TECHNO-ECONOMIC ANALYSIS OF INTERMITTENT RENEWABLE ENERGY PENETRATION WITH THE PROPOSED INDIA-SRI LANKA HVDC INTERCONNECTION

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Degree of Master of Science

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DECLARATION

“I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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M.D.V. Fernando

The above candidate has carried out research for the Masters dissertation under my supervision.

……………………… ………………………

Signature of the supervisor Date

Dr. W.D.A.S. Rodrigo

DEDICATION

To my family

ACKOWLEDGMENT

First, I wish to express my sincere gratitude to my supervisor Dr. W.D.A.S. Rodrigo for his continuous encouragement and guidance throughout my research work.

I extend my sincere gratitude to the all the lecturers of the Department of Electrical Engineering for the knowledge and wisdom provided during the course of the study period and for their valuable comments during the progress of the research in order to make it a success.

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ABSTRACT

This research is a techno-economic analysis carried out to identify the effect of level of intermittent renewable energy penetration in to the Sri Lankan power system with the proposed India-Sri Lanka HVDC interconnection. The focus on power generation using intermittent renewable energy gives rise to system operational issues leading to renewable energy curtailments. This research adopts a methodology to identify the level of RE penetration with the HVDC link compared to original power system planned with pump storage power plant.

Future power plant additions based on least cost principles are obtained using WASP software considering stage development of HVDC; 500 MW in 2025 and 1000 MW in 2028. This power plant schedule was input to long term dispatch simulation software SDDP in order to obtain the optimum hydro thermal generation mix for different seasons of the year namely, high wind and wet periods. Output of SDDP for each season was input to short term dispatch simulation software NCP in order to simulate the daily dispatch and obtain renewable curtailments to identify the RE penetration level. Renewable are modeled in detail with 30 minute resolution in the dispatch simulation software. This process was repeated to obtain the RE penetration level with 500 MW HVDC and 1000 MW HVDC for different scenarios assuming aggressive wind development, aggressive solar development and mix development.

The economic analysis was carried out to identify the cost impact of each scenario compared to the original power system. It was observed that the HVDC is economical for the initial RE capacities but the RE penetration can be increased with HVDC at an additional cost to the system. Therefore, sensitivity analysis was carried out to identify at what variable cost of HVDC the link would bring economic benefit to the country for each scenario. This methodology could be used when negotiating the pricing contract agreements with India to identify whether the HVDC link could bring economic benefit to Sri Lanka depending on the prevailing energy mix.

Keywords: HVDC, Intermittent Renewable Energy

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LIST OF ABBREVIATIONS

CEB	-	Ceylon Electricity Board
CSC	-	Current Source Converters
FIT	-	Feed-in-tariff
HVDC	-	High Voltage Direct Current
LDC	-	Load Duration Curve
LTGEP	-	Long Term Generation Expansion Plan
MMbtu	-	Million British Thermal Unit
O&M	-	Operation & Maintainance
ORE	-	Other Renewable Energy
PSPP	-	Pumped Storage Power Plant
PV	-	Present value
RE	-	Renewable Energy
SDDP	-	Stochastic Dual Dynamic program
SLSEA	-	Sri Lanka Sustainable Energy Authority
Solar_H	-	Solar Hambanthota
Solar_K	-	Solar Kilinochchi
SPPA	-	Small Power Purchase Agreement
VRE	-	Variable Renewable Energy
VSC	-	Voltage Source Converters
WASP	-	Wien Automation System Package
Wind_E	-	Wind Eastern
Wind_H	-	Wind Hill country
Wind_M	-	Wind Mannar
Wind_N	-	Wind Northern
Wind_P	-	Wind Puttalam

CHAPTER 1

INTRODUCTION

1.1 Background

Presently, Sri Lankan Power System has a total installed capacity of 4018MW approximately which includes dispatchable installed capacity of 3500MW and Other RE capacity of 518MW. Dispatchable capacity includes 1384MW of major hydro and 2115MW of thermal power plants. The recorded maximum peak demand is 2453MW whereas the electricity generation in year 2016 was 14,148GWh [1]. Sri Lankan power system is operated by Ceylon Electricity Board having a single buyer model with one Transmission System Operator and System Control Center.

Indian power system is separated into five geographical areas; Northern, Western, Southern, Eastern, North-Eastern. Total installed capacity is approximately 330GW which includes 219GW thermal 6.8GW nuclear, 45GW hydro and 60GW of renewable. [2] Power Grid Corporation Of India Limited, the Central Transmission Utility (CTU) of India under Ministry of Power is responsible for coordinated development of power transmission network and effective operation and management of Regional and National Grid.

Renewable sources for power generation are becoming more popular worldwide at present. Sri Lanka is also trying to keep up with the trend but being and island nation the system imposes constraints on the level of renewable energy that could be absorbed into the system. As at present the energy share from Other Renewable Energy (ORE) is reached 10%. The capacity and energy share of the Sri Lankan power system is shown in Figure 1.1. Wind Power & Solar Power potential in Sri Lanka has found to be around 5000MW and 6000MW respectively [3] without considering technical feasibility.

With the increasing level of renewable generation, the intermittency of wind and solar creates challenges for power system operators. Variability in generation sources requires additional actions to balance the system. Greater flexibility in the system may be needed to accommodate supply-side variability in addition to load variability. System operators need to ensure that there are sufficient resources to accommodate significant up or down ramps in intermittent renewable generation to maintain system balance. Another challenge occurs when wind or solar generation is available during low load levels. In such situations, conventional generators may need to turn down to their minimum generation levels.

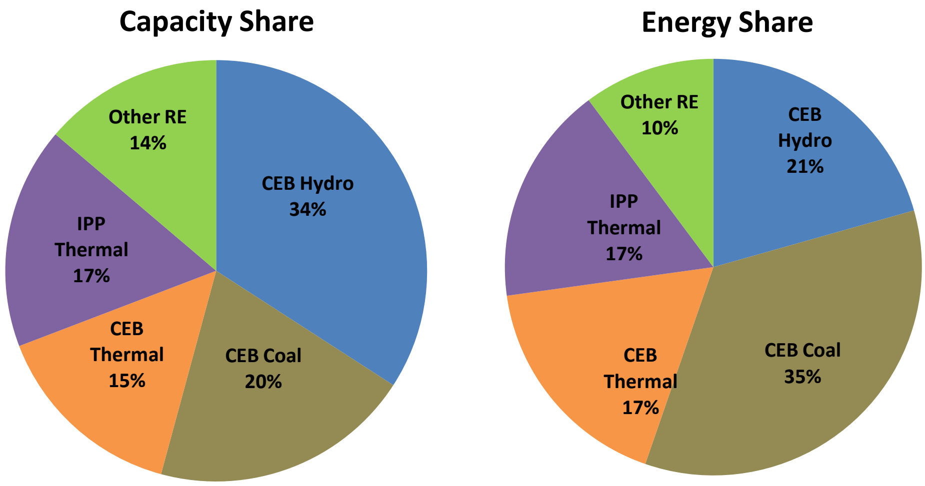

Figure 1.1: Capacity and energy mix of Sri Lanka 2016

Interconnection of the Sri Lankan and Indian Power Grids through HVDC link can bring benefits to both countries. Potential exists to share surplus capacity during off peak condition and to gain economic benefit through reserve capacity sharing. It could support the rapid development of Other Renewable Energy power plants in the Sri Lankan power system.

There are different technological options for HVDC interconnections worldwide mainly, line-commutated current-source converters (CSCs) using thyristors and forced-commutated voltage-source converters (VSCs) using gate-turn-off thyristors (GTOs) or insulated gate bipolar transistors (IGBTs) [4], [5], [6]. VSC technology is being developed at present and it has power flow controllability, fast response to disturbances and multi terminal configuration possibility with compared to CSC technology. [7]

Initial pre-feasibility was conducted in 2002 considering the India-Sri Lanka interconnection and feasibility studies have been continued afterwards[8], [9], [10]. Several researches have been carried out related to stability of the system. At present analysis is carried out at Ceylon Electricity Board to assess the feasibility of the HVDC link to import electricity. HVDC link is modeled as a thermal plant in the IAEA planning software WASP IV. Buying price is modeled as the unit cost of the thermal plant to quantify electricity import.

1.2 Objectives

The objective of this research is to assess the possible level of penetration in wind and solar power in Sri Lanka with the proposed India-Sri Lanka HVDC interconnectionand compare with other options.

Sri Lanka and India both are having ambitious renewable energy penetration targets and grid integration in Sri Lankan context gives rise to many issues. Sri Lanka power system has low demand during off peak hours (22:30 to 5:30 of the next day) which is approximately 40% of the peak demand which hinders the development of intermittent renewable energy.Rapid development in ORE power plants tends to give rise to grid stability issues and in future leading to curtailment requirements. On the other hand, with the increasing level of solar and wind India will have excess thermal capacity which Sri Lanka could import. The interconnection between two countries' power grids may enhance the capability of ORE development and reduce the level of curtailment required.Therefore it is necessary to assess the viability of energy transfer options with India.

Although present studies are carried out considering the rating of the interconnection to a capacity of 1000 MW, no specific justification is available [8] [9]. Therefore the phase development of HVDC was considered and dispatch simulation was carried out to identify the level of intermittent renewable energy (solar and wind considered) capacity addition. A comparison was carried out with the Pumped Storage Development option and neither HVDC or PSPP development option.

Further the economic analysis was carried out by considering above options and sensitivity analysis carried out by varying the unit cost of HVDC.

1.3 Organization of the dissertation

The organization of the dissertation is as follows.

Chapter 1 provides introduction to the dissertation. Background of the research and the objectives of the research are included here.

Chapter 2 comprises the literature review. Basics of the HVDC technology, India –Sri Lanka HVDC interconnection feasibility studies and the dynamic performance in Sri Lankan context are explained. Further literature related to renewable energy potential studies and grid integration studies have been described. This literature survey was used to obtain relevant data for the research as well as the renewable energy resource estimation.

Chapter 3describes the methodology used for the research as well as the input data used in the simulation. Optimization of power system using WASP software, dispatch analysis using SDDP and NCP software and the scenario selection for simulation was explained.

Chapter 4 contains the simulation results obtained according to the methodology explained in chapter 3. The optimum power plant schedules and the renewable penetration levels obtained for each of the scenarios are presented comprehensively in this chapter.

Chapter 5 contains the economic analysis of HVDC system with renewable and the comparison of cost with alternative system with Pump Storage Power Plant. Further it presents the sensitivity analysis to evaluate the effect of variation of HVDC cost.

Chapter 6 presents a detail discussion on the modeling and simulation results.

Chapter 7 gives the conclusion of the work done in this research study.

CHAPTER 2

LITERATURE REVIEW

2.1 HVDC Technology

The first commercial transnational interconnection was 20 MW, 100 kV undersea cable between the Swedish mainland and the island of Gotland commissioned in year 1954 [11]. At present, the HVDC transfer capacity has increased with innovative technologies.

There are mainly two technologies based on converter topologies. They are,

- Current Source Converter(CSC)
- Voltage Source Converters (VSC)

Current Source Converter is Line Commutated Converter with thyristors and this technology is also known as classical HVDC. It dates back to 1950's and it is a more mature technology. General ratings go up to 6400 MW, ±800kV. VSC is comparatively new technology and higher in cost. It is self-commutated technology with IGBT valves. Ratings go up to2400 MW, ±320 kV. Typical converter losses for CSC technology are in the range 2.5% - 4.5% and for VSC 4% - 6%.

First transformers with a transmission voltage of 1,100 kV for a record breaking power supply line in China are under construction. With a length of 3,284 kilometers and a transmission capacity of 12,000 MW, the new HVDC transmission line between Changji in the northwest of China and Guquan in the east is to be the largest HVDC project in the world. This is expected to enter service at the end of 2018 [12].

HVDC interconnection is a new concept to Sri Lankan power system although there are many HVDC links within India. There are several publications that had been done upon the India- Sri Lanka HVDC interconnection and proved the technical feasibility of the system.

2.2 India-Sri Lanka HVDC Interconnection

Viability of Developing a Transmission System Interconnection between India and Sri Lanka, February 2002 [7]

Initial pre-feasibility study related to interconnecting the transmission systems of India and Sri Lanka was carried out in 2002 with the objective of assessing the possible alternatives. The objective of such a transmission interconnection was to promote bilateral power exchange between the two countries. This interconnection was expected to provide significant benefits to the economies of the two countries through economical power exchange, increased efficiency in system operation, improved system reliability and diversity of supply, reduced environmental impacts and lower costs to consumers.

It was observed that an electrical grid interconnection could be developed with minor technical challenges and with reasonable investment since the countries are in the same region. Main objectives of the study was to identify the conditions needed to develop a transmission interconnection, to provide an initial cost benefit analysis and to determine the issues that need to be investigated further.

First phase of the study focused on preliminary technical and economic assessment of interconnection for power exchange between the two countries. The second phase evaluated both the technical and economic viability in detail as well as the environmental, operational, legal, regulatory and institutional aspects of the proposed interconnection.

Transmission and generation systems of Sri Lanka and India have been reviewed. CEBs' base load forecast at the time and generation and transmission plans have been assessed to identify future identified generation and transmission system. India's transmission system was being upgraded to interconnect its five regional grids and to increase power imports at the time. Eleventh Five Year Plan in India has been used along with the supply and demand situation analysis of the two countries.

Alternatives transmission Interconnections in 2002 Pre-Feasibility Study

The proposed transmission interconnection was expected to contribute to system reliability and security of supply and facilitate development of energy exchange between India and Sri Lanka. Following criteria have been considered in identifying the alternative transmission interconnections.

- Number of possible interconnecting locations (substations) in both India and Sri Lanka
- Number of possible power transmission technologies
- Type of possible transmission connections across the sea

Alternatives identified in the feasibility are,

- Madurai-Anuradhapura Interconnection using HVDC
- Tuticorin-Puttalam Interconnection using HVDC
- Madurai-Puttalam Interconnection using HVDC
- Madurai-Anuradhapura Interconnection using AC with back-to-back DC

For the Alternatives using HVDC, the following variations have been considered.

- Bipolar interconnection
- Monopolar interconnection

Advantage and disadvantages of each alternative with related to cost and reliability has been identified.

Technical Assessment in 2002 Pre-Feasibility Study

Typically AC transmissions pose technical difficulties and the ability to transmit power is decreased when the transmission distance becomes very long and the interconnecting systems have different frequencies. There are no such technical difficulties to an HVDC line. Due to the asynchronous nature of HVDC transmission, interconnecting two grids by HVDC allows them to retain individual frequency control.

Electrical losses in an HVDC link are also much lower than an AC link. One major disadvantage associated with an AC interconnection is high transmission loss which is approximately 5% of energy transmitted, compared to less than 1% for DC transmission.

A bipolar configuration offers the highest reliability since such a configuration can actually serve as a two-path system (2x250 MW). Each pole can operate as an independent path when the other pole is unavailable and each path in that case would carry half of the total power.

A major disadvantage of the mono-polar configuration is that in case of a fault with any of the converter/inverter or conductors, the full power is lost, and this may adversely affect the operation of the Sri Lankan system, which is much smaller than the Indian system.

A mono-polar system can be configured in three ways depending on the configuration of the return current path. If the entire interconnection is land-based, there is no need for a return conductor since the earth acts as the return current path. If the interconnection includes a water path, water can be used as a return conductor. But for environmental reasons, this is not done. Instead a return conductor is used. The third way is to provide a deep electrode station, well below the bottom of the water level, on each end of the interconnection. This avoids the need for a return conductor as well as avoids the use of water as the return current path.

Study conclusions are as follows;

- Power system stability studies and reliability studies would be required to assess the real system performance of these alternatives.
- A bipolar HVDC interconnection has an advantage over a mono-polar HVDC interconnection with respect to system availability.
- The proposed transmission interconnection should be fully integrated with generation and transmission expansion plans of the two countries in order to reap the maximum benefit for the total system.

- By introducing an interconnection between India and Sri Lanka, it will be possible to plan generation and transmission system expansion on a bilateral basis.
- The alternatives analyzed in the study do not indicate any technical obstacle to build a transmission interconnection between India and Sri Lanka that would benefit the two countries.

Economic Assessment

Investment requirements for the Indo-Sri Lanka transmission interconnection project were estimated to range from $116 million to $175 million, depending on the type of interconnection. Highest cost alternative was identified asTuticorin-Puttalam Interconnection using HVDC (bipolar) and the lowest cost alternative as Madurai-Anuradhapura Interconnection using HVDC (Mono-polar).

Power Transmission Interconnection Pre-Feasibility Study, 2006 [8]

Objective of the study has been to carry out the pre-feasibility study for power transmission interconnection between power grids of India-Bangladesh as well as India-Sri Lanka.

Power scenarios of the countries have been analysed as well as other inter-regional links in the world and their operations have been analysed. Different types of interconnections such as radial, asynchronous and synchronous have also been analysed.

When considering the quantum of power exchange 500MW has been initially recommended considering the power situation in the two countries and to expand to 1000MW depending on the demand increase.

Power flow studies have been carried out and it has been observed that for 1000MW expansion the network must be strengthened beyond interconnecting points. It was also observed that the interconnection would improve the voltage profile of the nearby stations.

The study concludes that the cross-border interconnection would benefit to both the countries. An AC interconnection would synchronize the two electrical grids and would bring complexities in frequency control and reactive power control. Therefore, HVDC bipolar connection has been identified as the best option. Considering the difficulty and cost of laying the transmission line including the submarine cables the quantum of power exchange should be significant for the project to be economically viable. Initially 500MW development and upgrade up to 1000MW depending on the demand increase has been recommended.

Feasibility Study on India-Sri Lanka Grid Interconnection Project, December 2011 [9]

The technical feasibility study for the Project has been completed in September 2011 by Power Grid Corporation of India Ltd (PGCIL). The study has evaluated three construction options and two technology options (CSC and VSC). The key outcomes of the technical feasibility study are the following.

Key outcomes of technical feasibility study

The interconnection was identified to be high voltage direct current (HVDC), operating at ±400 kV, connecting the Madurai 400 kV grid substation in the state of Tamil Nadu, India and the Anuradhapura 220 kV grid substation in the North Central Province, Sri Lanka.

The route of the interconnection has been identified as Madurai-Panaikulam (178 km overhead), Panaikulam-Thirukketiswaram (120 km, submarine) and Thirukketiswaram-Anuradhapura (160 km, overhead). In previous studies (NEXANT 2002, PGCIL 2006) the route for the Project has been taken as Madurai- ameshwaram-Thalaimannar- Anuradhapura. This change of routing has caused project costs to increase significantly.

The capacity of the interconnection was identified as 1000 MW. No specific justification has been provided to the rating of the interconnection to a capacity of 1000 MW. Stage development with initial 500MW has been recommended.

Three construction options with transfer capacity 1000 MW have been identified during technical feasibility study. Each construction option may be implemented either using the conventional ac/dc converter technology (line commutated) or the more recently developed voltage source conversion technology. No specific recommendation is provided in the technical feasibility study on the selection between the two technology options.

Options are as follows;

Option I:

Stage I- 2x250 MW bipolar interconnection (Figure 2.1)
Stage II- upgrading the above to 4x250 MW bipolar configuration

Option II:

Stage I- 1x500 MW mono-polar interconnection (Figure 2.2)
Stage II- upgrading the above to a 2x500 MW bipolar configuration

Option III: 2x500 MW bipolar configuration (built in a single stage)

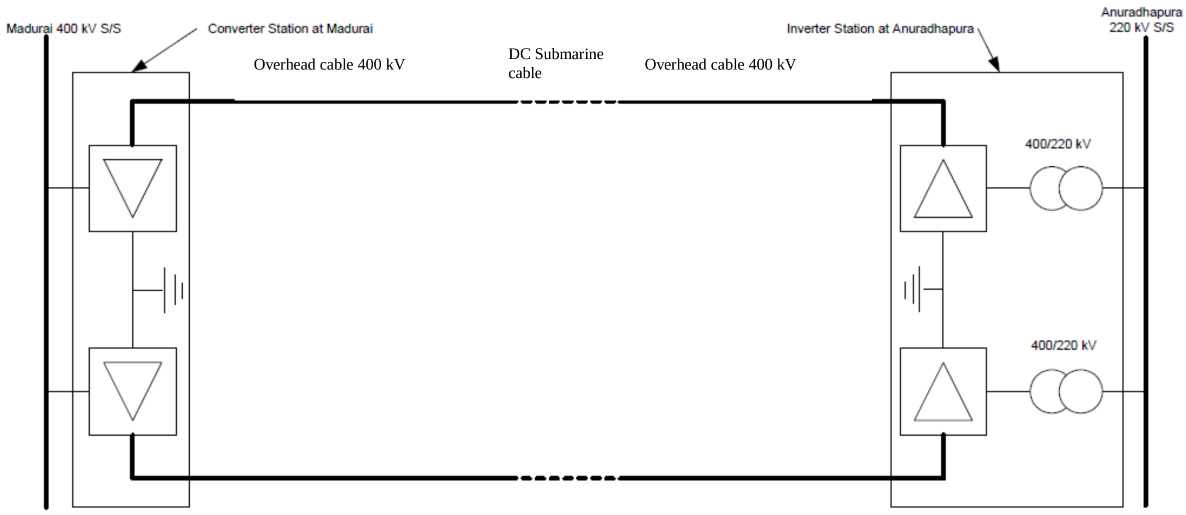

Figure 2.1: 2x 250 MW bipolar interconnection configuration

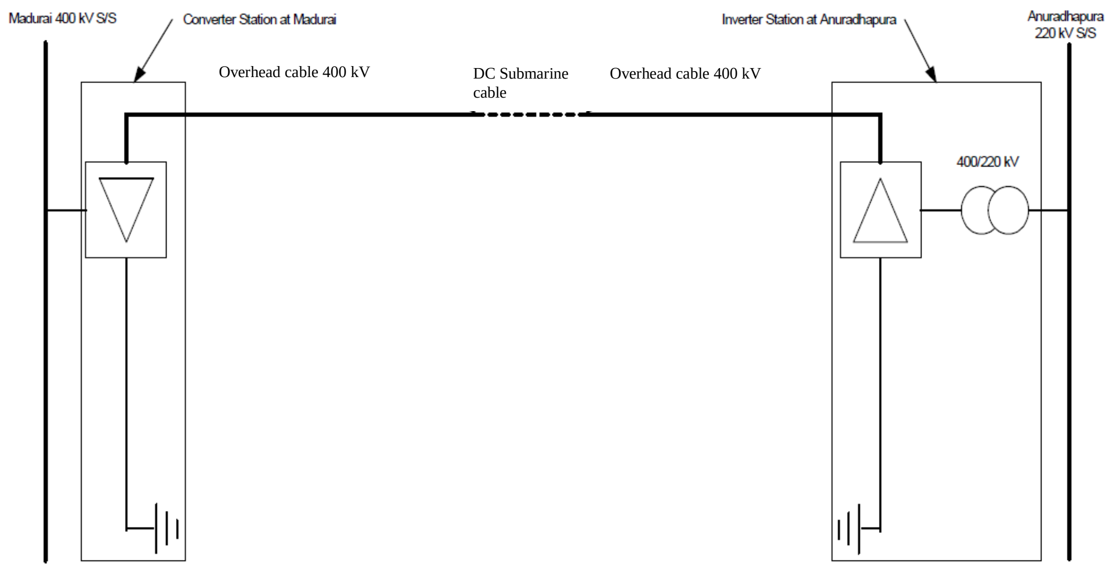

Figure 2.2: 1x500 MW mono-polarinterconnectionconfiguration

Investment Requirement

The project investments of the alternative construction and staged development and technology options, will be in the range 769 and 953 million USD once the full 1000 MW of capacity is developed, excluding customs duty and taxes.

Final Conclusion of the Economic and Financial Evaluation

The study concluded that the project must be structured as a 1x500 MW mono-polar interconnection with no specific assets or commitments at this stage to upgrade the capacity to 1000 MW considering economic viability. This is similar to construction option II stage 1 configuration (Figure 2.2). The evaluated cost during the study period in the technical feasibility study is 554 million USD. This cost can be further reduced by considering change of route.

The study concluded that pricing should consist of a levelised capacity charge not exceeding 1.81 UScts (based on a 7.2% discount rate), and fuel and O&M rate not exceeding 4.24 UScts/kWh (when indexed to an FOB price of USD 120 per tonne of 6000 kcal/kg coal).

It concluded that the project should carry a back to back Power Purchase Agreement with a power plant using imported coal in India for the full capacity of 500 MW. Both Sri Lanka and India will be allowed participation in the wholesale market in each other's country, with full options and freedom to participate in the short-term, day-ahead and unscheduled interchanges market.

Discussions after 2011

According to the inter-governmental discussions carried out after 2011, there are proposals to change the route in order to reduce the cost of the project. Feasibility studies need to be carried out for these new variations to identify the cost estimates. Therefore, the latest available data for this research was based on the feasibility study carried out in 2011.

2.3 HVDC Dynamic Performance in Sri Lankan Context

Rodrigo WDAS et al [13] had done modeling and transient analysis of HVDC bipolar link. They have studied about the dynamic behavior of the DC link and the AC systems in time domain. They have modeled the India and Sri Lanka power sources in thevenin's equivalent models. Jowsick, A.J.M.I. et al had implemented this interconnection in VSC technology [14]. They have studied about impact from the transients due to frequency fluctuation and country blackout on the HVDC transmission line's operations. Further the dynamic performance of the HVDC system has been modeled with detailed inverter side AC network and has studied about the impact on AC-DC interaction inverter side considering CSC technology [15].

