance its renewable energy capacity while ensuring grid stability. The findings of this research provide valuable insights for policymakers and energy planners, supporting the broader transition towards a sustainable and resilient energy system.

CHAPTER 8

FUTURE IMPLEMENTATIONS AND LIMITATIONS

8.1 Future Possible Implementations

A strong energy management system (EMS) should be implemented at the Victoria reservoir in order to fully capture the complementary operation of FSPV and hydropower. Based on demand trends, weather predictions, and reservoir levels, an advanced EMS with real-time monitoring and predictive analytics can optimize the dispatch of hydro and solar resources. In order to optimize efficiency and maintain grid stability, the EMS can dynamically modify power generation by combining machine learning (ML) and artificial intelligence (AI) algorithms.

Moreover, combining the FSPV-hydro hybrid model with battery energy storage systems (BESS) may assist reduce solar intermittency by storing excess solar energy during periods of peak output and using it during times of reduced generation. This would further optimize water resource management, lower the need for hydro peaking, and improve system resilience.

The integration of grid flexibility improvements and demand-side management (DSM) technologies is another crucial component of future implementation. Peak load shifting can be accomplished by coordinating residential and commercial energy use with FSPV-hydro power, increasing grid efficiency overall. Distributed energy resources and smart grid technology may also make it easier to integrate with the national grid. These developments would promote Sri Lanka's larger renewable energy objectives while guaranteeing that the Victoria hybrid system can deliver reliable, dispatchable power.

8.2 Research Limitations

Although this study shows that combining FSPV with Victoria hydropower station is feasible, some restrictions must be addressed.

The 133.5 GWh predicted yearly energy yield is based on reservoir level data and historical solar irradiation. However, seasonal variations and climate variability may have an effect on actual performance. Furthermore, financial feasibility study emphasizes the cost benefits, hence more research is necessary to fully understand issues such floating platform deterioration, maintenance expenses, and long-term operational difficulties. Since tariff structures, ancillary service needs, and grid interconnection laws may have an impact on the economic feasibility of large-scale FSPV deployment in Sri Lanka, future research should also examine regulatory and policy factors. Another limitation of complementary solar–hydro operation is the economic shift in generation costs since hydro power plant experiences increased LCOE due to reduced annual generation, but it is essential to consider the system as an integrated system rather than separate generation units in order to evaluate the financial feasibility of the system.

Despite these limitations, this study provides a strong foundation for future research and large-scale implementation, demonstrating that the hybrid FSPV-hydro model is a promising solution for Sri Lanka’s energy transition.

