THE IMPACT OF ENERGY STORAGE SYSTEM ON SECURITY CONSTRAINED UNIT COMMITMENT (SCUC) PROBLEM IN PRESENCE OF RENEWABLES

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ABSTRACT

THE IMPACT OF ENERGY STORAGE SYSTEM ON SECURITY CONSTRAINED UNIT COMMITMENT PROBLEM IN PRESENCE OF RENEWABLES

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In spite of the fact that there is a growing trend for the integration of Renewable Energy Sources (RES) to the existing power systems, the intermittency and volatility of these resources should be taken into consideration in the day ahead operational planning for the sake of security and reliability of the electrical energy. Besides, the adverse effects of high penetration of wind energy - the largest global installed RES capacity - to the system operation could be mitigated with the utilization of Energy Storage Systems (ESS).

The impact of ESS to the Security Constrained Unit Commitment (SCUC) problem in the presence of RES is going to be investigated throughout this thesis. SCUC is modeled using Mixed Integer Linear Programming (MILP) formulation. A

MATLAB code is generated in order to generate an input file to characterize the MILP SCUC problem that is to be fed to the IBM CPLEX 12.6 solver. Moreover, a method is proposed to generate and reduce stochastic Monte-Carlo scenarios and these are integrated to the SCUC problem in order to characterize the uncertainties in the wind power generation and system demand. The generated scenarios are reduced by “k-means” method using “R” software. A deterministic SCUC, which contains no uncertainty, is also generated in order to provide a benchmark for comparison purposes. Finally, the constructed deterministic and stochastic problems are solved using IBM CPLEX 12.6 solver, and a day ahead planning is obtained.

Even there are studies investigating the impact of ESS to the SCUC following either deterministic or stochastic approach, there is no publication considering both methods up to the authors knowledge. The main contribution of this study is that it considers both approaches to evaluate the impact of ESS on SCUC. Moreover, the impact of storage capacities and deployment locations of ESS to the reduction of operational cost and wind power curtailment is analyzed for the IEEE 24-bus power system.

Keywords: Security Constrained Unit Commitment, Energy Storage System, Mixed Integer Linear Programing, Renewable Energy Sources, Pumped–storage Hydro Unit, Battery Energy Storage Unit.

ÖZ

YENİLENEBİLİR ENERJİ KAYNAKLARININ BULUNDUĞU ŞEBEKEDE ENERJİ DEPOLAMA SİSTEMİNİN GÜVENLİK KISITLI ÜNİTE ATAMA ÜZERİNE ETKİSİ

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Yenilenebilir enerji kaynaklarının (YEK) varolan güç sistemlerine eklenmesine artan bir eğilim olduğu gerçeğine rağmen; yeterli ve güvenilir elektrik enerjisi için bu kaynakların değişkenliği ve kesikliliği gün öncesi işletme planlamasında göz önünde bulundurulmalıdır.Bununla birlikte en fazla kurulu güce sahip YEK olan rüzgar enerjisinin yaygınlığının sistem işletmesine olan olumsuz etkileri Enerji Depolama Sistemlerinin (EDS) kullanımıyla hafifletilebilir.

Bu tezde EDS'nin Güvenlik Kısıtlı Ünite Atama (GKÜA) problemine etkisi yenilenebilir enerji kaynaklarının bulunduğu örnek bir şebeke için incelenecektir. Bu amaçla GKÜA problemi Karışık Tamsayı Doğrusal Programlama (KTDP) formülleri kullanılarak modellenmiştir. IBM CPLEX 12.6 programı için veri dosyası olarak kullanılmak üzere KTDP tabanlı GKÜA problemi elde etmek için bir MATLAB kodu oluşturulmuştur. Bunun yanında, bu tezde , Monte Carlo senaryoların üretilme ve indirgeme yöntemi de ortaya konulmuştur ve bunlar rüzgardan elde edilen enerjinin ve yükün belirsizliğinin KTDP tabanlı GKÜA problemine dahil edilmesi için kullanılmıştır. Üretilen senaryolar “k-means” yöntemini kullanan ‘R’ programıyla indirgenmiştir. Belirsizlik içermeyen deterministik GKÜA problemi de oluşturularak karşılaştırma imkanı elde edilmiştir. Son olarak oluşturulan deterministik ve stokastik problemler CPLEX kullanılarak çözülmüş ve gün öncesi planlama elde edilmiştir.