The interconnection has been mathematically modeled inPSCAD/EMTDC software and analysed the system under thesteady state condition and perturbed conditions in the paper "Modeling and Simulation of Current Source Converter for Proposed India–Sri LankaHVDC Interconnection" [16] This system has been modeled with the basic DC control system and it concludes that the modeled AC-DCinteraction is asymptotic stable as it regain the pre-fault operating state after the fault is cleared.

2.4 Renewable Energy

2.4.1Introduction

International Energy Agency defines Renewable Energy as "Energy derived from natural processes (e.g. sunlight and wind) that are replenished at a faster rate than they are consumed."

Solar, wind, geothermal, hydro, and some forms of biomass are common sources of renewable energy. Intermittent renewable include wind, solar, wave and tidal energy, and are based on sources that fluctuate during the course of any given day or season. Variability is not new to power systems, which must constantly balance the supply and variable demand for electricity. In this research solar and wind are considered as variable renewable energy (VRE). However, large shares of variable renewable supply may increase pressure on power systems, which may need increased flexibility to respond to this balancing issue within short time step. More flexible generating capacities such as gas and hydro power plants, interconnections, storage (battery or with pumped-hydro plants)and demand side management supported by smart grids can be combined to provide the required flexibility.

Due to the reduction of green-house gas emission and sustainable nature of renewable energy sourcesthere is an increased trend in the implementation of renewable energy globally. However, both biomass and geothermal energy require wise management if they are to be used in a sustainable manner. For all of the other renewable, any realistic rate of use would be unlikely to approach their rate of replenishment by nature.

2.4.2 Sri Lankan Context

Sri Lanka has already harnessed its major hydro potential which is around 1600MW to its maximum level. Other Renewable Energy (ORE) development in Sri Lanka is very successful compared to other countries in the region. The growth achieved in the mini and micro hydro sector has also reached the full potential considering technical, economical and environmental feasibility.

In 1997,the grid connected operation of small Renewable Energy (RE) based power plants was regularized by the Ceylon Electricity Board (CEB). A standardized Small Power Purchase Agreement (SPPA) was introduced including a feed-in tariff (FIT) based on the avoided cost of fossil-based generation on the grid. This FIT was applicable for all renewable energy power plants with capacity less than 10 MW. This paved way for private developers to implement grid connected mini hydro power plants. This FIT, based on avoided cost principle was not sufficient for other technologies such as wind, solar and biomass to be developed.

In 2007, Sri Lanka Sustainable Energy Authority was established enacting the Sri Lanka Sustainable Energy Authority Act No. 35 of 2007of the Parliament of the Democratic Socialist Republic of Sri Lanka. The SLSEA was established in order to drive Sri Lanka towards sustainability in energy generation and usage, through increasing indigenous energy and improving energy efficiency and demand side management within the country [17].

National Energy Policy also has identified fuel diversity and energy security in electricity generation as a strategic objective and development of renewable energy projects was identified as a part of this strategy. In view of above, actions were taken up to introduce a cost based, technology specific and three-tier tariff instead of avoided cost based tariff with effect from year 2007. This paved the way for development of wind power as well. But only most recently the growth of solar power started with the technological development and the reduction of cost in solar power technology.

Therefore, major attention of ORE resources in future would be solar and wind for the immediate vicinity including biomass to possible extents. In this scenario wind & solar energy should be harnessed to the maximum potential giving due consideration towards the economic and technical viability of the power system.

Share of other renewable energy (ORE) based generation at present is 10% of total energy generation in Sri Lanka. Types of ORE connected to the national grid are mini hydropower, biomass, solar and wind power and total capacity contribution from ORE is about 555 MW. Table 2.1 shows the status of renewable energy in Sri Lanka as at

15th November 2016. The commissioned projects up until 1st August 2017 consists of 352 MW of mini hydropower, 24 MW of bio mass, 51 MW of solar power and 124MW of wind power indicating that only mini hydro and solar SPPA signed projects has been implemented.

Table 2.1: Present Status of Other Renewable Energy Sector (as at 2016 November 15)

	Commissioned Projects		**SPPA Signed Projects**	
	Number of Projects	**Capacity (MW)**	**Number of Projects**	**Capacity (MW)**
Mini Hydro Power	169	337.8	90	172.9
Wind Power	15	123.9	1	1.1
Biomass-Agricultural & Industrial Waste Power	4	13.1	**2**	**4.5**
Biomass/Dendro Power	5	11.0	13	66.0
Biomass-Municipal Waste	0	0.0	1	10.0
Solar Power	4	11.4	6	60.0
Total – Commissioned& SPPA Signed	**197**	**497.1**	**113**	**314.5**

Source: Sustainable Energy Authority

With the increase of non-dispatchable, renewable energy share, it creates several issues such as power quality, power system stability, economic operation due to intermittency, weakening of power system inertia, cost of ORE generation etc. Special attention should be especially paid when integration of wind and solar to the national grid due to the rapid variation of the power out of these sources. Therefore, a proper study has to be carried out in order to identify amount of ORE share both dispatchable and non-dispatchable that could be connected to system in terms of system operation and planning.

Figure 2.3 illustrates the historical contribution of Renewable energy sources for the total annual electricity generation.

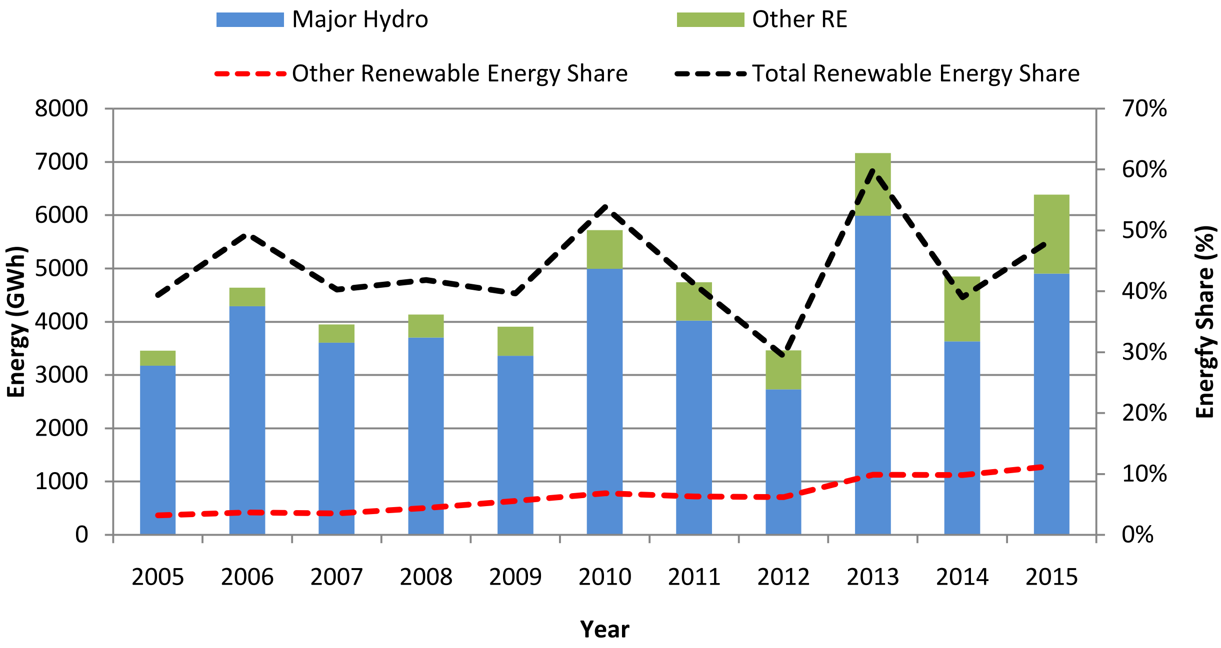

Figure 2.3: Historical Energy Contribution of Renewable Energy Sources 2005-2015

2.4.3 Indian Context

Indian power system consists of 330GW of Installed capacity of which 82% is conventional generation and 18% are other renewable based generation [18]. The use of renewable energy (RE) sources, primarily wind and solar generation, is to grow significantly within the Indian power system as well. The Government of India has established a target of 175 GWof installed RE capacity by 2022, including 60 GW of wind and 100 GW of solar, up from 29 GW wind and 9 GW solar at the beginning of 2017. There are about 46GW of coal power plants operating at low load factors which might need to be retired along with the penetration of solar and wind. [19] The energy from such power plants could be imported to Sri Lanka.

2.4.4 Renewable Energy Potential &Resource Estimation in Sri Lanka

Resource estimation is a major component in studying the integration of renewable energy based generation. Proper estimation of resource probabilities, seasonality and intermittencies is required for this kind of research. Resource estimation for this research was based on the report “Integration of Renewable Based Generation into Sri Lankan Grid 2017-2028” [20]

Major hydro being the largest renewable energy contributor, determination of its hydrological probabilities and total resource capability is important. Biomass and small hydro plants do not have significant short-term variation in generation. Generation from wind and solar plants are intermittent depending on the variations in the wind speed and solar radiation. As a result, integration of wind and solar plants into the power system will impact on other power system operation. It will also lead to additional reserve requirement. Therefore, profiles for other RE should be determined with best accuracy possible. Following section presents the resource estimation according to the report "Integration of Renewable Based Generation into Sri Lankan Grid 2017-2028".

2.4.4.1 Hydro

Major Hydro

The Sri Lankan power system is highly dependent on hydropower. Therefore, assessing the energy generating potential of the hydropower system precisely is essential. Some reservoirs are of multipurpose nature and have to satisfy downstream irrigation requirements which are a priority over power generation. The climatic conditions of Sri Lanka governed by the two monsoons and seasonal patterns of inflows to the reservoirs makes this assessment complicated. The annual energy variation of the existing hydro system, using the inflow data from 1979 to 2012, based on software simulation (Stochastic Dual Dynamic Program) is shown in Figure 2.4.

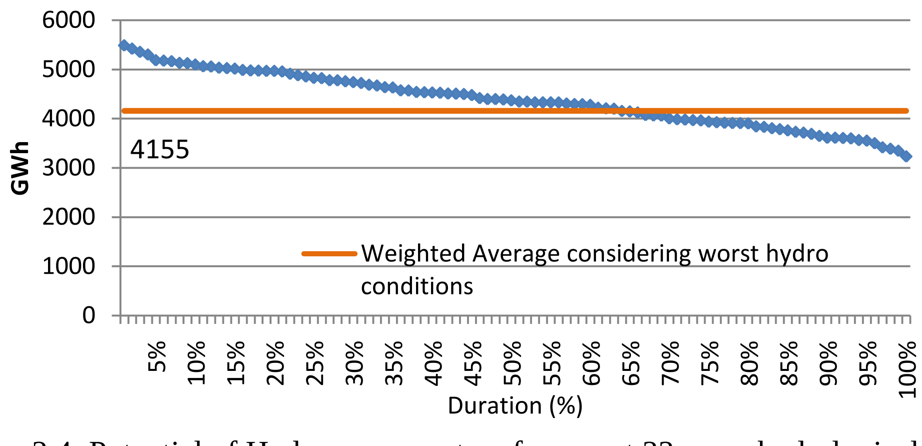

Figure 2.4: Potential of Hydropower system from past 33 years hydrological data
Source: [20]

Mini Hydro

Mini-hydro energy production is directly related to the hydrological condition of a given year and also exhibits a clear seasonal pattern. Historical data on Mini-hydro energy production has been analyzed for deriving a profile for mini Hydro model for simulation purpose. Seasonal pattern has been derived on monthly basis and the average annual plant factor is 36.3%. Figure 2.5 shows the mini hydro seasonal variation.

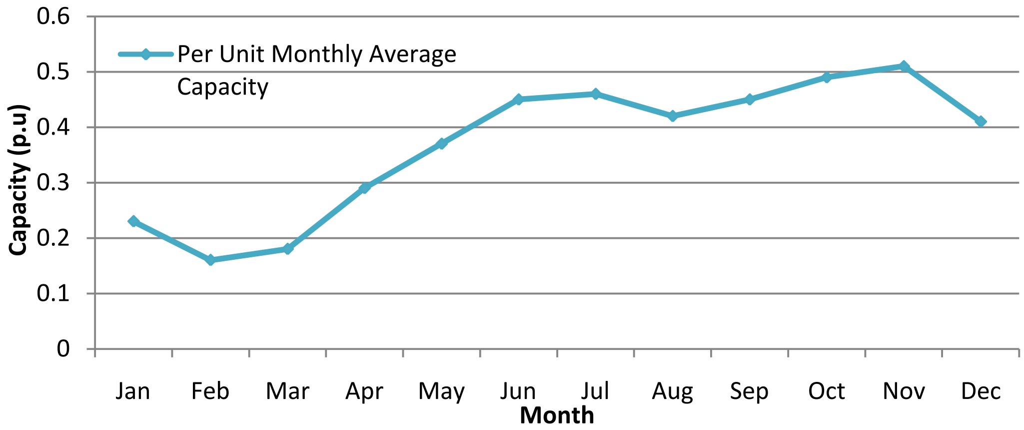

Figure 2.5: Per unit monthly average capacity of mini hydro plant
Source: [20]

2.4.4.2 Wind

The study has considered five main wind regimes for the modeling purpose, namely Mannar, Puttalam, Northern, Eastern and Hill Country to capture the diversity of wind portfolios throughout Sri Lanka. Accordingly the latest recorded data collected by Sri Lanka Sustainable Energy Authority (SLSEA) have been used for modeling the wind patterns and energy production of each regime. In cases where complete data sets were not available for 12 months continuously, estimating has been carried out with correlation techniques using the best available data from nearby sites.

Wind plant modeling to estimate annual energy production and hourly capacity variation has been carried out using the software named System Advisory Model (SAM 2014.1.14) developed by National Renewable Energy Laboratory, USA.SAM model is designed to make performance predictions and cost of energy estimates for grid-connected renewable power projects based on installation and operating costs and system design parameters that is specified as inputs to the model. Hourly wind speed data prepared for each site location is given as an input to the SAM software and then the wind plant is modeled specifying turbine and farm characteristics. Basic design parameters in Table 2.2have been considered in modeling each wind plant.

Table 2.2: Wind Plant modeling main parameters

Location	**Block Capacity**	**Turbine Capacity (MW)**	**Plant Availability**	**Wind Measurement Data**	**Hub Height (m)**
Mannar	25MW	2.5MW x10	91%	Nadukuda 2015	80
Puttalam	20MW	2MW x10	91%	Udappuwa 2009-2010	80
Hill Country	10.45MW	0.55MW x19	91%	Seethaeliya 2012-2014	50
Northern	20MW	2MW x10	91%	Pooneryn 2015	80
Eastern	20MW	2MWx10	91%	Kokkilai 2015	80

Source: [20]

In addition to the annual energy generation figures for wind energy given in Table 2.3, hourly variation of wind plant output can be obtained from the software output for the short-term dispatch analysis.

Table 2.3: Results on Wind plant modeling

Location	**Annual Plant Factor**	**Annual Energy(GWh)**
Mannar	36.71%	80
Puttalam	31.37%	55
Hill country	19.06%	17
Northern	34.07%	59.7
Eastern	37.32%	47.9

Source: [20]

2.4.4.3 Solar

Solar irradiance measurements have been obtained from the Sri Lanka Sustainable Energy Authority (SLSEA) in two locations namely, Hambantota and Kilinochchi. Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DHI) measurements were available with ten minute time step. Direct Normal Irradiance (DNI) has been estimated with the available GHI and DHI using solar zenith angle. Input data has been adjusted where there were distortions. Hourly inputs of solar irradiance measurements (W/m2) has been constructed for a complete year as input to SAM and it was used with site location inputs (latitude, longitude), elevation, and hourly temperature profile of the site. Availability of the plant has been assumed as 90% and typical commercial PV module and inverter characteristics in built in SAM has been used.

Resulted plant factors for the two locations are given in the Table 2.4 below.

Table 2.4: Solar output plant factor

Location	**Plant Factor**
Hambantota	16.3%
Kilinochchi	15.6%

Source: [20]

Figure 2.6shows the solar output variation with fifteen minute resolution in three days in March, June and November in 2016 in per kW terms for an installation at Hambanthota. This shows the intermittent nature of the resource and gives an indication of how it will affect the electricity generation from the solar PV plant.

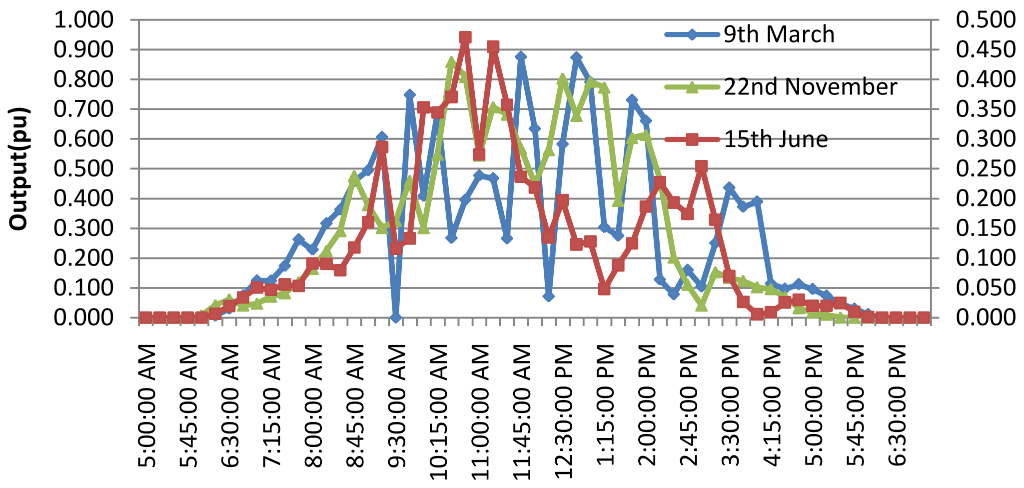

Figure 2.6: Variation of Solar PV Plant Output

2.5 System Reserve Requirement

With the higher penetration level of renewable energy, it brings more intermittency to the power system which makes the system operation more sophisticated activity. Therefore, it is necessary to identify the spinning reserve requirement of the power system. Most of the developed countries which promote the development of renewable energy do have day ahead forecasting mechanisms.

Accuracy of the wind and solar forecast strongly influence the system economics. Studies show that using forecasts in operations savessignificant money in fuel costs byallowing conventional units to be de-committed if sufficient wind and solar production is forecast.

Forecast error has been calculated by subtracting the actual value realized from the forecast value and based on the scale of the error and the forecast for the day ahead the additional reserve requirement is calculated. [21]

The Midwest ISO study keeps 10% cap on the total MW allowed for renewable. Although that 10% value has not been binding, Midwest ISO looks forward to relaxing the cap in the near future. [22]

CHAPTER 3

METHODOLOGY

3.1 Introduction

A number of different software was used in the modeling and simulation throughout the research study. Initially the Sri Lankan power system in 2025 and 2028 were developed with and without HVDC based on the Long Term Generation Expansion Plans. Wien Automation System Package (WASP) software was used in optimizing the generation expansion plan. Initial ORE development capacity was based on the draft LTGEP 2018-2037. After obtaining the power plant schedule, it was fed into SDDP to run the long term dispatch simulation and the hydro thermal optimization results were then fed into NCP; short term dispatch model. ORE capacity development was increased by allowing a curtailment limit of 5% demand and the maximum solar and wind capacity were obtained. The process was repeated for different scenarios and for different stages of HVDC development. To analyse the effect of two different technologies solar and wind this process was repeated for following scenarios.

- Solar Aggressive scenario
- Wind Aggressive scenario
- Solar &Wind Mix scenario

Figure 3.1 depicts the study methodology. Following sections will further describe the modeling approach and the input data requirement.

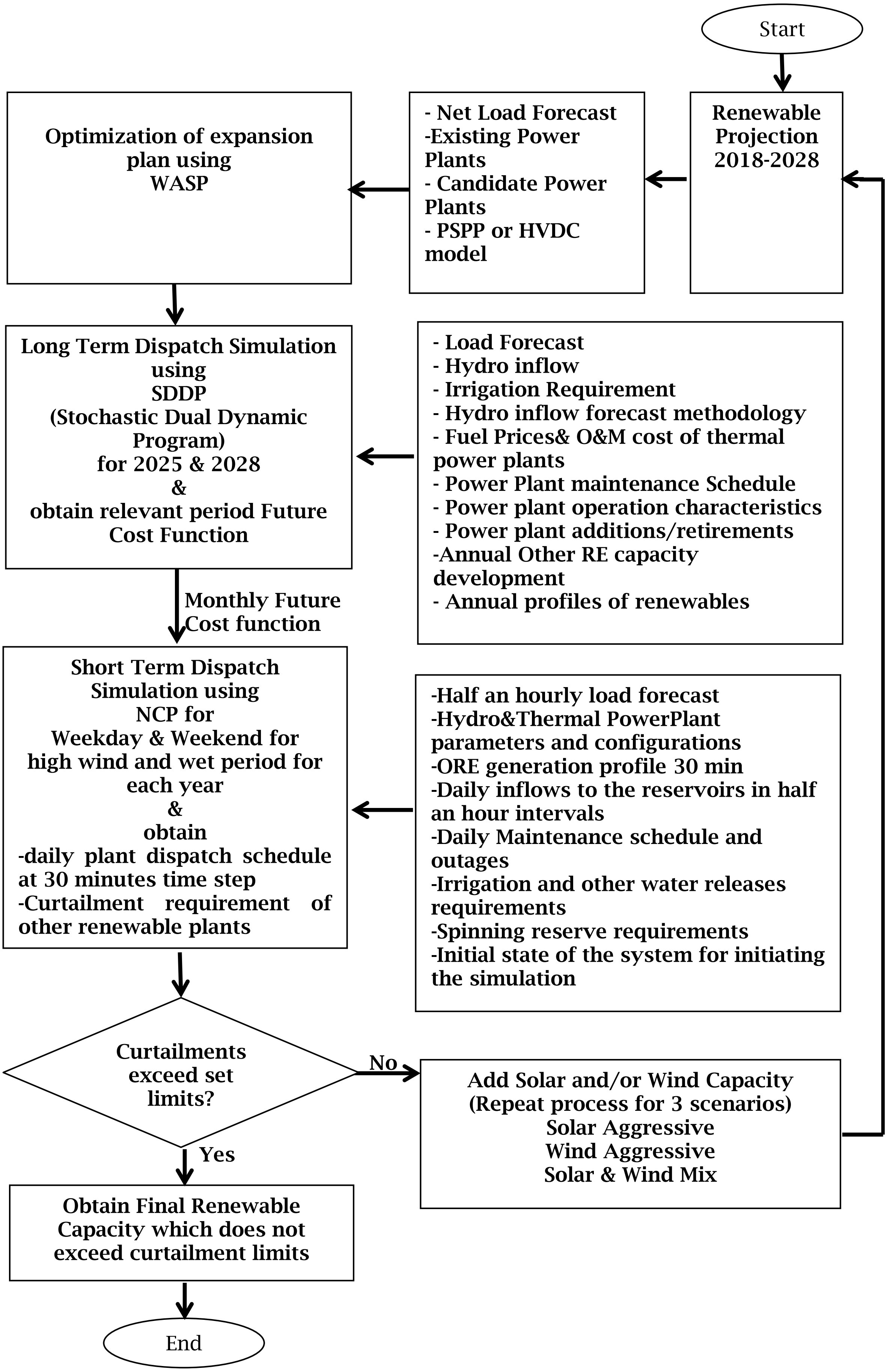

Figure 3.1: Research methodology

3.2 Optimization of Power Plant Schedule

Optimum power generation mix was derived based on the draft LTGEP 2018-2037 for year 2025 & 2028 using WASP software [23]. WASP determines the Generating System Expansion Plan that meets demand at minimum cost, while satisfying certain user specified constraints for the system. Initial Solar and Wind capacity was determined based on draft LTGEP 2018-2037. Based on the resource estimation explained in chapter 2, half hourly resource profiles were obtained for five wind regimes and two solar regimes. This was deducted from the half hourly load profiles and the net load was input to the system. 2018-2028 period was considered in the optimization.

Following scenarios were considered and optimized using WASP.

- Power system with HVDC

2018-2028 system was optimized by considering the phase development of HVDC; 500MW in 2025 and next 500MW by 2028.

- Power system with PSPP (for alternative comparison)

2018-2028 system was optimized by considering the phase development of PSPP; 200MW each in 2025, 2026 and 2027.

- Power system with HVDC and increased renewable penetration

Input Data

- Demand

Net demand was input as monthly load duration curve for the period 2018-2028. Annual Peak Demand considered for the two years of the simulation are as follows;

→ For 500MW HVDC system in 2025: 3836MW

→ For 1000MW HVDC system in 2028: 4398MW

Table 3.1: Load Forecast

Year	Generation		Peak
	(GWh)	Growth Rate (%)	(MW)
2018	15348	6.8%	2788
2019	16394	6.8%	2954
2020	17512	6.8%	3131
2021	18376	4.9%	3259
2022	19283	4.9%	3394
2023	20238	5.0%	3534
2024	21243	5.0%	3681
2025	22303	5.0%	3836
2026	23421	5.0%	4014
2027	24601	5.0%	4203
2028	25829	5.0%	4398

Source: LTGEP [24]

Initial projection of ORE capacity addition was based on LTGEP 2018-2037. These capacity additions were based on the five wind regimes and two solar regimes as discussed in literature review. These capacity additions and the per unit resource profiles were based to develop the ORE 30 minute profiles and this was deducted from the 30 minute load data projection to derive the net demand forecast for the period 2018-2028. Figure 3.2 shows the net LDC of a selected day in 2025 June for simulation.

