TECHNO - ECONOMIC COMPARISON BETWEEN GENERATION CAPACITY RESERVES AND UTILITY SCALE BATTERY STORAGE TO FACILITATE VARIABLE RENEWABLE ENERGY INTEGRATION IN SRI LANKA

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Degree of Master of Science in Electrical Engineering

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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Prof. K.T.M.U. Hemapala

Abstract

At present, the Sri Lankan power system has a total installed capacity of approximately 4,087 MW by end of year 2017 with a total dispatchable capacity of 3,525 MW. The maximum demand recorded in 2017 was 2,523 MW.

Sri Lanka is a country with abundance of renewable energy sources which could be utilized to generate clean energy at zero fuel cost. Currently the Sri Lankan power system has renewable capacity (except major hydro) of 609 MW, and by the Long Term Generation Expansion Plan (LTGEP) 2018-2037 of Ceylon Electricity Board (CEB), a considerable increase in integration of renewable energy into the system is projected.

But integrating variable renewable energy (VRE) sources such as wind and solar energy to an islanded power system like Sri Lanka presents numerous technical and economic constraints. These constraints rise due to the inherent qualities of VRE such as intermittency of the resource, lack of inertial response for frequency regulation, high capital cost and the cost of maintaining adequate generation capacity reserves to compensate for variability and uncertainty of VRE. Therefore successfully overcoming the technical and economic barriers is essential in integrating more renewable energy in to the power system.

Utility scale battery storage systems are considered as a possible solution to the variability and uncertainty of VRE, by facilitating energy storage from solar PV plants during the day and inject stored energy to the system at night. The battery storage system also can be used for ancillary services such as voltage support, frequency control and load smoothing, as well as ramp rate control in order to maintain grid stability. This study specifically explores the use of battery storage

KEYWORDS: Variable Renewable Energy, Operating Reserves, Utility Scale Battery Storage

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Firstly, I would like to express my sincere gratitude to my supervisor Prof. K.T.M.U Hemapala for his valuable insights and perspective with much patience throughout the entire period and his continuous support with immense knowledge motivating me to do this research. Thank you very much for giving me the opportunity to work with you.

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List of Abbreviations

Abbreviation	Description
LTGEP	Long Term Generation Expansion Plan
VRE	Variable Renewable Energy
CEB	Ceylon Electricity Board
MW	Mega Watt
GWh	Giga Watt hour
NPV	Net Present Value
SAM	System Advisory Model
NREL	National Renewable Energy Laboratory

1. INTRODUCTION

The intermittency and variability of wind and solar (Variable Renewable Energy-VRE) affect the requirement for operating reserves in the system when a substantial scale of integration of VRE has taken place. As the level of VRE in the system increases, the increase in power variations necessitate additional capacity balancing and regulation capabilities due to the variability and uncertainty in the power output of VRE.

From a power system planning perspective, it is imperative to properly account for the increased operating reserve requirement due to the substantial level of VRE integration forecasted in the Sri Lankan context. At the present context, conventional thermal and hydro generators with high ramp rates are being used to provide the required operating reserves of the system. But as the system grows and the VRE integration increases, it is vital evaluate the suitability of keeping the conventional generators as operating reserves as opposed to the emerging technologies such as utility scale battery storage.

In the recent years, Utility Scale Battery Storage has emerged as a viable alternative to provide operating reserves compared to the conventional generators. Utility scale batteries have primarily been deployed as an energy shifting mechanism in the past. However, due to a fast sub-second response, high energy density and reversible nature, battery storage has been utilized for ancillary services such as frequency regulation and operating reserves. Figure 1.1 shows the utility-scale Lithium-Ion battery storage projects (>10 MW) commissioned worldwide in recent years (Source: DOE Global ES Database). The present trends indicate that the utility scale battery deployment have grown not only in quantity, but also in size and duration.

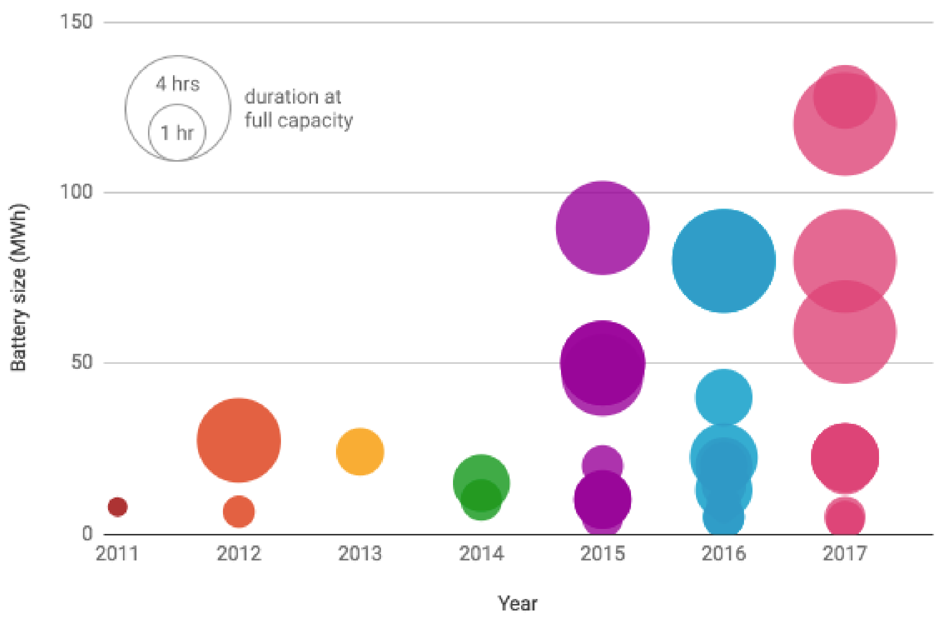


Figure 1.1: Large Utility-Scale Li-ion Battery Storage Projects (>10 MW) Commissioned Worldwide in Recent Years

This study focuses on use of utility scale battery storage compared to conventional thermal generators to provide the increased operating reserve requirement due to the high level of VRE integration proposed in the future.

1.1 Importance of the Research

Sri Lanka has envisaged an ambitious target for renewable integration to the power system as indicated through Long Term Generation Expansion Plan 2018-2037 which maintains a 20% energy share from non-conventional renewable sources while maintaining approximately 30% from total installed capacity for the planning horizon. This capacity addition is mainly comprised of Wind and Solar, both of which are variable sources which affects the operation and stability of the system. Therefore, it is important to integrate sufficient reserve capacity to the system in order to compensate for the variability of the renewable sources. Currently, this function is carried out through the existing hydro and thermal power plants as the variable renewable integration is relatively low at present. But with these ambitious targets of integrating high level of VRE, it is vital to explore different cost effective methods and approaches in providing reserves to compensate for variability in Wind and Solar.

1.2 Main Objectives of Research

The main objective of this research is to evaluate the advantage of using battery energy storage to provide operating reserves to compensate for variability of VRE over using conventional thermal power plants in a system with high level of VRE integration such as the future Sri Lankan system projected in LTGEP. The main objective of this research was approached in two phases as follows:

1. Estimation of the required operating reserve capacity to be maintained to integrate the projected amount of VRE applying the available techniques used in power systems worldwide

2. Comparing the use of conventional generators and utility scale battery storage to maintain the required level of generation capacity reserves in **economic and technical perspective** to facilitate the projected VRE integration to the system (Using Dispatch Analysis and Economic Analysis)

1.3 Research Methodology

Research methodology is summarized in Figure 1.2.

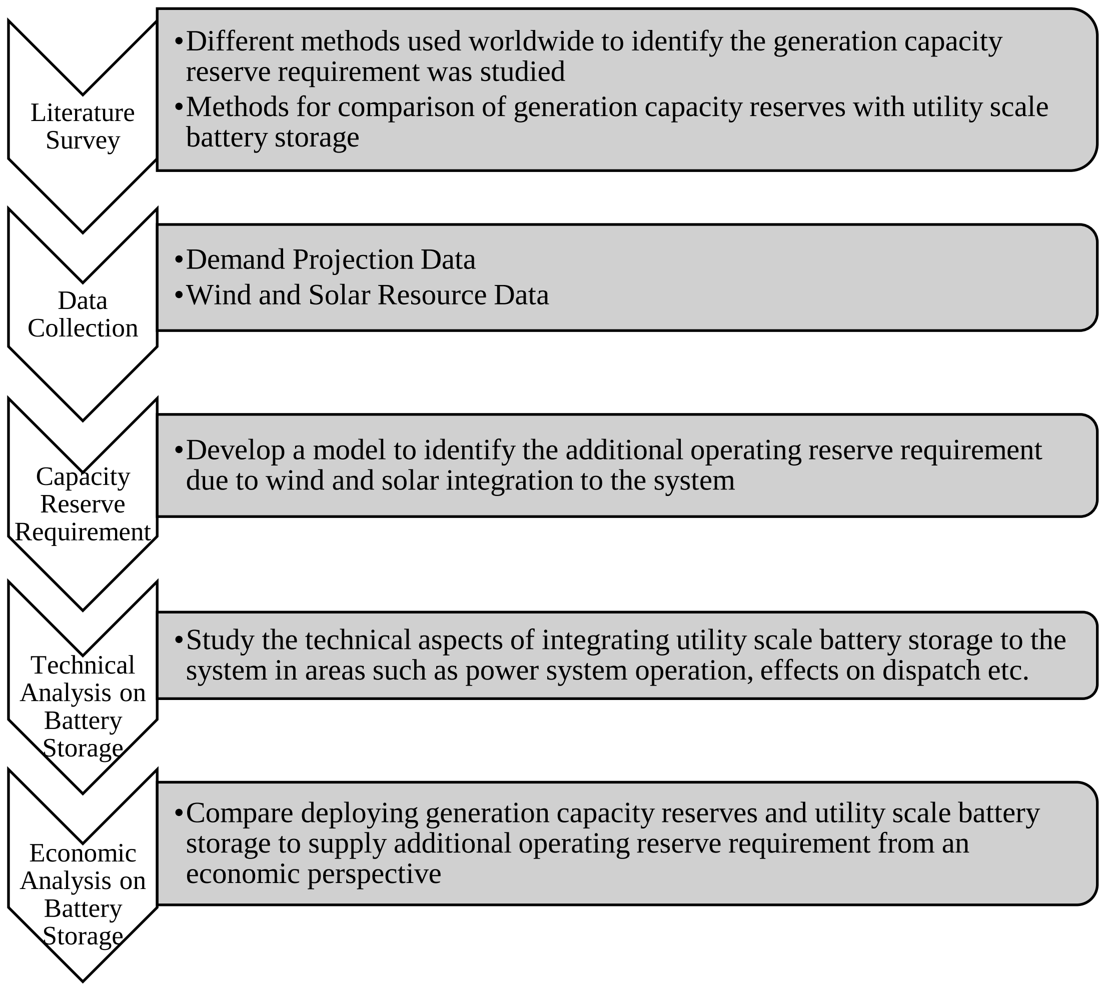


Figure 1.2: Basic Overview of the Methodology Used for this Study

1.4 Overview of Thesis

The dissertation discusses in detail the salient features and details of this study and information on literature survey of related ongoing and completed studies. The development of thesis is based on the order which the study has been approached and the chapters are ordered according to the chronological steps in the study. A summary of content of each chapter is as follows.

1. Introduction:

   Introduces the study and briefly discusses the background and the problem statement on which the study has been based on. This also discusses the motivation for selecting the specific study, objective, methodology and organization of the report.

2. Overview of the Study:

   This chapter describes the theoretical background on operating reserves of a power system on a broader prospective and analyses in detail about the impact of VRE on operating reserves. It also describes the role of regulating reserves and following reserves which are components of operating reserves and how the operating reserves are kept by the conventional generators in the present system. Then it discusses how the utility scale battery storage has evolved to supply the ancillary services such as operating reserves and how it compares with the conventional generators.

3. Methodology and System Modelling

   This chapter provides a detailed overview of the methodology adopted in conducting the study including the literature survey, data collection, determining the operating reserve requirement for the Sri Lankan test system and developing the model for the test system using Stochastic Dual Dynamic Programming (SDDP). It also gives a comprehensive outline about the Dispatch Analysis and the Economic Analysis carried out on the comparison of Utility Scale Battery vs. Conventional Thermal Power Plants assigned as operating Reserves

4. Results

   This chapter presents a comprehensive analysis on the requirement of operating reserves with the integration levels of Wind and Solar to the Sri Lankan test system used for the study. It also discusses in detail the results of the dispatch analysis and the economic analysis carried out between utility scale battery storage and the conventional thermal generators for providing operating reserves.

5. Conclusion:

   Summarizes the study indicating how the objectives are achieved and discusses how the results could be adopted in an actual power system and the future direction for the research.

2. OVERVIEW OF THE STUDY

The main purpose of power system operations is to continuously match energy supply from electric generators to consumer demand at all times. This involves long term, medium term and short term planning to ensure that the generation system has sufficient energy, capacity and load balancing capability to compensate the monthly, daily, hourly and instantaneous variations in load and generation.

Operating reserves play an important role in ensuring the grid reliability through participating in the above balancing of variations in load and generation. The variability and uncertainty of both load and generation sides of the system are the main reasons behind the requirement for Operating Reserves. Figure 2.1 shows an example of variability and uncertainty for VRE output.

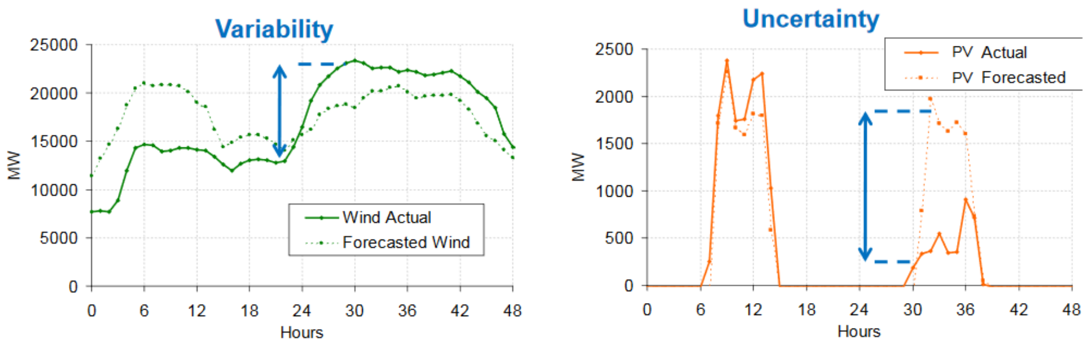


Figure 2.1: Uncertainty and Variability of VRE

Many aspects of the power system, including its generation and load both vary with time. Therefore, additional capacity over the actual demand is required and this can be called as operating reserves.

Operating reserve categories include event reserves (the capability of responding to a major contingency such as an sudden power plant or transmission line outage) and non-event reserves (the capability of responding to small, random fluctuations around the usual load pattern). This study mainly focuses on the non-event reserve requirement which is needed to address the increased variability and uncertainty created by renewable energy sources such as wind and solar. Generally, Operating reserves are provided by a mix of generation options which could change output in a short period.

Figure 2.2 depicts traditional operating reserve categories as defined by "North American Electric Reliability Corporation (NERC)". The variability and uncertainty of VRE (wind and solar) generation would directly affect the requirement of this category of reserves.

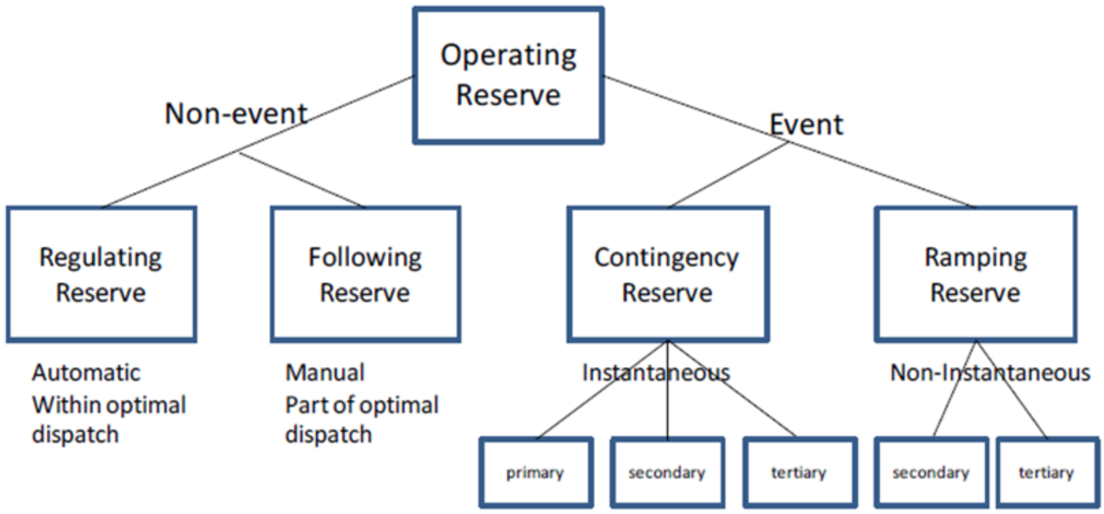


Figure 2.2: Operating reserve categories as defined by "North American Electric Reliability Corporation (NERC)"

2.1. Operating Reserves

To identify the operating reserve requirement, different entities use varying methods to quantify the requirement of Operating Reserves, which generators are assigned to provide it, and the duration it should be deployed. The standards are usually based on reliability levels stipulated and the risk profile of the entities, and differ from country to country. These methodologies are evaluated in detail in the literature review of this study.

Many studies have pointed out that with high integration of VRE, these standard methodologies should be modified through innovative models and rules and policies should be adjusted to account for the increased variability and uncertainty.

2.2. Impact of Variable Renewable Generation on Operating Reserves

In recent years, with increased level of renewable integration on the power systems, huge quantities of wind and solar power, has been added to the power systems worldwide and both of these technologies are referred to as VRE.

Increases in VRE integration impact on mainly the non-event Operating Reserve. During normal operation, the fluctuations of VRE will add to the fluctuations of load and other generators. The increased variability that VRE introduces leads way to the increased requirement of Following Reserve and Regulation Reserve.

For an example Figure 2.3 demonstrates the system load variation, VRE variation and combined cycle power plant operation for 6 consecutive days in 2025 for Sri Lankan system with combined cycle plants set to provide operating reserves. It could be observed that with the variations in VRE, the dispatch of the combined cycle power plants vary to compensate for the variability.