Birçok çalışmada EDS’nin GKÜA problemine olan etkisi determistik veya stokastik yaklaşımlarda incelenmesine rağmen, her iki yaklaşımın tek bir çalışmada birleştirildiği bir çalışma yazarın bildiği kadarıyla bulunmamaktadır. Bu çalışmanın ana katkısı EDS’nin GKÜA problemine etkisi her iki yaklaşım da kullanılarak incelenmesidir. Ayrıca EDS’nin depolama kapasitesitesinin ve konumunun işletme maliyetinin azaltılmasına ve rüzgar enerjisinin kullanımına olan etkileri IEEE 24 baralı sistemi için incelenmiştir.

Anahtar Kelimeler: Güvenlik Kısıtlı Ünite Atama, Enerji Depolama Sistemi, Karışık Tamsayı Doğrusal Programlama, Yenilenebilir Enerji Kaynakları, Pompaj Depolamalı HES, Batarya Enerji Depolama Ünitesi.

To My Parents
And My Brother

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i	Index of conventional units
h	Index of Pumped Storage Hydro (PSH)
k	Index of Battery Energy Storage System (BESS)
l	Index of lines
m	Index of a piecewise or stepwise cost curve segments
s	Index of scenario
t	Index of time periods (hour)
w	Index of wind units

Dimensions

I	Number of conventional units
K	Number of ESS unit
NT	Number of hours
S	Number of scenarios
W	Number of wind units

Variables

$A_{k,t,s}$	Energy level of BESS at hour t in scenario s (MWh)
$p_{i,t,s}$	Generation of conventional unit ‘i’ at hour t in scenario s (MW)
$pw_{w,t,s}$	Utilized generation of wind unit ‘w’ at hour t in scenario s (MW)
$px_{i,m,t,s}$	Used power amount in segment ‘m’ of unit ‘i’ at hour t, scenario s
$p_{k,t,s}^{ch}$	Charging power of BESS at hour t in scenario s (MW)
$P_{k,t,s}^{dch}$	Discharging power of BESS at hour t in scenario s (MW)

$p_{h,t,s}^{pump}$	Pumping power of PSH at hour t in scenario s (MW)
$p_{h,t,s}^{gen}$	Generating power of PSH at hour t in scenario s (MW)
$sr_{i,t,s}$	Spinning reserve support amount of unit 'i' at hour t in scenario s (MW)
$or_{i,t,s}$	Operating reserve support amount of unit 'i' at hour t in scenario s (MW)
$u_{i,t}$	Conventional unit status indicator (binary) (1means unit 'i' is ON at hour t)
$uc_{k,t,s}$	BESS charging mode status indicator at hour t in scenario s (binary)
$u_{k,t,s}$	BESS discharging mode status indicator at hour t in scenario s (binary)
$u_{h,t,s}$	PSH generating mode status indicator (binary)
$up_{h,t,s}$	PSH pumping mode status indicator (binary)
$Vol_{h,t,s}$	Upper reservoir water level of PSH at hour t in scenario s (hm^3)
$y_{i,t}$	Conventional unit startup indicator (binary) (1 means unit 'i' is started up at hour t)
$z_{i,t}$	Conventional unit startup indicator shut down indicator (binary) (1 means unit 'i' is shut down at hour t)