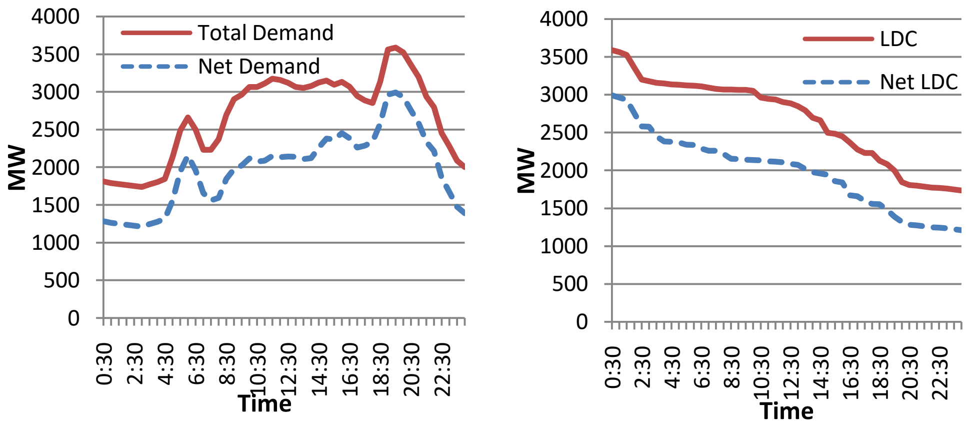

Figure 3.2: Demand Curve & LDC of a typical day in 2025 June

- Existing Power System

  Existing Power Plants and their respective retirements was based on draft LTGEP 2018-2037

- Candidate Power Plants for Optimization

  Candidate Power Plants Parameters are given in Table 3.2 and Table 3.3.

- Solar and Wind Power Parameters

  Table 3.4 gives the other renewable energy initial capacities considered according to LTGEP. This was considered as the basis for the simulation.

  Table 3.5 gives the cost parameter of ORE power plants used in the economic evaluation.

Table 3.2: Candidate Power Plant Characteristics

Plant	Net Capacity (MW)	Heat Rate (kCal/kWh)		Full Load Efficiency %	FOR %	Scheduled Maint. Days (per year)
		At Min. Load	Avg. Incr.			
Gas Turbine-Auto Diesel	35	3060	-	28.1	8	30
Gas Turbine-Auto Diesel	105	4105	2310	30.1	8	30
Combined Cycle Plant -Auto Diesel	144	2614	1462	46.7	8	30
Combined Cycle Plant -Auto Diesel	288	2457	1454	48.2	8	30
Combined Cycle Plant-LNG	144	2574	1462	48	8	30
Combined Cycle Plant-LNG	287	2462	1462	48	8	30
High Efficient Coal Plant	270	2810	1935	38.4	3	45
Super Critical Coal Plant	564	2248	1833	41.3	3	45
Reciprocating Engine	15	2210	-	38.9	5	60

Source:LTGEP [24]

Table 3.3: Candidate Power Plant Cost Parameters

Plant	Net Capacity (MW)	Total Unit Cost Incl. of IDC (Net) (US$/kW)	Construction Period Years	Economic Life Years	Fixed O&M Cost ($/kW Month)	Variable O&M Cost (USCts/ kWh)
Gas Turbine-Auto Diesel	35	785.9	1.5	20	0.69	0.552
Gas Turbine-Auto Diesel	105	534.5	1.5	20	0.52	0.414
Combined Cycle Plant -Auto Diesel	144	1668.9	3	30	0.54	0.467
Combined Cycle Plant -Auto Diesel	288	1264.9	3	30	0.41	0.352
Combined Cycle Plant-LNG	144	1314	3	30	0.25	0.497
Combined Cycle Plant-LNG	287	1265.9	3	30	0.38	0.497
High Efficient Coal Plant	270	2117.2	4	30	4.47	0.582
Super Critical Coal Plant	564	2272	4	30	4.79	0.582
Reciprocating Engine	15	1011.9	1.5	20	2.38	0.634

Source:LTGEP [24]

Table 3.4: ORE Initial Capacity

Year	Cumulative Wind Capacity (MW)	Cumulative Solar Capacity (MW)	Cumulative Min Hydro Capacity (MW)	Cumulative Biomass Capacity (MW)
2018	144	210	344	39
2019	194	305	359	44
2020	414	410	374	49
2021	489	465	384	54
2022	539	471	394	59
2023	599	526	404	64
2024	644	581	414	69
2025	730	685	424	74
2026	729	740	434	79
2027	754	795	444	84
2028	800	900	454	89

Source:LTGEP [24]

Table 3.5: Renewable Power Plant Cost Parameters

	Capital Cost $/kW	Fixed O&M Cost	Var. O&M Cost (USCts/ kWh)
Mini hydro	1729.0	3.0% of capital cost	-
Wind	1525.0	1.5% of capital cost	-
Solar	900.0-1400.0	0.7% of capital cost	-
Biomass	1814.2	2.43 $/kW Month	4.46

Source: LTGEP [24]

- Fuel Characteristics

  Oil, coal and natural gas prices and characteristics were based on draft LTGEP 2018-2037 and are as follows.

Table 3.6: Oil Prices and Characteristics for Analysis

Fuel Type	Heat Content (kCal/kg)	Specific Gravity	Market Prices		CIF Price	
			($/bbl)	Rs/l	($/bbl)	Rs/l
Auto Diesel	10500	0.84	101.5	95	53.1	47.9
Fuel oil	10300	0.94	85.4	80	46.2	41.7
Residual oil	10300	0.94	85.4	80	45.3	40.9
Naphtha	10880	0.76	79.03	74	48.8	44

Source: LTGEP [24]

Table 3.7: Coal Prices and Characteristics for Analysis

Fuel Type	Heat Content (kCal/kg)	Market Price ($/MTon)
Coal for Lakvijaya Power Plant	6300	75.9
Coal for High Efficiency Coal Power Plants	5900	69.8

Source: LTGEP [24]

Imported regasifiednatural gas delivered price at power plant was considered as 10$/MMbtu and heat content considered as 13000 kCal/kg. [24]

- Pumped Storage Power Plant Parameters

Initially 11 candidate sites have been identified for the development of pumped storage power projects during the studies carried out by JICA and then screening has been carried out to select the most promising candidate site [24].Most promising candidate site has been selected based on geological evaluation, ease of the construction works, the power system analysis, the manufacturing limitation, the construction cost, and the natural/social environmental evaluation. MahaOya site location has been identified as the most promising site for the development of the future Pumped Storage Power Plant.

All candidate sites have the installed plant capacity of 600 MW. Therefore, the base cases composed of three sets of a unit capacity 200 MW, and the alternative cases composed of four sets of a unit capacity 150 MW during the evaluation phase of the study. It concludes that the optimum capacity of the proposed Pump Storage power plant should be 600MW considering the peaking requirement beyond 2025.The unit capacity of pump storage power plant has been determined considering the system limitations in terms of frequency deviations and manufacturing limitations of high head turbines. The study recommended that unit size will be finalized during the detail design stage. Therefore the base case which is 3 units of 200MW is considered for the simulation.The parameters of PSPP used in the simulation are given in Table 3.8.

Table 3.8: PSPP Parameters

Parameter	Value
Capacity	3 x 200MW
Capital Cost	1291.3 $/kW
Construction time	5 years
Plant lifetime	50 years
Cycle Efficiency	70%
Fixed O&M	0.83 USD/kW-month

Source: PSPP Feasibility [25]

- HVDC Parameters

HVDC was modeled in WASP as a thermal power plant. The key element in this model is that Sri Lanka and India enter into a long-term PPA for the transfer of power.Apossibility is for Sri Lanka to enter into a long-term PPA for thetransfer of the required capacity (to be equal to the capacity of the interconnection), with an ultra-mega power plant in India. The parameters of HVDC used in the simulation are given in Table 3.9. [10]

Table 3.9: HVDC Parameters

Parameter	**Value**
Capacity	2 x 500 MW
Capital Cost	1286$/kW
Construction time	4 years
Plant lifetime	40 years
FOR	1%
Scheduled Maintenance days	11
Typical losses	4.5%
Tariff	70USD/MWh (including wheeling charge)

Source: [10]

- Reliability criteria
  → Reserve margin between 2.5% and 20%
  → LOLP 1.5
  Source: [26]

Figure 3.3 shows the area of optimization in the WASP software.

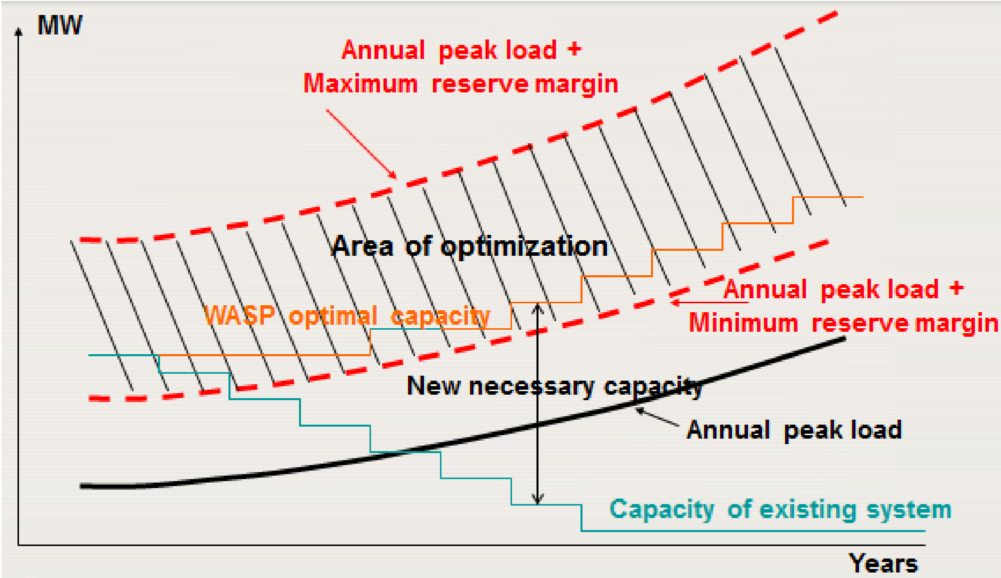

Figure 3.3: WASP Optimization within Reserve Margin criteria
Source: [23]

- Spinning Reserve Criteria

10% of intermittent renewable capacity was kept as spinning reserve as additional to 5% of demand. [22]

- Discount rate used for the economic analysis 10%

Above data was input and the optimization was carried out using WASP-IVsoftware. Simulation and optimization methods used in WASP-IV are as follows. [23]

In WASP-IV, **Probabilistic Simulation** is used to evaluate the expected electricity generation by each unit, operation cost, unserved energy and system reliability and **Linear Programming** is used to find optimal dispatch for a given generating system configuration satisfying given constraints (fuel availability, electricity generation).

Dynamic Programming is used to select the optimal expansion plan for the power generating system. Optimization of power generating system expansion with WASP-IV is to find the one alternative that minimizes the total discounted expansion and operation cost (investment, O&M, fuel, unserved energy etc.) over the study period considered, while meeting certain constraints (reliability, spinning reserve, loading order), among the alternative expansion paths (sequence of power unit additions to the system) proposed.

Using above input data and the methodology the optimum plant dispatch schedule within the known constraints was obtained.

3.3 Dispatch Simulation to Identify Optimum Renewable Penetration

3.3.1 Long Term Dispatch

Objective was to analyze the economical plant dispatch of power system, embedded with renewable energy, on yearly basis by running Stochastic Dual Dynamic Programing (SDDP) software [27] for the two years 2025 & 2028. Following were input to the software.

Input Data

- Demand Data

Demand data input was prepared based on the Annual Energy Demand Forecast (2015-2034) from Generation planning unit of CEB. Monthly energy was obtained for the period using ½ hour energy demand profile.

- Hydro Inflow Data

Historical Monthly inflows from 1979 to 2014 (35 years) to hydro reservoirs and ponds have been used. Initial year of hydrology was used as 2012.

- Forecast of future Irrigation requirement

Irrigation water requirement was calculated based on latest Seasonal operational plan provided by Mahaweli authority assuming constant irrigation release over the study period

- Hydro inflow forecast methodology

Periodic autoregressive model is used for forecasting hydro inflow.

- Fuel Prices and O&M cost of thermal plants

2016 prices and cost data values were used.

- Annual power plant additions/retirements for the period 2018-2028

Future hydro/thermal plant additions and retirements were modeled as per the plant addition/ retirement plan of draft LTGEP 2018-2037.

- Plant maintenance schedule

Maintenance schedule of hydro plants and thermal plants excluding coal plants were prepared based on the current maintenance scheduling practice adopted by the system control center.

- Other operational characteristics of power plants

Other characteristics of hydro power plants such as mean production coefficient, turbine flow rate were input to SDDP. For thermal power plants fuel specific consumption, combined cycle configuration data were input. Data for existing power plants were input as per CEB, system control center present operational procedure.

- Annual Other RE capacity development for initial system

Initial system other renewable energy capacity development was based on the draft LTGEP 2018-2037.

- Other RE resource profiles

Other RE profiles were determined as described in Chapter 2 and they were fed into the SDDP software.

Using above data hydro thermal dispatch is simulated for the period 2018-2018. In, SDDP methodology system is operated to minimize the total cost of the system considering optimum hydro dispatch by looking at the immediate cost of using/saving water and future cost associated as depicted in Figure 3.4.

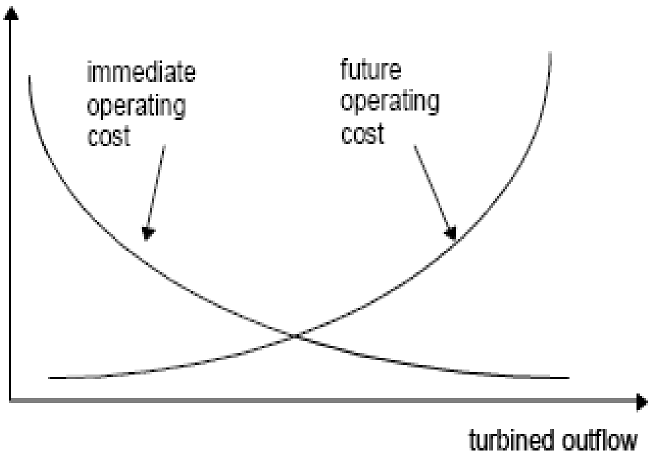

Figure 3.4: Immediate and Future Cost Function Variation with Turbine Outflow

3.3.2 Short Term Dispatch

NCP software tool provides the economic dispatch of power plants for systems that comprise of hydro, thermal and renewable generation sources. It considers the operational constraints of each type of generation resource and other system operational limitations to conduct the economic dispatch to meet the load [28]. Further when the specified generation constraints cannot be satisfied, the NCP determines the excess amount of renewable energy generation and provides the output on curtailment requirement. Hydro thermal optimization result obtained from the SDDP simulation (future cost function which determines the state of hydro reservoirs and thermal generation), is one of the main input for NCP in formulating the daily dispatch simulation.

Seasonal Variation Approximation

In this study, NCP software tool was used to simulate daily dispatch of selected days in 30minute time step and the curtailment requirement of renewable energy production was identified. All the system constraints were modelled according to the present operational procedures of the CEB system control center.

NCP is a short-term dispatch simulation model and a single NCP simulation requires considerable amount of time for execution. Therefore, to make a better approximation, a given year was divided into three periods to capture the seasonal variations of hydro conditions, renewable variations and demand variations namely dry period, wet period and high wind period. According to "Integration of Renewable Based Generation into Sri Lankan Grid 2017-2028", CEB, no curtailments were observed during dry period in the system with initial wind and solar capacities. Therefore only wet and high wind periods were taken into analysis as they are the limiting criteria for renewable development. Future cost function for the respective month was obtained from SDDP as an input to NCP along with the following inputs to obtain the results.

Thereafter two days per each period, a weekday and a weekend day were selected which represents the demand variations. Dates were selected in a way that they provide the best justification for the final results.

The inputs that were used for the model and specified constraints are mentioned below.

Inputs Data for Short Term Model

- Future Cost Function of the corresponding month obtained from SDDP simulation
- Half an hourly load forecast
- Hydro Plant parameters and configurations
  (Unit Generation and turbine outflow constraints, Reservoir operation constrains, Cascade hydro plant topologies, Irrigation requirements, Must run hydro power plants)
- Thermal Plant parameters and configurations
  (Minimum loading level constraints, plant startup costs, Minimum up time and minimum down time (hours), Maximum ramp up and Maximum ramp down (MW/min) rates)
- ORE generation profile in half an hour intervals
- Daily inflows to the reservoirs in half an hour intervals
- Daily Maintenance schedule and outages of all generation units
- Irrigation and other water releases requirements from the reservoirs

- Initial state of the system for initiating the simulation
- System Operation Constraints

  - Spinning reserve from all hydro plants for frequency control

  - Total secondary Spinning reserve requirement is specified as 5% of demand

  - Largest Generation unit online should not be greater than 30% of the system load

- Renewable Power Plants

  - Must run condition for wind, biomass, solar and Mini hydro

  - Curtailment is allowed at instances where above constraints cannot be met

Interpretation of Output Results

For each simulation representing each season the half hourly generation and the excess renewable outputs were obtained. As depicted in Figure 3.1, the renewable capacity was increased and the simulation was repeated until curtailment/excess renewable generation reached the set limits. In the report "Integration of Renewable Based Generation into Sri Lankan Grid 2017-2028", curtailments can be observed in the original system up to 380MW during some days. [22] Power system with HVDC was developed and increased the solar and wind capacity development along with the development of HVDC and limited curtailments up to 5% of demand.

3.4 Scenario Selection

To analyse the effect of penetration of two different technologies solar and wind with the development of HVDC this process was repeated for following scenarios.

- ➢ Solar Aggressive scenario
  Original wind capacity was unchanged and the solar capacity was increased until the curtailment limits are reached

- ➢ Wind Aggressive scenario
  Original solar capacity was unchanged and the wind capacity was increased until the curtailment limits are reached

- Solar &Wind Mix scenario

  A mix of solar and wind was increaseduntil the curtailment limits are reached

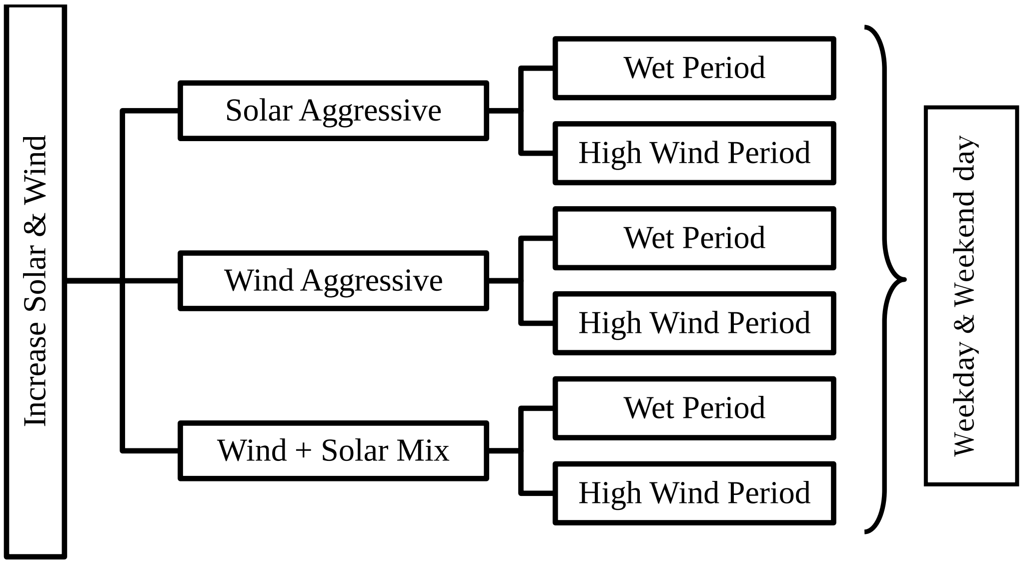

Figure 3.5: Scenarios for simulation

3.5 Assumptions

- Future wind, solar and mini-hydro generation profiles are estimated based on measured data and past performance and it was assumed there are no significant variation in future years.

- Future power plant additions and retirements are according to the daft LTGEP 2018-2037.

- Maintenance plans of major power plants (Coal fired and Combined cycle Plants) for future years were prepared as per the maintenance requirement and CEB present practice in maintenance scheduling.

- Off-peak low demand constraints considered for wind development, usually occurring on weekends. Day peak constraint mainly for solar development is reflected on weekend day time demand.

- Since CEB keeps 5% of demand as spinning reserve, the curtailments are allowed up to that level

- Transmission infrastructure to cater for the development of renewable are developed in parallel.

- Economic analysis do not consider the institutional, regulatory and legislative framework related cost and assume no barriers for exchange

- Economic analysis assumes that the total cost of HVDC development is borne by Sri Lanka.

CHAPTER 4

SIMULATION RESULTS

4.1 Introduction

As discussed in Chapter 3, research was conducted for phase development of HVDC and comparison carried out with compared to original system with PSPP. Phase development was considered as below.

- 500MW HVDC in 2025
- Next 500MW in 2028

Further weekday and weekend sample days for high wind and wet periods were considered in the simulation. Following sections will describe the simulation results obtained.

4.2 Optimized Capacity Additions

For the phase development of HVDC and PSPP the optimized capacity additions were obtained from WASP for the year 2025 and 2028 as shown in Table 4.1.

Table 4.1: Capacity additions of the system with initial renewable capacities

Considered year for simulation	2025		2028	
	Original System with PSPP	With 500MW HVDC	Original System with PSPP	With 1000MW HVDC
Major hydro	1578	1578	1578	1578
Coal Existing	540	540	540	540
Coal New Addition	540	270	540	270
Combined Cycle Existing	595	595	595	595
Combined Cycle New Addition	540	540	540	540
GT New Addition	105	105	105	105
Other thermal	24	24	24	24
Mini hydro	424	424	454	454
Biomass	23.5	23.5	23.5	23.5
Wind	730	730	800	800
Solar	685	685	900	900
PSPP	200	0	600	0
HVDC	0	500	0	1000
Total Installed Capacity	5985	6015	6700	6830
Total Installed Capacity without intermittent renewable*	4146	4176	4546	4676
Demand	3836	3836	4398	4398

*Solar, wind and mini hydro are considered as intermittent renewable

4.3 System Comparison with PSPP and HVDC for Phase 1 of HVDC

By taking into account the capacity additions given in Table 4.1, dispatch simulation was carried out. With the initial solar and wind capacities of 685MW and 730MW respectively power system with PSPP and HVDC was simulated to obtain renewable excess generation as follows.

Simulation results for wet period and high wind period weekdays and weekends are presented here.