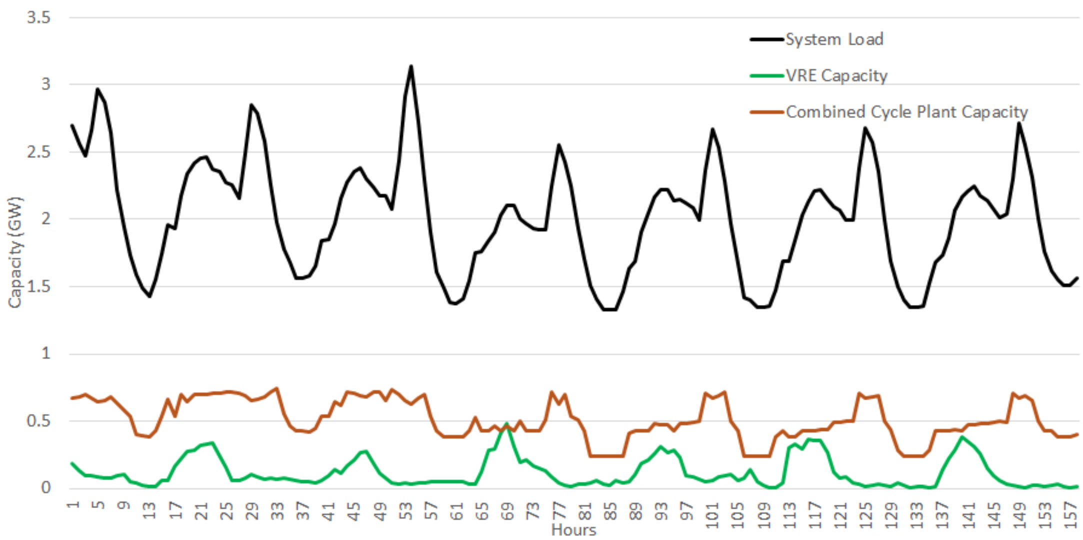


Figure 2.3: Load, VRE and Combined Cycle hourly Variations for 6 Consecutive Days in Year 2025

Different generation technologies are suited at providing different types of operating reserves. Conventional thermal and hydro generating units are inherently limited in the amount of spinning reserve they can provide by their ramp rates, although hydro generating units and gas turbines have faster ramp rates than steam turbine generators. Some internal combustion engine driven generators, aero-derivative combustion turbines, and hydro plants can start fast enough to provide non-spinning reserves even if they are not currently operating.

Large Coal and Nuclear units have historically been built for base load and therefore usually do not provide operating reserves. Coal and Nuclear plant governors are typically blocked, preventing them from providing frequency responsive reserve. Large thermal plants operating with their valves fully open to maximize efficiency (sliding pressure or boiler follow mode) effectively disable the governor and do not provide frequency response either.

As a recent trend, Utility Scale Battery Storage has emerged as a potential technology to provide operating reserves and this study focus mainly on this particular aspect.

2.3 Utility Scale Battery Storage

Utility scale battery storage has emerged as a technology which could play a vital role in the global energy mix. It provides a solution to one of the main challenges faced by renewable generation – the intermittency and variability of renewable sources – presenting a method to capture clean energy and balance energy generation against load.

The main advantage for utility-level energy storage is the rapidly decreasing capital cost, and the vast array of benefits provided by energy storage to the power systems in general and to power systems with high renewable energy integration in particular.

The characteristics of energy storage differ according to the application of the energy storage. Applications such as long-duration load shifting needs a large energy storage capacity and applications such as frequency regulation and provision of reserves require power to be absorbed or injected. Figure 2.4 shows a broad categorization of utility scale energy storage systems.

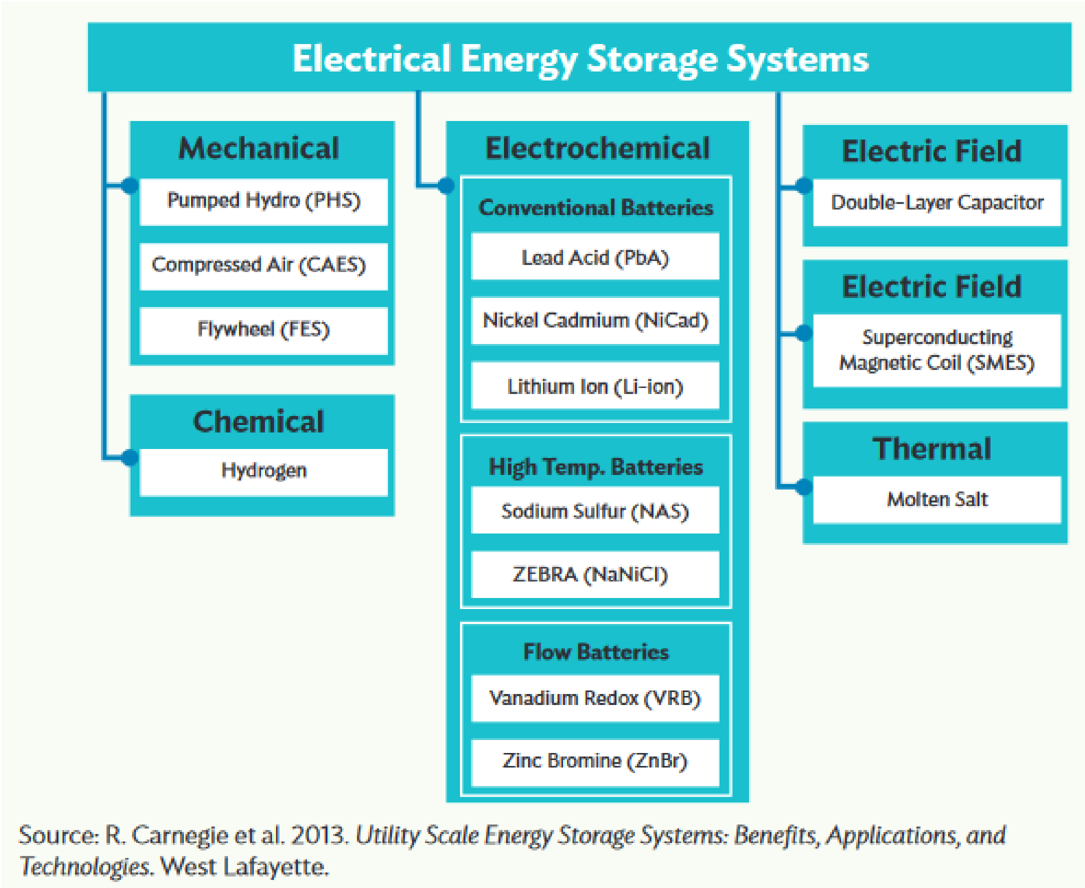


Figure 2.4: Classification of Storage-Based on Technologies

A summary of the above storage technologies with the duration, maturity and applications are presented in Table 2.1.

Table 2.1: Storage Technologies and Their Duration, Maturity, and Applications

Storage	Duration (hrs)	Maturity	Application
Mechanical Energy Storage System			
Pumped hydroelectric	6–10	Mature	• Load leveling • Peak shaving • Renewable integration
Compressed air energy storage (underground)	20	Commercial	• Load leveling • Renewable integration
Flywheels	0.25	Commercial	• Frequency regulation
Electrical and Magnetic Storage System			

Superconductive magnetic energy storage		Demo	• Power quality • Frequency regulation • Voltage Support
Electrochemical capacitors	~1 min	Demo	• Power quality • Frequency regulation • Voltage Support
Electrochemical Storage System			
Advanced lead acid batteries	4	Demo	• Power quality • Frequency regulation • Voltage support • Renewable source • integration
Lithium ion batteries	0.25-1	Commercial	• Power quality • Frequency regulation
Sodium sulfur	7.2	Commercial	• Time shifting • Frequency regulation • Renewable source • integration
Vanadium flow redox	5	Demo	• Peak shaving • Time shifting • Frequency regulation • Renewable source • integration

2.4 Functions of Utility Scale Energy Storage

Utility scale energy storage provides a range of benefits to a contemporary power system with more variable and distributed generation. Figure 2.5 presents a broader categorization of the functions that could be utilized through energy storage.

Bulk Energy Services	Transmission Infrastructure Services
Electric Energy Time-Shift (Arbitrage)	Transmission Upgrade Deferral
Electric Supply Capacity	Transmission Congestion Relief
Ancillary Services	**Distribution Infrastructure Services**
Regulation	Distribution Upgrade Deferral
Spinning, Non-Spinning, and Supplemental Reserves	Voltage Support
Voltage Support	**Customer Energy Management Services**
Black Start	Power Quality
Other Related Uses	Power Reliability
	Retail Electric Energy Time-Shift
	Demand Charge Management

Figure 2.5: Functions of energy storage on a grid

In grids with high penetration of VRE, instability can result because when high renewable energy production periods coincide with off peak where only must-run base load generators operate; the lack of sufficient amounts of operating reserves during such periods can cause grid instability because the changes in net load (load–renewable energy generation) cannot be supplied by operating reserves. Energy storage can plug into this need by quickly providing energy to the grid. The energy storage unit thus becomes a provider of operating reserve.

On a minute-by-minute basis, the variation and uncertainty in net demand is managed by load-following generators, which sense frequency rise or drop to determine the power output using governor controls. When the rate of change in renewable energy production is large, then the rate of change of net demand could become larger than the ramp response that can be provided by the load following generators in the grid. Electrochemical batteries can support the grid with minute-by-minute response.

On an hour-by-hour or longer timeframe, electrochemical batteries, pumped storage, and compressed air energy storage can store and provide energy for longer periods.

2.5 Lithium-ion (Li-ion) batteries

Lithium-ion (Li-ion) batteries have become the prominent and well established battery technology for utility-scale energy storage.

For short to medium level storage durations, lithium batteries are currently the most cost-effective technology, and indicates the best energy density relative to the other technologies. For longer durations, the cost effectiveness of these batteries depend on the application, particularly when considering lifetime costs. These batteries are also easy to configure into various sizes to cater for a wide range of voltages, power ratings, or energy increments. This enables application-specific designs which ranges from low capacity low duration storage, up to high capacity long duration storage that may be used for various applications.

3. METHODOLOGY AND SYSTEM MODELLING

3.1 Literature Review

To identify and understand the similar research carried out in this area and to devise a proper methodology to achieve objectives 1 and 2, a literature survey was carried out at the initial phase of the study. Numerous conference papers, journal publications, articles, software manuals etc. were referred during the literature review phase and the key highlights of the findings are listed below.

In the process of identifying the basis for the research, the main document referred was the Long Term Generation Expansion Plan 2018-2037 prepared by the Ceylon Electricity Board. It projects a substantial capacity integration of VRE (Wind and Solar) to the system in the study horizon of 20 years as shown in Figure 3.1.

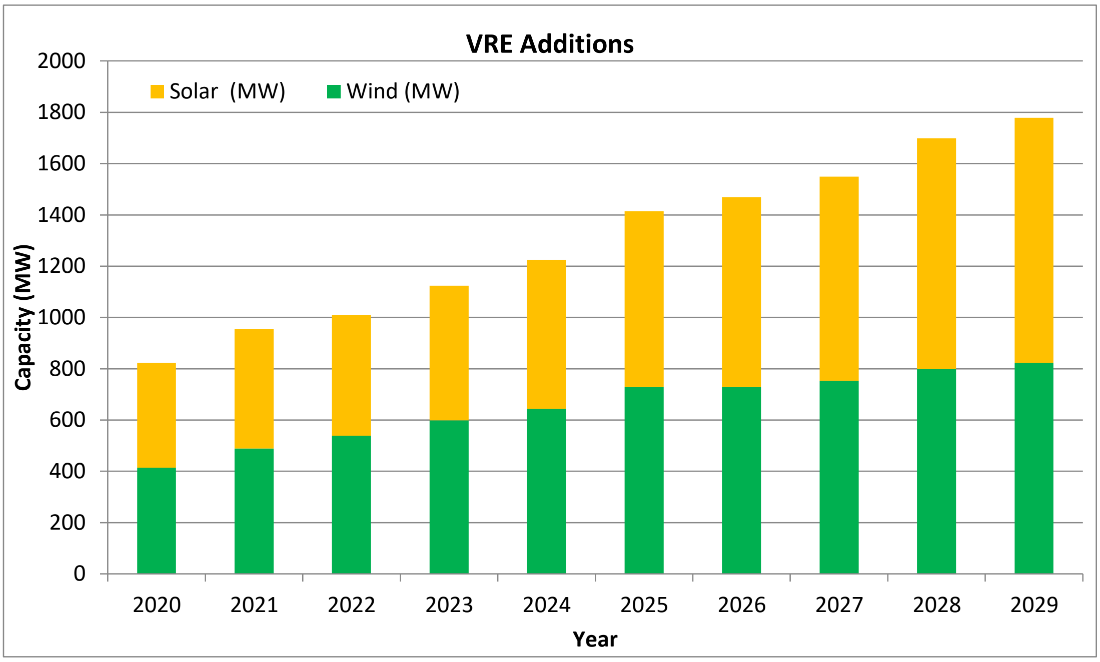


Figure 3.1: Wind and Solar Capacity Additions during 2020-2030 as per LTGEP 2018-2037

But the document itself does not specifically address the provision of operating reserves to absorb the uncertainty and variability of the VRE. Therefore, it is given that the existing conventional generators would provide the operating reserves as practised in the present context also. But with the rapid advancement in the utility scale battery storage systems in the world, it is useful to compare the provision of operating reserves by battery storage as opposed to the conventional thermal generators in the perspective of technical and economic aspects.

To identify the impact of VRE on the operating reserves, a Technical Report published by the National Renewable Energy Laboratory (NREL) titled “Operating Reserves and Variable Generation” was referred. The study presented by the report generalizes the requirements of the power system as it relates to the needs of operating reserves. It also categorizes the various types of operating reserves and role of reserves in the future with higher integration of variable generation.

For the purpose of understanding the economics of maintaining operating reserves, another Technical Report by National Renewable Energy Laboratory (NREL) titled “Fundamental Drivers of the Cost and Price of Operating Reserves” was referred. This analyzes the economic impact of operating reserves on the operation of the power system and evolving the generation mix if wind and solar power reach high penetration levels.

With regard to Objective 1 of the study, several publications were studied in order to develop a methodology to identify the additional reserve requirement due to the integration of VRE. “Using Standard Deviation as a Measure of Increased Operational Reserve Requirement for Wind Power” was used as the main reference document for this purpose. This publication extensively discusses using Standard deviation of variability in load and net load (load –VRE) when determining the effect of VRE on the operating reserves of the power system.

Additionally, “Fundamental Drivers of the Cost and Price of Operating Reserves” also provided insight on mathematically representing the variability of load and VRE separately and in combination.

To identify the operating reserve requirement mainly three methods were identified through the literature review and they are summarized in Table 3.1.

Table 3.1: Summary of the methods for Objective 1 extracted through literature review

Method	Advantages	Disadvantages
Development of a curve between peak load and required operating reserve	• Easy to develop • Only load data is needed.	• Only captures the load variability
The Statistical Approach Based on Sigma (Standard Deviation)	• Could capture load as well as VRE variability • Could vary the multiplier of sigma	• Needs development of a statistical model with load and VRE data
The Statistical Approach Based on Exceedance Level	• Could capture load as well as VRE variability	• Needs development of a statistical model with load and VRE data • Only a predetermined sigma value could be used

Out of the above three methods, the Statistical Approach Based on Sigma (Standard Deviation) was selected to determine the operating reserve requirement considering the availability of data and the accuracy level needed. This method is straightforward and easy to use when time-series data on VRE and load exist. Net load variability compared to load variability gives an estimate for the needs of the system to react to large scale VRE. This method also gives estimates for the range of variability, for example taking ±4σ as the range will cover most variations (99.99 % of all variations are inside this range). It was observed that the multiple of sigma has been on the order of 6σ for regulation reserves, and in the range of 2-3σ for load following reserves.

From the literature survey, a basic outline of the methodology for Objective 1 was developed and it was as follows:

- Half hourly load data would be used to develop hourly load data for the test year.

- The wind and solar measurement data are fed into System Advisory Model (SAM) to get the hourly output capacity of the respective wind and solar regimes.
- Hourly data for load, wind output and solar PV output would be used to develop the duration curves.
- Sets of net load duration curves would be developed using the geometric addition of the load, wind and solar variability to calculate the combined variance of uncorrelated random variables
- These duration curves would be used in the statistical analysis with the various multipliers of the standard deviation of the data sets.
- With the standard deviation which captures 99.99% of the variability, the results could be obtained as to what is the requirement of the spinning reserves for the test year.

With a method identified for Objective 1, the literature survey was continued to explore background studies and a methodology to achieve Objective 2 which is the Techno-Economic analysis of supplying spinning reserve from utility scale battery storage against conventional thermal plants. The Technical Report by NREL on "Fundamental Drivers of the Cost and Price of Operating Reserves" was referred in devising a methodology to appraise the technical and economic impact of maintaining operating reserves in a power system and usage of utility scale battery storage in spinning reserves. This study has used a commercial grid simulation and dispatching tool called "PLEXOS" to evaluate the cost and price of several operating reserve services, and has modelled the conventional generation fleet with wind and solar power to identify the dispatch patterns and cost implications of maintaining operating reserves. After several other studies regarding operational reserves were studied, it could be deduced that, a software with the capability of dispatch simulation is needed for the study of the operational costs of spinning reserves and comparison of battery storage in providing the reserves. Most of the international studies have used PLEXOS software which is currently not available with CEB.

“Stochastic Dual Dynamic Programming (SDDP)” tool by PSR Inc. is a similar software which is a dispatch model which could be used to identify the optimum dispatch of an electrical system composed by hydro and thermal generation plants. This software is currently being used by CEB for medium term simulation of economic dispatch of power plants together with hydro-thermal coordination. Upon studying the Methodology Manual and User Manual of this tool, it was identified that this tool could be used to distinguish the dispatch of spinning reserves as well as the economics of the operation.

It also has the options of incorporating the battery storage option in to the dispatch equation and simulate the system to output the optimum dispatch and the related cost figures.

A snapshot of the user interface of SDDP is shown in Figure 3.2.