Constants

C_{i0}	No-load cost of unit 'i' ($)
$D_{t,s}$	System load demand at hour t in scenario s (MW)
IC_{im}	Incremental cost at segment m for unit 'i' ($/MW)
MD_i	Maximum down time of unit 'i' (hours)
MW_{im}	Maximum MW at segment m for unit 'i' (MW)
MSR_i	Maximum sustained rate of unit i(MW/min)
MU_i	Minimum up time of unit 'i' (hours)
$OR_{t,s}$	System operating reserve requirement of system at hour t in scenario s (MW)
$PMAX_i$	Maximum capacity of unit 'i' (MW)
$PMIN_i$	Minimum capacity of unit 'i' (MW)
$FWP_{w,t,s}$	Forecasted wind power generation of 'w' wind unit at hour t in scenario s (MW)

QSC_i	Quick start capability of unit ‘i’ (MW)
RD_i	Ramp down rate for unit ‘i’ (MW/hour)
RU_i	Ramp up rate for unit ‘i’ (MW/hour)
SD_i	Constant shutdown cost for unit ‘i’ ($)
$SR_{t,s}$	System spinning reserve requirement of system at hour t in scenario s (MW)
ST_i	Constant startup cost for unit ‘i’($)
TD_{i0}	Number of hours unit ‘i’ has been offline initially (hours)
TU_{i0}	Number of hours unit ‘i’ has been online initially (hours)
u_{i0}	Initial commitment status of unit (1 if it is online, 0 otherwise)

Abbreviations:

BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
DAM	Day-Ahead Market
ERCOT	Electric Reliability Council of Texas (ISO)
ESS	Energy Storage System
IEEE	Institute Of Electrical and Electronics Engineers
ISO	Independent System Operator
LAUC	Look-Ahead Unit Commitment
MILP	Mixed Integer Linear Program
MIP	Mixed Integer Program
MISO	Midcontinent Independent System Operator
NP	Non-Deterministic Polynomial-Time
OR	Operating Reserve
PJM	Pennsylvania-New Jersey-Maryland (ISO)
PSH	Pumped Storage Hydro
PX	Power Exchange
RES	Renewable Energy Sources
RTM	Real-Time Market
RUC	Day-Ahead Unit Commitment for Reliability
SCUC	Security Constrained Unit Commitment
SR	Spinning Reserve
UC	Unit Commitment
WPG	Wind Power Generation
WU	Wind Unit

CHAPTER 1

INTRODUCTION

In electrical system, the electricity generation and the consumption must be equal at any time instant. SCUC algorithms determine the schedule of units to minimize operating cost while considering several constraints such as ramp rate limits, minimum up and down time limits, load balance, system spinning reserve requirement of system and network flow constraints. In different day-ahead power markets, the independent system operators (ISO) such as NYISO and California ISO make a day ahead schedule by using SCUC algorithms.

The technological improvements in generation technologies, governmental incentives and limited adverse effects of renewable resources on environment have given way to an increase in the share of renewable sources contribution to annual electric energy generation. On the other hand, the variability of the wind speed and hence the generated energy bring new challenges to power system operations in order to maintain system security and reliability. Consequently, reserve determination and SCUC should be done by considering existence of wind units at power system.

Challenges associated with the integration of renewable sources to power system operation are a largely discussed issue in literature at recent years. Volatility and intermittency of wind power energy is main difficulty, which should be considered in Unit Commitment (UC) problem. Energy Storage Systems (ESS) are utilized as one of the possible solution to problems caused by volatility and intermittency of wind power. The impact of ESS on UC or Security Constraint Unit Commitment (SCUC) problems are examined in some works in which benefits of ESS on power production cost and wind power curtailment are evaluated in these works. Details of these works are briefly explained in literature review part of this thesis. In some studies, similar examinations are done in deterministic SCUC problem. On the other hand, the effect of ESS on stochastic UC problem is chosen as a main subject at some other ones. Different coordination strategies for wind unit (WU) and constant ESS storage size are also proposed for stochastic SCUC problem at one of the recent published paper. Although one of the possible approaches (deterministic or stochastic) is chosen to examine the effect of ESS on SCUC problem in several studies in literature, in this study, the effect of ESS on SCUC problem is examined in both approaches. In addition to this contribution of this thesis, the effect of storage size of ESS and location of ESS on cost reduction performance of ESS in SCUC problem are also examined and combined in this study.