Wet Period

2025 Power System with 200 MW PSPP (685MW Solar, 730MW Wind)

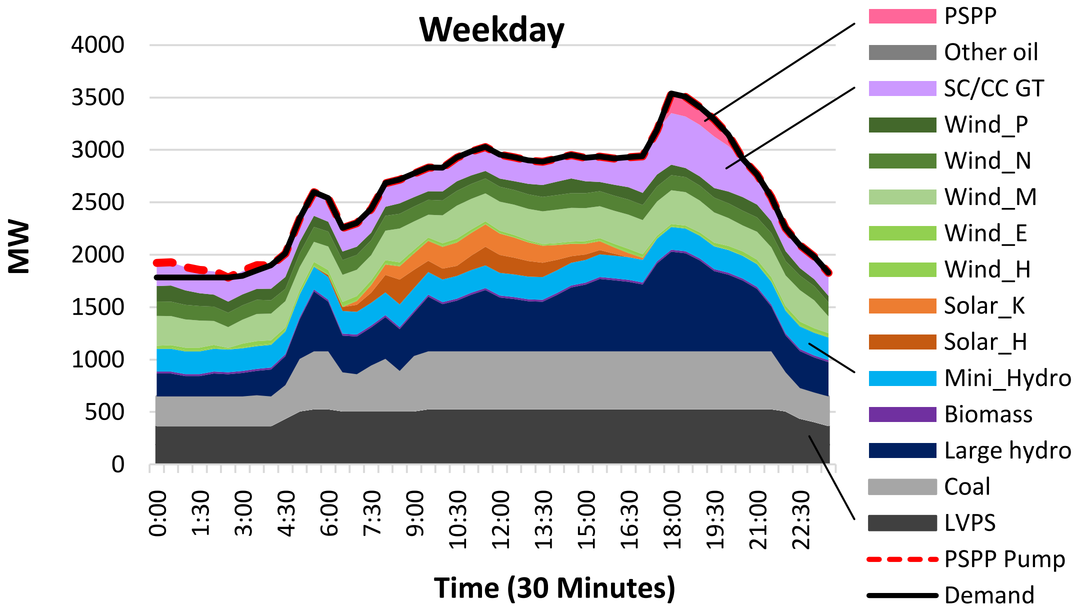

Figure 4.1 (a): Power plant dispatch with 200MW PSPP in 2025 wet period weekday

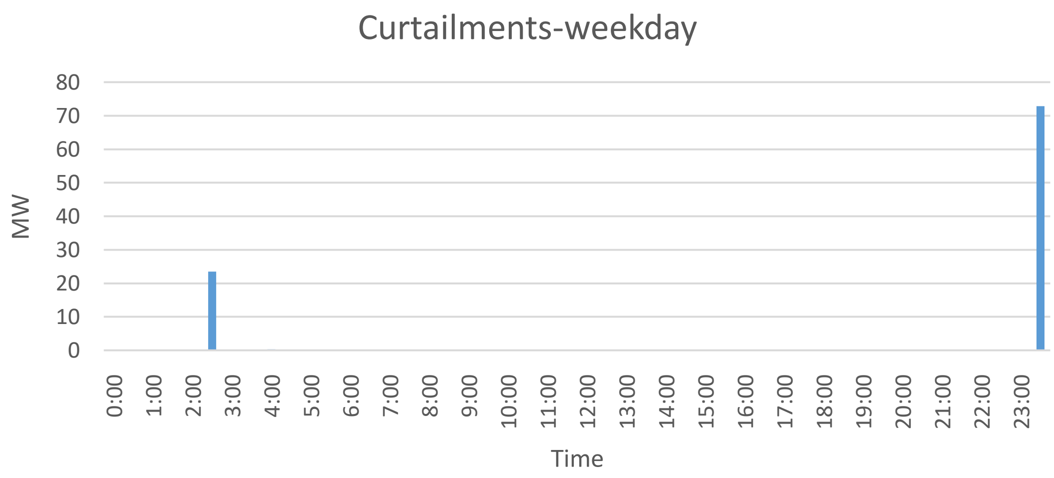

Figure 4.1 (b): Curtailments of Renewable Generation with 200MW PSPP in 2025 wet period weekday

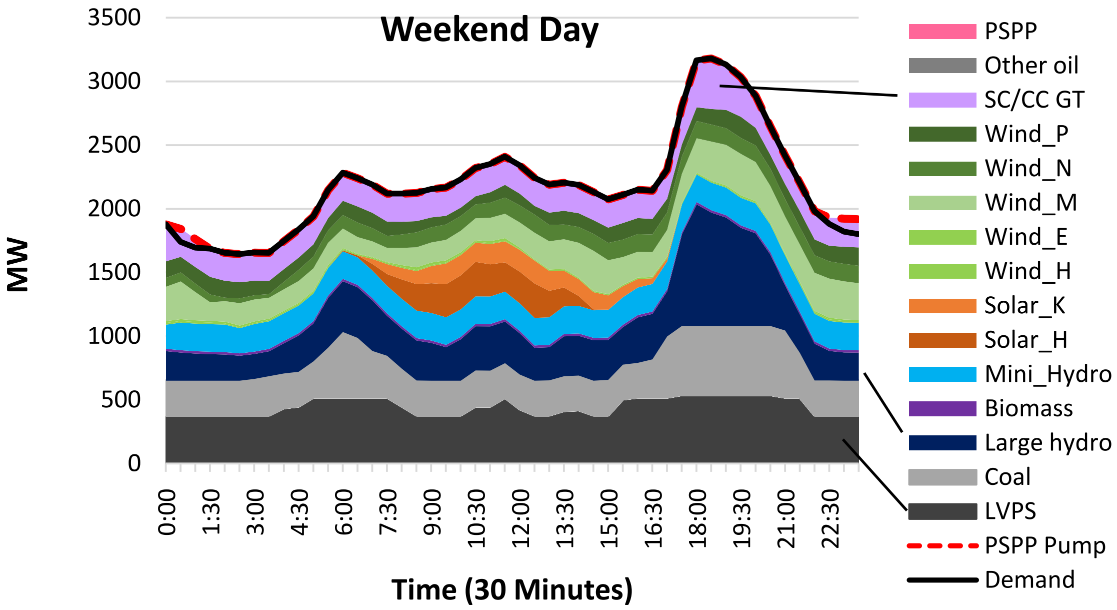

Figure 4.2 (a): Power plant dispatch with 200MW PSPP in 2025 wet period weekend day

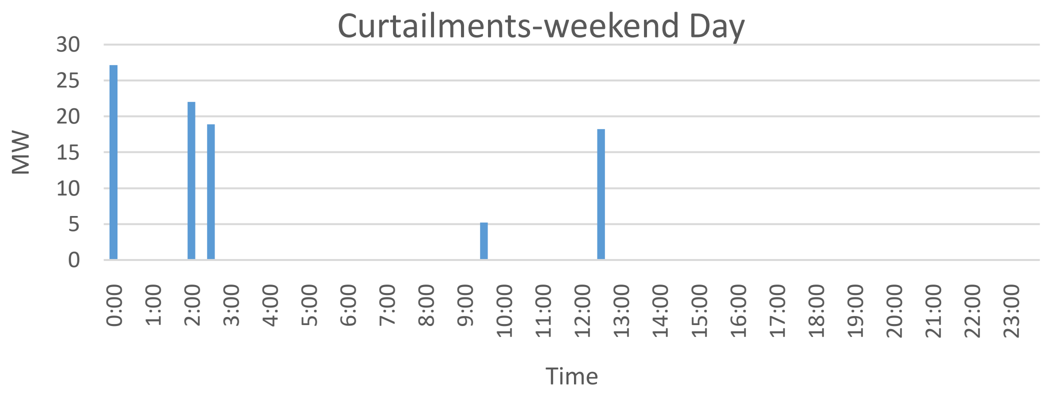

Figure 4.2 (b): Curtailments of Renewable Generation with 200MW PSPP in 2025 wet period weekend day

Simulation results for wet period in 2025 power system with PSPP are shown in Figure 4.1 & Figure 4.2. With 685MW solar and 730MW wind, curtailments could be observed due to wind during off peak hours in the range up to 75MW. Curtailments due to solar can be seen during day time of weekend.

2025 Power System with 500 MW HVDC (685MW Solar, 730MW Wind)

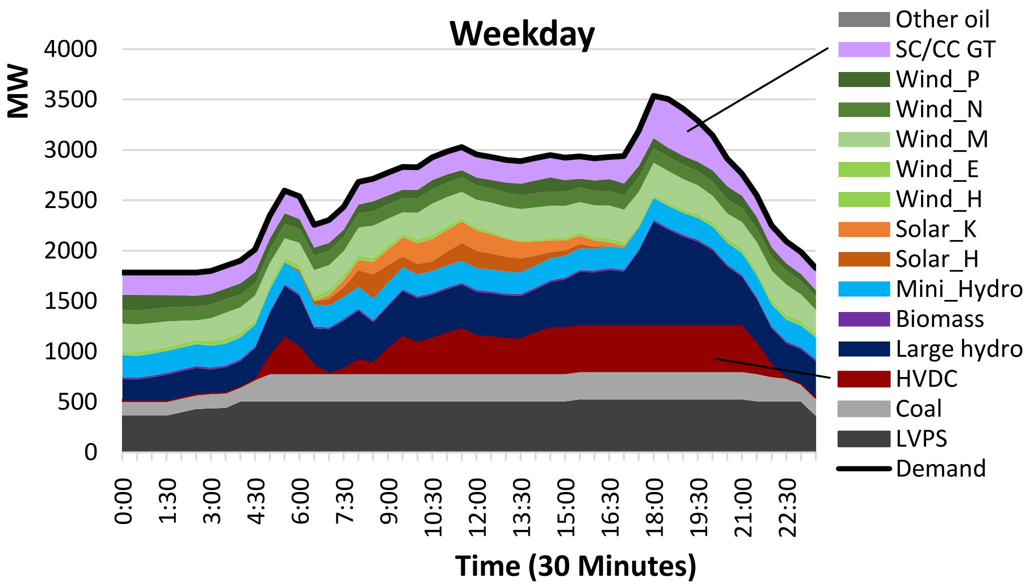

Figure 4.3: Power plant dispatch with 500MW HVDC in 2025 wet period weekday

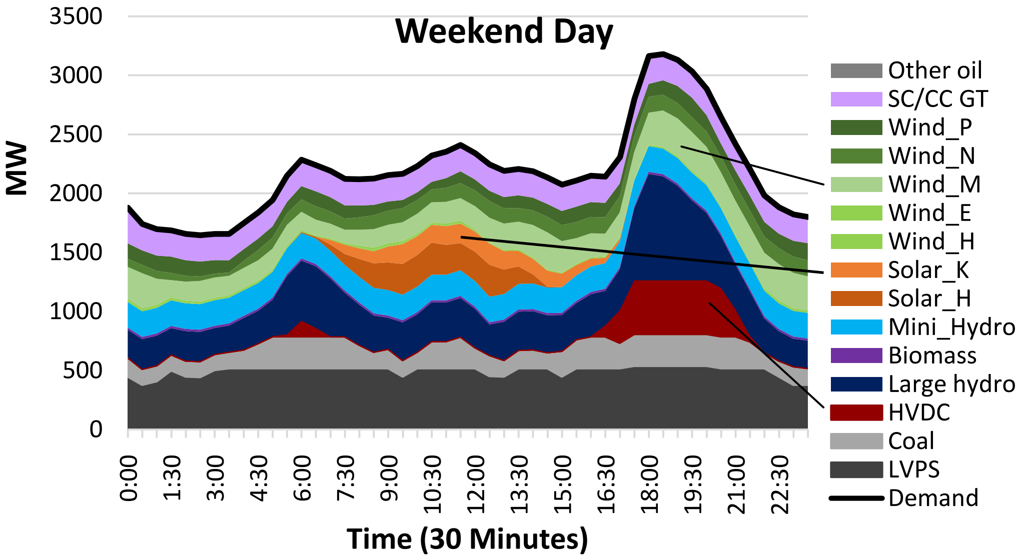

Figure 4.4: Power plant dispatch with 500MW HVDC in 2025 wet period weekend

In the simulation results for 2025 power system (wet period) with HVDC for the same initial renewable capacities there were no curtailments observed. HVDC has import energy during day time & night peak in a weekday and during day peak & night peak in a weekend day.

High Wind Period

2025 Power System with 200 MW PSPP (685MW Solar, 730MW Wind)

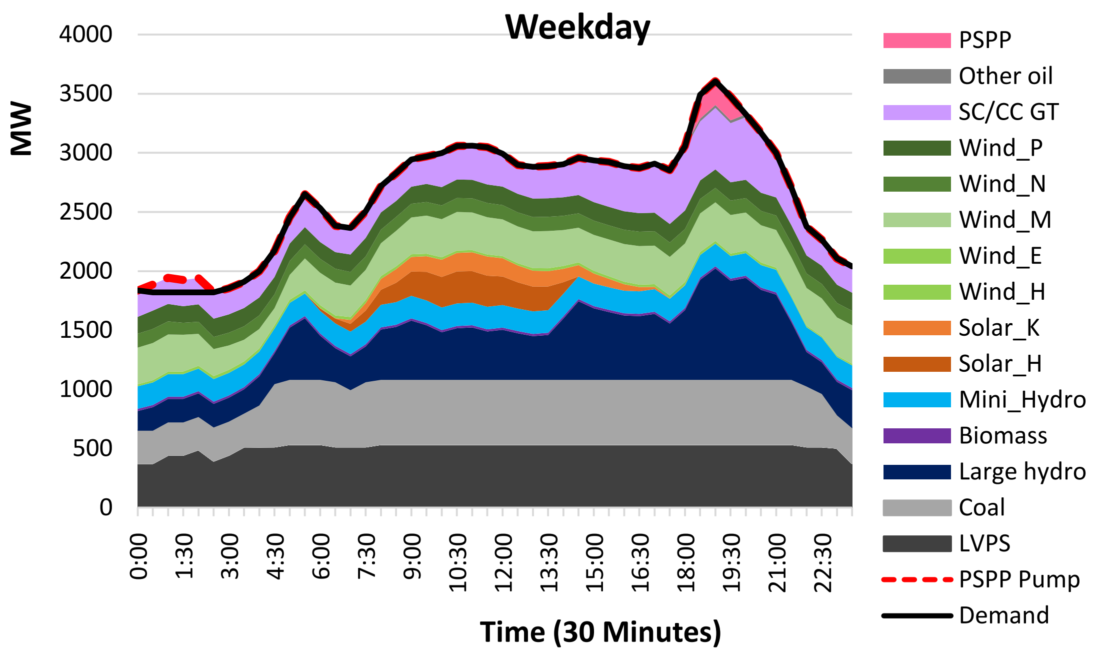

Figure 4.5 (a): Power plant dispatch with 200MW PSPP in 2025 high wind period weekday

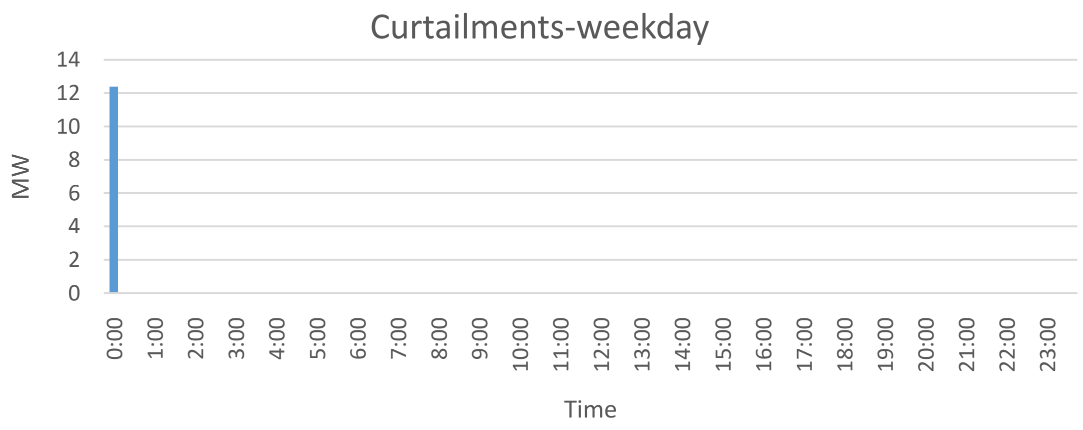

Figure 4.5 (b): Curtailments of Renewable Generation with 200MW PSPP in 2025 high wind period weekday

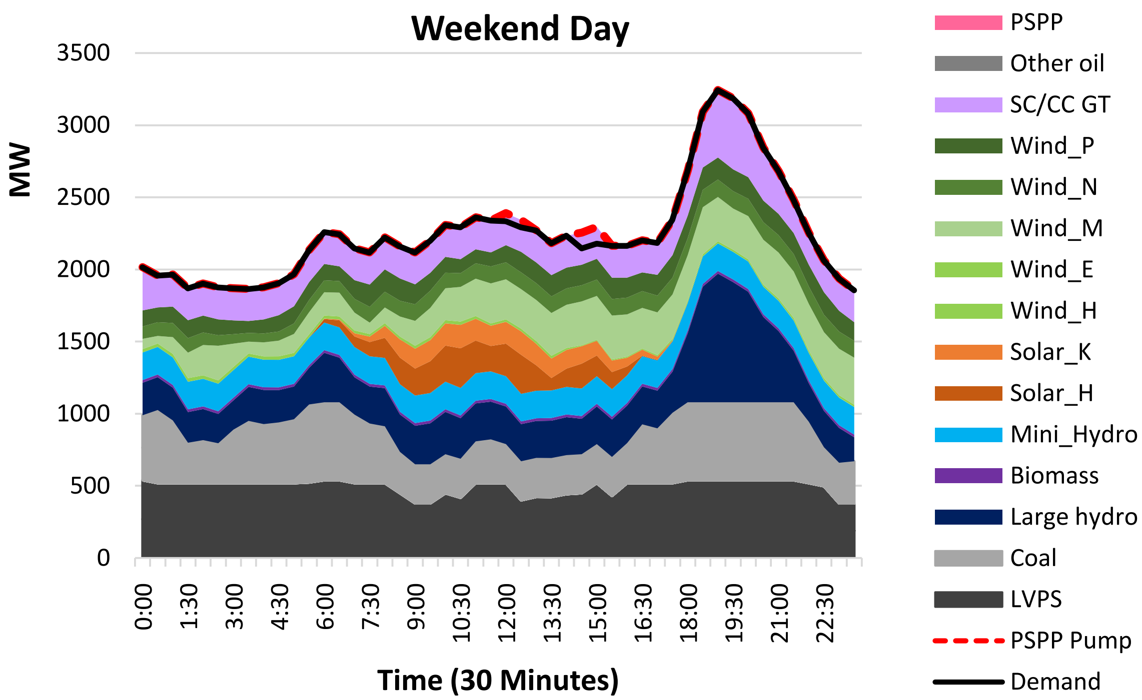

Figure 4.6 (a): Power plant dispatch with 200MW PSPP in 2025 high wind period weekend day

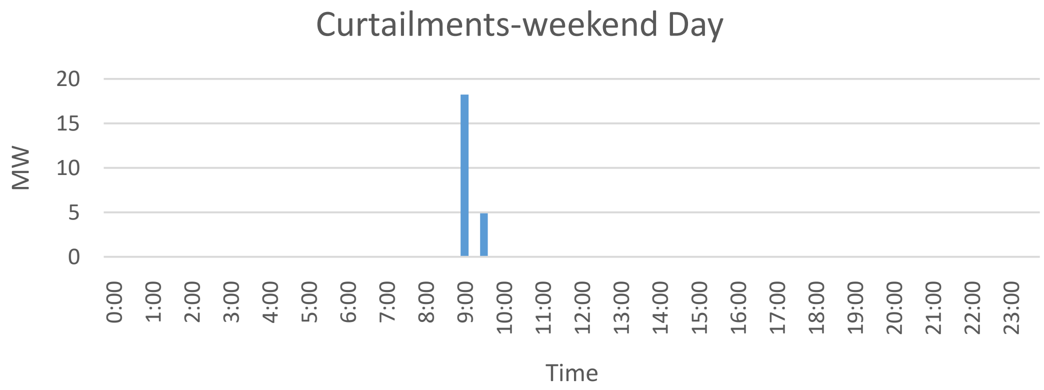

Figure 4.6 (b): Curtailments of Renewable Generation with 200MW PSPP in 2025 high wind period weekend day

Simulation results for high wind period in 2025 power system with PSPP are shown in Figure 4.5 & Figure 4.6. With 685MW solar and 730MW wind capacities, curtailments could be observed but much lesser compared to wet period curtailments when comparing with Figure 4.1 (b) & Figure 4.2 (b).

2025 Power System with 500 MW HVDC (685MW Solar, 730MW Wind)

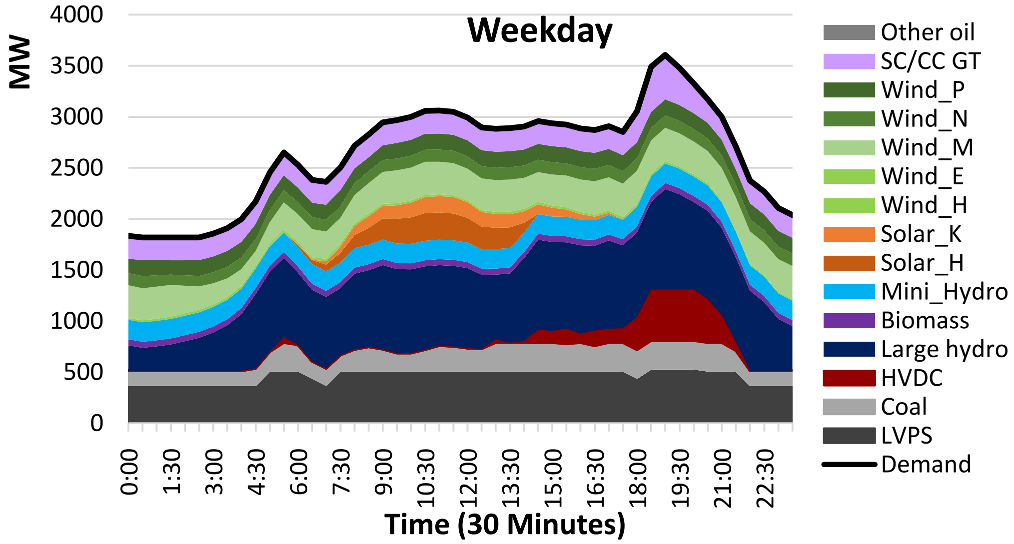

Figure 4.7: Power plant dispatch with 500MW HVDC in 2025 high wind period weekday

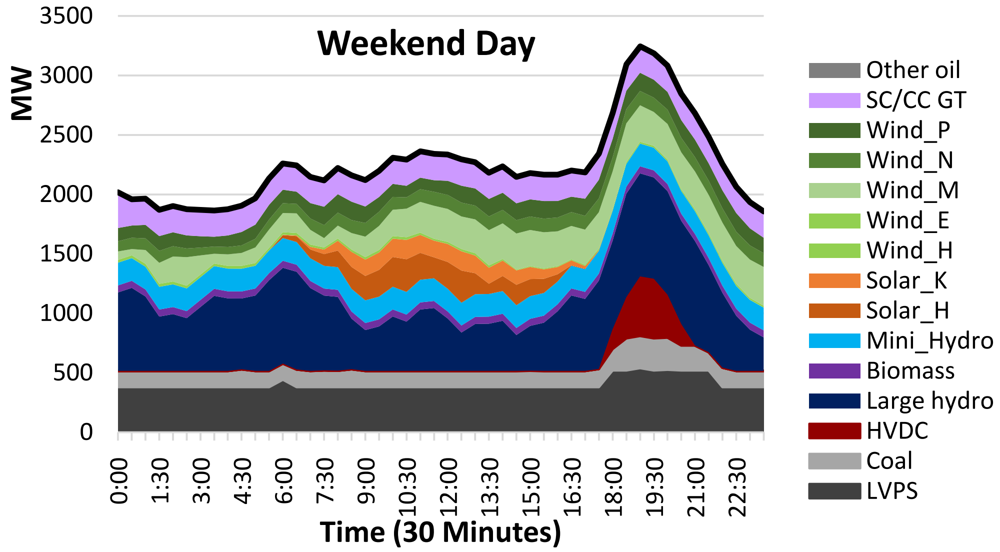

Figure 4.8: Power plant dispatch with 500MW HVDC in 2025 high wind period weekend day

Simulation results for high wind period 2025 power system also did not give rise to curtailments similar to wet period simulation with HVDC. HVDC has import energy mainly during night peak time.

4.4 Renewable Penetration with Development of 500MW HVDC in 2025

As discussed in section 4.3, when considering the power system with initial renewable capacities of 685MW solar and 730MW wind, the system with PSPP had curtailments of renewable energy. With the HVDC there were no curtailments observed. When considering Figures 4.3, 4.4, 4.7 & 4.8, it can be seen that the energy has been imported during the day time as well as night peak. Therefore, it is worthwhile to analyse the effect of solar and wind penetration separately as well.

Therefore, as mentioned in Chapter 3, solar aggressive, wind aggressive and solar & wind mix scenarios were separately simulated.

Solar Aggressive Scenario

In the solar aggressive scenario original wind capacity of 730MW was unchanged and the solar capacity was increased until the curtailment limits are reached.

Wet Period

Solar power capacity could be increased up to 875MW (Addition of 190MW) with 500MW HVDC in the system. The resulting dispatch and curtailment results are shown in Figure 4.9 & Figure 4.10.