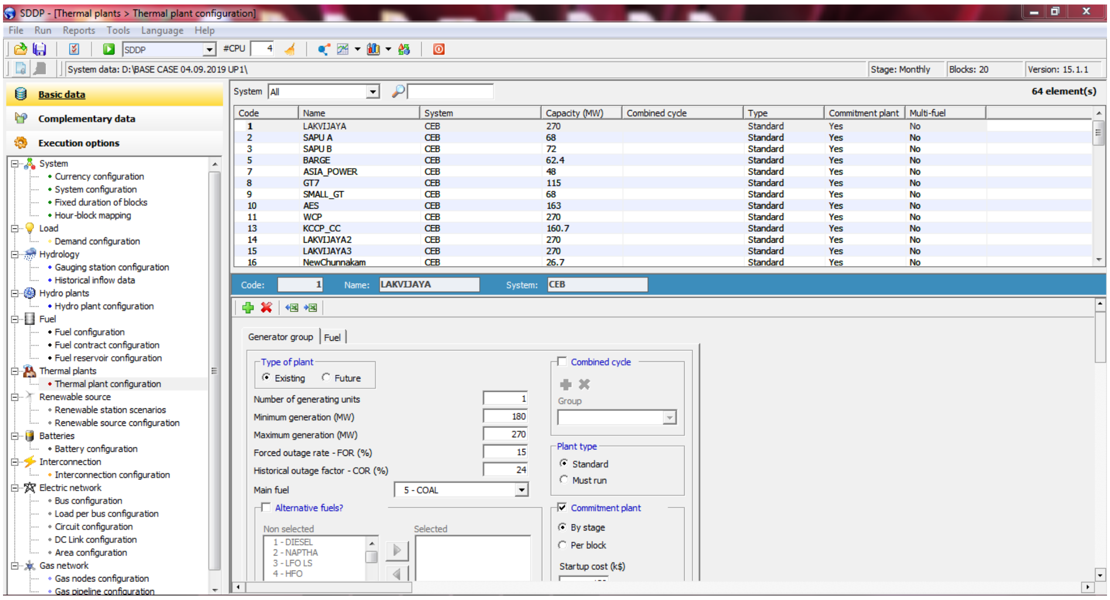


Figure 3.2: A snapshot of the SDDP user interface

3.1.1 Selection of Battery Energy Storage Systems (BESS)

As for the selection of battery storage system, several options were available each with its own pros and cons. For this study, chemical battery storage systems were considered due to its emergence as a stable utility scale storage medium.

Table 3.2 depicts a basic description and pros/cons of the battery options considered for the study.

Table 3.2: Comparison of the battery options considered for the study

Flow Battery	Flow batteries store energy through chemically changing the electrolyte (vanadium) or plating zinc (zinc bromide). Physically, systems typically contain two electrolyte solutions in two separate tanks, circulated through two independent loops, separated by a membrane. Emerging alternatives allow for simpler and less costly designs utilizing a single tank, single loop, and no membrane. The subcategories of flow batteries are defined by the chemical composition of the electrolyte solution; the most prevalent of such solutions are vanadium and zinc-bromide. Other solutions include zinc-chloride, ferrochrome and zinc chromate.
Lead-Acid	Lead-acid batteries date from the 19th century and are the most common batteries; they are low-cost and adaptable to numerous uses (e.g., electric vehicles, off-grid power systems, uninterruptible power supplies, etc.) Advanced Lead-acid battery technology adds ultra-capacitors, increasing efficiency, lifetimes and improve partial state of- charge operability
Lithium-Ion	Lithium-ion batteries have historically been used in electronics and advanced transportation industries; they are increasingly replacing lead-acid batteries in many applications, and have relatively high energy density, low self-discharge and high charging efficiency

	Lithium-ion systems designed for energy applications are designed to have a higher efficiency and longer life at slower discharges, while systems designed for power applications are designed to support faster charging and discharging rates, requiring extra capital equipment

As the Battery Energy Storage Systems (BESS) for this study, lithium-ion technology based Battery System, have been considered. This type of energy storage is suitable for the provision of the ancillary services related to system frequency stability, especially FCR.

The reasoning is found in the fact that the cost of lithium-ion technology has been decreasing in the last years. Moreover, its characteristics, such as fast response, scalability and low self-discharge make it adequate for the provision of frequency reserves.

3.2 Test System Used for the Study and Data Collection

As this study focused on the impact of VRE generation on the operating reserves, the test system selected for the dispatch analysis should contain a considerable annual integration of VRE capacity. Therefore, the capacity composition for 2020-2029 (10 Years) period of CEB's Long Term Generation Expansion Plan (LTGEP) 2018-2037 was selected as the test system for the study.

For Objective 1 of study the following data were required and most of the data was acquired through the Long Term Generation Expansion Plan 2018-2037.

- VRE (Wind and Solar) integration capacities for the study period
- National Load/Demand Data for the study period
- Wind and Solar Measurement Data

3.2.1 VRE (Wind and Solar) integration capacities for the study period:

The VRE capacity forecast for 2020-2029 period of LTGEP 2018-2037 is shown in Figure 3.1. The breakdown of the total figure into the different wind and solar regimes is presented in Table 3.3.

Table 3.3: Cumulative capacity for each Wind and Solar Regime for the study horizon

Year	**Cumulative Capacity in the System (MW)**						
	Wind - Mannar	**Wind-Puttalam**	**Wind-Northern**	**Wind-Eastern**	**Wind-Hill Country**	**Solar-Kilinochchi**	**Solar-Hambanthota**
2018	0	100	40	0	3.8	75	135
2019	0	100	90	0	3.8	125	180
2020	200	120	90	0	3.8	175	235
2021	250	120	115	0	3.8	175	290
2022	300	120	115	0	3.8	175	296
2023	325	140	115	15	3.8	225	301
2024	350	160	115	15	3.8	275	306
2025	375	180	140	30	3.8	275	410
2026	375	180	140	30	3.8	325	415
2027	375	180	165	30	3.8	375	420
2028	375	200	190	30	3.8	375	525
2029	375	200	215	30	3.8	425	529
2030	375	220	265	30	3.8	475	534

As evident from Figure 3.1 and Table 3.2, a considerable capacity of Wind and Solar based power plants are proposed to be integrated to the system during the study horizon. These figures have been taken as the base VRE integration level of the study.

3.2.2 National Load/Demand Data for the study period

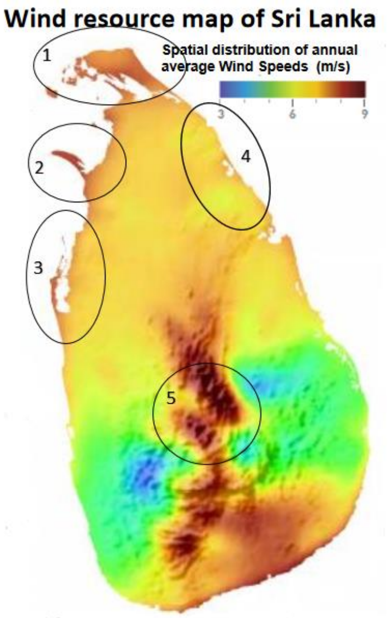
Demand forecast data was extracted from the draft LTGEP 2018-2037 for the period of 2018 to 2037. For the generation planning purposes, projected hourly demand data for 2018 to 2037 has been prepared by taking 2017 as the base year.

A combination of Time Trend modelling and Econometric approach has been adopted by CEB for the preparation of future electricity demand forecast. For the medium term as the first four years, Time Trend modelling has been adopted by capturing recent electricity sales pattern and the growth. For the long term, econometric approach has been adopted by analysing past electricity sales figures with significant independent variables.

For this particular study, hourly demand data from 2020 to 2029 has been used.

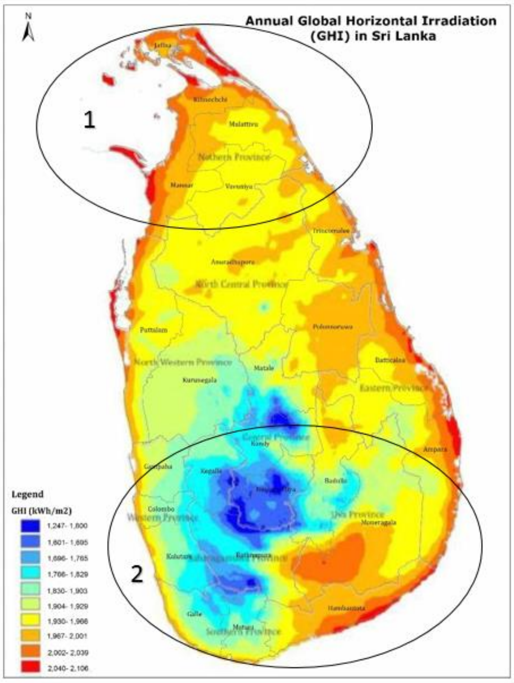
3.2.3 Wind and Solar measurement data

Wind and Solar measurement data was acquired from Sustainable Energy Authority in 10 minute intervals. For the resource estimation purpose, the measurement data was categorized into regimes as follows:



No.	Wind Regime
1	Northern
2	Mannar
3	Puttalam
4	Eastern
5	Hill Country

Figure 3.3: Wind Regimes in Sri Lanka Considered for the Study



No.	Solar Regime
1	Kilinochchi
2	Hambantota

Figure 3.4: Solar Regimes in Sri Lanka Considered for the Study

Wind and Solar contribution is derived from the actual resource profiles given by Sustainable Energy Authority. For the Wind, five regimes (Mannar, Puttalam, Northern, Eastern and Hill Country) were considered (as shown in Figure 3.3) and for the Solar, two regimes (Hambantota and Kilinochchi) (as shown in Figure 3.4) were considered to capture the diversity of the profiles. The annual resource profiles for each regime derived from the raw data are presented below:

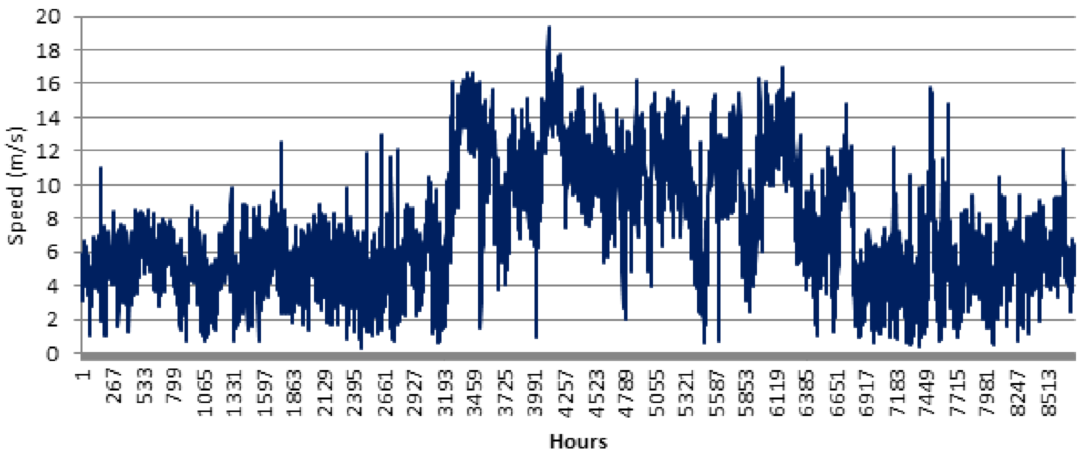


Figure 3.5: Annual Wind Speed Variation in Northern Regime

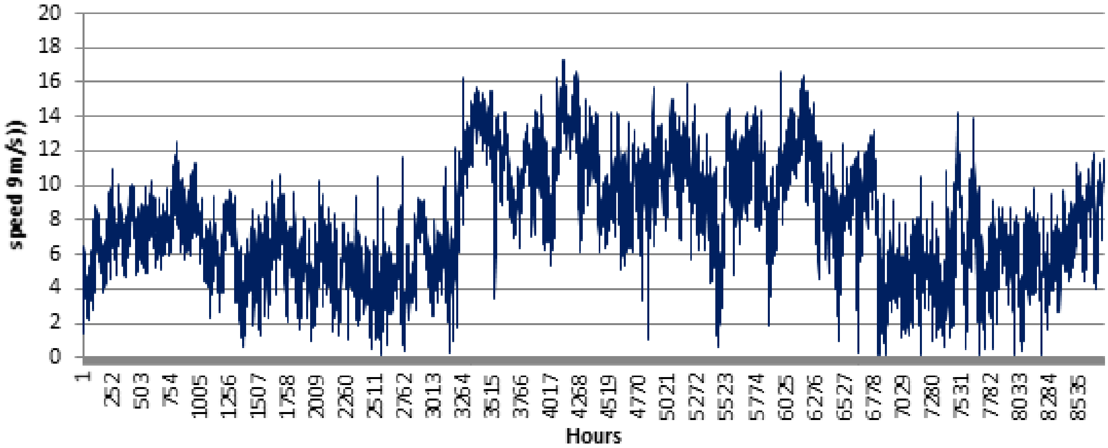


Figure 3.6: Annual Wind Speed Variation in Mannar Regime

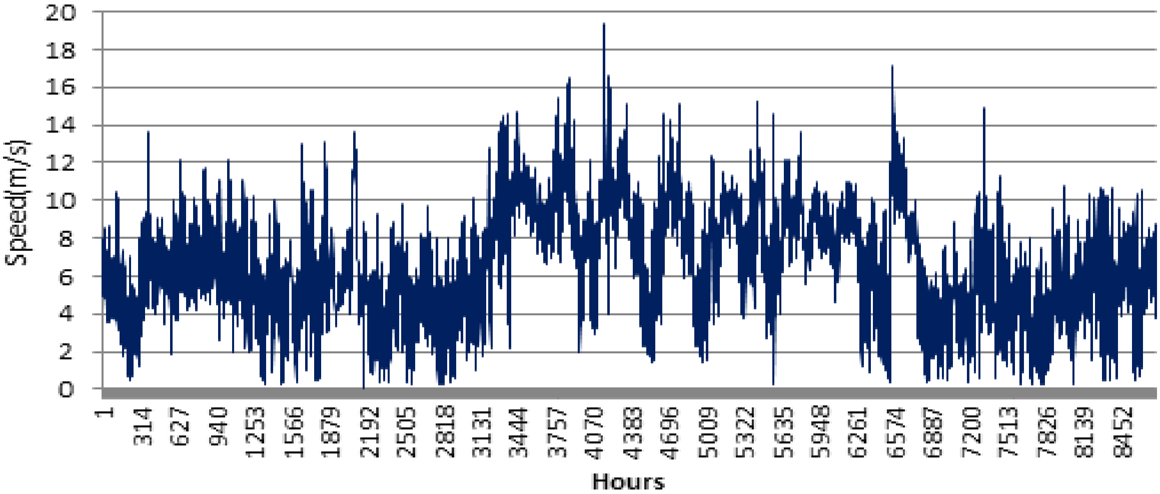


Figure 3.7: Annual Wind Speed Variation in Puttalam Regime

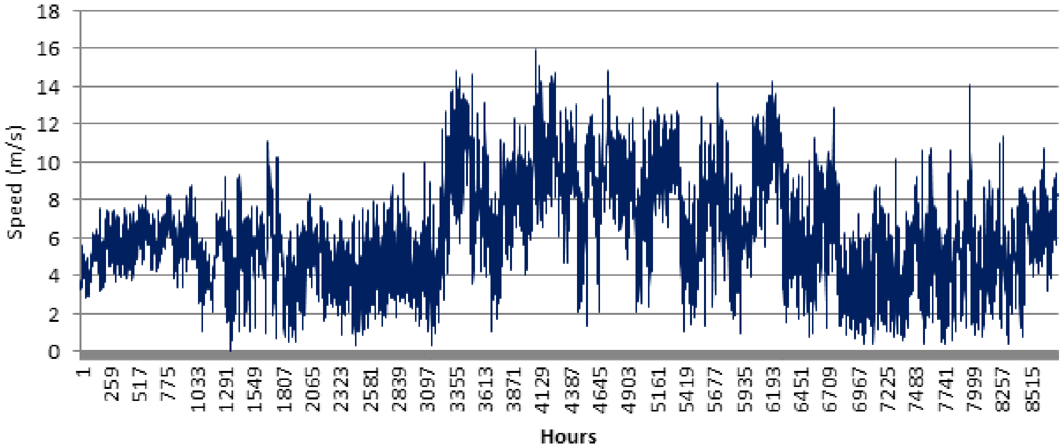


Figure 3.8: Annual Wind Speed Variation in Eastern Regime

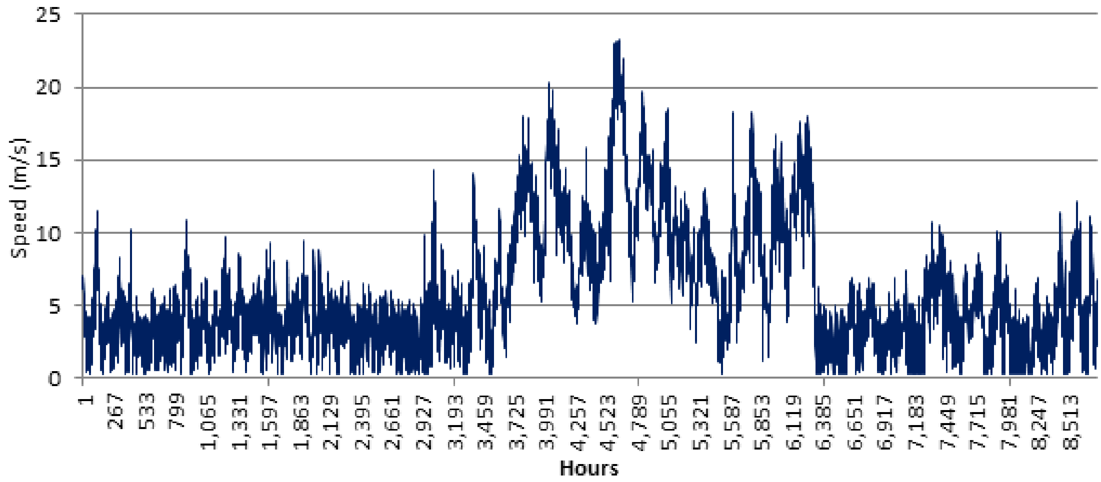


Figure 3.9: Annual Wind Speed Variation in Hill Country Regime

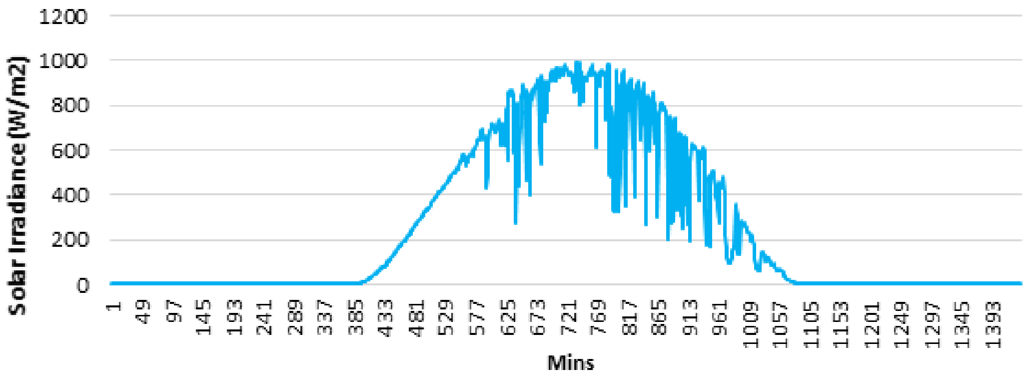


Figure 3.10: Daily Irradiance Variation in a Solar Regime

Figures 3.5 to 3.9 demonstrate the hourly variation of wind speed in a year and the Figure 3.10 shows a typical variation in solar irradiance in a day. Capacity and energy contribution estimation for each technology is explained comprehensively in section 5.6. Based on the resource profiles and the future capacity additions annual hourly Wind and Solar generation profiles were derived for the study horizon of 10 years.