In this thesis, SCUC problem is solved in both deterministic and stochastic approaches for a power system, which has WUs and ESS in addition to conventional units. Scenario generation and reduction process is proposed and applied to obtain stochastic scenarios. The effects of different sizes and location of ESS on cost reduction and wind power utilization is also examined for a sample modified IEEE 24 bus system.

Outline of this thesis can be formed as follows;

- In chapter 2, general background on unit commitment and ESS system are provided. Literature review on related issues with main theme of thesis are also provided at the second part of this chapter.

- In chapter 3, modelling of proposed SCUC algorithm is provided. Brief explanation about deterministic and stochastic approaches is also given and scenario generation and reduction process is also explained.

- Demonstration of the proposed algorithm using deterministic and stochastic case studies are provided and evaluated in chapter 4.

- Chapter 5 concludes the study.

- In chapter 6, possible future works on that subject are also discussed and provided.

CHAPTER 2

GENERAL BACKGROUND AND LITERATURE REVIEW

2.1 Unit Commitment

“Unit commitment (UC) is the activity of changing the state of a generating unit from unsynchronized stop to synchronized and delivering power to the grid” [1]. However, the problem is to determine which generating units should be committed at which operation point in order to obtain power generation in most economical way. Minimizing system operating costs while supplying the system load is main objective of traditional UC model, in this model various system and unit constrains are also considered and satisfied [2]. These constraints can be listed as load balance, system spinning reserve, ramp rate limits, fuel constraints, multiple emission requirements as well as minimum up and down time limits [3].

To solve the UC problem, various approaches are developed. Abstract definitions of them are written below [4, 5, 6, 7];

- Exhaustive enumeration [7]

The UC problem had been earlier solved by enumerating all possible combinations of the generating units and then the combination, which has the lowest cost, are chosen as optimal solution. However, for large size electricity utility, this method is not applicable.

- Priority list [7]

In this method, generating units are sorted from cheapest to the most expensive one. And then predetermined order is used for UC such that load demand is satisfied.

- Dynamic programming [7]

The earliest optimization-based method for UC problem is dynamic programming (DP). It is used extensively throughout the world. Usage on problems with various sizes and simplicity of modification on model characteristics can be listed as advantages of this method. Requirement to limit the commitments considered at any hour and its suboptimal treatment of minimum up and downtime constraints and time-dependent startup costs are disadvantage of the dynamic programming.

- Integer and linear programing [4, 7]

UC problem can be portioned, by using bender decomposition, into two problems, nonlinear economic dispatch problem and pure integer nonlinear UC problem. Whereas the mixed integer programming (MIP) approach solves the UC by reducing the solution search space through rejecting infeasible subsets. A linear UC problem can be solved by using two different approaches. The first one can be expressed as decompose the whole problems into subproblems and then each subproblem is solved using linear programming. On the other hand, the problem can be solved directly by revised simplex technique in second approach.

MIP can be solved by using branch and bound procedure. This procedure is based on four repetitive steps,

- ✓ solution space (i.e., set of decision variables under considerations) is portioned into subsets in ‘branching’ step,
- ✓ subset is eliminated from further consideration, if all elements of that subset violate the constraints of optimization problem in ‘elimination’ step
- ✓ lower bounds of subsets are determined in ‘bounding’ step
- ✓ each subset, which has higher lower bound than the upper bound of the minimization problem , is also eliminated in ‘selection’ step

Convergence takes place when algorithm reaches only one subset of decision variables, whose upper and lower bounds are equal.