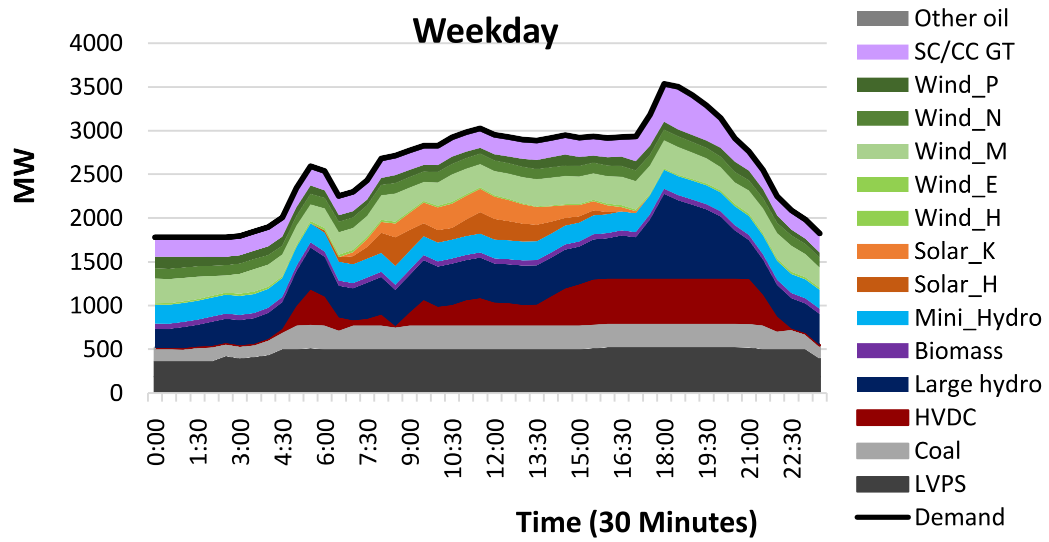

Figure 4.9 (a): Power plant dispatch with maximum solar penetration with 500MW HVDC in wet period weekday

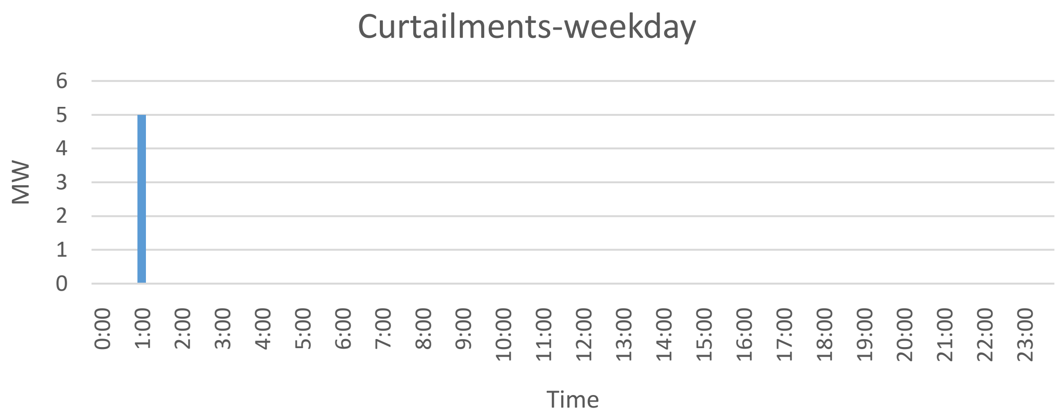

Figure 4.9 (b): Curtailments with maximum solar penetration with 500MW HVDC in wet period weekday

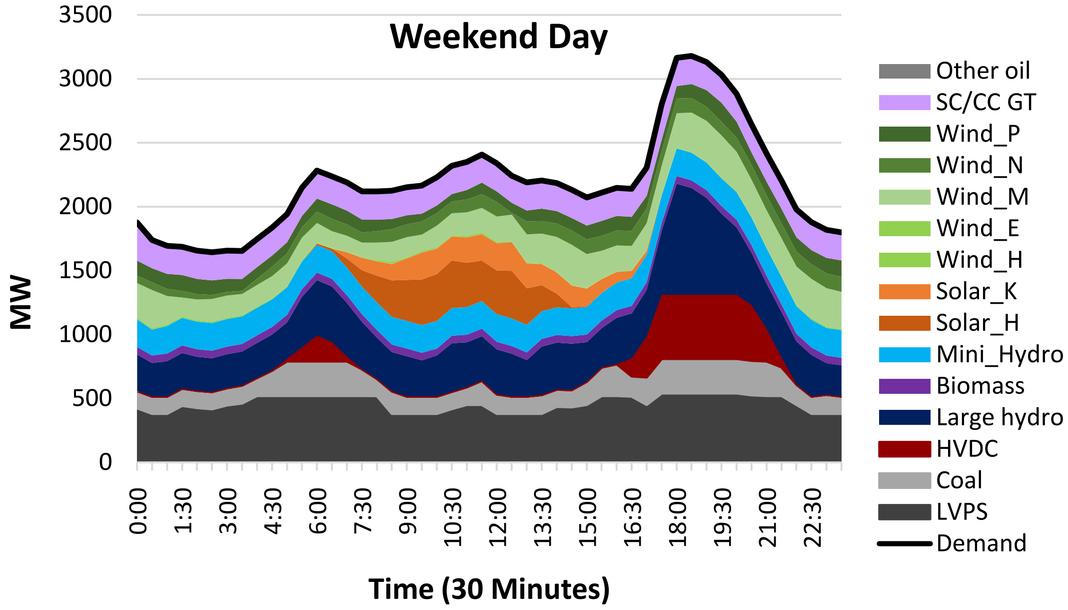

Figure 4.10 (a): Power plant dispatch with maximum solar penetration with 500MW HVDC in wet period weekend day

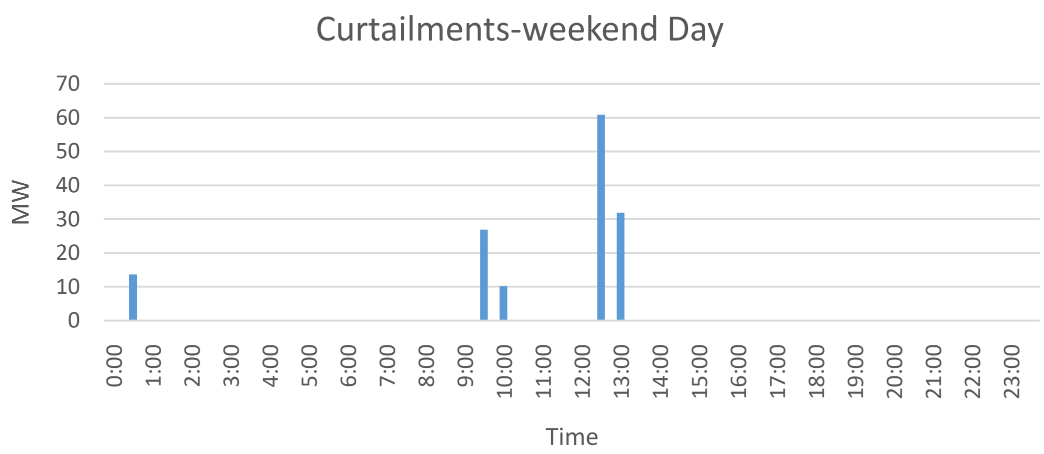

Figure 4.10 (b): Curtailments with maximum solar penetration with 500MW HVDC in wet period weekend day

When considering Figure 4.9 (b) and 4.10 (b), highest curtailments were observed during day time of a weekend. Therefore solar capacity was increased until weekend day time curtailments are limited to less than 5% of demand. Final solar capacity was obtained as 875MW considering wet period.

High Wind Period

Similarly solar power capacity could be increased up to 885MW (Addition of 200MW) with 500MW HVDC in the system in the high wind period. The resulting dispatch and curtailment results are shown in Figure 4.11 & Figure 4.12.

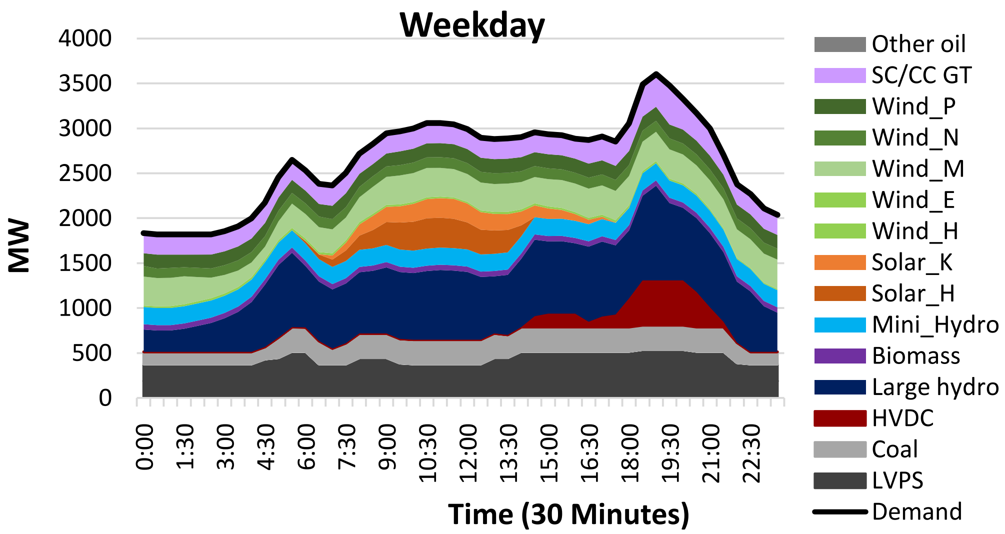

Figure 4.11 (a): Power plant dispatch with maximum solar penetration with 500MW HVDC in high wind period weekday

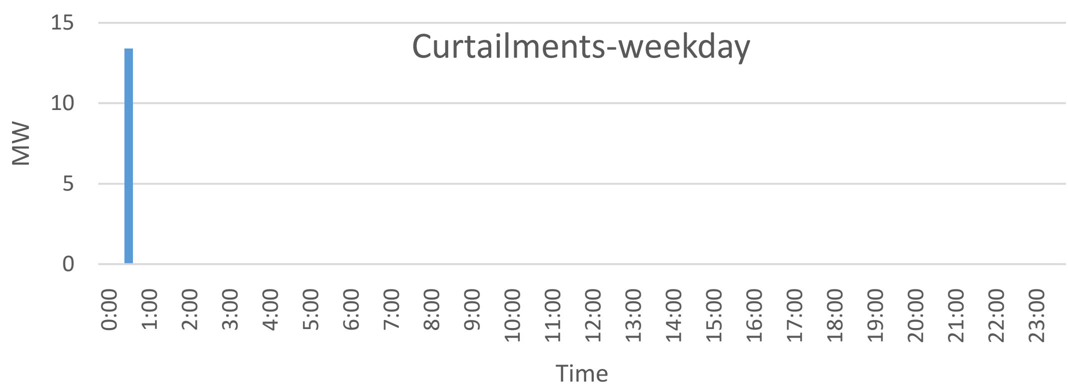

Figure 4.11 (b): Curtailments with maximum solar penetration with 500MW HVDC in high wind period weekday

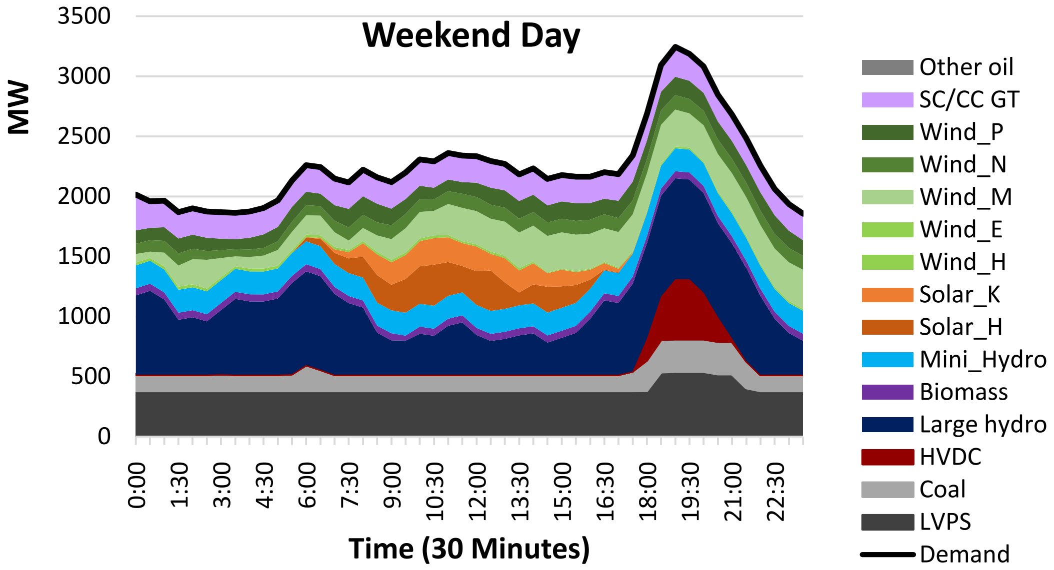

Figure 4.12 (a): Power plant dispatch with maximum solar penetration with 500MW HVDC in high wind period weekend day

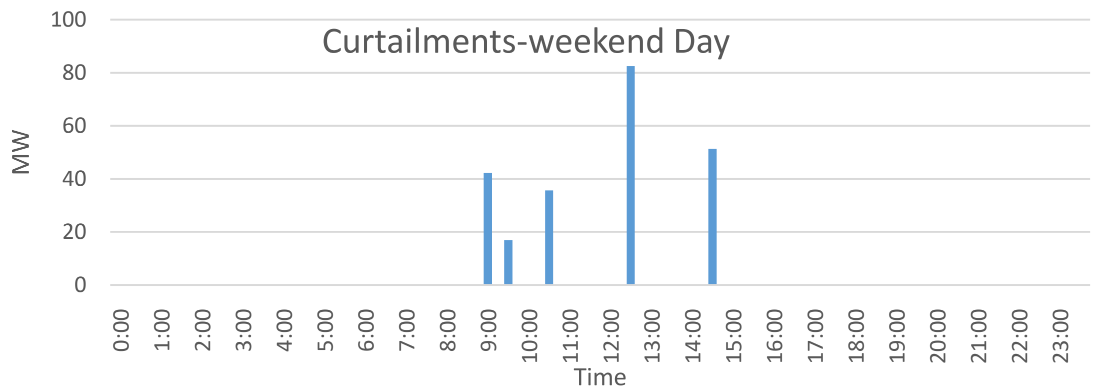

Figure 4.12 (b): Curtailments with maximum solar penetration with 500MW HVDC in high wind period weekend day

When considering Figure 4.11 (b) and 4.12 (b), highest curtailments were observed during day time of a weekend similar to wet period simulation. Therefore solar capacity was increased and simulation was carried out until curtailments are reached set limits. Final solar capacity was obtained as 885MW considering high wind period.

When considering wet period simulation the solar capacity was obtained as 875MW and it indicates that the annual capacity addition is limited by the dispatch constraints in the wet period.

Wind Aggressive Scenario

In the wind aggressive scenario original solar capacity of 685MW was unchanged and the wind capacity was increased until the curtailment limits are reached.

Wet Period

Considering the wet period simulation, wind power capacity could be increased up to 810MW which is an addition of 80MW, with 500MW HVDC in the system. The resulting dispatch and curtailment results are shown in Figure 4.13 & Figure 4.14 for weekday and weekend respectively.

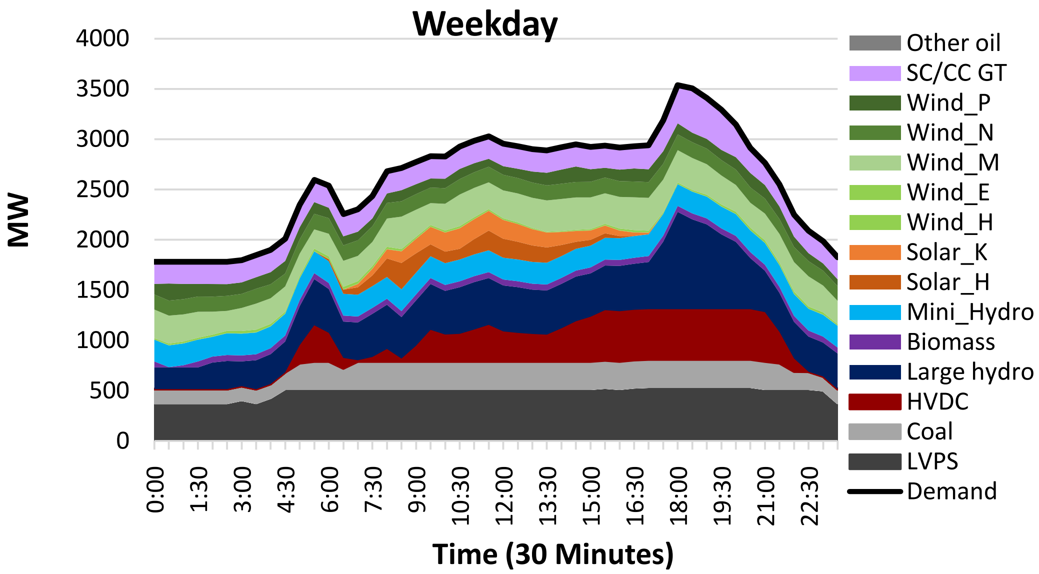

Figure 4.13 (a): Power plant dispatch with maximum wind penetration with 500MW HVDC in wet period weekday

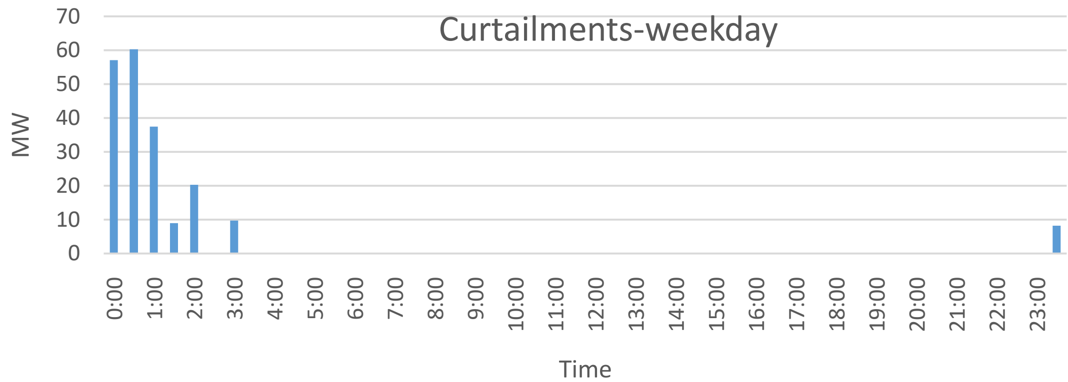

Figure 4.13 (b): Curtailments with maximum wind penetration with 500MW HVDC in wet period weekday

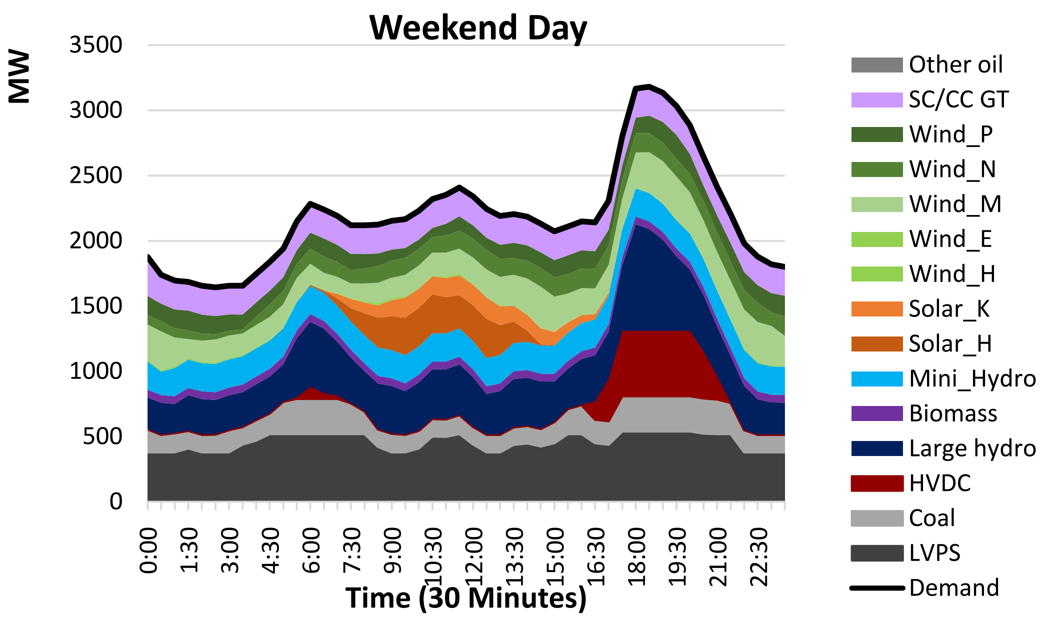

Figure 4.14 (a): Power plant dispatch with maximum wind penetration with 500MW HVDC in wet period weekend day

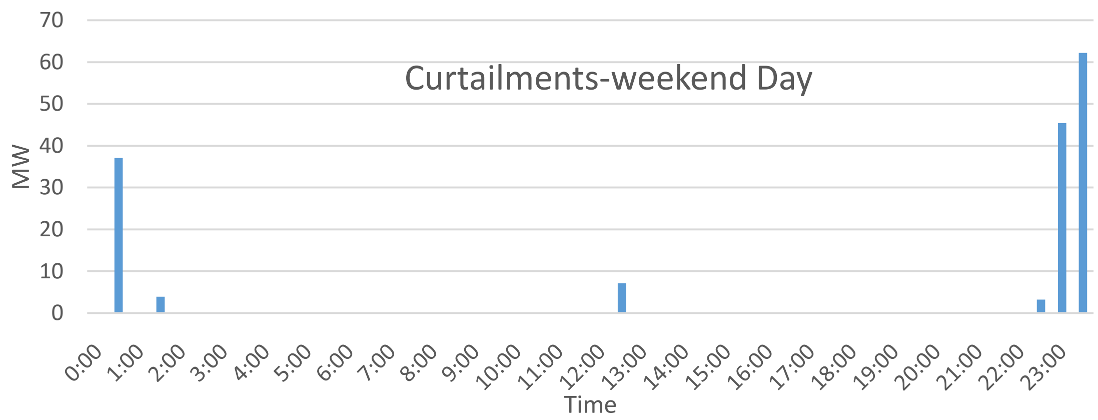

Figure 4.14 (b): Curtailments with maximum wind penetration with 500MW HVDC in wet period weekend day

When considering Figure 4.13 (b) & Figure 4.14 (b) it could be observed that the highest curtailments in the wind aggressive scenario are occurred during off peak time. Therefore the wind capacity was increased and dispatch simulation carried out until off peak curtailments are not exceeded. Considering wet period the final wind capacity was obtained as 810MW.

High Wind Period

Considering high wind period, wind power capacity could be increased up to 815MW (Addition of 85MW) with 500MW HVDC in the system. The resulting dispatch and curtailment results are shown in Figure 4.15 & Figure 4.16 for weekday and weekend respectively.

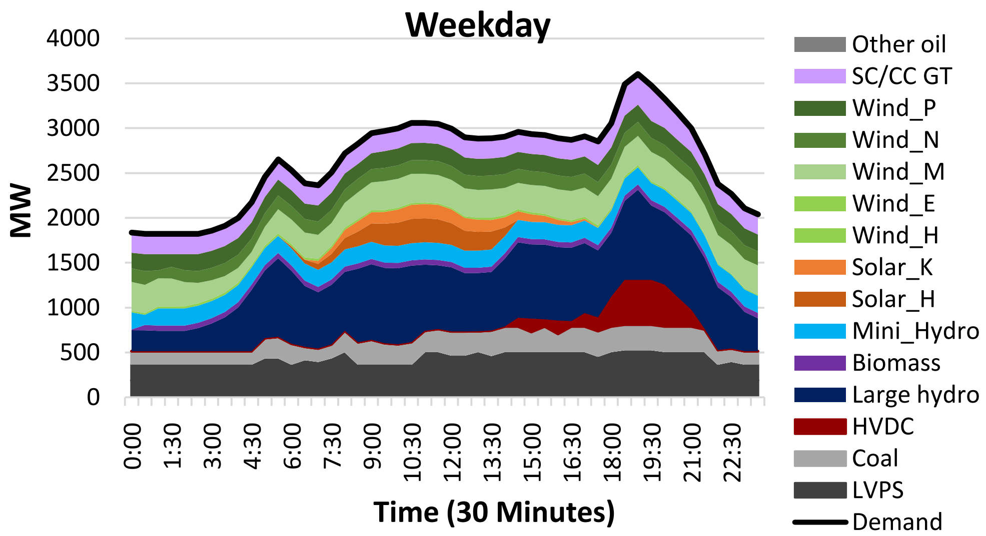

Figure 4.15 (a): Power plant dispatch with maximum wind penetration with 500MW HVDC in high wind period weekday

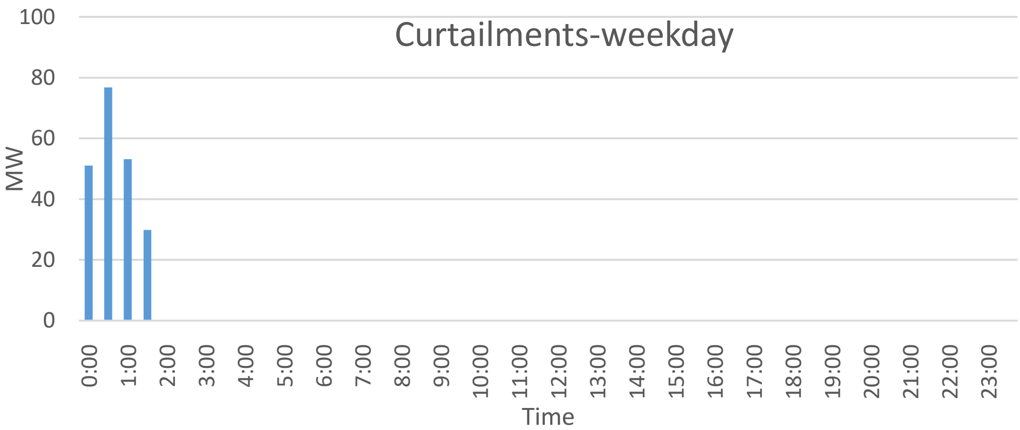

Figure 4.15 (b): Curtailments with maximum wind penetration with 500MW HVDC in high wind period weekday

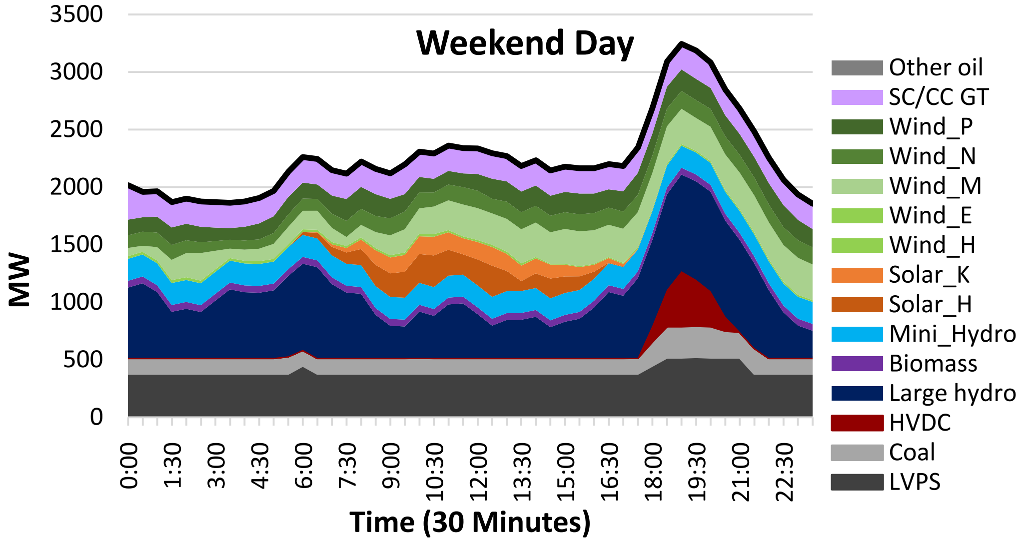

Figure 4.16 (a): Power plant dispatch with maximum wind penetration with 500MW HVDC in high wind period weekend day

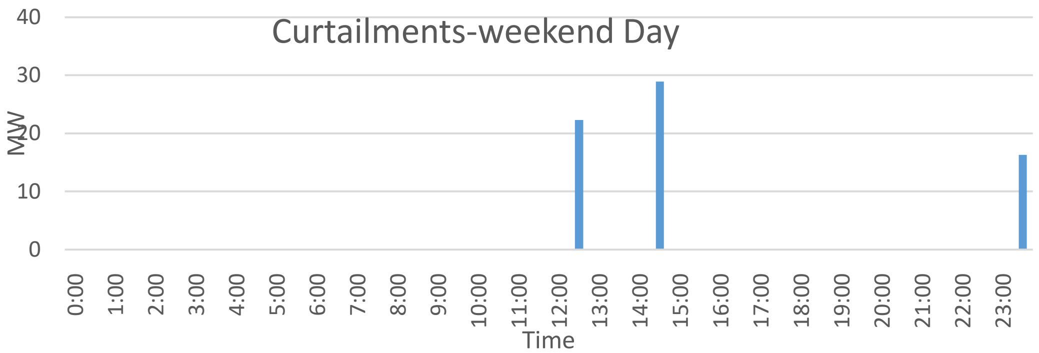

Figure 4.16 (b): Curtailments with maximum wind penetration with 500MW HVDC in high wind period weekend day

When considering Figure 4.15 (b) & Figure 4.16 (b) it could be observed that the highest curtailments in the high wind period for the wind aggressive scenario also occur during off peak time similar to wet period. Therefore the wind capacity was increased and dispatch simulation carried out until off peak curtailments are not exceeded. Considering the high wind period the final wind capacity was obtained as 815MW.