3.2.4 Test System Used for the Study

For the identification of the operating reserve requirement and for the simulation of economic dispatch, the generation system proposed by LTGEP 2018-2037 has been selected. The test years were considered as 2020-2029 and the proposed VRE additions are considered as the base integration level for the study.

Figure 3.11 presents the capacity balance proposed by LTGEP 2018-2037 up to year 2030.

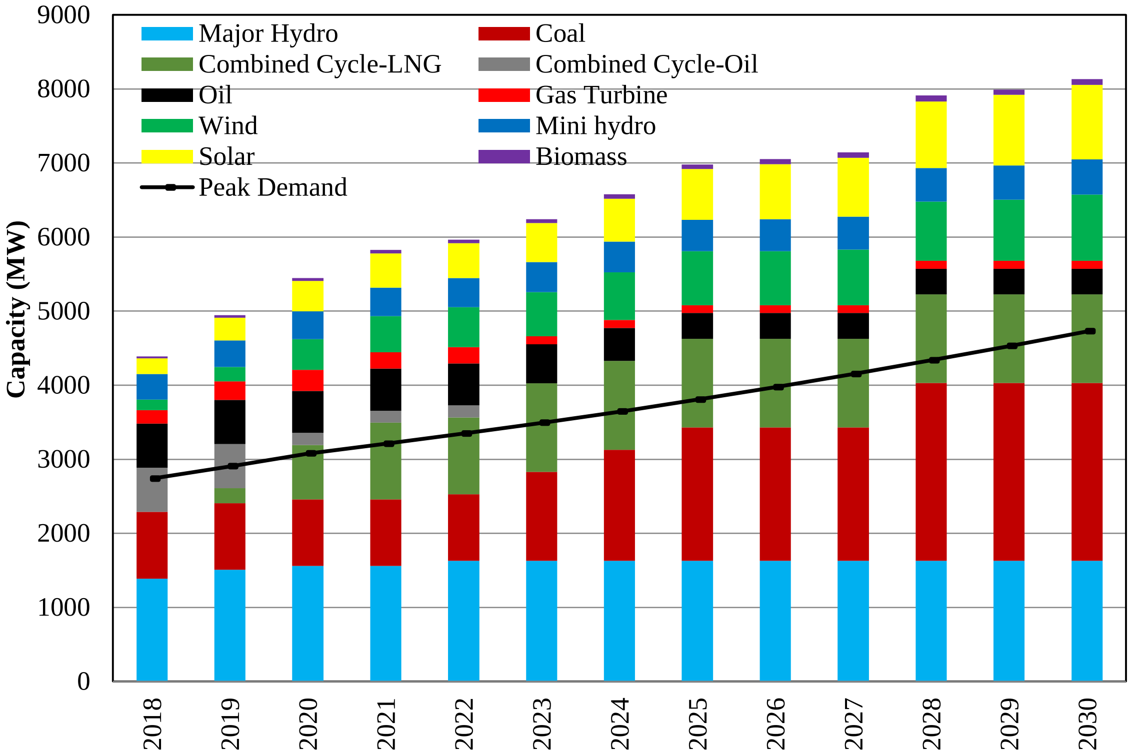


Figure 3.11: Capacity Balance for years 2018-2030 as per LTGEP 2018-2037

3.3 Methodology to Determine the Additional Operating Reserve Requirement due to VRE Integration

The first part of the study was carried out with the objective of identifying the additional spinning reserve capacity needed with the proposed VRE capacity additions to the system in the period of 2020-2030.

From the literature survey, the methodology indicated in Figure 3.12 has been devised to achieve the objective.

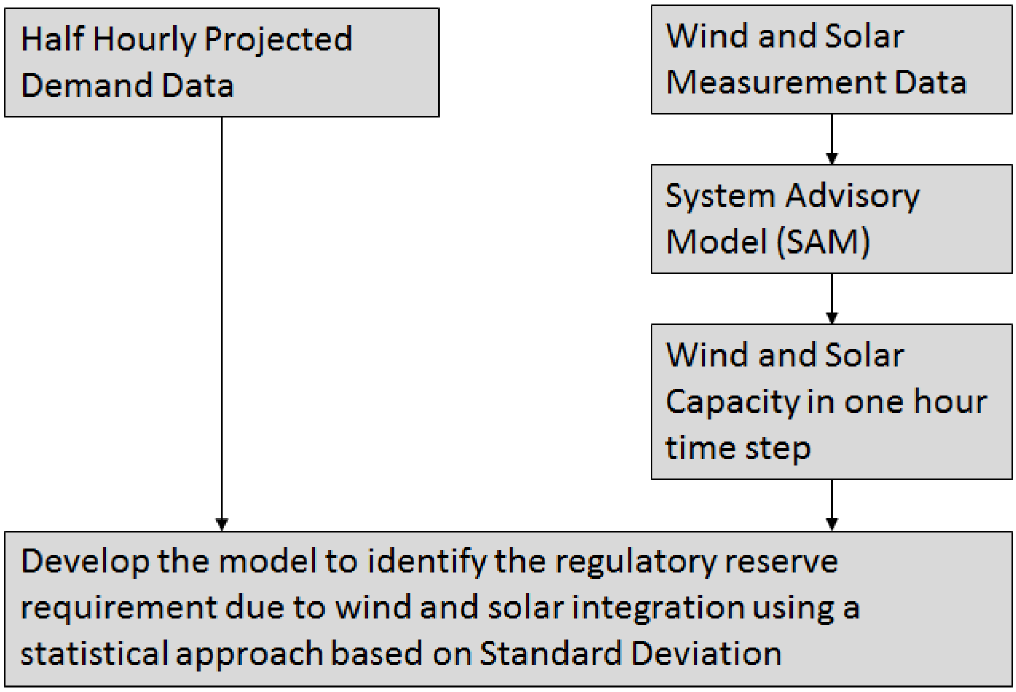


Figure 3.12: Methodology used for identifying the Operating Reserve Requirement

3.3.1 Demand Projection

As explained in Section 3.2.2, during the data collection phase, the hourly load data has been extracted from the Demand forecast data of the LTGEP 2018-2037 for the period of 2018 to 2037.

The load data considered for this study was with hourly time step as it is the resolution which matches the VRE profiles available at present. But the model will be developed with the provision for smaller time steps (if available in future).

3.3.2 Resource Estimation

10 minute wind and solar measurement data obtained from Sustainable Energy Authority was used in developing wind and solar generation profiles for each regime considered.

For this purpose, System Advisory Model (SAM) has been used which is a tool developed by NREL to make performance predictions and cost of energy estimates for grid-connected power projects based on installation and operating costs and system design parameters that the user specify as inputs to the model.

A brief overview of the process that takes place within the tool is presented in Figure 3.13.

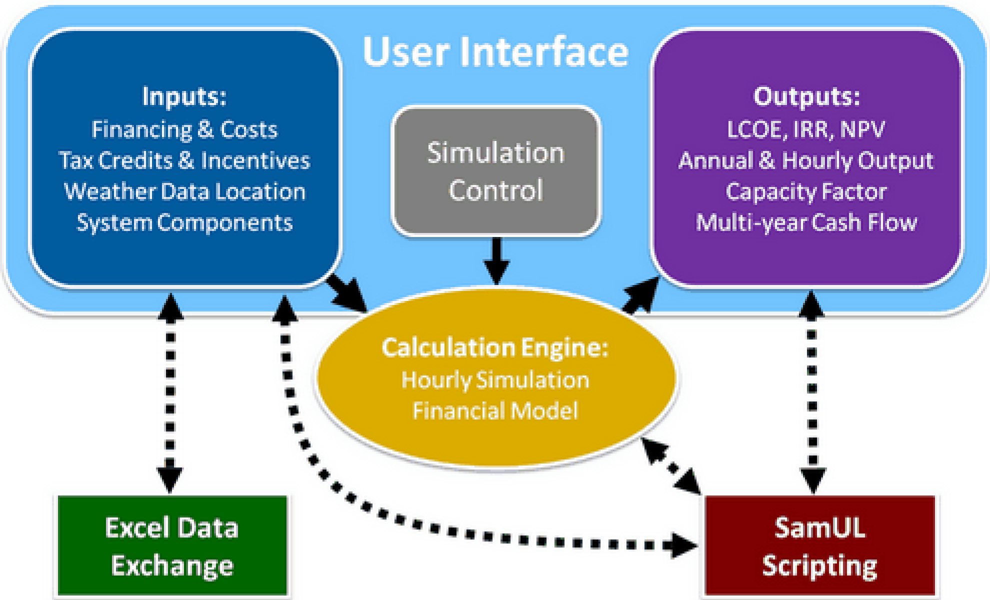


Figure 3.13: Overview of the Process in SAM Tool

As shown in Figure 3.12 several inputs are needed for the hourly simulation of the performance model in SAM. The inputs needed for this study purpose are as follows:

For a Wind Plant Simulation:

- Weather Data specific to the location (For a wind plant, wind speed, wind direction, ambient temperature and atmospheric pressure)
- The wind turbine parameters specifying the turbine power curve and hub height of a single turbine.
- The Wind Farm layout specifying the number of turbines in the project and a simple representation of the wind farm layout to estimate wake effect losses that result when upwind turbines interfere with wind flow to downwind turbines.

For a solar power plant

- Weather Data specific to the location (DNI: Direct normal irradiance, DHI: Diffuse horizontal irradiance and/or GHI: Global horizontal irradiance, temperature, Relative Humidity etc.)
- A model to represent the photovoltaic module's performance
- An inverter performance model with choice of selecting an inverter from a list, or enter inverter parameters from a manufacturer's data sheet using either a weighted efficiency or a table of part-load efficiency values.
- System Sizing variables including number of modules in the system, string configuration, and number of inverters in the system.

3.3.3 Example Resource Estimation for Eastern Wind Regime

As the main input, SAM requires a weather data file describing the renewable energy resource and weather conditions at the project location. For this, the 10 minute measurement data was adjusted as hourly resource data and fed to the model as the main input. A brief snapshot of the input data file of Eastern wind regime is shown in Figure 3.14. In the input data file, hourly wind speed, wind direction, temperature and pressure at a specific height (at this instance 60m) are tabulated.

```
Kokilai,North East,SriLanka,2015,7,81,80,1,8760, SEA
Speed,Direction,Temperature,Pressure
m/s,degrees,C,atm
60,60,60,60
3.429506475,69.9,26.91,1
3.6183878225,90.3,26.76,1
3.732961575,82.65,26.65,1
3.3476125025,88.75,26.42,1
3.546219975,73.75,26.39,1
3.3036504175,77.95,26.26,1
3.3915745875,74.6,26.26,1
4.264008,78.65,26.3,1
4.297076825,76.1,26.78,1
4.2173226,79.85,27.23,1
3.5012852775,104.65,27.25,1
4.2603120725,92.7,27.6,1
4.43907825,99.05,27.85,1
4.01112875,90.55,27.91,1
4.62581985,100.3,27.78,1
5.242456175,105.6,28.02,1
5.586761,114.7,28.38,1
5.42725255,114.65,28.5,1
5.557582625,111.7,27.88,1
5.296922475,110.85,27.54,1
5.475883175,105.55,27.31,1
5.2366205,98.1,27.27,1
4.744478575,101.5,27.03,1
5.1432497,101.75,26.9,1
4.748369025,94.35,26.78,1
4.12006135,98,26.54,1
4.3729406,89.8,26.4,1
4.806725775,76.95,26.45,1
```

Figure 3.14: A Snapshot of the Input Resource Data File to SAM Tool

After the location specific weather data has been fed to the model, the next step requires specifying wind turbine parameters for the selected wind plant. For Eastern wind regime, 20 MW Wind power plant is modeled with Gamesa G90 - 2.0 MW wind turbines for which the parameters are built in to the SAM tool. The rated power of this turbine is 2000kW and the turbine power curve is shown in Figure 3.15.

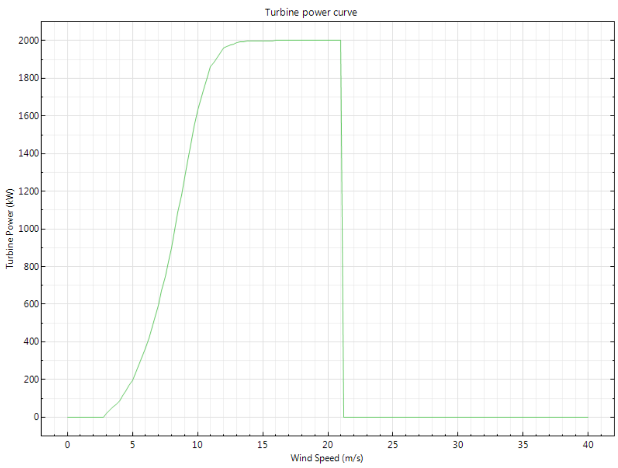


Figure 3.15: Wind Turbine Power Curve for Gamesa G90 - 2.0 MW

Next step was to specify a wind turbine layout . A typical layout was provided to the model corresponding to the wind plant capacity of 20MW. The layout for the Eastern model wind plant is presented in Figure 3.16.

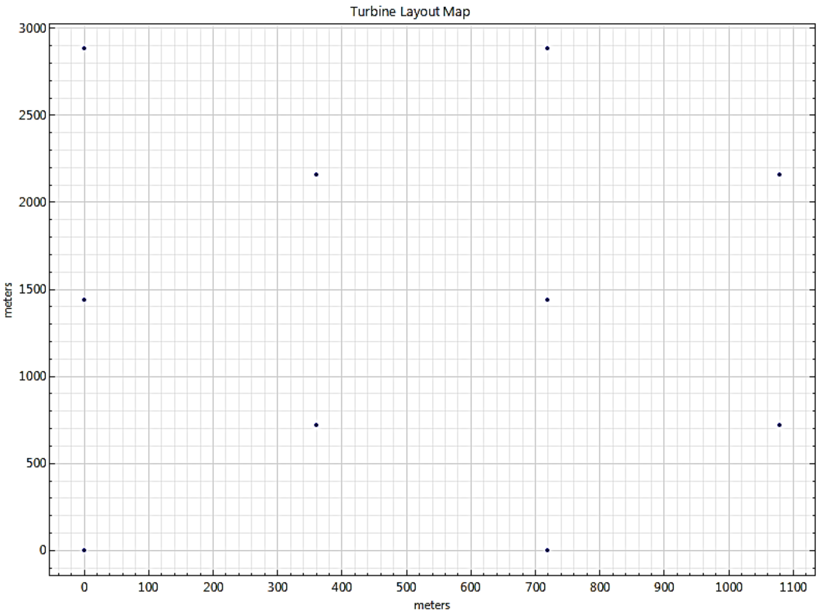


Figure 3.16: Proposed Plant Layout for 20MW Eastern Wind Power Plant

After all the required input data is fed to the model, SAM's performance module runs the simulation making hour-by-hour calculations of wind plant's electric output, generating a set of 8,760 hourly values that represent the plant's electricity production over a single year.

Simulation results provide the plant's performance characteristics in detail through tables and graphs of the hourly and monthly performance data, or performance metrics such as the system's total annual output and capacity factor for more general performance evaluations.

The input wind measurement data and the resultant simulation result of hourly wind plant output for the Eastern wind regime is presented in Figure 3.17(a) and 3.17(b).

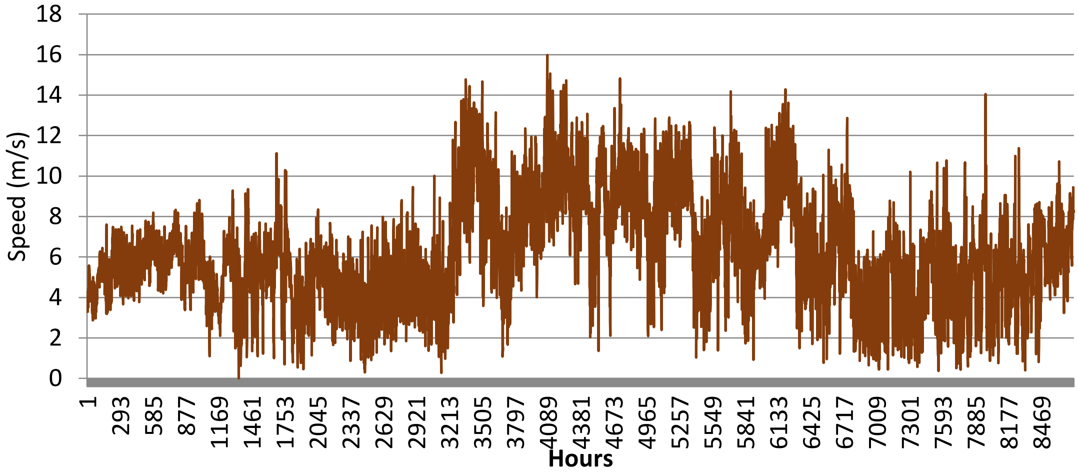


Figure 3.17(a): Annual Wind Speed Variation in Eastern Regime (Input)

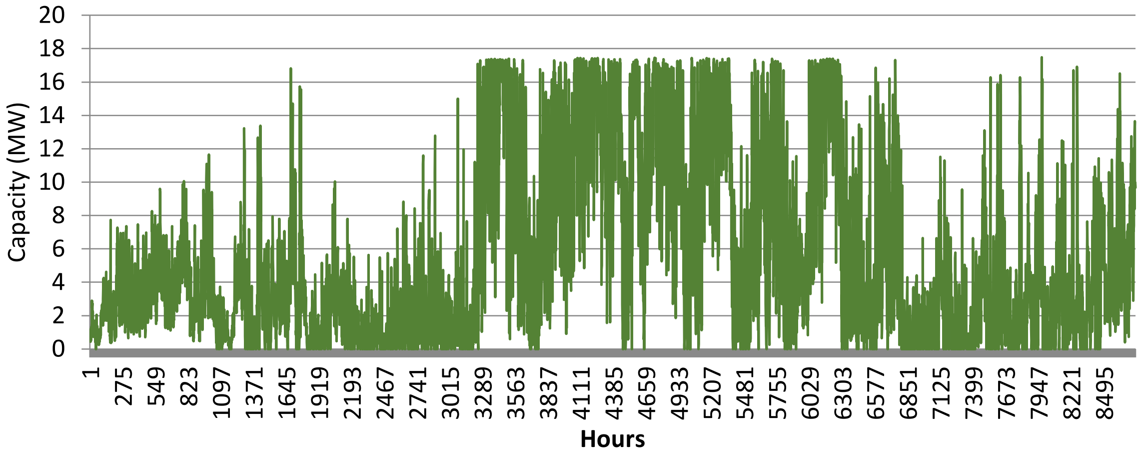


Figure 3.17(a): Annual 20MW Wind Power Plant Capacity Variation in Eastern Regime (Output)

Similar to the example, the annual resource profiles for all the wind regimes and solar regimes were obtained through the performance module of SAM tool. The annual resource profiles of other four wind regimes and two solar regimes are shown in Annex 1.