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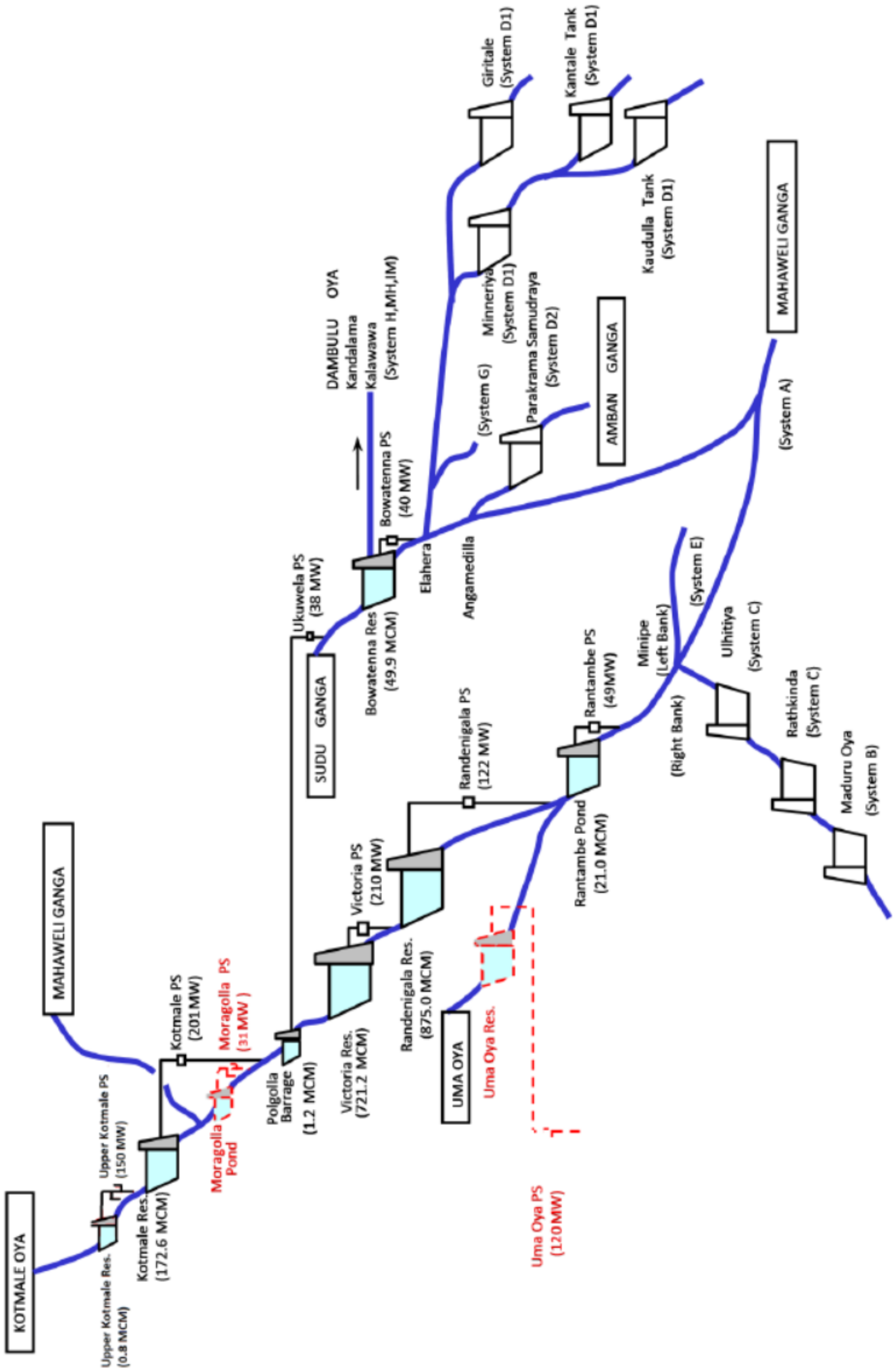
LIST OF APPENDICES