Considering wet period simulation the wind capacity was obtained as 810MW. Therefore similar to solar aggressive scenario the annual capacity addition is limited by the dispatch constraints in the wet period.

Solar and Wind Mix Scenario

In this scenario a mix of solar and wind capacities were increased.

Wet Period

Solar capacity could be increased up to 795MW (Addition of 110MW) and wind capacity could be increased up to 780MW (Addition of 50MW) with 500MW HVDC in the system. The resulting dispatch and curtailments are shown in Figure 4.17 & Figure 4.18 for weekday and weekend respectively.

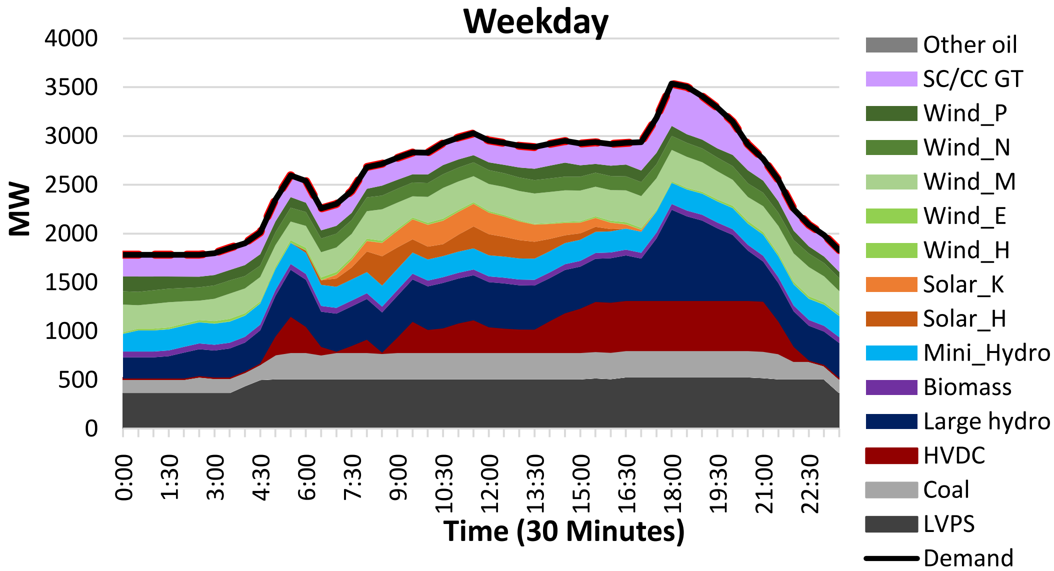

Figure 4.17 (a): Power plant dispatch with maximum renewable penetration with 500MW HVDC in wet period weekday

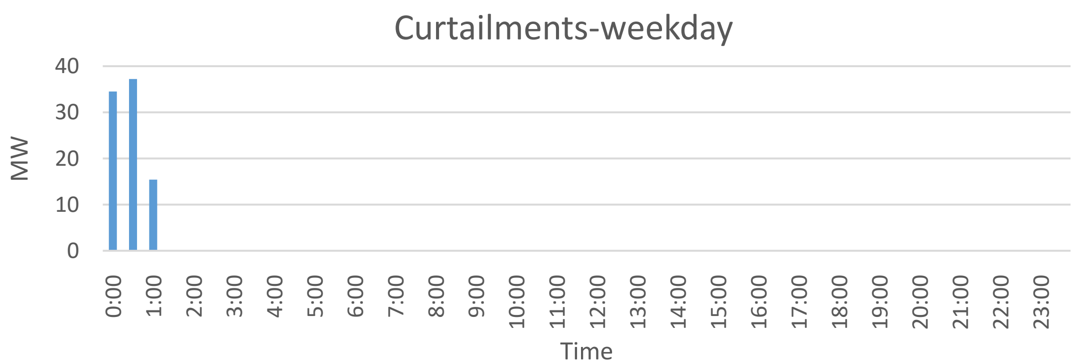

Figure 4.17 (b): Curtailments with maximum renewable penetration with 500MW HVDC in wet period weekday

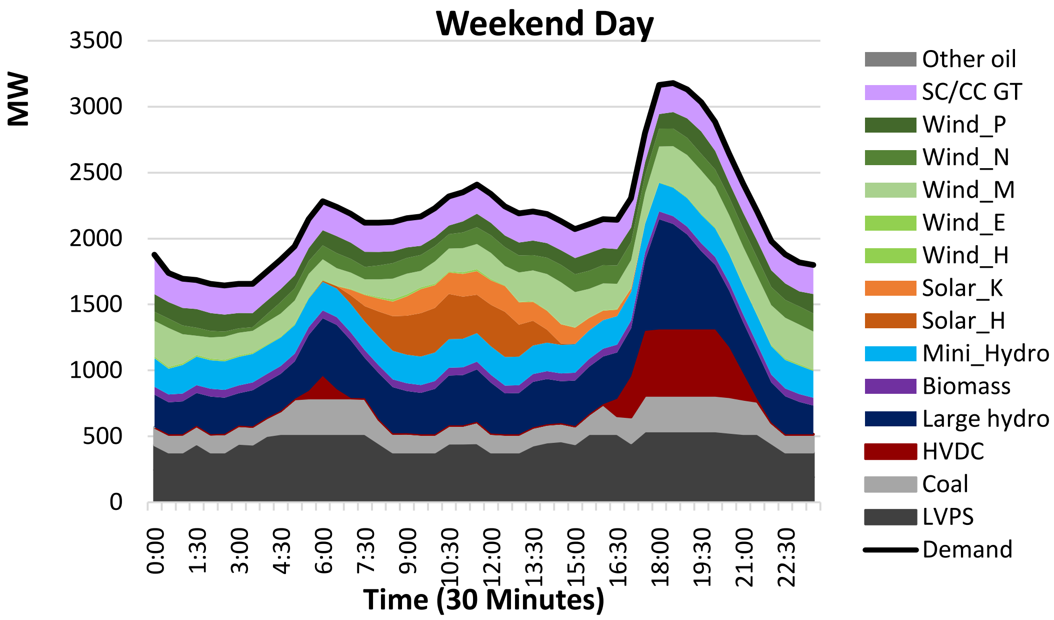

Figure 4.18 (a): Power plant dispatch with maximum renewable penetration with 500MW HVDC in wet period weekend day

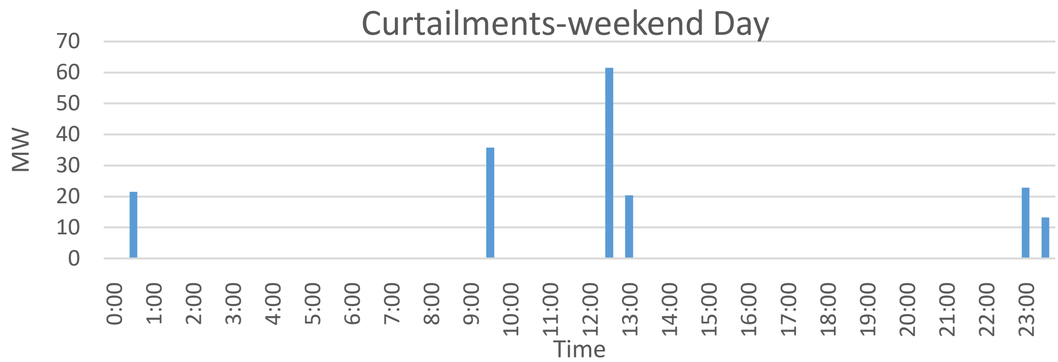

Figure 4.18 (b): Curtailments with maximum renewable penetration with 500MW HVDC in wet period weekend day

In this scenario curtailments could be observed during day time as well as off peak time. The final capacities were obtained as 795MW of solar and 780MW of wind considering the wet period.

High Wind Period

Solar capacity could be increased up to 800MW (Addition of 115MW) and wind capacity could be increased up to 780MW (Addition of 50MW) with 500MW HVDC in the system. The resulting dispatch and curtailments are shown in Figure 4.19 & Figure 4.20 for weekday and weekend respectively.

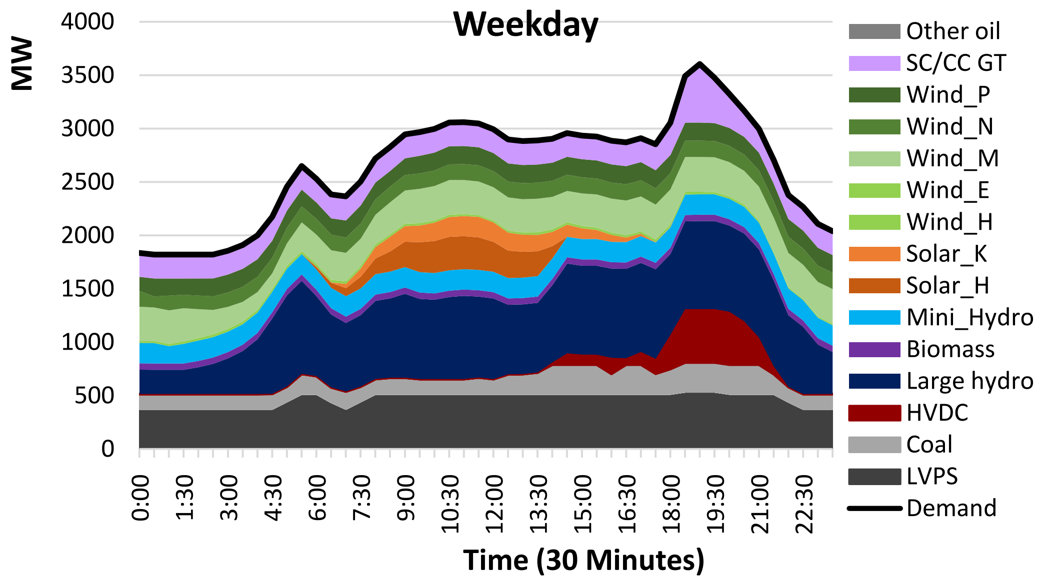

Figure 4.19 (a): Power plant dispatch with maximum renewable penetration with 500MW HVDC in high wind period weekday

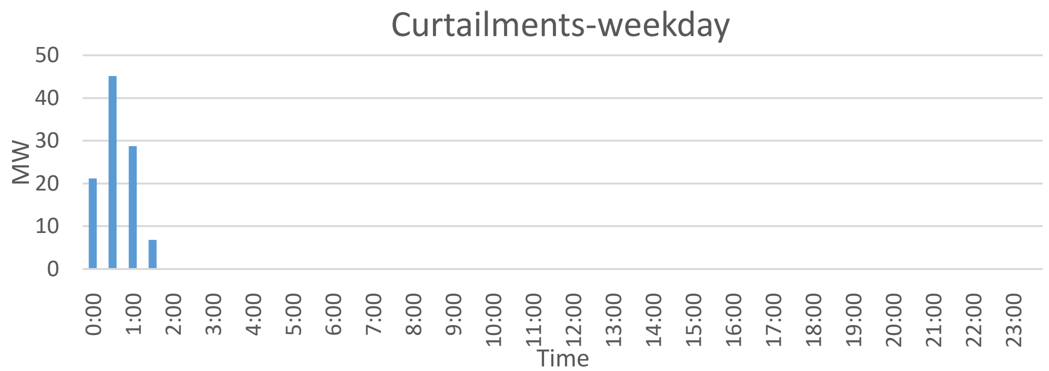

Figure 4.19 (b): Curtailments with maximum renewable penetration with 500MW HVDC in high wind period weekday

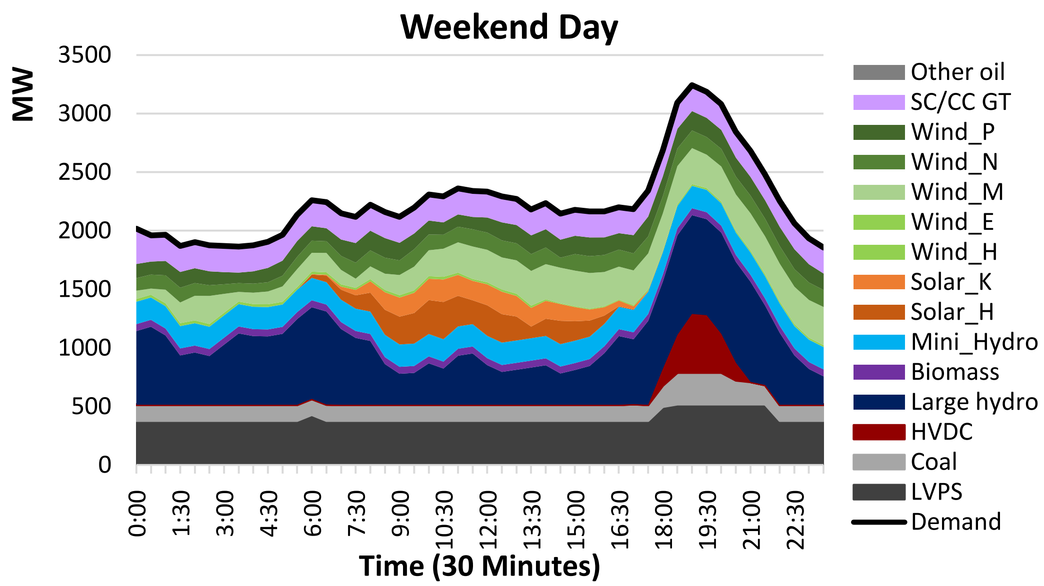

Figure 4.20 (a): Power plant dispatch with maximum renewable penetration with 500MW HVDC in high wind period weekend day

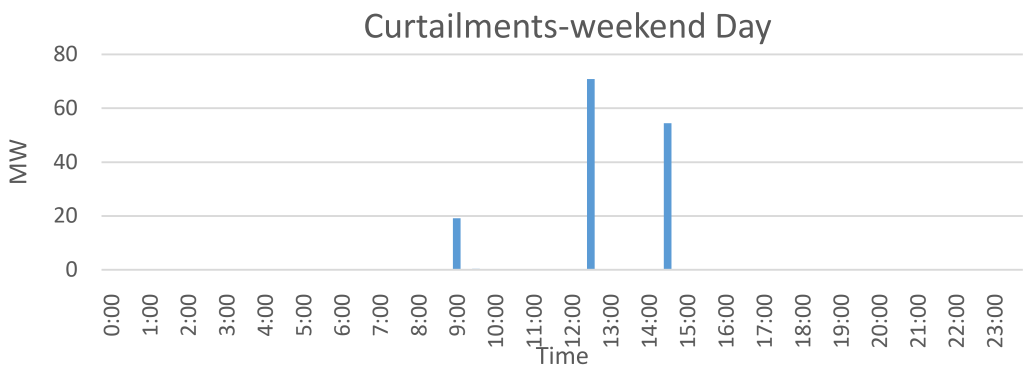

Figure 4.20 (b): Curtailments with maximum renewable penetration with 500MW HVDC in high wind period weekend day

Similar to wet period simulation, curtailments could be observed during day time as well as off peak time. Final capacities were obtained as 800MW of solar and 780MW of wind considering the wet period.

Further it was noted that energy is imported during night peak in all the scenarios and there are no imports during off peak time. Depending on the dispatch constraints in each of the scenario, energy is imported through day time during most weekdays and much less imports are seen during weekends due to low demand constraint.

Table 4.2 summarizes the simulation results with 500MW HVDC development in 2025.

Table 4.2: Summary of results with 500MW HVDC

	Scenario	**Penetration level MW ***	**Total RE share (Wind & Solar Share)**
	With PSPP	685 MW Solar 730 MW Wind	51% (26%)
Wet Period	Aggressive Solar	875 MW Solar (+190)	54% (25%)
	Aggressive Wind	810 MW Wind (+80)	54% (26%)
	Wind & Solar Mix	795 MW Solar, 780 MW Wind (+110 Solar, +50 Wind)	54% (26%)
High Wind Period	Aggressive Solar	885 MW Solar (+200)	63% (28%)
	Aggressive Wind	815 MW Wind (+85)	63% (29%)
	Wind & Solar Mix	800 MW Solar, 780 MW Wind (+115 Solar, +50 Wind)	63% (29%)

*With subject to curtailment limit of 5% of minimum demand and additional spinning reserve of 10% of renewable capacity

When comparing the wet period and high wind period results the capacity additions are limited by the dispatch constraints in the wet period. Therefore, only wet period was considered for the simulation with 1000MW HVDC.

4.5 System Comparison with PSPP and HVDC for Phase 11 of HVDC

By taking into account the capacity additions in Table 4.1, dispatch simulation was carried out. With the initial solar and wind capacities of 900MW and 800MW respectively power system with PSPP and HVDC was simulated to obtain renewable excess generation as follows.

From the simulation of the 2025 system it was observed that the limiting criteria occur in the wet period. Therefore simulation was carried out for wet period weekdays and weekends and the results are presented here.

Wet Period

2028 Power System with 600 MW PSPP (900MW Solar, 800MW Wind)

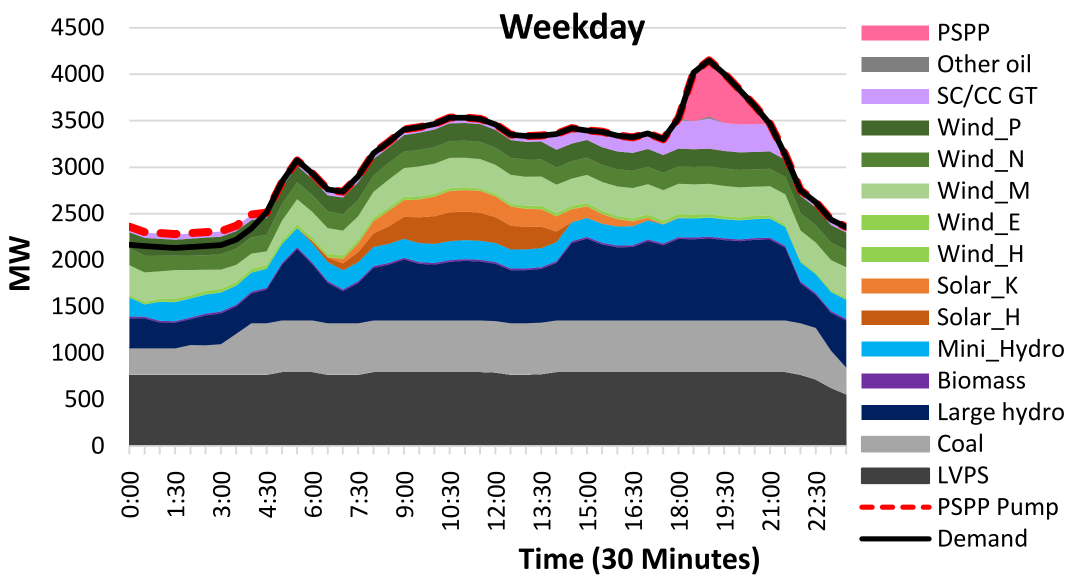

Figure 4.21 (a): Power plant dispatch with 600MW PSPP in 2028 wet period weekday

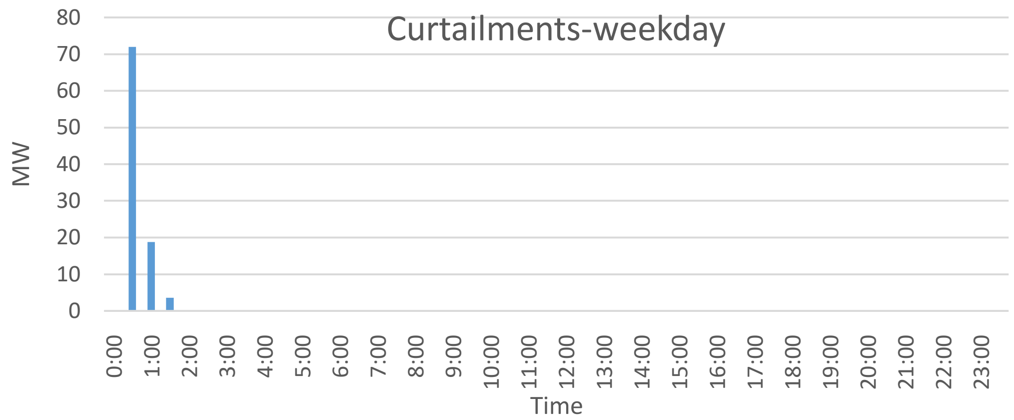

Figure 4.21 (b): Curtailments of Renewable Generation with 600MW PSPP in 2028 wet period weekday

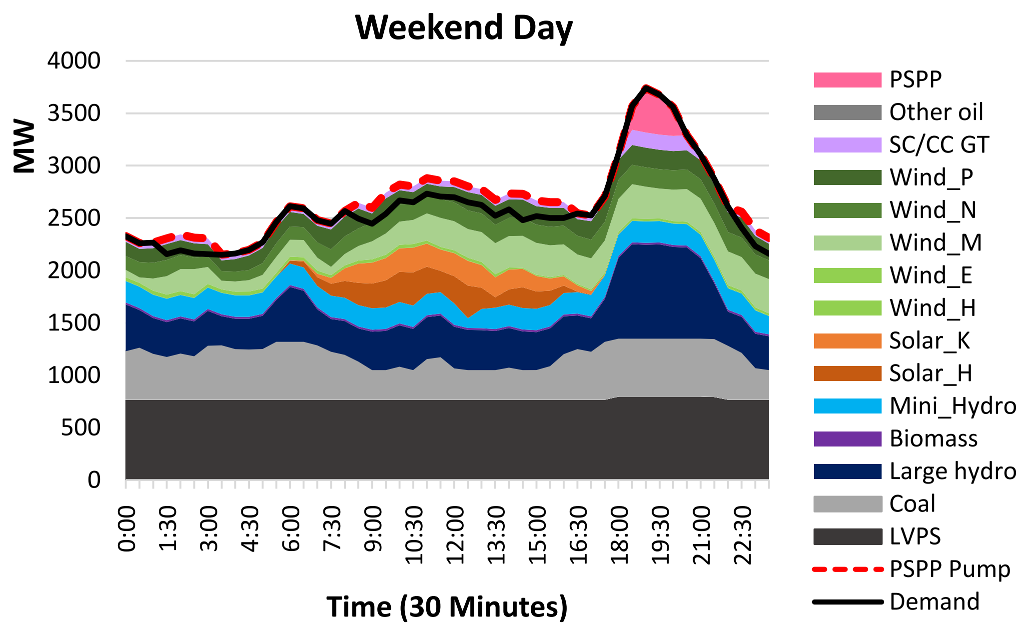

Figure 4.22 (a): Power plant dispatch with 600MW PSPP in 2028 wet periodweekend day

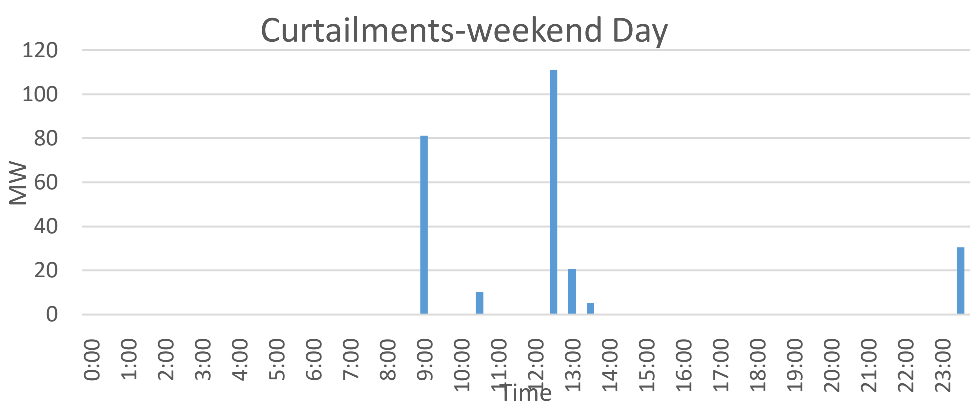

Figure 4.22 (b): Curtailments of Renewable Generation with 600MW PSPP in 2028wet period weekend day

Simulation results for wet period in 2028 power system with PSPP are shown in Figure 4.21 & Figure 4.22. With 900MW solar and 800MW wind, curtailments of more than 70MW could be observed due to wind during off peak hours. Curtailments due to solar can be seen during day time of weekend which exceeds 100MW.