3.4 Developing the model to determine the operating reserve capacity requirement due to VRE integration

As explained in Section 3.1, the Statistical Approach Based on Sigma (Standard Deviation) was selected to determine the spinning reserve requirement and the basic overview of the method adopted to determine the reserve requirement for a specific test year is as shown in Figure 3.18.

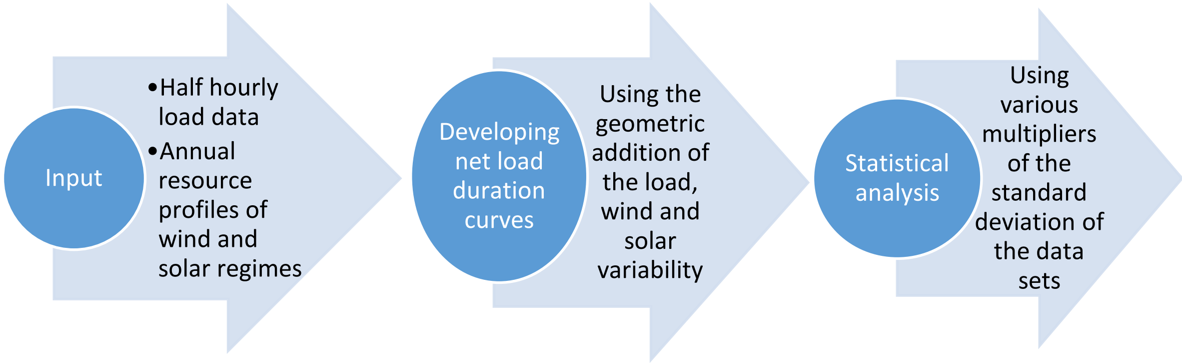


Figure 3.18: Methodology to determine the Operating Reserve Requirement using Standard Deviation Method

After all the input data has been finalized, the next step was to develop the load duration curves and net load duration curves to identify the variations in VRE generation.

From projected demand data, load curves could be developed and by subtracting the VRE capacity profiles from load curves, net load curves could be established. A sample load curve and netload curve for a period of 3 consecutive days in 2030 is shown in Figure 3.19.

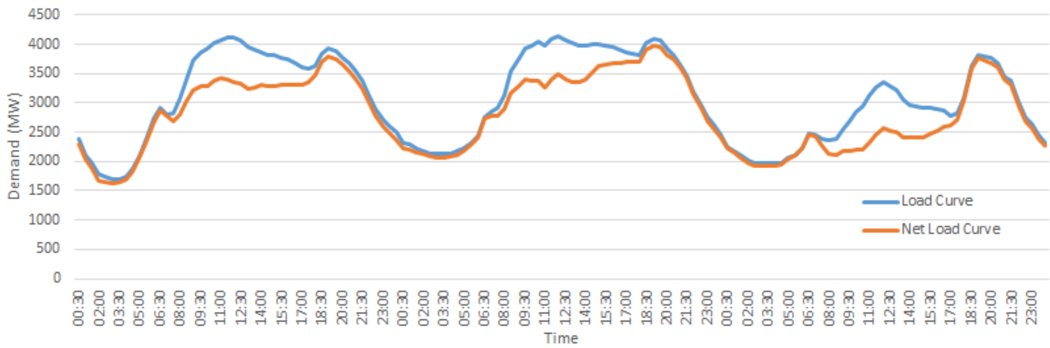


Figure 3.19: Load Curve and Net Load Curve for Consecutive 3 days in 2030

To determine the variations in the load and net load curves, respective duration curves were developed with the time series data available. The process followed in establishing the duration curves is as follows:

- Development of the half hourly load variations using the demand projection data obtained as input.

$$\Delta L_i = L_i - L_{i-1} \qquad (3.1)$$

(L_i = Projected load for the ith hour)

- From hourly capacity variations for each wind and solar regime blocks:
    - Developed half hourly capacity variations in per unit values using an average of two hours
    - Determined the half hourly variations of the total wind and solar capacity in the system for the corresponding year

$$\Delta P_i = P_i - P_{i-1} \qquad (3.2)$$

(P_i = Total capacity from wind and solar plants for the ith hour)

- Using the above two series of variations:
    - Developed the net load variations to capture the reserves needed due to the integration of wind and solar

$$NL_i = L_i - P_i \qquad (3.3)$$

$$\Delta NL_i = NL_i - NL_{i-1} = (L_i - P_i) - (L_{i-1} - P_{i-1}) \qquad (3.4)$$

(NL_i= Projected net load for the ith hour)

The snapshot of the model which developed to compute the Load and Net Load variations is shown in Figure 3.20. In the model, for a specific year, the load data, hourly capacities for wind and solar regimes for all 8760 hours are considered.

2030			Cumulative Capacity in the System (MW)							Total Wind and Solar (MW)	Wind and Solar Capacity Variation(MW)		
			375	220	265	30	3.8	475	534.4546				
			Annual Profile in pu Values										
Time	Load Data (MW)	Load Variation (MW)	Wind - Mannar	Wind-Puttalam	Wind-Northern	Wind-Eastern	Wind-Hill Country	Solar-Kilinochchi	Solar-Hambanthota			Net Load (MW)	Net Load Variation (MW)
1	2278		0.00	0.24	0.07	0.03	0.15	0.00	0.00	72.82		2205.18	
2	1958	-320	0.00	0.40	0.06	0.03	0.11	0.00	0.00	105.22	32.40	1852.78	-352.40
3	1692	-266	0.00	0.31	0.05	0.03	0.16	0.00	0.00	82.96	-22.26	1609.04	-243.74
4	1692	0	0.00	0.17	0.05	0.03	0.10	0.00	0.00	51.93	-31.03	1640.07	31.03
5	1699	7	0.00	0.10	0.05	0.03	0.03	0.00	0.00	36.26	-15.67	1662.74	22.67
6	1816	117	0.04	0.16	0.02	0.02	0.00	0.00	0.00	56.10	19.84	1759.90	97.16
7	1963	147	0.02	0.14	0.02	0.02	0.03	0.00	0.00	44.31	-11.79	1918.69	158.79
8	1902	-61	0.07	0.13	0.03	0.05	0.01	0.12	0.16	206.85	162.54	1695.15	-223.54
9	1947	45	0.06	0.13	0.09	0.06	0.01	0.32	0.39	437.23	230.37	1509.77	-185.37
10	2215	268	0.04	0.19	0.08	0.06	0.04	0.46	0.59	613.78	176.55	1601.22	91.45
11	2436	221	0.01	0.22	0.13	0.03	0.01	0.44	0.67	654.62	40.84	1781.38	180.16
12	2545	109	0.01	0.34	0.13	0.05	0.00	0.54	0.67	729.08	74.46	1815.92	34.54
13	2494	-51	0.04	0.42	0.10	0.07	0.00	0.49	0.65	716.15	-12.94	1777.85	-38.06
14	2268	-226	0.02	0.40	0.09	0.05	0.01	0.33	0.59	592.97	-123.18	1675.03	-102.82
15	2160	-108	0.03	0.41	0.12	0.07	0.01	0.29	0.48	529.68	-63.29	1630.32	-44.71
16	2144	-16	0.14	0.50	0.09	0.11	0.03	0.21	0.31	455.19	-74.48	1688.81	58.48
17	2028	-116	0.14	0.49	0.15	0.14	0.01	0.15	0.10	328.98	-126.21	1699.02	10.21
18	2006	-22	0.10	0.37	0.16	0.14	0.00	0.04	0.01	189.84	-139.14	1816.16	117.14
19	2773	767	0.07	0.27	0.21	0.14	0.00	0.00	0.00	145.50	-44.34	2627.50	811.34
20	3206	433	0.10	0.19	0.17	0.13	0.00	0.00	0.00	128.25	-17.25	3077.75	450.25
21	3191	-15	0.12	0.27	0.15	0.13	0.00	0.00	0.00	148.05	19.80	3042.95	-34.80
22	3026	-165	0.12	0.24	0.13	0.12	0.00	0.00	0.00	135.85	-12.20	2890.15	-152.80

Figure 3.20: Snapshot of the MS Excel Model used to Determine Net Load Variations

From the above mentioned process, net load curves for each year is shown in Figure 3.21. The effect from increased variability of VRE can be observed when comparing the net load with the original load duration curves:

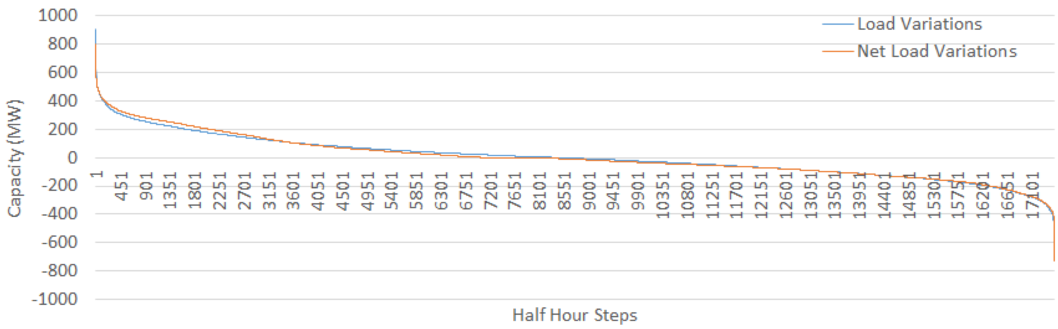


Figure 3.21: Load and Net Load Variations in a Sample Year

In Figure 3.21, the amount of hourly variations that the system sees is depicted showing one year of data in decreasing order (duration curve). There are two curves, the load variations without VRE and load variations together with VRE (the hourly variations of net load). The difference in the maximum values of capacity of variations with and without VRE indicates the amount that the operating reserve capacity must be increased. The same capacity can in principle be used for both up and down regulation, and variations as well as the increase should essentially be symmetrical. Either up or down (positive or negative) variations can determine a need for an increase in the reserves.

Planning a power system is based on probabilities and risk. Operating reserves in the power system – with or without VRE – are generally determined so that variability within a certain probability are covered, for example 99.99 % of the variability. For this study purpose also, the variability is kept within a specified probability level.

For a normally distributed probability distribution, the standard deviation σ is a measure indicating that about 68 % of the data is inside ±σ of the mean value. Taking a range of ±3σ will cover 99 %, and ±4σ will cover 99.99 % of all variability.

For hourly variations, the mean value is 0 by definition. The graphical representation is shown in Figure 3.22.

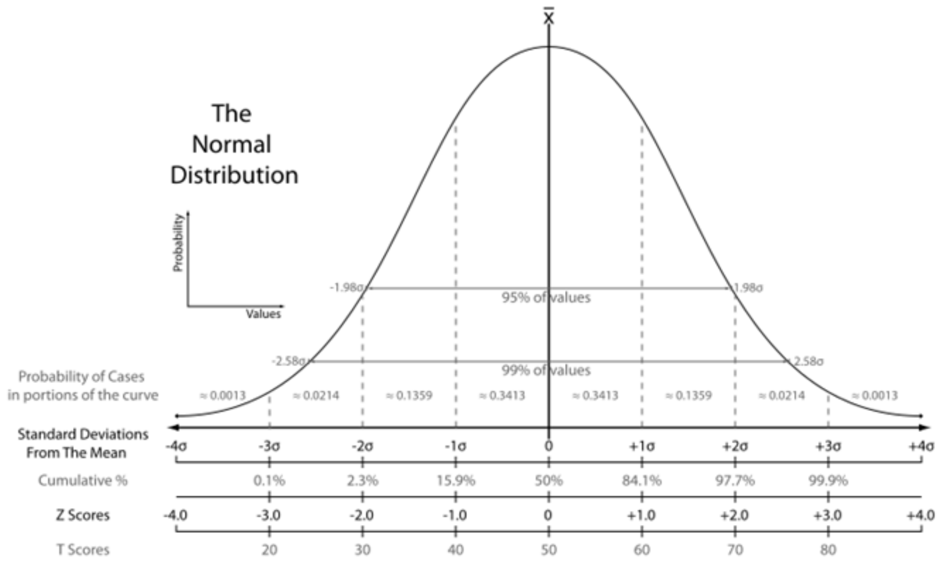


Figure 3.22: Standard Deviation Range of a Normal Distribution

The standard deviation (σ) of a time series presents the variability of the time series; it denotes the average deviation from the mean value of the series (μ):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}} \qquad (3.5)$$

When the load variations and net load variations were considered mainly two reserve categories could be identified:

1. Reserve Requirement due to Load Variations
2. Reserve Requirement due to Wind and Solar Generation Variations

The additional reserve requirement from wind and solar additions need to be identified separately from load variations. For this purpose, an equation has been derived in the study, "Using Standard Deviation as a Measure of Increased Operational Reserve Requirement for Wind Power" by Hannele Holttinen, Michael Milligan, Brendan Kirby, Tom Acker, Viktoria Neimane, and Tom Molinski.

Assuming the load variations and wind/solar variations are uncorrelated, the following equation extracted from the aforementioned study has been used for the net load variation as the variation does not follow a normal distribution:

$$\boldsymbol{\sigma_{NL} = \sqrt{{\sigma_L}^2 + {\sigma_P}^2}} \tag{3.6}$$

Standard Deviation of Load Variations= σ_L

Standard Deviation of Wind and Solar Variations = σ_P

Standard Deviation of Net Load Variations = σ_{NL}

To identify the additional reserve requirement due to wind and solar additions, the same reference study has derived the following equation (As 4σ would cover 99.99% of variations in a normal distribution):

$$\boldsymbol{Reserve(R) = 4(\sigma_{NL} - \sigma_L)} \tag{3.7}$$

The results pertaining to Objective 1 in this study is discussed in detail in Chapter 4.

3.5 Techno Economic Comparison of Providing Operating Reserves with Thermal Generators vs. Utility Scale Battery Storage

This analysis constitutes for the principal part of this particular study and the methodology was derived based on an hourly generation dispatch model which could simulate the economic dispatch of generation units in hourly time scale in order to identify the behaviour of power plants in supplying the operating reserves of the system.

For the simulation of economic dispatch in consideration with hydro-thermal coordination, CEB currently uses Stochastic Dual Dynamic Programming (SDDP) and for this study also, the same tool has been used to simulate the generation dispatch of the study horizon on hourly time scale.

Development of the Model for Power System Using Stochastic Dual Dynamic Programming (SDDP):

The dispatch model for the Sri Lankan power system was developed using the Stochastic Dual Dynamic Programming (SDDP) tool to compare the use of conventional generators and utility scale battery storage to maintain the required level of generation capacity reserves in economic and technical perspective to facilitate the projected VRE integration to the system.

A basic overview of the process in the SDDP tool is presented in Figure 3.23.

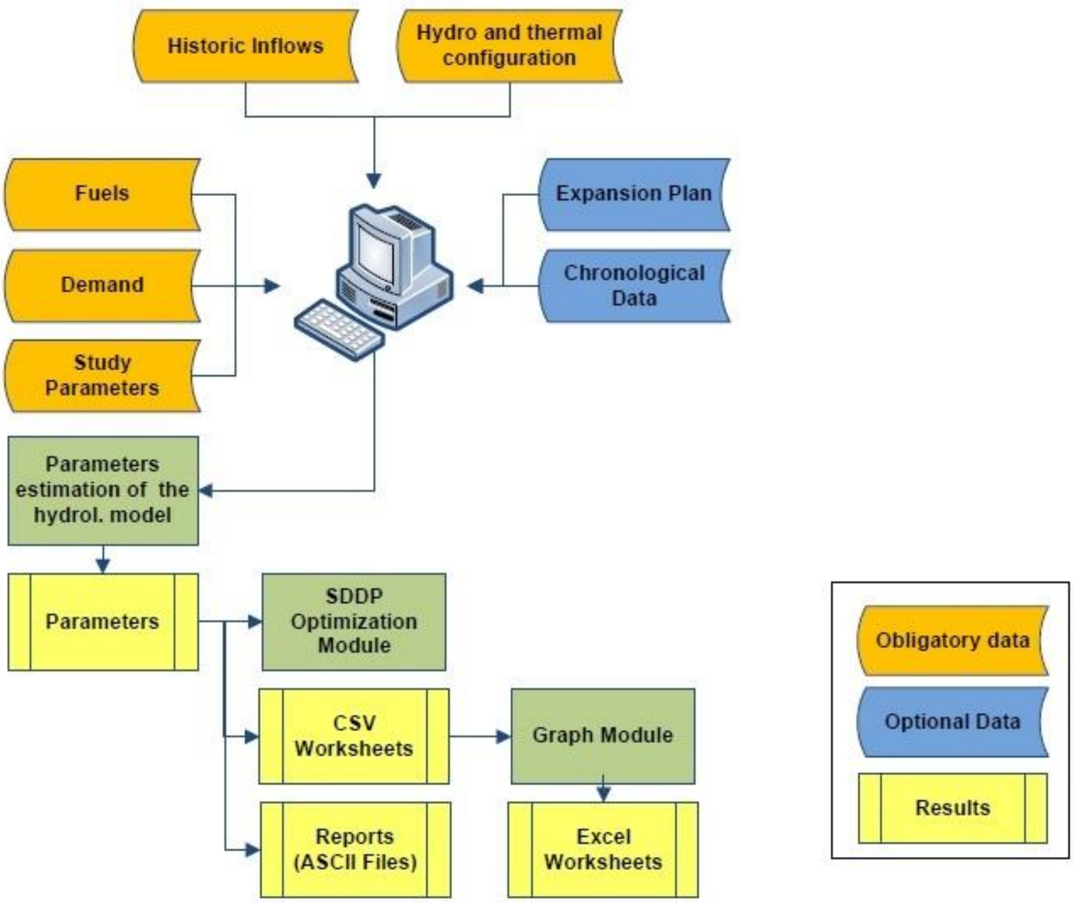


Figure 3.23: Process Diagram for SDDP

SDDP is a hydrothermal dispatch model with representation of the transmission network used for short, medium and long term operation studies. The model was used to simulate the hourly dispatch in consideration with the least-cost stochastic operating policy of the hydrothermal system of the country, taking into account the following inputs as shown in Figure 3.23:

- Operational details of hydro plants (water balance, limits on storage and turbine outflow, spillage, filtration etc.)
- Detailed thermal plant modelling (unit commitment, "take or pay" fuel contracts, concave and convex efficiency curves, fuel consumption constraints, multiple fuels etc.)
- Renewable resource profiles and associated renewable generation plant modelling

- Modelling of fast response energy storage devices connected to the grid considering hourly time steps.
- Load variation per load level, with hourly levels

The developed model was mainly used to identify the dispatch patterns of the conventional generators (For this particular study, Combined Cycle Power Plants) when assigned to provide the Operating Reserves and the effect of utility scale batteries on the provision of operating reserves by conventional thermal power plants.