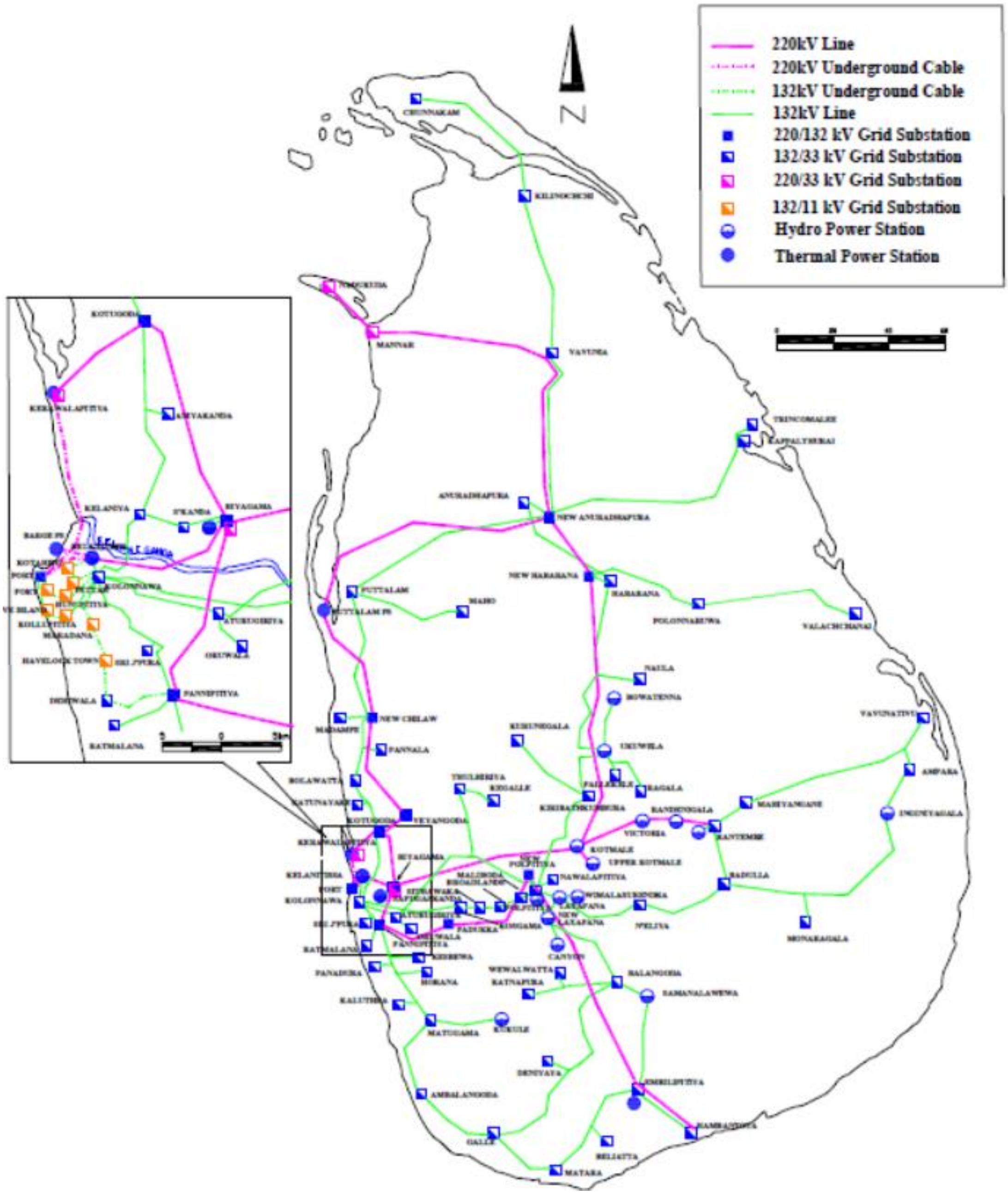
Appendix A

Appendix A - Mahaweli Scheme Hydro Reservoir Network



Appendix B

Appendix B- The Map of Sri Lankan Transmission Network 2023



Appendix C

Appendix C- Trina Solar Vertex N Series Datasheet

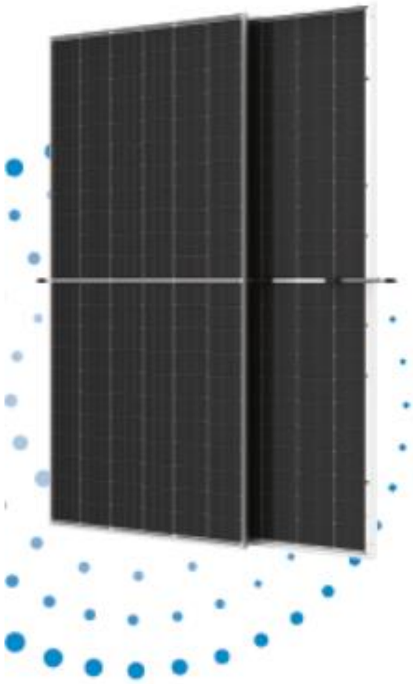
Mono Multi Solutions

Vertex N

N-type i-TOPCon bifacial dual glass
Monocrystalline module

PRODUCT: TSM-NEG19RC.20
POWER RANGE: 590-620W

620W	0~+5W	23.0%
MAXIMUM POWER OUTPUT	POSITIVE POWER TOLERANCE	MAXIMUM EFFICIENCY



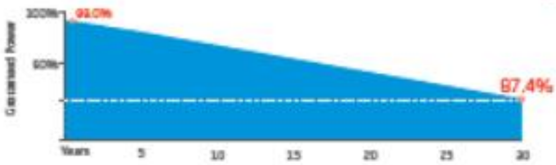
High customer value
- Lower LCOE, reduced BOS cost, better ROI
- Lowest guaranteed first year and annual degradation
- Optimized compatibility with existing mainstream system components

High power up to 620W
- Up to 23.0% module efficiency
- High density interconnection provides improved power density
- MBB technology improves light trapping effect and current collection, while lowering series resistance

High reliability
- Minimized micro-cracks with innovative non-destructive cutting technology minimizes micro-cracking
- Ensured PID resistance through improved cell process and module material control
- Resistant to harsh environments
- Mechanical performance up to +5400/-2400 Pa

High energy yield
- Excellent IAM and low irradiation performance, validated by 3rd party certifications
- The unique design provides optimized energy production under inter-row shading conditions
- Lower temperature coefficient (-0.29%/°C) and operating temperature
- Up to 30% additional power gain from back side

Trina Solar's Vertex Bifacial Dual Glass Performance Warranty



Comprehensive Products and System Certificates

IEC61215/IEC61730/IEC61701/IEC62716/UL61730
ISO 9001: Quality Management System
ISO 14001: Environmental Management System