- Lagrange relaxation (LR) [6, 7]

UC problem can be written by using three terms in Lagrange relaxation method. First term is a cost function that is sum of terms each related with a single unit. Second term is a set of constraints related with a single unit. The last term is that a set of coupling constraints, which is one for each hour in commitment period, are related with all of the units. Utilization of that method in production UC is more recent than DP. Preferring this method for solving UC problem is more beneficial for utilities with large number of units, since the degree of suboptimality goes to zero as the number of units increases. However, inherent suboptimality is the main disadvantage of this method.

- Tabu search [7]

Tabu search is an applied powerful optimization procedure to solve combinatorial optimization problems. However this technique is not suitable for large-scale systems since searching process does not guarantee an optimum solution.

- Expert system [7]

Expert system is a computer-based tool which has knowledge from the experiences of the system operators and existing problem.

- Artificial neural network [7]

Artificial neural networks is principally based on modeling the behavior of biological neural networks. This method has the motivation of using parallel processor computing instead of traditional serial computing.

- Fuzzy Systems [5]

Behaviour of a system, the systems' characteristic, and response are qualitatively described in fuzzy system without the necessity of exact mathematical formulation.

- Genetic Algorithms [7]

It is a general-purpose stochastic and parallel search method which uses the mechanism of natural selection and natural genetics. Although the constraints can be easily integrated to algorithm, global optimum schedule is not guaranteed for genetic algorithm (GA).

- Evolutionary Programming [5]

Although evolutionary programing is quite similar to genetic algorithm, it has an advantage of good convergence performance and significant speedup over traditional GA.

Range of these methods is from basic rule-of-thumb techniques to reasonably complex and theoretically complicated approaches [4]. Integer and Linear Programming method is recently preferred one among these methods, since the representation of the problem is straightforward while solution techniques for the Mixed Integer Linear Programs (MILP) are well developed. Details of mixed integer linear programming will explain in following part.

2.2 Security Constrained Unit Commitment

Adequacy and security of power system is defined as "The reliability of a system is interpreted as satisfying two functions: adequacy and security. An adequate amount of capacity resources must be available to meet the peak demand (adequacy), and the system must be able to withstand changes or contingencies on a daily and hourly basis (security)" in reference [8]. In classical unit commitment problem, adequate power system operation is guaranteed. However transmission line capacities are not considered in optimization process. Consequently, commitment result can be possibly violating the power carrying capacity of transmission lines.

In literature, new unit commitment concept Security Constraint Unit Commitment (SCUC), is introduced as a program to plan a secure and economical hourly generation schedule which the independent system operator (ISO) executes for the Day-ahead Market (DAM) [9]. SCUC can be defined as unit commitment model which takes into account network characteristics and constraints [10]. In addition to unit commitment problem, line power carrying capacity limit constraints are integrated into optimization problem in SCUC problem in order to commit units by avoiding power line capacity violation.

Additional constraints of SCUC problem are defined by used load flow analysis method. If DC load flow analysis is used in commitment problem, only line flow constraints are inserted into algorithm. DC load flow generally is adequate in SCUC problem. When AC load flow analysis is used in security check of system, bus voltage constraint should also be inserted to SCUC algorithm in addition to line flow constraint. In this thesis, A DC power flow embedded algorithm is used so only the active power flows on transmission lines are considered in order to check thermal limits of lines.

SCUC algorithm utilizes the detailed information submitted by market participants, such as the properties of generating units, availability of transmission capacity, generation offers or generation costs and demand bids or forecasted demand in order to determine the lowest cost unit commitment decisions while considering all system and unit’ constraints. Some ISOs make a schedule by using SCUC in some power markets in the world. As it is stated in [8], there are two possible structures for an ISO. In first structure (MINISO) is mainly focus on transmission security in the operation of the power market. This type of ISO such as California ISO has no legal power over forward energy markets and very limited control over actual generating unit schedules. In second structure for an ISO is defined as MaxISO. At that structure, power exchange (PX) is integrated to ISO’s operation. The PX is defined as an independent, non-governmental and non-profit entity. The market-clearing price (MCP) based on the highest price bid in the market is calculated by the PX. In some market, some extensive data, such as cost data for every generator, and daily demand for every consumer or load, must be provided, by market participants. PJM ISO and National Grid Company (NGC) in the United Kingdom are examples of MaxISO which have wide range authority and control [8].