In developing the dispatch model using SDDP tool, the following aspects were taken into account:

1. As SDDP Model was used to determine the hourly dispatch forecast for the power plants in the power system, all thermal, hydro and renewable power plants were modelled using the parameters specified in LTGEP 2018-2037
2. The economic analysis was carried out with a time horizon of 10 years. As dispatch results are a main input to the economic analysis, the dispatch study was carried out for the time horizon of 2020-2029 (10 Years) by running the SDDP model.
3. Methodology adopted in developing the base model:
   - ✓ All the thermal, hydro and renewable additions in the 2020-2029 horizon were kept as same as the LTGEP 2018-2037
   - ✓ For the study purpose, only combined cycle plants were assigned to provide operating reserve (including regulating reserves) requirement of the system.
   - ✓ Alternative scenarios were developed with combined cycle power plants released from providing operating reserves and battery storage included to provide reserves.

Scenario 1	Scenario 2	Scenario 3
• Model ***without*** assigning Operating Reserves from Combined Cycle Power Plants	• Base Model ***with*** assigning Operating Reserves from Combined Cycle Power Plants	• Alternative Model ***with*** assigning Operating Reserves from Battery Storage

Scenario 1 – Only major hydro power plants and other thermal generators such as gas turbines, reciprocating engines were assigned to provide operating reserves

Scenario 2 – Only combined cycle power plants were assigned to provide operating reserves

Scenario 3 – Only battery storage and major hydro power plants were assigned to provide operating reserves

In addition to the above scenarios, specific models were developed to study the sensitivities of the alternative model which would be discussed in the economic analysis.

1. The following Combined Cycle Power Plants were assigned to provide Operating Reserves in the study horizon:
   - ✓ 300 MW Combined Cycle Power Plant in 2020
   - ✓ 300 MW Combined Cycle Power Plant in 2021
   - ✓ Existing Combined Cycle Power Plants in the System (Kelanitissa, West Coast and Sojitz Kelanitissa)
2. Batteries were introduced in phases as per the indicated schedule in Table 3.4. (In line with the identified Operating Reserve requirement from Objective 1)

Table 3.4: Phase Development of Batteries (Capacity and Energy)

Year	Capacity (MW)	Energy (MWh)
2020	20	40
2021	30	60
2022	40	80
2023	50	100
2024	60	120
2025	70	140
2026	80	160
2027	90	180
2028	100	200
2029	110	220

Results from the dispatch analysis are discussed in detail in Section 4.

3.6 Economic Analysis of Providing Operating Reserves with Thermal Generators Vs. Utility Scale Battery Storage

In assessing the economic values of a project, the most commonly adopted approach is cost-benefit analysis (CBA). In this study, CBA was carried out to address the economic benefits of adding energy storage to the entire power system. It focused on the direct and indirect impacts of energy storage on the power system through providing operating reserves to the system compared to conventional thermal generators.

3.6.1 Cost Estimation

For a battery storage system, there are two main cost categories namely the Capital costs and O&M costs. Capital costs include the costs of purchasing battery cells and packs, hardware costs (such as inverters), soft costs (such as industry education, licensing fees and labour costs and the engineering, procurement, and construction (EPC) costs). These expenditures usually happen at the beginning of the project.

O&M costs usually happen during the whole life cycle of the project. It includes upkeep costs (inspection and maintenance, spare parts, facilities costs, insurance) and electricity purchasing (costs to charge the battery).

Charging cost is the most significant O&M cost. Batteries need to be charged before they can release energy back to the grid. Therefore, energy input is necessary from other sources which can be either the grid supply or purpose build battery charging resources. Charging cost relates to the cost of purchasing electricity and is estimated as the product of the amount of energy input and the price the unit of energy input.

3.6.2 Benefit Estimation

Benefits are usually classified into two main categories: market-based and non-market-based. Market-based benefits depend on the services that the battery system provides. In this specific study, the reduction in generation cost of the conventional thermal generators in providing operating reserves was considered as the principal benefit.

3.6.3 Output Indicators

Several output indicators are used to compare cost with benefit, such as net present value, benefit-cost ratio and payback period.

- Net present value (NPV)

NPV represents a summary of net benefits (differences between benefits and costs) in each specific period (monthly; quarterly; yearly). It is usually estimated as follows:

$$\mathrm{NPV} = -C_0 + \frac{C_1}{(1+r)} + \frac{C_2}{(1+r)^2} + \ldots + \frac{C_t}{(1+r)^t} \qquad (3.8)$$

where:

C_0 is the initial investment;

C_1 is the net cash flow in period 1;

C_2 is the net cash flow in period 2;

C_t is the net cash flow in period t;

r is the discount rate (the rate used to discount future cash flows to the present value).

- Benefit-cost ratio (BCR)

BCR summarizes the overall value of a project. It is calculated as the NPV of benefits divided by the NPV of total costs. If the BCR value is greater than 1, then the project can derive a positive benefit.

- Payback Period

Payback period is used to illustrate the time required for total benefits to outweigh total costs. If there is only one option, the calculated payback period can be compared with expected payback period to determine if the project is within the expectation in terms of return. With multi-choices, the shorter the payback period, the more profitable the project is.

3.6.4 Input Values and Assumptions for Cost Benefit Analysis:

The input values for Utility Scale Battery Storage used to carry out the economic analysis are tabulated in Table 3.5. These values were primarily extracted from Lazard's Levelized Cost of Storage Analysis[1].

Table 3.5: Input Parameters of Utility Scale Battery Storage

	Value	Unit
Power Capacity (Initial)	10	MW
Energy Capacity (Initial)	20	MWh
System Efficiency	90	%
Discount Rate	10	%
Project lifetime	10	Years
Power Conversion System cost[1]	1,519	USD/kW

Storage section costs[1]	380	USD/kWh
Fixed O&M cost[1]	3	% of Capital Cost
Depreciation	Straight Line Method	
Disposal and Recycling cost	20	% of Capital Cost

3.6.5 Basic Cost and Benefit Components used for the Analysis:

Cost/Benefit Factor	Major Contributor
Profit and Savings	Annual Cost Reduction from Combined Cycle Operation
Investment Cost	Cost of Storage, Cost of Power Conversion System, Cost of Balance System
Operational Cost	Maintenance Cost of Batteries, Charging Cost related to providing reserves
Disposal and Recycling Cost	Disposal Cost for Batteries at the end of lifetime, Recycling of usable batteries and other related components

3.6.6 Basis for calculating the annual cost reduction and the charging cost:

SDDP model output contains the hourly dispatch and operating cost of Combined Cycle Power Plants. Upon studying the output, a set of equations were derived to determine the primary benefit of introducing battery storage to replace thermal plants in operating reserves and to identify the charging cost of batteries related to this specific purpose.

Annual Cost Reduction:

$$\text{Annual Cost Reduction} = \sum_{i=1}^{8760}(CT_i - CB_i) \qquad (3.9)$$

Where:

CT_i is the operational cost with reserves from thermal generators in i^{th} hour;

CB_i is the operational cost with reserves from battery storage in i^{th} hour;

Battery Charging Cost:

$$\text{Battery Charging Cost} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{8760}} (\boldsymbol{DR_i} \times \boldsymbol{MC_i}) \qquad (3.10)$$

Where:

DR_i is the dispatch reduction of thermal generators providing operating reserves in i^{th} hour;

MC_i is the marginal cost of battery storage in i^{th} hour

4. RESULTS

4.1 Variation of the Required Reserve Capacity with the Level of Wind and Solar Integration (Objective 1)

The study horizon for this study was 2020-2029 (10 years) and for each year the approximate operating reserve capacity requirement was determined with the methodology discussed in detail in Section 3.3.

An example of estimating the increase in hourly variability could be seen by the distribution plot of the hourly load and net load variations for year 2029 as indicated in Figure 4.1. It could be observed that the plot follows approximately a normal distribution and this is observable for all the years in the study horizon. As this study focuses only on an approximation of the reserve requirement, the statistical approach based on standard deviation was used both for upward and downward reserve calculation as discussed in detail in Section 3.3.

By considering the standard deviation of the distributions for this particular sample year, there is a difference of 66 MW in the 4σ coverage of the variability (1058-997 MW).

$$4\sigma_L = 997 \text{ MW}$$

$$4\sigma_{NL} = 1{,}058 \text{ MW}$$

$$\text{Additional Reserve Requirement} = 4(\sigma_{NL} - \sigma_L) = 61 \text{ MW}$$

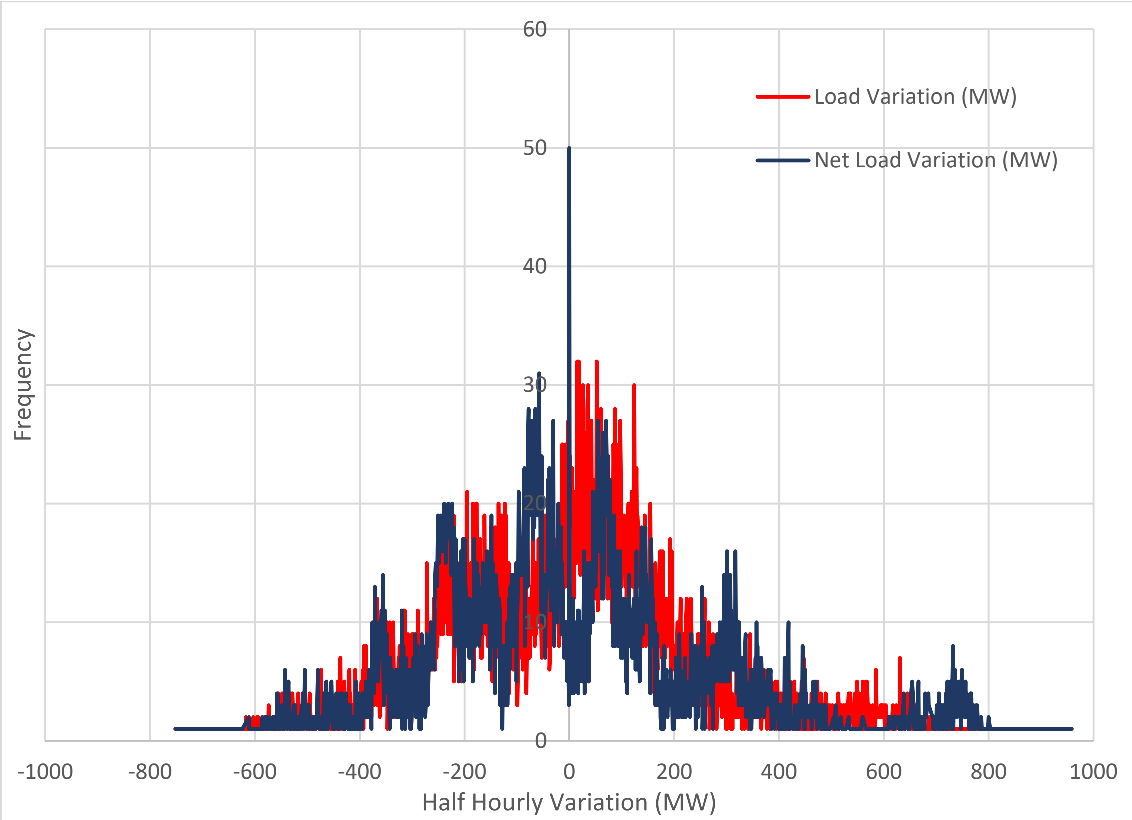


Figure 4.1: Frequency Distribution Plot of Hourly Load and Net Load Variation for Year 2029

The same method was used to determine the additional reserve capacity requirement due to integration of VRE for all the years in the study horizon. The resultant additional reserve capacity together with the total VRE capacity of the corresponding year is tabulated in Table 4.1.

Table 4.1: Variation of Additional Reserve Capacity Requirement due to VRE Integration

Year	Required Additional Reserve Capacity (MW)	Total Wind and Solar Capacity (MW)	Percentage of Reserve Capacity as a Share of Total Wind & Solar
2020	17.7	823.51	2%
2021	22.25	953.83	2%
2022	23.21	1,009.79	2%
2023	26.88	1,124.41	2%
2024	30.72	1,224.67	3%
2025	40.42	1,413.94	3%
2026	43.21	1,469.20	3%
2027	47.22	1,548.46	3%
2028	57.84	1,698.73	3%
2029	61.48	1,777.99	3%
2030	66.07	1,903.25	3%

The results are graphically represented in Figure 4.2.

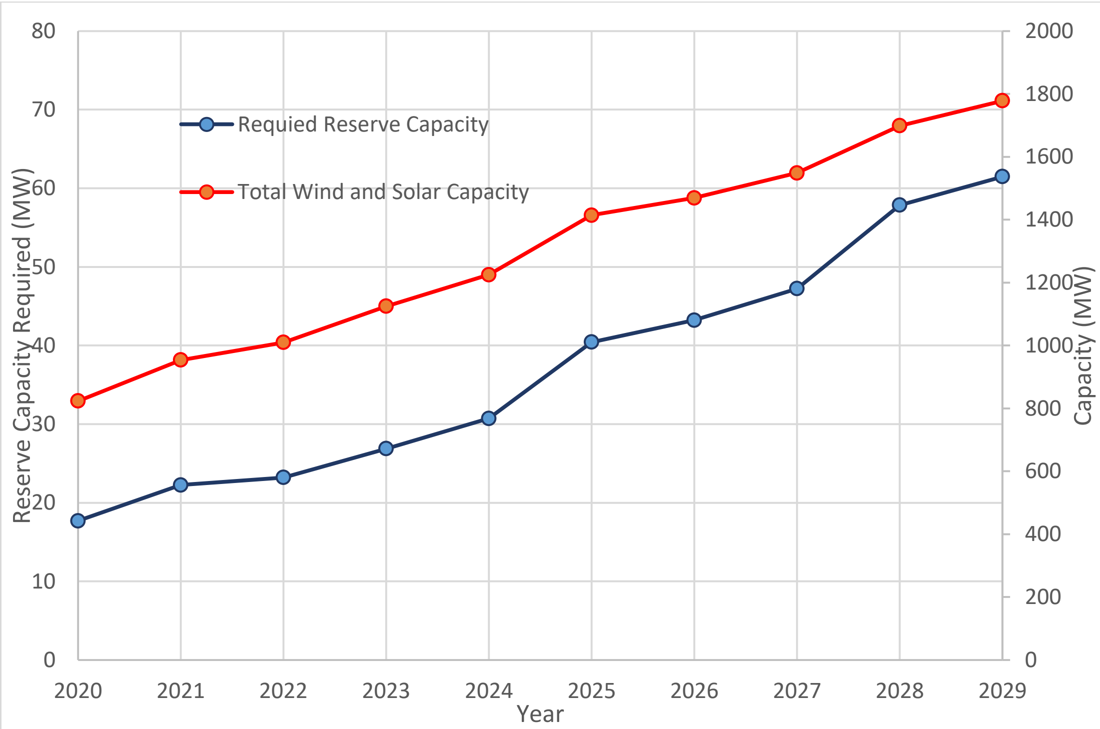


Figure 4.2: Variation of Additional Reserve Capacity Requirement due to VRE Integration

From the results it could be observed that, the requirement of additional reserves increase in parallel with the wind and solar integration level to the system. In the planning horizon, the additional reserve capacity ranges from 2% -3% of the wind and solar cumulative capacity of the respective year.

This value provides only an approximation of the operating reserve capacity requirement with the integration of VRE. Load and net load variations with smaller time steps need to be analysed to determine the exact value of reserves for regulation, load following etc. and the required ramping up/down rates for the reserves.

Utility scale battery storage provides a better alternative option to supply the additional reserves with higher ramping rates.

4.2 Techno Economic Comparison of Providing Operating Reserves with Thermal Generators vs. Utility Scale Battery Storage (Objective 2)

4.2.1 Dispatch Analysis

The SDDP model includes constrained unit commitment and economic dispatch. After feeding the model with input data described in Section 3.5, the model performs a chronological unit commitment and economic dispatch. This analysis presents the results of the hourly unit commitment simulations using hourly load forecasts and hourly resource profiles for wind and solar generation and an optimization horizon of one year.

SDDP includes energy storage, with a large number of input parameters, including size (both energy and power), efficiency during charge and discharge, and other operational considerations such as efficiency, operational range, ramp rates etc.

For this study, two main impacts of introducing utility scale battery storage for providing operating reserves were evaluated:

1. Impact on the dispatch of combined cycle power plants and the possible reduction in hourly variation of generation
2. Reduction of curtailment of VRE by introducing battery storage to facilitate for operating reserves

4.2.1.1 Impact on the dispatch of combined cycle power plants and the possible reduction in hourly variation of generation:

To evaluate the impact of introducing battery storage for providing operating reserves replacing thermal generators, three scenarios described in Section 3.5 were simulated in SDDP and the hourly dispatch of combined cycle power plants and battery storage was analysed.

In order to clearly demonstrate the changes in the dispatch, a week in May 2025 was selected and the hourly dispatch of Combined Cycle Power Plants in Scenario 1, Scenario 2, Scenario 3 and Battery Dispatch of Scenario 3 for that week is presented in Figures 4.3 (a) – 4.3 (d).