ISO14064: Greenhouse Gases Emissions Verification
ISO45001: Occupational Health and Safety Management System

Trinasolar

Appendix D

Appendix D-Trina Solar 620Wp Electrical and Mechanical Data

MECHANICAL DATA

Solar Cells	N-type i-TOPcon Monocrystalline
No. of cells	132 cells
Module Dimensions	2382×1134×30 mm (93.78×44.65×1.18 inches)
Weight	33.7kg (74.3 lb)
Front Glass	2.0 mm (0.08 inches), High Transmission, AR Coated Heat Strengthened Glass
Encapsulant material	POE/EVA
Back Glass	2.0 mm (0.08 inches), Heat Strengthened Glass (White Grid Glass)

Frame	30mm(1.18 inches) Anodized Aluminium Alloy
J-Box	IP 68 rated
Cables	Photovoltaic Technology Cable 4.0 mm² (0.006 in²) Portrait: 350/280 mm (13.78/11.02 in) Landscape: 1400/1400 mm (55.1/55.1 in) *
Connector	MC4 EV02/ TS4 Plus/ TS4**
Fire Type	Type 29

*Please refer to regional datasheet for specified connector. **Customer to choose connector type

ELECTRICAL DATA (STC & NOCT)

Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Peak Power Watts-P_{MAX} (Wp)*	590	450	595	454	600	459	605	462	610	466	615	470	620	474
Power Tolerance-P_{MAX} (W)	0 ~ +5													
Maximum Power Voltage-V_{MPP} (V)	39.7	37.4	40.0	37.6	40.3	37.9	40.5	38.1	40.8	38.3	41.1	38.6	41.4	38.8
Maximum Power Current-I_{MPP} (A)	14.86	12.05	14.89	12.07	14.91	12.11	14.94	12.13	14.96	12.16	14.98	12.19	14.99	12.20
Open Circuit Voltage-Voc (V)	47.8	45.4	48.1	45.7	48.4	46.0	48.7	46.2	49.0	46.5	49.3	46.8	49.6	47.1
Short Circuit Current-Isc (A)	15.72	12.67	15.76	12.69	15.80	12.73	15.83	12.75	15.86	12.78	15.89	12.80	15.91	12.82
Module Efficiency η m (%)	21.8		22.0		22.2		22.4		22.6		22.8		23.0	

STC: Irradiance 1000W/m2, Cell Temperature 25°C, Air Mass AM1.5. NOCT: Irradiance at 800W/m², Ambient Temperature 20°C, Wind Speed 1m/s. *Measuring tolerance: ±3%.