2028 Power System with 1000 MW HVDC (900MW Solar, 800MW Wind)

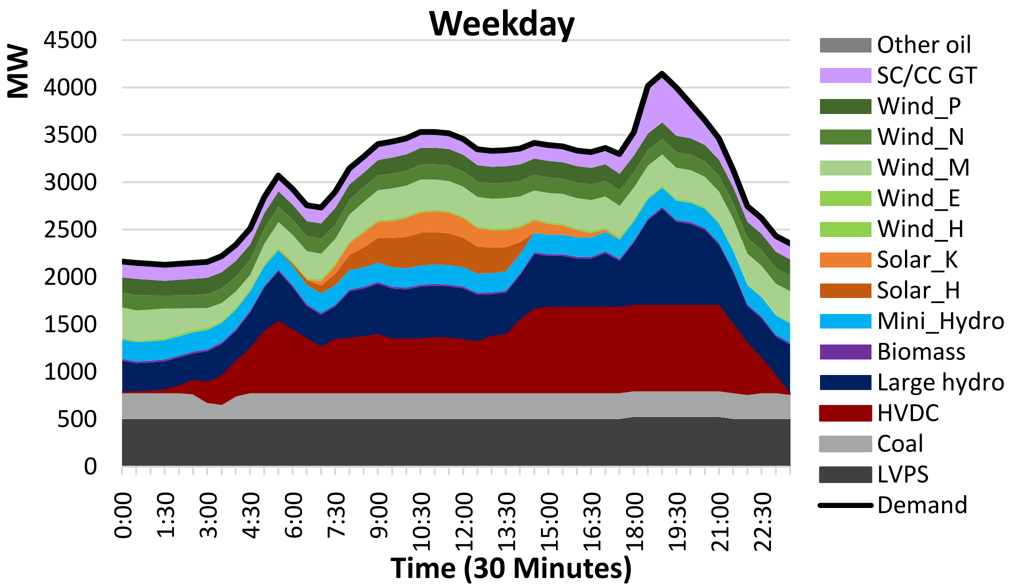

Figure 4.23: Power plant dispatch with 500MW HVDC in 2025 wet period weekday

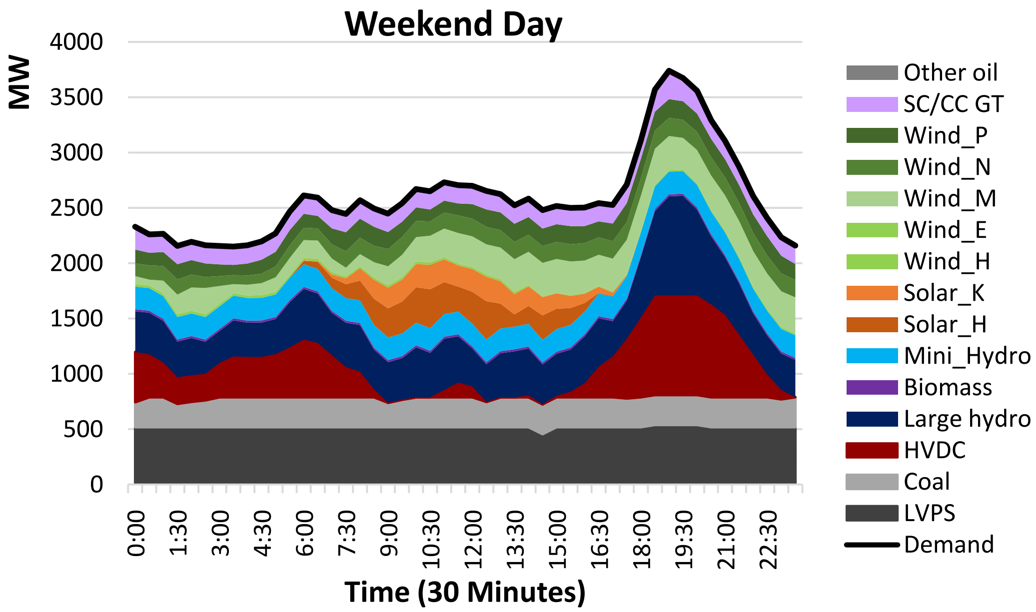

Figure 4.24: Power plant dispatch with 500MW HVDC in 2025 wet period weekend

In the simulation results for 2028 power system with HVDC for the same initial renewable capacities there were no curtailments observed. HVDC has import energy during most part of the day.

4.6 Renewable Penetration with Development of 1000MW HVDC in 2028

Solar Aggressive Scenario

In the solar aggressive scenario original wind capacity of 800MW was unchanged and the solar capacity was increased until the curtailment limits are reached.

Wet Period

Solar power capacity could be increased up to 910MW (Addition of 10MW) with 1000MW HVDC in the system. The resulting dispatch and curtailment results are shown in Figure 4.25 & Figure 4.26.

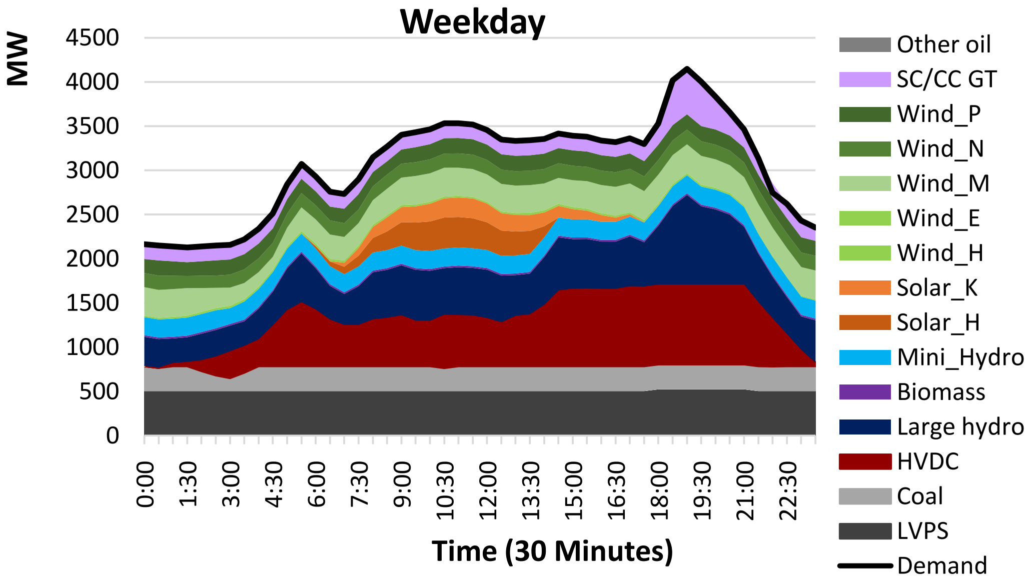

Figure 4.25 (a): Power plant dispatch with maximum solar penetration with 1000MW HVDC in wet period weekday

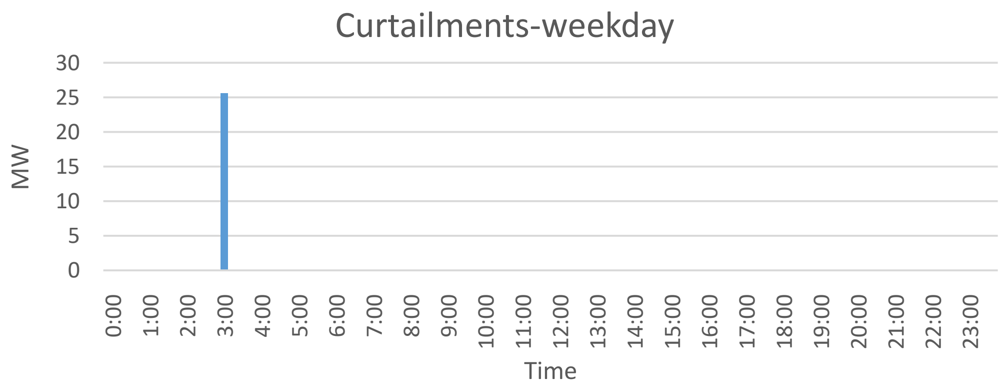

Figure 4.25 (b): Curtailments with maximum solar penetration with 1000MW HVDC in wet period weekday

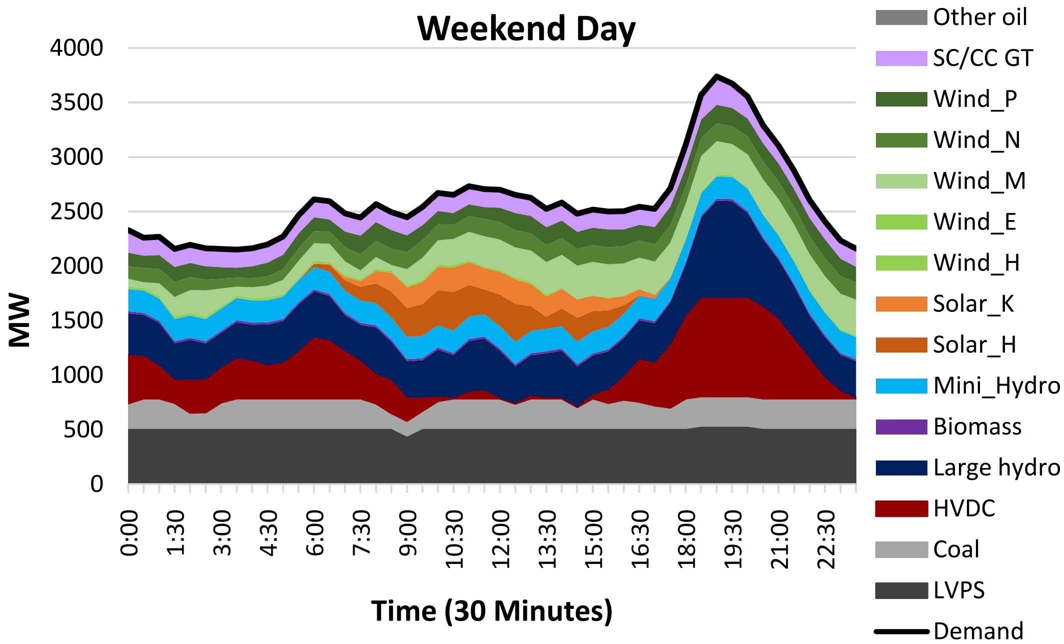

Figure 4.26 (a): Power plant dispatch with maximum solar penetration with 1000MW HVDC in wet period weekend day

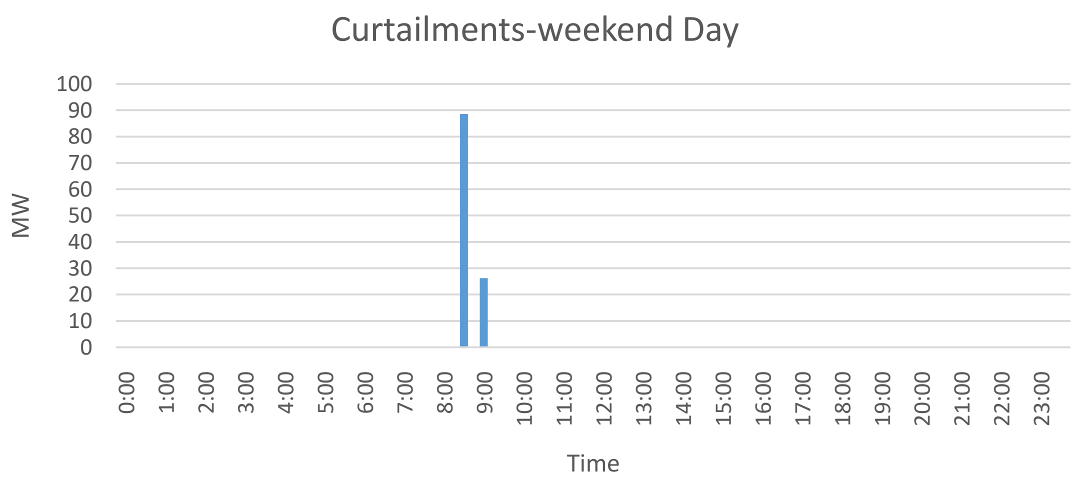

Figure 4.26 (b): Curtailments with maximum solar penetration with 1000MW HVDC in wet period weekend day

When considering Figure 4.25 (b) and 4.26 (b), highest curtailments were observed during day time of a weekend. Therefore solar capacity was increased until weekend day time curtailments are limited to less than 5% of demand. Final solar capacity was obtained as 910MW considering wet period.

Wind Aggressive Scenario

In the wind aggressive scenario original solar capacity of 900MW was unchanged and the wind capacity was increased until the curtailment limits are reached.

Wet Period

Wind power capacity could be increased up to 830MW (Addition of 30MW) with 1000MW HVDC in the system. The resulting dispatch and curtailment results are shown in Figure 4.27 & Figure 4.28 for weekday and weekend respectively.

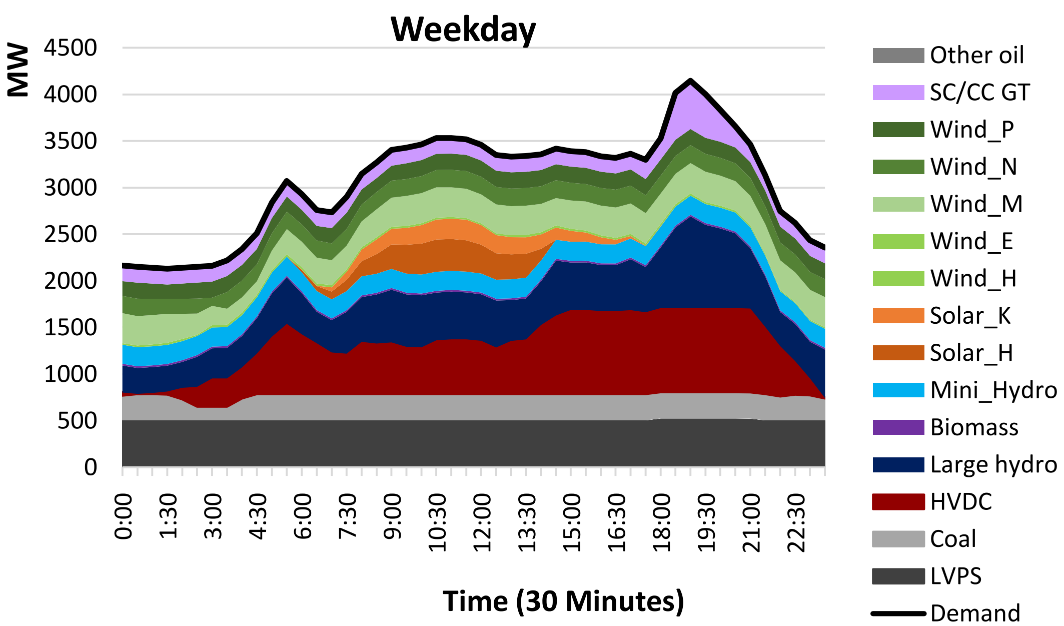

Figure 4.27 (a): Power plant dispatch with maximum wind penetration with 1000MW HVDC in wet period weekday

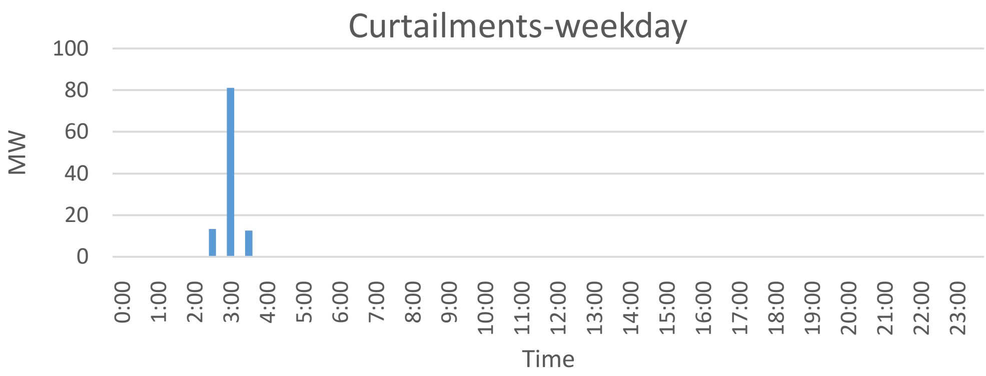

Figure 4.27 (b): Curtailments with maximum wind penetration with 1000MW HVDC in wet period weekday

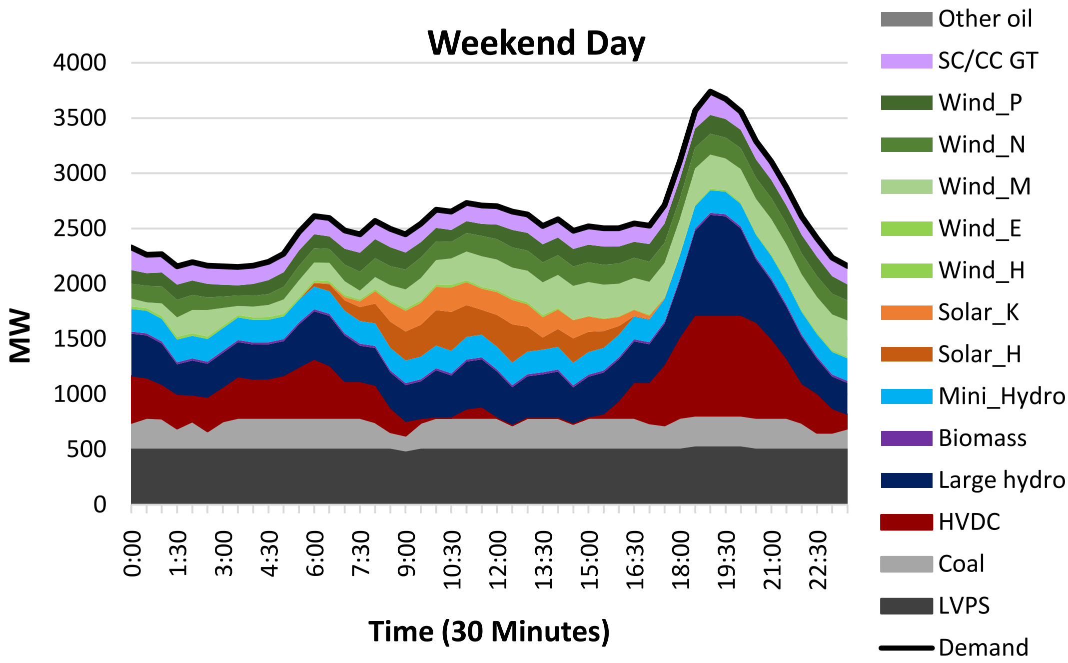

Figure 4.28 (a): Power plant dispatch with maximum wind penetration with 1000MW HVDC in wet period weekend day

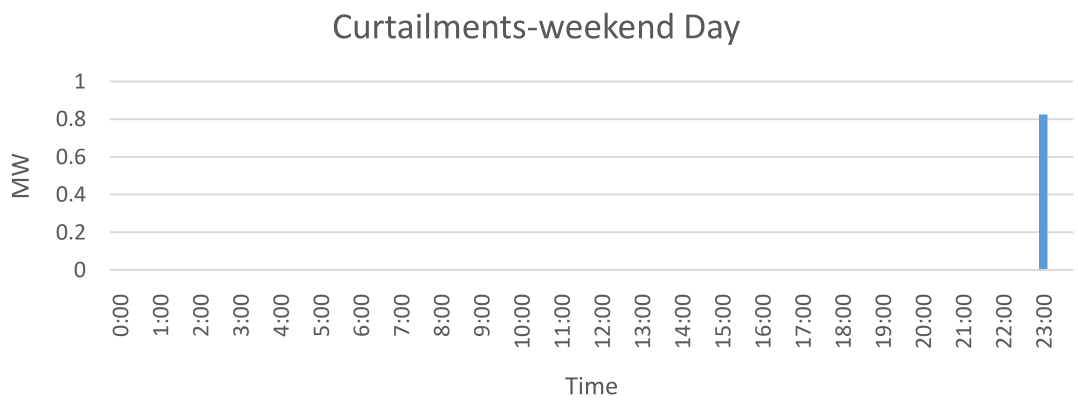

Figure 4.28 (b): Curtailments with maximum wind penetration with 1000MW HVDC in wet period weekend day

When considering Figure 4.27 (b) & Figure 4.28 (b) it could be observed that the highest curtailments in the wind aggressive scenario are occurred during off peak time. Therefore the wind capacity was increased and dispatch simulation carried out until off peak curtailments are not exceeded. Considering wet period the final wind capacity was obtained as 830MW.

Solar and Wind Mix Scenario

In this scenario a mix of solar and wind capacities were increased.

Wet Period

Solar capacity could be increased up to 905MW (Addition of 5MW) and wind capacity could be increased up to 850MW (Addition of 50MW) with 1000MW HVDC in the system. The resulting dispatch and curtailments are shown in Figure 4.29 & Figure 4.30 for weekday and weekend respectively.

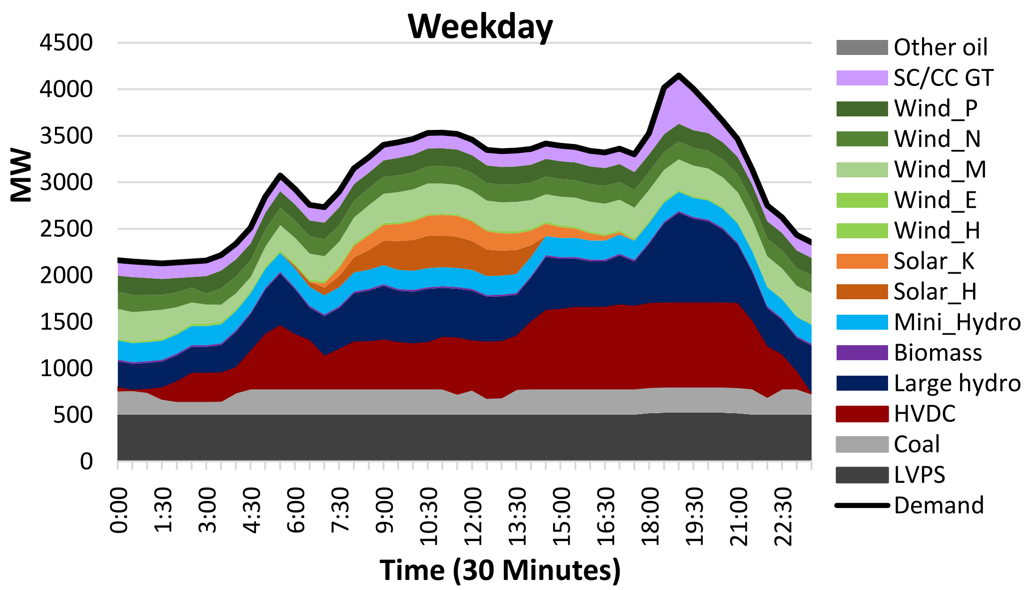

Figure 4.29 (a): Power plant dispatch with maximum renewable penetration with 1000MW HVDC in wet period weekday

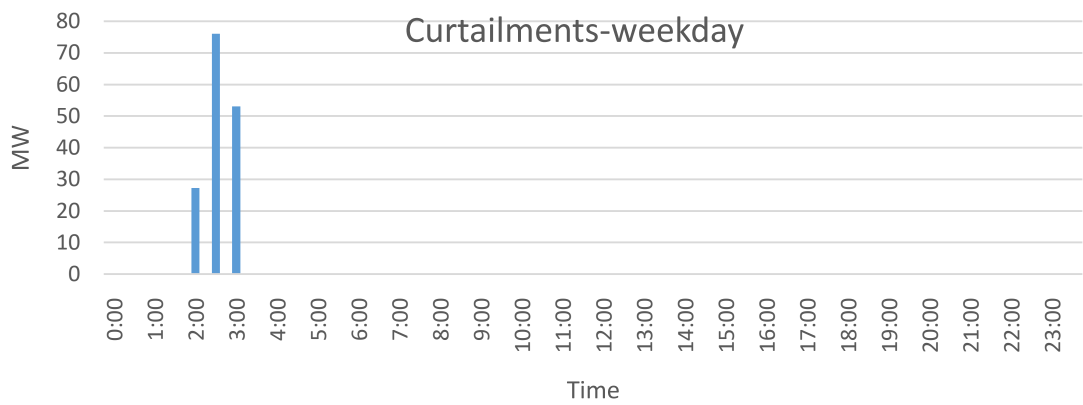

Figure 4.29 (b): Curtailments with maximum renewable penetration with 1000MW HVDC in wet period weekday

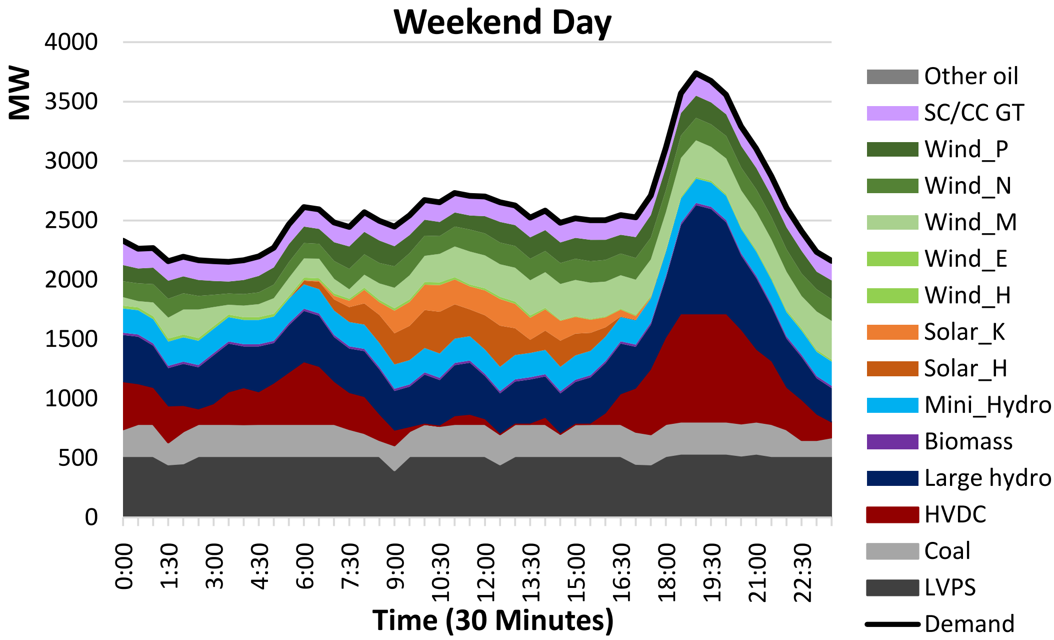

Figure 4.30 (a): Power plant dispatch with maximum renewable penetration with 1000MW HVDC in wet period weekend day

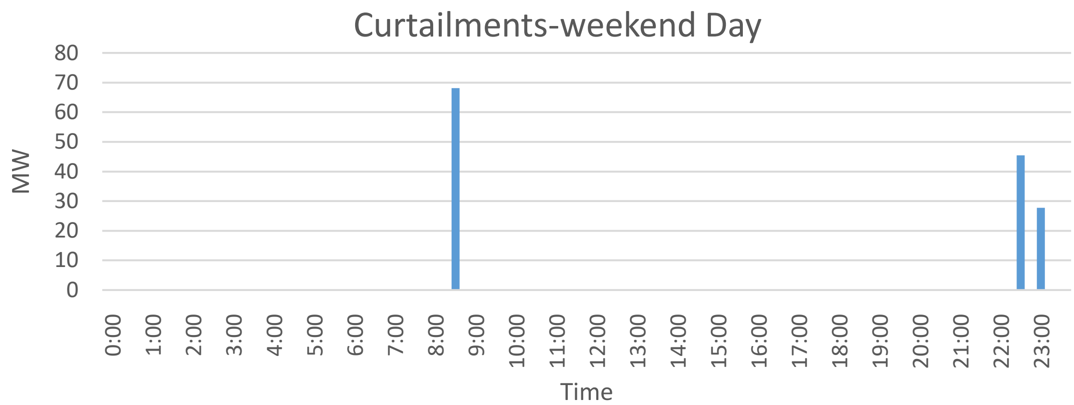

Figure 4.30 (b): Curtailments with maximum renewable penetration with 1000MW HVDC in wet period weekend day

In the solar and wind mix development scenario curtailments could be observed during day time as well as off peak time. The final capacities were obtained as 905MW of solar and 850MW of wind considering the wet period.