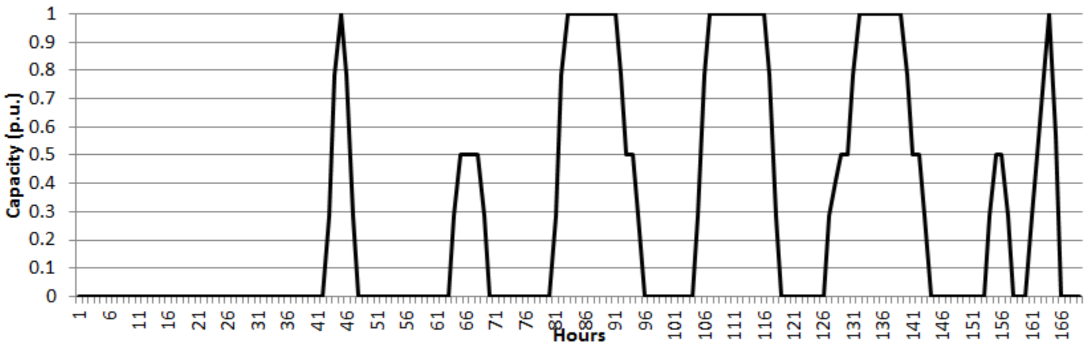


Figure 4.3(a): Hourly Dispatch of Combined Cycle Power Plants in Scenario 1

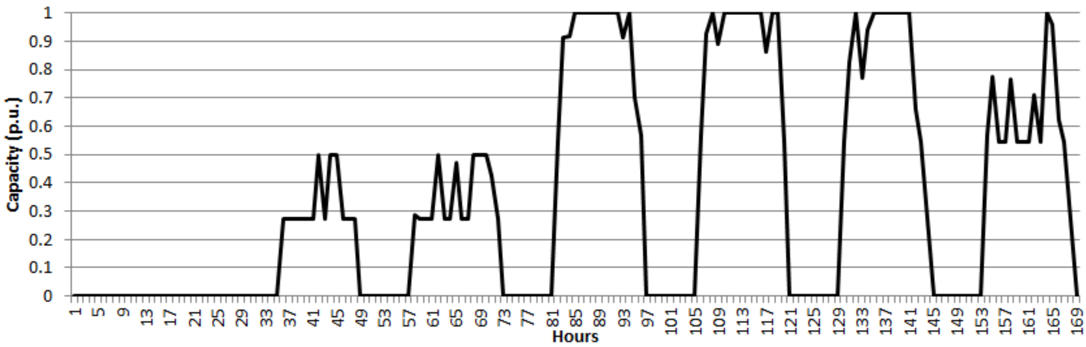


Figure 4.3(b): Hourly Dispatch of Combined Cycle Power Plants in Scenario 2

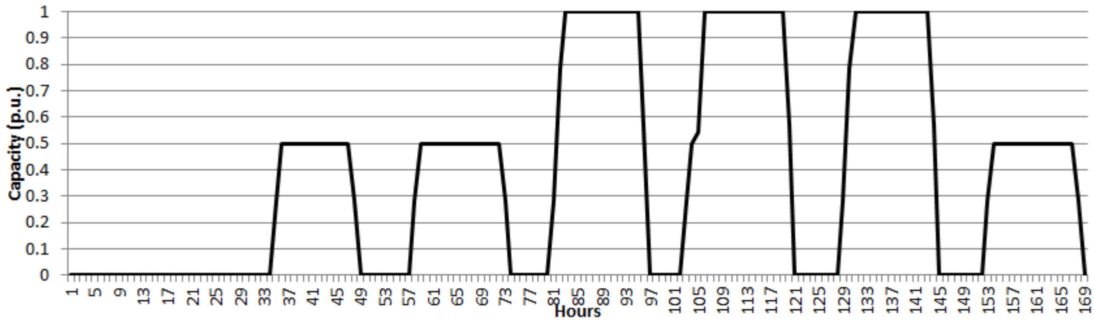


Figure 4.3(c): Hourly Dispatch of Combined Cycle Power Plants in Scenario 3

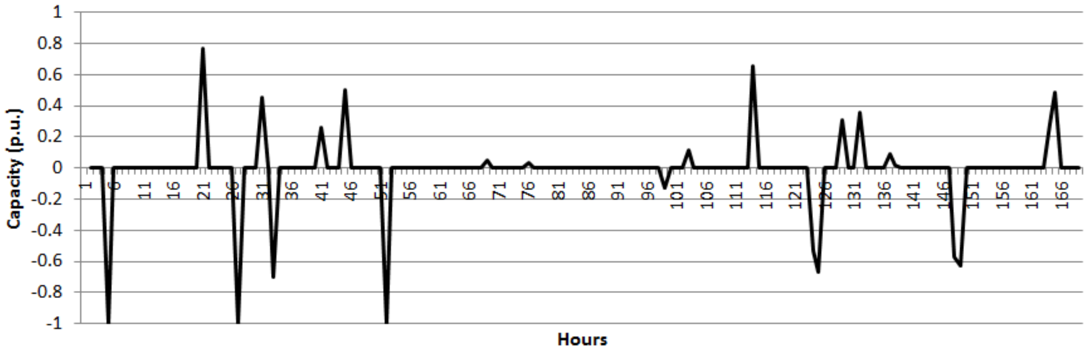


Figure 4.3(d): Hourly net generation of battery storage system in Scenario 3

It could be clearly observed from the above figures that a significant difference between the dispatch of combined cycle power plants in total is evident between three scenarios.

In Scenario 1, combined cycle power plants follow a cyclic operation between the maximum capacity and off state at most of the instances.

But in Scenario 2, when supplying operating reserves is assigned, the hourly output of the power plants oscillate more between intermediate states (neither maximum capacity nor minimum) in most of the time which leads to uneconomical operation of the power plants.

When battery storage is introduced in Scenario 3 to provide operating reserves replacing combined cycle power plants, it is clearly evident that the oscillating nature of the output of the power plant is decreased to a minimum level and shows a similar operating pattern to Scenario 1 but with a more stable operation at maximum capacity and off state. This would significantly reduce the operating costs of the combined cycle power plants as operating at maximum capacity improves the efficiency of the power plant than at part load and in the economic analysis of the study, this aspect is considered as the major benefit of introducing battery storage for operating reserves.

To further elaborate the reduction in the variability of the combined cycle power plant output with introduction of battery storage, the annual hourly dispatch of combined cycle power plants for year 2025 in Scenario 2 and Scenario 3 was analysed. Figures 4.4(a) and 4.4(b) depicts the dispatch of Scenario 2 and 3 respectively.

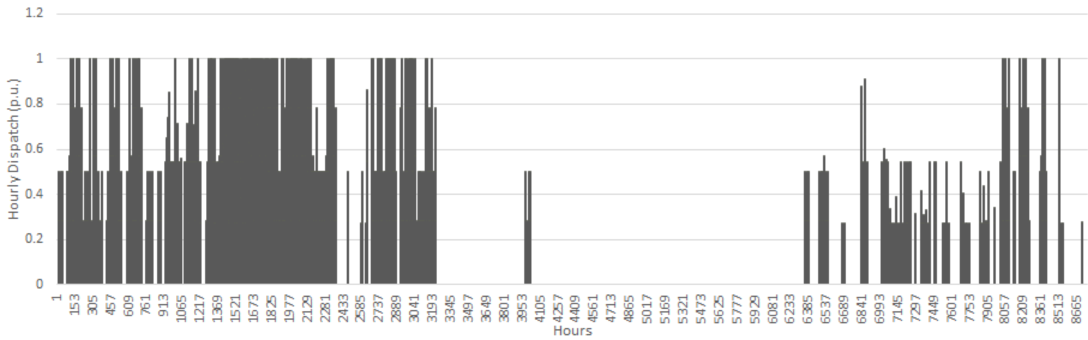


Figure 4.4(a): Hourly Dispatch of Combined Cycle Power Plants in Scenario 2 for Year 2025

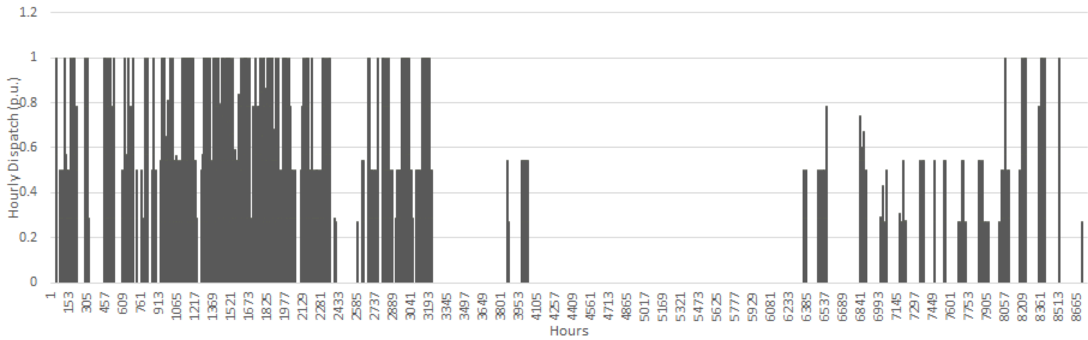


Figure 4.4(b): Hourly Dispatch of Combined Cycle Power Plants in Scenario 3 for Year 2025

By studying the above figures, it is evident that part load dispatch of combined cycle power plants reduce considerably with the introduction of battery storage. This feature is more clearly observable through Table 4.2 which shows the percentage of time the combined cycle power plants operated in their full load, intermediate load, minimum load and off states for year 2025. A reduction in part load operation with an increase in off state and full load operation is evident through the results.

Table 4.2: Percentage of time operated in load level states of combined cycle power plants for year 2025

	Scenario 2 (Without Battery)	Scenario 3 (With Battery)
Full Load	15%	16%
Intermediate Load	5%	4%
Minimum Load	6%	4%
Off	74%	76%

The above results clearly demonstrate that introduction of battery storage as operating reserves prompt the combined cycle power plants to increase operation in full load state or off state and reduce part load operation which leads to more economical operation of the system.

Another benefit of replacing combined cycle power plants with battery storage for operating reserves is better utilization of major hydro power plants. With battery storage providing a comparatively robust source of operating reserves, energy generation from both reservoir based and run of the river hydro power plants could be optimized and it drives the total operating cost of the system down. This phenomenon is evident through Table 4.3 which indicates the annual dispatch of power plant categories of three scenarios for year 2025.

Table 4.3: For a Sample Year (Year 2025), the difference in Annual Dispatch of the Power Plant Categories

	Scenario 1	Scenario 2	Scenario 3	Diff. (1-2)	Diff. (2-3)
Hydro	5499	5217	5743	282	-526
Coal	7425	7453	7434	-28	20
Combined Cycle	4221	4428	3966	-207	462
Oil	19	62	18	-43	44

4.2.1.2 Reduction of curtailment of VRE by introducing battery storage to facilitate for operating reserves

From a generation planning perspective, curtailment of VRE generation is one of the major obstacles in integrating more renewable to the system. Curtailment can be defined as a reduction in the output of a generator from what it could otherwise produce given available resources, typically on an involuntary basis. Curtailment of VRE generation occurs when system operators reduce the output from wind and solar generators to manage the generation mix under various system conditions such as excess generation during low load periods that could cause base load generators to reach minimum generation thresholds, high hydro generation periods, or to maintain frequency requirements, particularly for isolated grids like Sri Lanka.

As renewable energy sources such as wind and solar generators have substantial capital costs, maximizing output is the only way for developers to improve their ability to recover capital costs. Also from a utility perspective, it is more economical to maximize the output from wind and solar, as they have zero fuel cost unlike other thermal generators and maximum generation from VRE would reduce the overall cost of generation. Both the above factors contribute to the necessity for utilities to reduce curtailment of VRE generation in system operation as well as in long term planning.

To utilize more VRE and reduce curtailment, utilities around the world have adopted multiple strategies through conventional generation units, energy storage, and demand response. These strategies include reducing minimum loads on low cost units, running units at lower load levels, modifying units for daily cycling operation, incorporating demand response into operating reserves, utilizing energy storage to store excess VRE generation (lithium ion batteries, pumped storage etc.) and introducing smart grid technology that improve control over distributed VRE. In the recent years, more novel approaches with regard to energy storage such as installing electric vehicles (EVs) charging stations and incorporating variable speed drives to Pumped Storage power plants have been tried and appraised with successful results.

From the aforementioned approaches, this study has specifically addressed the role of Battery Storage as an approach in reducing VRE curtailments.

For a system with adequate transmission capacity, VRE curtailments are caused by a combination of generation system flexibility and patterns of renewable supply and electricity demand. When analyzing the ability to reduce curtailment with energy storage, a comprehensive assessment of the dispatch of the generation system together with daily and seasonal patterns of VRE generation is required.

For this purpose, the results from dispatch analysis for year 2029 was considered and the analysis comprised of the hourly dispatch of the same two scenarios considered for Section 4.2.1.1.

Scenario 2 – Only combined cycle power plants were assigned to provide operating reserves

Scenario 3 – Only battery storage and major hydro power plants were assigned to provide operating reserves

In both scenarios, hourly dispatch analysis was carried out for year 2029 and the resultant VRE curtailment levels together with the dispatch of thermal, major hydro and RE power plants were obtained from SDDP simulation. Figures 4.5(a) and 4.5(b) shows the hourly VRE curtailments and battery net generation for consecutive five days in May, which is in the high wind season.

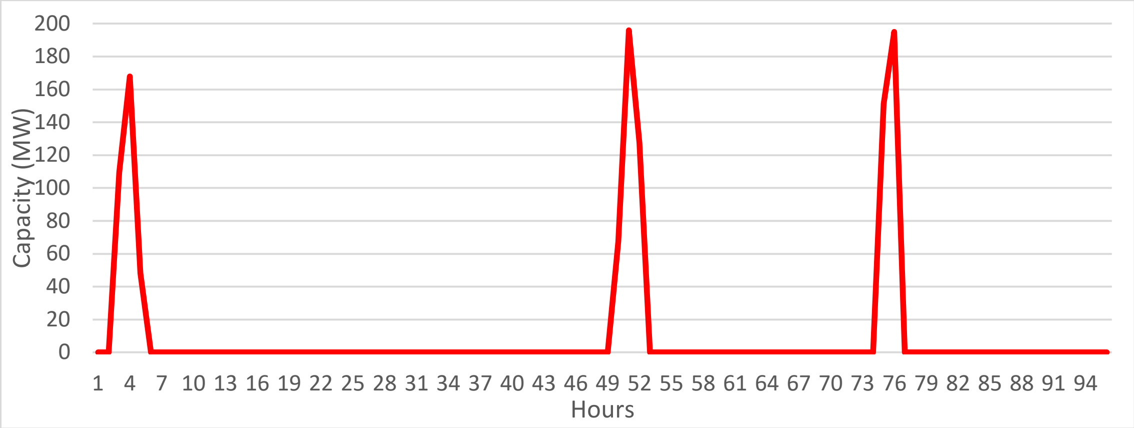


Figure 4.5(a): VRE Capacity Curtailment in Scenario 2 for 5 days in May 2029

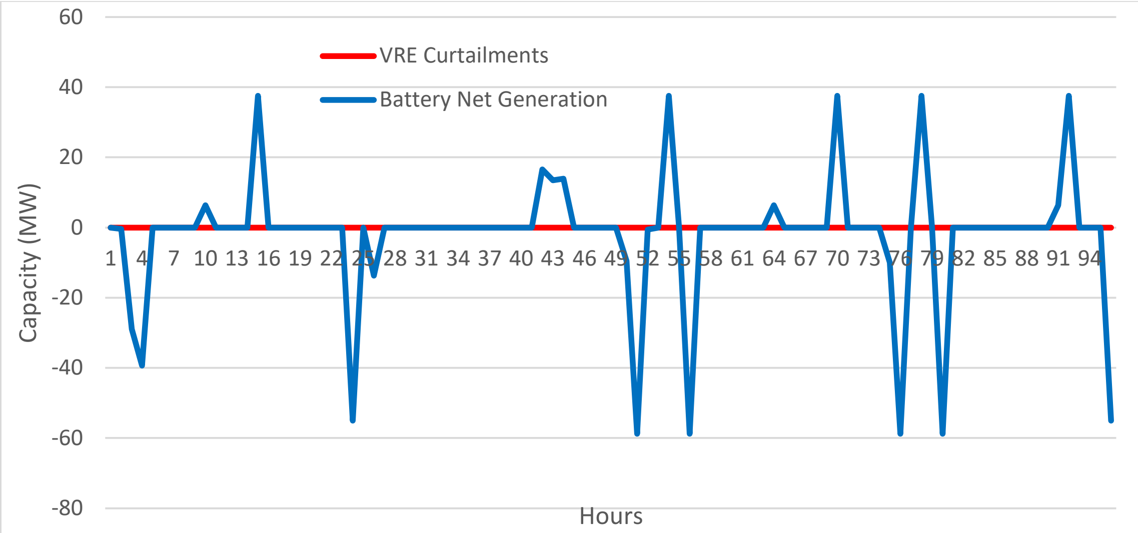


Figure 4.5(b): VRE Capacity Curtailment and Battery Net Generation in Scenario 3 for the Same 5 days in May 2029

From the above analysis, it could be clearly indicated that with the introduction of battery storage, VRE curtailment levels reduce substantially (in this case to zero) and in the corresponding hours where VRE curtailments happened, charging of batteries have caused the reduction in curtailments. When annual figures are considered, the total VRE energy curtailed in Scenario 2 amounts to a negligible amount (~5GWh). However, in high wind and Solar seasons capacity wise, considerable curtailments occur and battery storage could minimize the capacity curtailments. This phenomenon could be observed throughout the study horizon.

Due to the low energy curtailment values, reduction in curtailments was not considered as a benefit in the economic analysis of the study.

4.2.2 Economic Analysis

The economic analysis was carried out primarily with relevant costs taken from the results from SDDP simulation of Scenario 2 and 3. Table 4.3 indicates some of the cost elements including both initial costs (such as capacity cost and installation cost) and O&M cost elements (such as maintenance cost and insurance cost). Apart from that, battery charging cost was calculated for all the years in study horizon as per Equation 3.10. Since it is assumed that the battery is charged by a mix of excess energy sources available at the time of charging, marginal cost of battery storage was used which is an output of SDDP simulation.

The economic benefit of providing reserves from battery storage replacing combined cycle power plants is the operating cost reduction of thermal power plants. For thermal power plants, maximum efficiency occurs at full-load, so operating a large thermal unit at part-load reduces the efficiency of power generation considerably, and the need for part-load operation may impact on the operational range of the power station due to the need to comply with emissions regulations. In addition, cycling of the units, ramping up and down in load, can create the need for more frequent maintenance and power station outages. Cycling operation also reduces part life and severely impacts plant economic returns and in some cases, overall viability.

Therefore, as evident from the dispatch analysis, with the introduction of battery storage substantially reduces the part load operation of combined cycle power plants which translates in to overall operational cost reduction (Calculated from Equation 3.9) and this cost reduction is considered as the main benefit from battery storage for this study. The benefit was also calculated for the study horizon.

The results are indicated in Table 4.4.

Table 4.4: Battery Charging Cost for years 2020-2029 in Scenario 3 and Operating

Year	Battery Charging Cost (USD million)	Operating Cost Reduction of Combined Cycle Power Plants (USD million)
2020	1.83	9.58
2021	1.21	6.90
2022	0.06	0.16
2023	5.06	18.96
2024	1.76	13.06
2025	3.04	12.01
2026	1.61	6.81
2027	3.19	14.68
2028	1.90	9.25
2029	2.56	10.21

Cost Reduction between Scenario 2 and Scenario 3

The economic analysis was carried out with the parameters in Table 3.5 and Table 4.4 and a summary of the working (in USD millions) is demonstrated in Table 4.5.