Electrical characteristics with different power bin (reference to 5% & 10% backside power gain)

Backside Power Gain	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%
Total Equivalent power - P_{MAX} (Wp)	620	649	625	655	630	660	635	666	641	671	646	677	651	682
Maximum Power Voltage-V_{MPP} (V)	39.7	39.7	40.0	40.0	40.3	40.3	40.5	40.5	40.8	40.8	41.1	41.1	41.4	41.4
Maximum Power Current-I_{MPP} (A)	15.60	16.35	15.63	16.38	15.66	16.40	15.69	16.43	15.71	16.46	15.73	16.48	15.74	16.49
Open Circuit Voltage-Voc (V)	47.8	47.8	48.1	48.1	48.4	48.4	48.7	48.7	49.0	49.0	49.3	49.3	49.6	49.6
Short Circuit Current-Isc (A)	16.51	17.29	16.55	17.34	16.59	17.38	16.62	17.41	16.65	17.45	16.68	17.48	16.71	17.50

Power Bifaciality: 80±5%.

TEMPERATURE RATINGS

NOCT (Nominal Operating Cell Temperature)	43°C (±2°C)
Temperature Coefficient of P_{MAX}	- 0.29%/°C
Temperature Coefficient of Voc	- 0.24%/°C
Temperature Coefficient of Isc	0.04%/°C

MAXIMUM RATINGS

Operational Temperature	-40~+85° C
Maximum System Voltage	1500V DC (IEC) 1500V DC (UL)
Max Series Fuse Rating	30A*

*This is for customers engineering to decide

WARRANTY

12 year Product Workmanship Warranty

30 year Power Warranty

1% first year degradation

0.40% Annual Power Attenuation

(Please refer to product warranty for details)

PACKAGING CONFIGURATION

Modules per box: 36 pieces

Modules per 40' container: 540 pieces

Pallets per 40' container: 15 pieces

Appendix E

Appendix E- PVSyst Energy Simulation Summa

PVSYST V6.88	Alpha Solar Energy Systems (Pvt) Ltd / SOLAR THERM (Sri Lanka)	23/02/25	Page 2/4

Grid-Connected System: Main results

Project : **Msc Research- FSPV Plant Sizing**

Simulation variant : **New simulation variant**

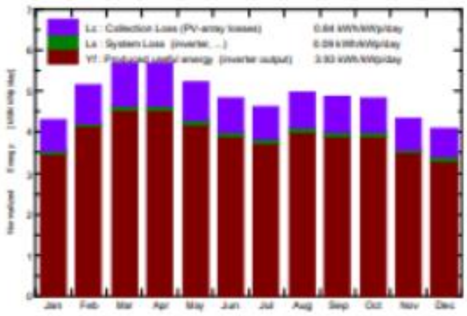
Simulation for the 20th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	7°	azimuth	180°
PV modules	Model	TSM-620NEG19RC.20	Pnom	620 Wp
PV Array	Nb. of modules	150000	Pnom total	**93000 kWp**
Inverter	Model	SG3000HV	Pnom	3000 kW ac
Inverter pack	Nb. of units	27.0	Pnom total	**81000 kW ac**
User's needs	Unlimited load (grid)			

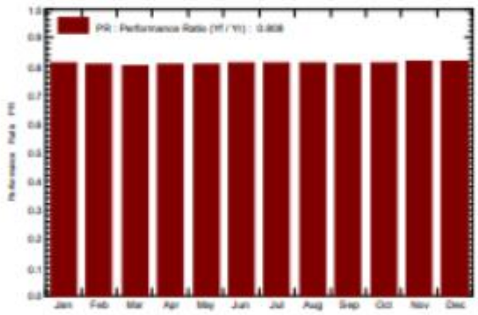
Main simulation results

System Production	**Produced Energy**	**133521 MWh/year**	Specific prod.	1436 kWh/kWp/year
	Performance Ratio PR	80.80 %		