When considering the dispatch of solar aggressive, wind aggressive and mix scenarios with 1000MW HVDC it can be seen that energy imports has been lowered during off peak time and day peak time in order to absorb more renewable in the Sri Lankan power system.

Table 4.3 summarizes the simulation results with 1000MW HVDC development in 2028.

Table 4.3: Summary of results with 1000MW HVDC

Scenario	**Penetration level MW***	**Total RE share (Wind & Solar Share)**
With PSPP	900 MW Solar 800 MW Wind	51% (26%)
Aggressive Solar	910 MW Solar (+10)	51% (26%)
Aggressive Wind	830 MW Wind (+30)	51% (27%)
Wind & Solar Mix	905 MW Solar, 850 MW Wind (+5 Solar, +50 Wind)	51% (27%)

*With subject to curtailment limit of 5% of minimum demand and additional spinning reserve of 10% of renewable capacity

It could be observed that whichever the scenario the energy share from solar and wind do not differ significantly.

4.7 Summary of Results

Table 4.4 summarizes the final results of solar and wind capacities for each scenario.

Table 4.4: Summary of renewable capacities (MW)

Year	Without PSPP or HVDC		With PSPP		With HVDC		Scenario
	Wind	Solar	Wind	Solar	Wind	Solar	
2025	649	635	730	685	730	875	AS
					810	685	AW
					780	795	Mix
2028	719	850	800	900	800	910	AS
					830	900	AW
					850	905	Mix

AS-Aggressive Solar, AW-Aggressive Wind, Mix- Solar & Wind Mix

Figure 4.31 shows the composition of each solar and wind capacities for the three scenarios with HVDC development.

It could be observed that with 1000MW HVDC in 2028, a significant capacity could not be increased from the originally planned compared to 500MW HVDC in 2025. Therefore the second phase of HVDC should not bring much benefit in terms of increasing renewable immediately.

In Figure 4.31, 'New wind' and 'New solar' are the additions with the HVDC development. When comparing solar aggressive and wind aggressive scenarios in 2025 power system it can be seen that wind aggressive scenario has lesser cumulative capacity of solar and wind comparatively. Depending on the solar and wind capacity mix, power system with 500MW HVDC in 2025 could absorb cumulative solar & wind capacity approximate in the range 1500MW to 1600MW. This could be increased up to 1750MW with 1000MW HVDC in 2028.

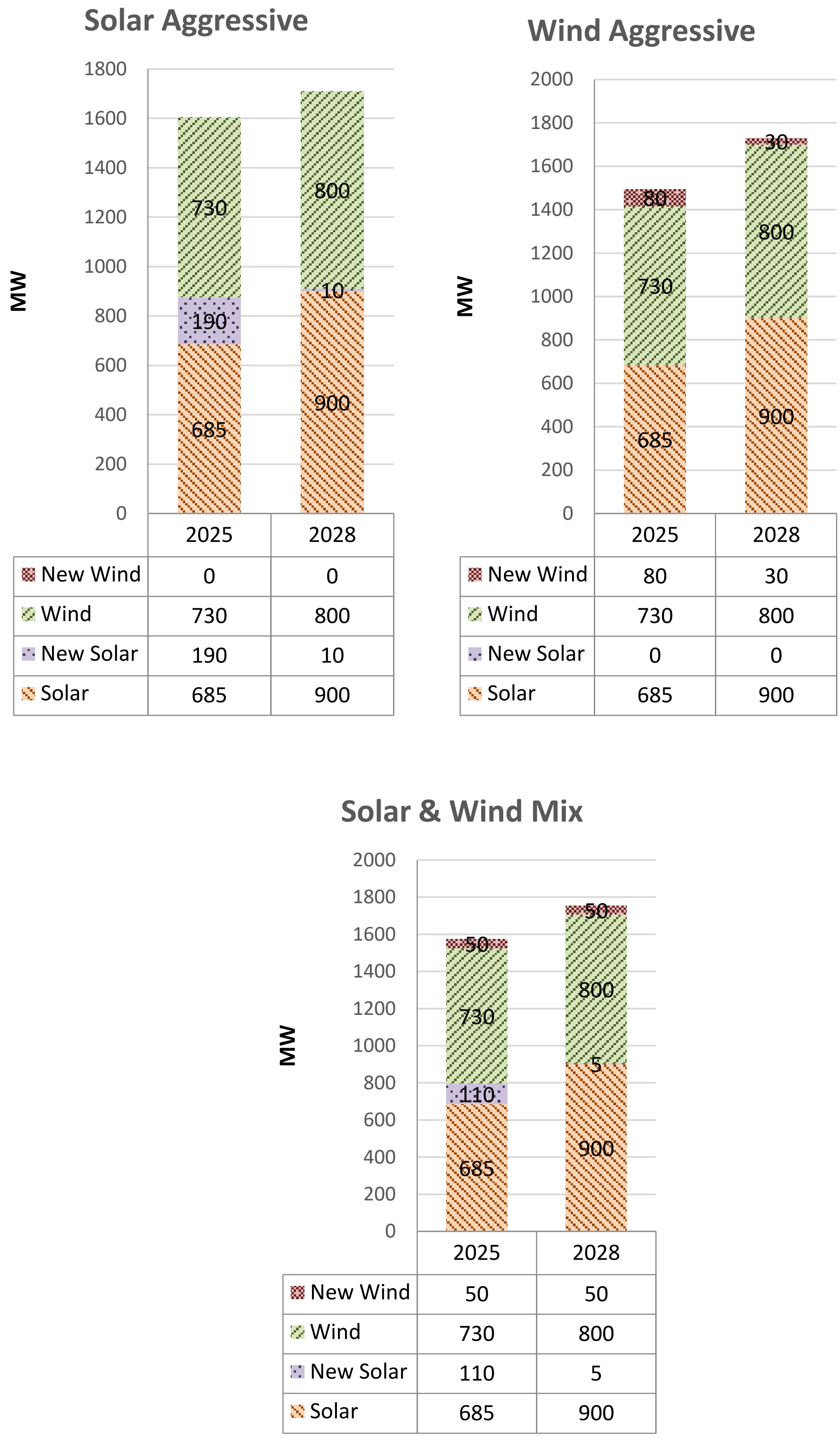

Figure 4.31: Summary of renewable capacity addition

CHAPTER 5

ECONOMIC ANALYSIS

5.1 Methodology

Economic evaluation aims at measuring the economicimpact brought about to a country by implementing a project from a viewpoint of national economy. Here, a comparison of costs expressed in terms of economic costs was used and the Discount Cash Flow Method was used. Evaluation index obtained was the Present Value (PV) of cost of implementing each of the scenarios. Phase 1-500MW HVDC development was considered for the economic analysis.

Table 5.1: Capacity additionsof the system for the scenarios

Scenario	1	2	3	4	5
	Original System with PSPP	500MW HVDC	HVDC & Solar Aggressive	HVDC & Wind Aggressive	HVDC & Solar, Wind Mix
Major hydro	1578	1578	1578	1578	1578
Coal Existing	540	540	540	540	540
Coal New Addition	540	270	270	270	270
Combined Cycle Existing	595	595	595	595	595
Combined Cycle New Addition	540	540	540	540	540
GT New Addition	105	105	105	105	105
Other thermal	24	24	24	24	24
Mini hydro	424	424	424	424	424
Biomass	23.5	23.5	23.5	23.5	23.5
Wind	730	730	730	810	780
Solar	685	685	875	685	795
PSPP	200	0	0	0	0
HVDC	0	500	500	500	500
Total Installed Capacity	5985	6015	6205	6095	6175
Total Installed Capacity without Solar & Wind	4570	4600	4600	4600	4600

According to the methodology described in chapter 3, renewable penetration was obtained for different scenarios. Corresponding results are given in Table 4.4 in chapter 4. These capacity additions were taken into account to derive the net load as described in section 3.2 of chapter 3. These net load data were fed in to WASP software to obtain the present value of each scenario. The capacity additions of the scenarios obtained from this methodology are given in Table 5.1. In all above scenarios Reserve Margin without Intermittent Renewable is 10%.

Following parameters were used in economic evaluation.

- Discount Rate
  A discount rate of 10% was used which is the basis used in national planning.
- Project capital and O&M costs, Economic Life, Construction Period, Fuel Cost
  Refer section 3.2 for the parameters used.
- Tax
  Taxes and duties, including VAT, were excluded from the economic analysis, being a transfer item

5.2 Economic Cost of the Scenarios

Firstly, a comparison was carried out between PSPP and HVDC development in 2025 considering initial solar and wind capacities of 685MW and 730MW respectively. PV of annual costs up to 2025 for each scenario is as follows.

Scenario 1- PSPP development scenario

	USD million
PV cost of total investment and operation of renewable power plants	1,407.20
PV cost of total investment and operation of other power plants	6,531.34
Total PV Cost	7,938.54

Scenario 2- HVDC development scenario

	USD million
PV cost of total investment and operation of renewable power plants	1,407.20
PV cost of total investment and operation of other power plants	6,520.71
Total PV Cost	7,927.91

Then for the scenarios with renewable additions the same PV cost was analysed.

Scenario 3 - HVDC and solar aggressive development

	USD million
PV cost of total investment and operation of renewable power plants	1489.00
PV cost of total investment and operation of other power plants	6512.48
Total PV Cost	8001.48

Scenario 4 - HVDC and wind aggressive development

	USD million
PV cost of total investment and operation of renewable power plants	1465.70
PV cost of total investment and operation of other power plants	6514.10
Total PV Cost	7979.80

Scenario 5 - HVDC and solar & wind mix development

	USD million
PV cost of total investment and operation of renewable power plants	1486.30
PV cost of total investment and operation of other power plants	6511.72
Total PV Cost	7998.02

When comparing scenario 1 & 2, it could be observed that for the initial renewable capacity the PV cost of the HVDC development scenario is less compared to PSPP development scenario.

When the renewable are integrated along with the HVDC, PV cost increases compared to PSPP. Cost difference is given in Table 5.2.

Table 5.2: Cost Difference of Scenarios

	Total PV cost USD million	PV Cost Difference USD million
Scenario 1	7,938.54	-
Scenario 2	7,927.91	(10.63)
Scenario 3	8001.48	62.93
Scenario 4	7979.80	41.26
Scenario 5	7998.02	59.48

There is a 10.63 USD million reduction of PV cost in the scenario with HVDC with compared to PSPP.

Allocating the total benefit of cost reduction from HVDC also to the renewable, the cost increase per unit of renewable capacity is obtained. According to wind aggressive scenario the cost increase per unit of wind capacity is 516 $/kW. Considering solar aggressive scenario, the unit cost increase was obtained as 331 $/kW.

5.3 Sensitivity Analysis

According to Table 3.9 in chapter 3, the economic analysis was carried out for unit cost of HVDC 70 USD/MWh including wheeling charge. It was observed that the scenario with HVDC is economical compared to PSPP but with the renewable integration the PV cost of scenarios are comparatively higher.

A sensitivity analysis was carried out by varying the unit cost of HVDC for each scenario and the PV cost comparison carried out against the PV cost of PSPP scenario.

Figure 5.1 shows the cost of each scenario for different variable cost of HVDC.

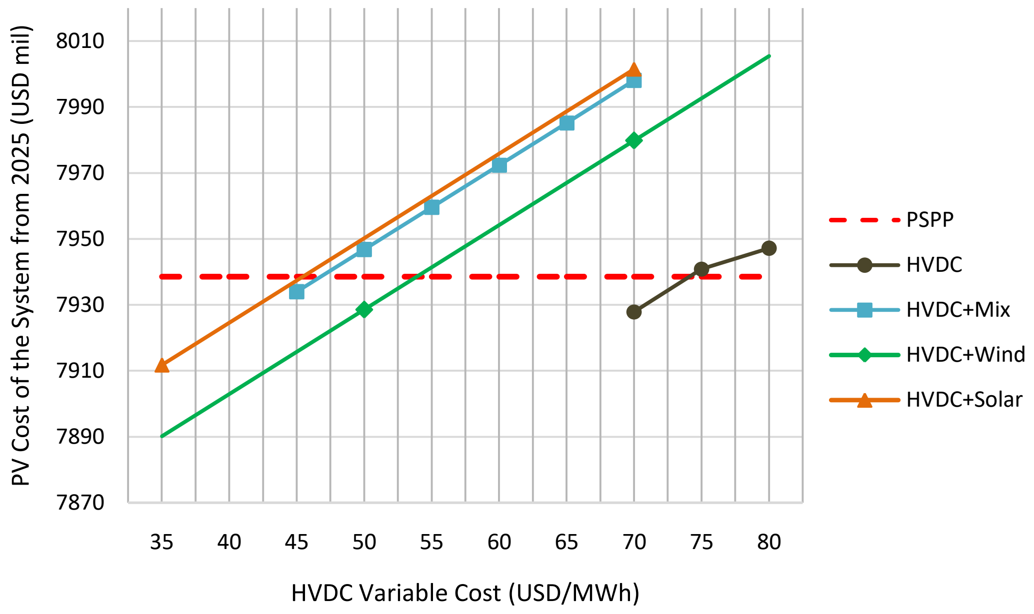

Figure 5.1: Variation of PV cost of scenarios with HVDC variable cost

<u>HVDC development scenario with 685 MW solar 730MW wind</u>

It could be observed that HVDC scenario with same solar and wind capacities as PSPP scenario was economical at 70 USD/MWh. It could be increased up to 74 USD/MWh (11.0 LKR/kWh) until breakeven with the PSPP development scenario.

<u>Solar Aggressive Scenario with 875MW solar and 730MW wind</u>

It could be observed from Figure 5.1 that the breakeven for the solar aggressive scenario occurs at 45 USD/MWh (7.0 LKR/kWh)

<u>Wind Aggressive Scenario with 685MW solar and 810MW wind</u>

It could be observed from Figure 5.1 that the breakeven for the wind aggressive scenario occurs at 54 USD/MWh (8.0 LKR/kWh)

<u>Solar and Wind Mix Scenario with 795MW solar and 780MW wind</u>

It could be observed from Figure 5.1 that the breakeven for the solar and wind mix development scenario occurs at 47 USD/MWh (7.2 LKR/kWh)

CHAPTER 6

DISCUSSION

The objective of this research was to assess the possible level of penetration in wind and solar power in Sri Lanka with the proposed India-Sri Lanka HVDC interconnectionand compare with other options.For this initially the Sri Lankan power system in 2025 and 2028 were developed with and without HVDC based on the Long Term Generation Expansion Plans using Wien Automation System Package (WASP) software and the long term and short term dispatch simulation was carried out using SDDP and NCP software.

When observing the system with PSPP and without PSPP or HVDC there were renewable curtailments with the capacities of 685MW solar and 730MW wind during 2025. The system with 500MW HVDC did not give rise to any curtailments and hence it was observed that the intermittent renewable capacity could be increased further. Therefore, the simulation process was repeated while renewable capacity is increased limiting the curtailments to 5% of demand for different scenarios and for different stages of HVDC development. To analyse the effect of two different technologies solar and wind, solar aggressive, wind aggressive and solar & wind mix scenarios were considered. To represent seasonal variation wet and high wind periods were considered and to represent demand variation weekday and weekend days were considered as samples.

When considering the solar aggressive scenario the wind capacity was fixed at initial 730MW and solar capacity was increased until 875MW which is a 190MW addition to initial solar capacity during wet period. During high wind period it could be increased up to 885MW which is a 200MW addition. When considering the annual capacity addition the wet period has become the limiting criteria. Due to higher availability of hydro resource the renewable excess generation is higher in the wet period. Therefore in the solar aggressive scenario with 500MW HVDC the solar capacity will be limited to 875MW during 2025 which is a 190MW addition.

Similarly considering the wind aggressive scenario solar capacity was fixed at initial 685MW and wind capacity was increased. Within the allowable curtailment limits wind capacity could be increased to 810MW (80MW addition to initial capacity) during wet period and up to 815MW (85MW addition to initial capacity) during high wind period. Therefore in the wind aggressive scenario with 500MW HVDC the wind capacity will be limited to 810MW during 2025 which is an 80MW addition which again occurs during wet period.

When considering the above two scenarios; solar aggressive with 875MW solar and 730MW wind (total of 1605MW) and wind aggressive scenario with 685MW solar and 810MW wind (total of 1495MW), the total renewable energy share including major hydro is 54%. The share of wind and solar energy in solar aggressive scenario is 25% and in wind aggressive scenario 26%. Even though the total renewable capacity is lesser in the wind aggressive scenario energy share is slightly higher than the solar aggressive scenario due to higher plant factor of the wind resource compared to solar.

During high wind period simulation this energy share could be increased to 63% total renewable share of which 28% and 29% solar and wind energy share could be observed for solar aggressive and wind aggressive scenarios respectively. This is with a higher level of capacity additions as mentioned above.

Next a solar and wind mix scenario was simulated by considering wet period. Both solar and wind capacities were increased to achieve the 26% of energy share from solar and wind and within allowable curtailment limits. In the mix scenario solar and wind capacities were able to increase up to 795MW solar (addition of 110MW to the initial capacity) and 780MW wind (addition of 50MW).

During high wind period the capacity limit could be increased to 800MW solar (addition of 115MW to the initial capacity) and 780MW wind (addition of 50MW) with total renewable energy share of 63% of which 29% is from solar and wind.

When comparing the capacity additions in wet and high wind period it can be observed that the capacity addition is slightly less in the wet period to allow curtailments within 5% of demand range. Therefore as the annual capacity additions possible with HVDC, the wet period additions were considered. Further for the second phase of HVDC development in 2028 the only wet period simulation was carried out to obtain the solar and wind capacity limit.

Similarly, system with PSPP and without PSPP gave rise to curtailment of renewable generation with 800MW wind and 900MW solar capacities in 2028. With 1000MW HVDC there were no renewable curtailments observed. Therefore, with 1000MW of HVDC in 2028 solar aggressive, wind aggressive and wind & solar mix scenarios were simulated.

With solar aggressive scenario the wind capacity was fixed at 800MW and solar capacity was increased until 910MW which is only 10MW addition to initial solar capacity. In wind aggressive scenario solar capacity was fixed at 900MW and wind capacity was increased. Within the allowable curtailment limits wind capacity could be increased to 830MW which is 30MW addition to initial capacity. In both scenarios total renewable energy share could be increased to 51% of which solar and wind share was 26% in solar aggressive scenario and 27% in wind aggressive scenario.

As summarized in Table 4.2 & Table 4.3, it was observed that irrespective of the scenario of aggressive solar or wind or mix, the energy share from renewable cannot be increased significantly. Therefore, to achieve a growth in renewable energy share it is wiser to develop a wind aggressive scenario.

It could be observed that the increase in renewable capacity additions with HVDC compared to PSPP is not very significant with the second phase. Therefore the economic analysis was carried out for 500MW HVDC development and compared with the system with PSPP.

Initially, a comparison was carried out for the initial capacities of 685MW solar and 730MW for the PSPP and HVDC development in 2025 considering the variable cost of 70 USD/MWh. It was observed that there is a 10.63 USD million reduction of PV cost in the scenario with HVDC with compared to PSPP at a 10% discount rate. Then each scenario PV cost up to 2025 was obtained for comparison. When considering

Table 5.2 wind aggressive scenario has the minimum incremental cost and hence becomes the most economical.

Further, sensitivity analysis was carried out to identify at which cost each scenario would be economical. It was found that the original scenario is economical even at 74 USD/MWh (11.0 LKR/kWh) while solar aggressive scenario is economical at 45 USD/MWh (7.0 LKR/kWh), wind aggressive scenario at 54 USD/MWh (8.0 LKR/kWh) and mix scenario at 47 USD/MWh (7.2 LKR/kWh). Exchange rate used for conversion is 148 LKR/USD.

When considering the reserve requirement of the power system the higher penetration of variable renewable energy such as solar and wind brings issues to power system operation which needs to be addressed by additional spinning reserves. Although developed countries use the statistics based on the forecast error of the intermittent renewable, Sri Lanka does not yet have such forecasting systems. Therefore spinning reserve of 10% was kept from intermittent capacity for each scenario in addition to 5% of demand.

CHAPTER 7

CONCLUSION & RECOMMENDATION

7.1 Conclusion & Recommendation

The purpose of this research was to identify the penetration level of intermittent renewable energy namely; solar and wind with the implementation of proposed HVDC interconnection with India. According to the research findings the following conclusions and recommendations can be made.

- Solar and wind penetration can be increased with the introduction of HVDC, but at an additional cost to the system for the variable cost of 70 USD/MWh for the imports from India.
- Summary of solar and wind capacities(MW) that can be absorbed to the Sri Lankan power system with the introduction of HVDC and the comparison with system with PSPP are as given below.

Table 7.1: Scenario summary &renewable capacities (MW)

Year	**Capacities in MW**						**Scenario**
	Without PSPP or HVDC		**With PSPP**		**With HVDC**		
	Wind	Solar	Wind	Solar	Wind	Solar	
2025	649	635	730	685	730	875	AS
					810	685	AW
					780	795	Mix
2028	719	850	800	900	800	910	AS
					830	900	AW
					850	905	Mix

AS-Aggressive Solar, AW-Aggressive Wind, Mix- Solar & Wind Mix

- From the sensitivity analysis it was found that HVDC is economical for each scenario for variable cost of HVDC as given below.
  - Original Scenario 74 USD/MWh (11.0 LKR/kWh)
  - Solar Aggressive Scenario 45 USD/MWh (7.0 LKR/kWh)
  - Wind Aggressive Scenario 54 USD/MWh (8.0 LKR/kWh)
  - Mix Scenario 47 USD/MWh (7.2 LKR/kWh)

  (Exchange Rate used 148 LKR/USD)

This sensitivity analysis could be used when renegotiating the transfer price terms during the preparation of financial agreements with India.

- To achieve higher RE share at a comparatively economical cost the wind aggressive scenario is recommended to be implemented.

- It is recommended to introduce day ahead and hourly forecasting system with higher level of RE penetration to relax the reserve requirement of 10% of intermittent renewable capacity.

- It is recommended to implement planned network strengthening projectsas scheduled for RE integration.

- Sri Lanka is envisioned towards achieving 100% energy self-sufficiency. In view of that, it is beneficial for interconnection through HVDC in order to export any excess electricity generation.

7.2 Limitations

- All economic cost data were based on the values from LTGEP 2018-2037 [24] and the exchange rate of 148 LKR/USD has been used.

- If the renewable energy curtailment allowed limits are varied more renewable energy capacity could be absorbed into the power system. Since there are no such curtailment rights prevail in Sri Lankan power system yet, the curtailments are limited to an amount by which can be regulated by the spinning reserves kept as a practice.

- Price data/Unit cost of electricity from HVDC interconnection used in the research is based on the feasibility study carried out in 2011. The financial terms may be renegotiated based on future discussions.

- The production cost model used in the research cannot be used to simulate the transient stability analysis of the power system.

7.3 Future Work

In addition to the research findings there are many potential aspects which could be evaluated with related to HVDC interconnection. Following are some of the topics which could be recommended for future research.

- Since the research only considers the operational problem it is worthwhile to investigate the stability criteria of the Sri Lankan power system with the increased level of RE penetration.

- In this research it was only assumed of energy import from India and curtailments were limited to allowable range in order for the smooth operation of the power system. It could also be further studied the energy export option and hence the curtailed energy will bring benefits to the country. In this view, it seems possible that the load factor of the Sri Lankan power system could be increased which may need further research to validate.

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