Table 4.5: Summary Workings of the Economic Analysis (in USD millions)

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Total Profit and Savings											
Cost Reduction in combined cycle PP due to battery		9.58	6.90	0.16	18.96	13.06	12.01	6.81	14.68	9.25	10.21
- -	-	-	-	-	-	-	-	-	-	-	-
Total Operating Costs											
Maintenance Costs		0.06	0.12	0.18	0.24	0.3	0.36	0.42	0.48	0.54	0.6
Charging Cost		1.83	1.21	0.06	5.06	1.76	3.04	1.61	3.19	1.90	2.56
Total Investment Cost											
Battery Module	15.19	7.595	6.8355	6.076	5.3165	4.557	3.7975	3.038	2.2785	1.519	0.7595
Power Conversion System	7.6	3.8	3.42	3.04	2.66	2.28	1.9	1.52	1.14	0.76	0.38
Total Disposal and Recycling Cost											4.558
Net Benefit	-22.79	-3.71	-4.68	-9.20	5.68	4.16	2.91	0.23	7.59	4.53	1.36

The results derived from the economic analysis is indicated in Table 4.6.

Table 4.6: Results of Economic Analysis

Parameter	Value
Net Present Value	-20.66 USD million
Benefit/Cost Ratio	0.003
Payback	10+ Years

The key output indicators were calculated based on the assumption mentioned in the Methodology section and the results are interpreted under VRE and other plant additions as per the base case plan of LTGEP 2018-2037. This would help to examine the additional benefits that the battery system can derive under a baseline scenario which is close to the actual implementation of Sri Lanka power system.

All key output indicators are on the negative spectrum which renders introduction of battery storage under baseline scenario economically infeasible (see Table 4.6). For example, the NPV of the project is -20.66 USD million; the benefit to cost ratio is almost a negligible value; and the payback is 10+ years, which means the project becomes highly infeasible economically from the utility perspective as well as consumer perspective.

4.2.2.1 Sensitivity Analysis

To assess the project parameters which renders the addition of batteries economically feasible, a sensitivity analysis was carried out by studying the changes in NPV associated with changes in different parameters.

Different parameters were examined with the changing scales (10%, 20% and 30%) and it was evident that changes in capacity cost, charging price and system lifespan have significant implications to the NPV of the project. By contrast, escalation rate and discount rate make minor contribution to NPV changes.

Capital cost (capacity cost) of the batteries are on a rapid downward trend in the world and therefore, this study focused on the sensitivity of economic parameters to the changes in battery capacity cost. Battery capital cost was reduced in the scales of 10%, 15%, 20% … and the NPV was calculated at each capacity cost. The results are demonstrated in Figure 4.6.

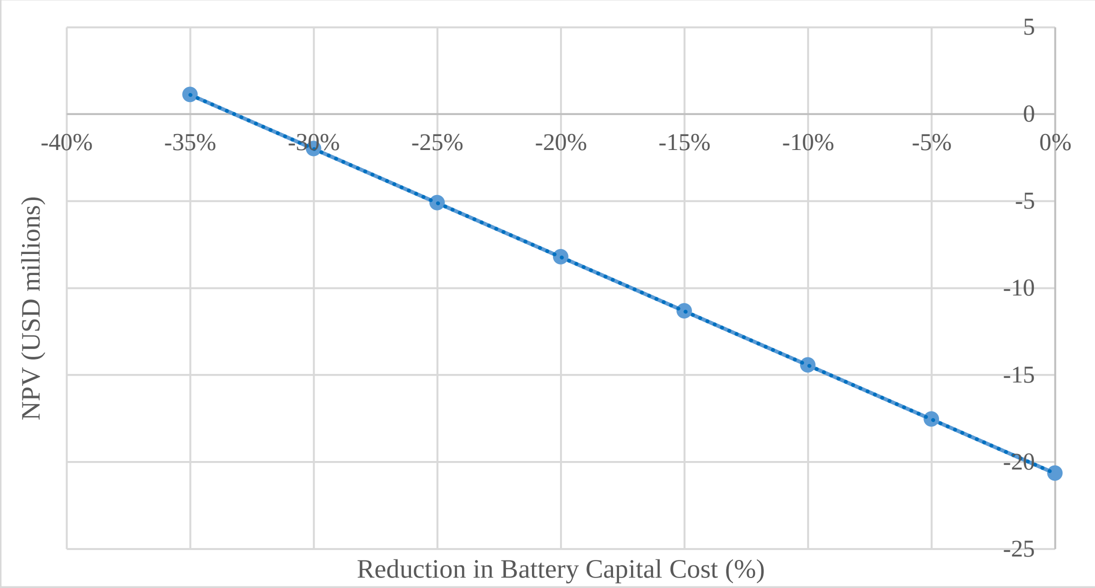


Figure 4.6: Results of Sensitivity Analysis on Battery Capital Cost

It was indicated from the results of this sensitivity analysis that at least a 35% decrease of battery capacity would make introduction of battery storage feasible under the conditions of LTGEP 2018-2037. The key indicators when the capacity cost of battery decreased by 35% are demonstrated in Table 4.7.

Table 4.7: Results of Sensitivity Analysis on Battery Capital Cost

Parameter	Value
Net Present Value	1.12 USD million
Benefit/Cost Ratio	1.08
Payback	6.9 Years

Another aspect examined through the economic analysis was the possibility of increasing the VRE integration to the system by 10%. Through dispatch analysis it was established that increased VRE integration could be supported through replacing thermal generation reserves with battery storage. However, the increase of battery capacity under present capacity costs for the project to be feasible was evaluated through this analysis.

Analysis was carried out in parallel with the dispatch analysis and the final economically feasible result is indicated in Table 4.8 and Table 4.9 and it could be observed that at least 50% increase of battery storage capacity for each year is needed for the facilitation of 10% increase of VRE integration level in an economically feasible condition.

Table 4.8: Battery Capacity Requirement to Facilitate Operating Reserves under proposed VRE integration Level and 10% Increased VRE Integration Level

Year	Battery Capacity (MW)	
	VRE as per LTGEP (MW)	10% Increased VRE
2020	20	30
2021	30	45
2022	40	60
2023	50	75
2024	60	90
2025	70	105
2026	80	120
2027	90	135
2028	100	150
2029	110	165

Table 4.9: Results for Economic Parameters under 10% Increased VRE Level

Parameter	Value
Net Present Value	4.03 USD million
Benefit/Cost Ratio	1.15
Payback	6.5 Years

The workings for the sensitivity analysis are presented in Annex 2 and Annex 3.

5. CONCLUSIONS

5.1 Technical Analysis

The first objective of the technical analysis of the study was to formulate a methodology to approximate the operating reserve requirement of the power system with the integration of VRE. The variability and intermittency inherent of VRE production will require increased flexibility in the power system when a significant amount of load is covered by VRE. With the references discovered through literature review, a methodology was developed using statistical analysis based on standard deviation. Standard deviation of variability for load and net load (load minus VRE) has been used when estimating the effect of VRE on the short term reserves of the power system. This method is straightforward and easy to use when time-series data on VRE resource data and load exist. Net load variability compared to load variability gives an estimate for the additional operating reserve requirement of the system to react to large scale VRE integration. A statistical approach using the standard deviation (σ) values gives estimates for the range of variability, and for this study $\pm 4\sigma$ was taken as the range which will cover most variations (99.99 % of all variations are inside this range).

As majority of the data relevant to this purpose were available on hourly basis, the analysis was carried out on hourly timescale and from the results, it could be estimated that the requirement of additional reserves increase in parallel with the wind and solar integration level to the system. In the planning horizon, the additional reserve capacity ranges from 2% -3% of the wind and solar cumulative capacity of the respective year.

The second objective of the technical study was to compare the provision of operating reserves through thermal generators and battery storage. For this purpose, an hourly dispatch analysis was carried out using Stochastic Dual Dynamic Programming (SDDP) tool. From the results of the dispatch analysis carried out, the main conclusions derived are as follows:

1. The introduction of battery storage directly contributes to the reduction in variations of Combined Cycle power plant output (providing regulating + other operating reserves) which leads to more efficient operation of power plant with steady loading levels.

2. With battery storage providing a comparatively robust source of operating reserves, energy generation from both reservoir based and run of the river hydro power plants could be optimized and it drives the total operating cost of the system down.
3. With the introduction of battery storage, VRE curtailment levels reduce substantially compared to the case with combined cycle power plants providing operating reserves.

5.2 Economic Analysis

For the baseline scenario analysed through the technical analysis which follows the plant additions proposed in LTGEP 2018-2037, all output indicators, namely NPV, BCR, and payback period, have been negative when the required capacity of battery storage is introduced. This is mainly due to the high capital cost of battery storage which outweighs the benefits during the study horizon.

Given battery storage projects are highly capital intensive, capacity cost is a vital element in every investment decision. Although battery storage in general is not cost competitive now, significant declines in capacity costs for various types of batteries are evident in global scale. To examine this aspect, a sensitivity analysis was carried out with declining capacity costs and the project becomes financially attractive when capacity cost is declined by 35%.

	Original	**To be feasible**
Power Conversion System cost	1519 USD/kW	987 USD/kW
Storage section costs	380 USD/kWh	247 USD/kWh

To examine the feasibility of introducing battery storage for operating reserves under increases VRE levels were studied together with a dispatch analysis and it was observed that, for increased integration of VRE by 10%, the battery capacity needs to be increased by at least 50% for the introduction of battery to be technically and economically feasible.

6. REFERENCES

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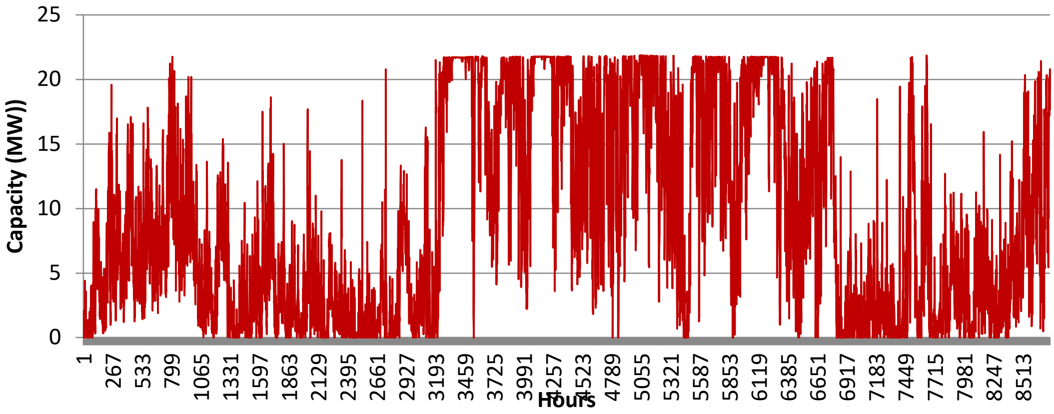
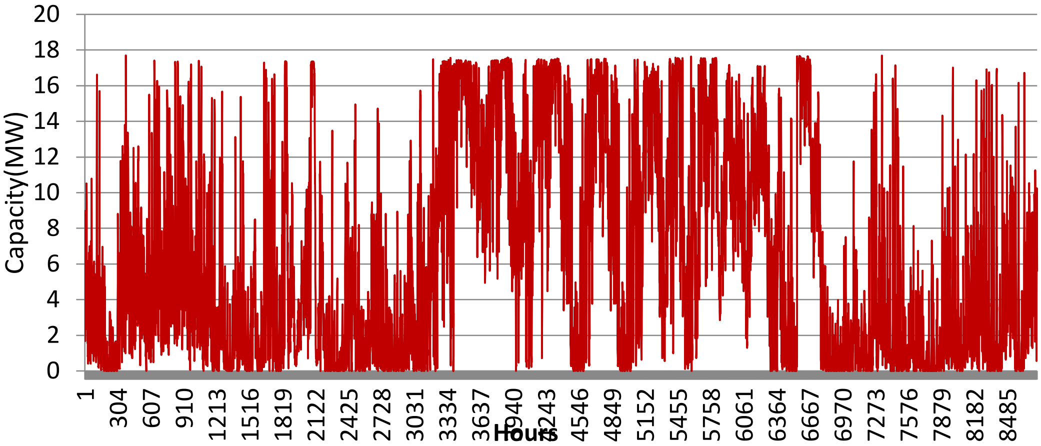
Annex 1

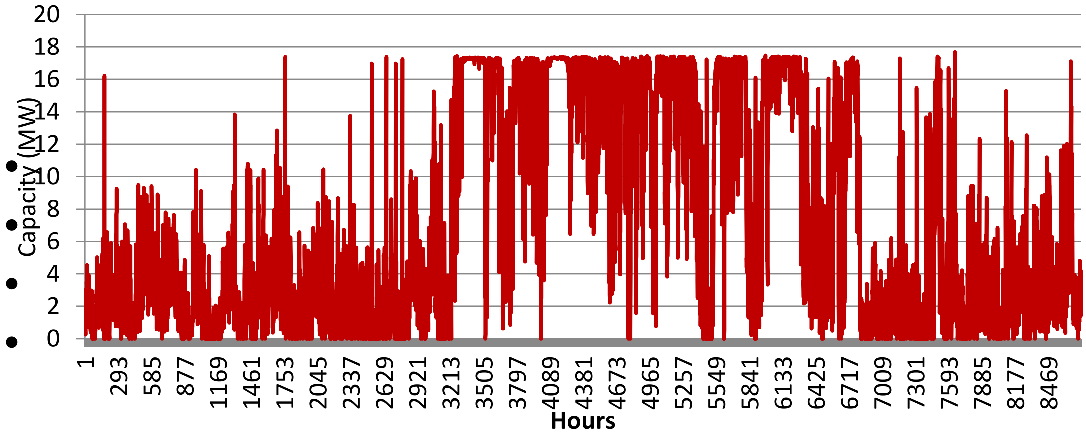
- Mannar 25MW Wind Plant Output



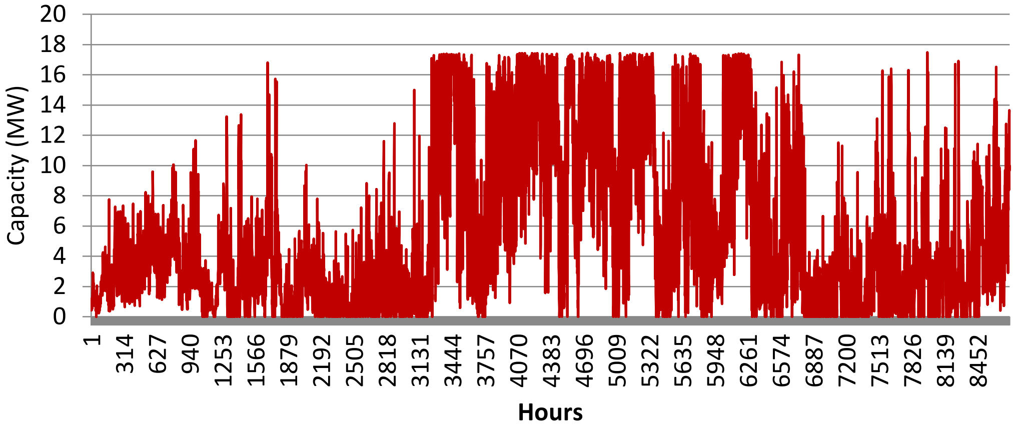
- Puttalam 20MW Wind Plant Output



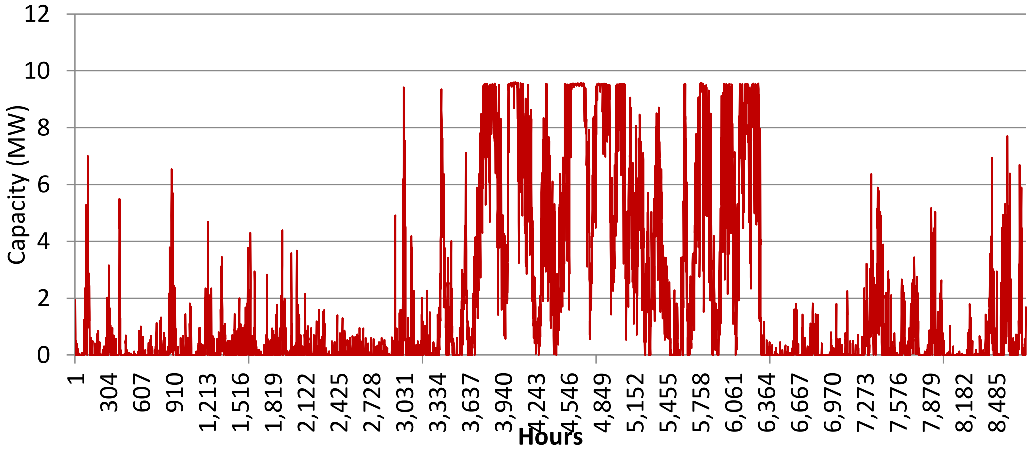
- Northern 20MW Wind Plant Output



- Eastern 20MW Wind Plant Output



- Hill Country 10MW Wind Plant Output



Annex 2

With the reduction of Battery Storage Capital Cost by 35%,

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Total Profit and Savings											
Cost Reduction in combined cycle PP due to battery		9.58	6.90	0.16	18.96	13.06	12.01	6.81	14.68	9.25	10.21
-	-	-	-	-	-	-	-	-	-	-	
Total Operating Costs											
Maintenance Costs		0.06	0.12	0.18	0.24	0.3	0.36	0.42	0.48	0.54	0.6
Charging Cost		1.83	1.21	0.06	5.06	1.76	3.04	1.61	3.19	1.90	2.56
Total Investment Cost											
Battery Module	9.874	4.937	4.4433	3.9496	3.4559	2.9622	2.4685	1.9748	1.4811	0.9874	0.4937
Power Conversion System	4.94	2.47	2.223	1.976	1.729	1.482	1.235	0.988	0.741	0.494	0.247
Total Disposal and Recycling Cost											2.9627
Net Benefit	-14.814	0.28	-1.10	-6.01	8.47	6.55	4.91	1.82	8.79	5.33	3.35

Annex 3

With the increase of battery capacity initially by 5 MW and annual additions by 5 MW,

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Total Profit and Savings											
Cost Reduction in combined cycle PP due to battery		11.71	10.28	10.37	31.26	17.49	28.68	34.38	30.13	23.75	31.81
-	-	-	-	-	-	-	-	-	-	-	
Total Operating Costs											
Maintenance Costs		0.06	0.09	0.12	0.15	0.18	0.21	0.24	0.27	0.3	0.33
Charging Cost		1.79	1.40	1.66	8.67	3.98	7.25	7.57	7.17	5.01	7.80
Total Investment Cost											
Battery Module	22.785	15.19	13.671	12.152	10.633	9.114	7.595	6.076	4.557	3.038	1.519
Power Conversion System	7.6	3.8	3.42	3.04	2.66	2.28	1.9	1.52	1.14	0.76	0.38
Total Disposal and Recycling Cost											6.077
Net Benefit	-30.39	-7.23	-6.40	-4.71	11.05	3.83	13.63	20.88	18.89	16.54	15.70