Normalized productions (per installed kWp): Nominal power 93000 kWp



Performance Ratio PR



New simulation variant

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	141.2	65.68	24.34	132.7	130.7	10229	9990	0.809
February	150.6	63.44	24.92	143.9	142.1	11041	10793	0.806
March	179.2	71.72	25.62	175.7	173.7	13400	13091	0.801
April	168.6	66.11	25.30	169.7	167.9	12982	12685	0.804
May	157.4	75.72	26.57	161.6	159.6	12382	12102	0.805
June	140.3	78.25	25.59	144.7	142.8	11174	10921	0.812
July	139.6	70.37	25.77	143.4	141.7	11047	10787	0.809
August	151.6	84.18	25.68	153.6	151.8	11838	11566	0.810
September	146.9	72.03	25.09	145.5	143.7	11199	10937	0.808
October	155.2	77.31	24.95	150.1	148.1	11560	11293	0.809
November	136.5	67.71	23.95	129.6	127.9	10041	9801	0.813
December	134.7	70.78	24.18	126.3	124.4	9789	9555	0.814
Year	1801.6	863.30	25.17	1776.8	1754.3	136682	133521	0.808

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	T amb.	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	PR	Performance Ratio

Appendix F

Appendix F- PVSyst System Losses

PVSYST V6.88	Alpha Solar Energy Systems (Pvt) Ltd / SOLAR THERM (Sri Lanka)	23/02/25	Page 4/4

Grid-Connected System: Loss diagram

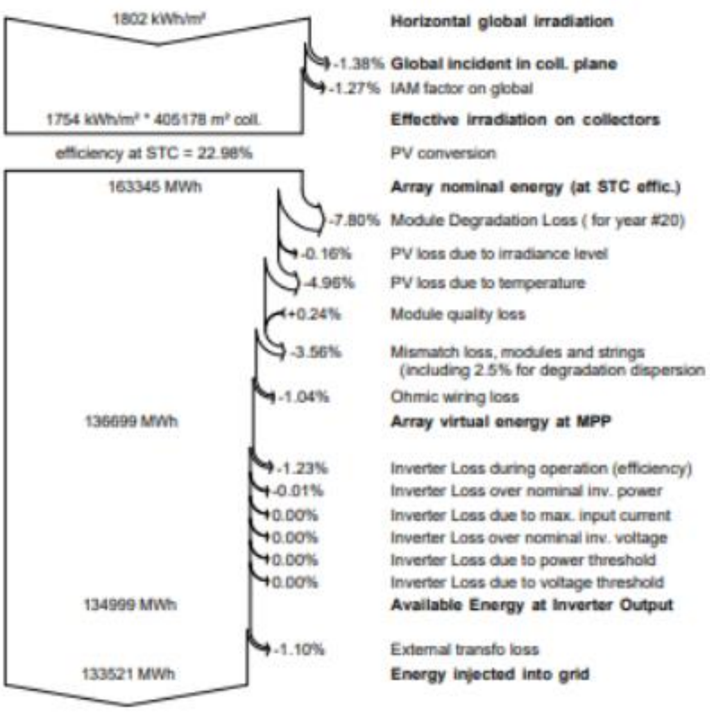
Project : **Msc Research- FSPV Plant Sizing**

Simulation variant : **New simulation variant**

Simulation for the 20th year of operation

Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	7°	azimuth	180°
PV modules	Model	TSM-620NEG19RC.20	Pnom	620 Wp
PV Array	Nb. of modules	150000	Pnom total	**93000 kWp**
Inverter	Model	SG3000HV	Pnom	3000 kW ac
Inverter pack	Nb. of units	27.0	Pnom total	**81000 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



Appendix G

Appendix G – Simulation Parameters Considered in PSS/E