SCUC engine has been used by the many United States' ISOs such as PJM, MISO, ISO New England, California ISO, New York ISO and ERCOT in Day-ahead market (DAM), day-ahead unit commitment for reliability (RUC), look-ahead unit commitment (LAUC), and real-time market (RTM) applications. Those SCUC applications are briefly described as follows in reference [11];

- "DAM determines the 24-h status of the generating units for the following day based on financial bidding information such as generation offers and demand bids".
- "RUC, which focuses on physical system security based on forecasted system load, is implemented daily to ensure sufficient hourly generation capacity at the proper locations".
- "LAUC, as a bridge between day-ahead and real-time scheduling, constantly adjusts the hourly status of fast start generating units to be ready to meet the system changes usually within the coming 3–6 h, especially for incorporating large-scale intermittent renewable energy like wind and solar into the power system".
- "RTM further recommits the very fast start generating units based on actual system operating conditions usually within the coming two hours in 15-min intervals"[11].

2.3 Mixed Integer Programming

"Mathematically, SCUC is a nonconvex, nonlinear, large-scale, mixed-integer optimization problem with a large number of 0–1 variables, continuous and discrete control variables, and a series of prevailing equality and inequality constraints. From the viewpoint of computational complexity, SCUC is in the class of **N**on-deterministic **P**olynomial-time hard (NP-hard) problems and cannot be solved in the polynomial time. Therefore, some efficient algorithms have to be studied in order to obtain the optimal or near-optimal solution of SCUC" [11].

Although various optimization techniques can be used to solve unit commitment problem; LR and MIP methods are the most widely applied methods to solve SCUC [12]. Advantage of MIP over other UC models is listed in reference [13] as global optimality, more flexibility and accuracy in modelling capabilities and direct measure of optimality of a solution. The MIP solver guarantees indeed globally optimal solution. In MIP approach, cost functions and constraints are accurately and easily modelled.

Although MIP's tremendous computational burden seems as an obstacle for applying MIP approach to solve SCUC problem in the past, MIP is becoming widely used in the electricity sector due to significant improvements on MIP solvers [14]. For example; PJM, which operates the largest wholesale electricity market in the world with a peak electricity demand of 165,500 MW (at 2014), prefer to use MIP-based commitment program instead of unit commitment program that was based on a LR algorithm in 2005 [15].

An MIP-based UC optimization problem has the following general form:

$$\text{Min } \boldsymbol{c}^{\boldsymbol{T}}\boldsymbol{x} + \boldsymbol{d}^{\boldsymbol{T}}\boldsymbol{y}$$
$$\textbf{s.t. } \text{Min } \mathrm{A}\,\boldsymbol{x} + \mathrm{E}\,\boldsymbol{y} \le \boldsymbol{b}$$
$$\boldsymbol{x} \in \{0,1\}, \boldsymbol{y} \ge \boldsymbol{b}$$

where

x binary (e.g., unit commitment states) decision variables
and **y** continuous (e.g., unit MW generation) decision variables,
c and **d** are corresponding cost vectors,
A, E and $\boldsymbol{b}$ are proper linear coefficient matrices.

A mixed integer-programming problem may contain both integer and continuous variables. If the problem contains an objective function without a quadratic term, (a linear objective), then the problem is termed a MILP. Definitions of different types of MIP are tabulated in Table 1.

In order to build the MILP model, all cost functions of generating units and UC constraints have to be linearized. Generally two general algorithms, branch-and-bound and cutting planes, are developed to solve MIP problems. Successful branch-and-cut algorithm is obtained by combining advantages of these two algorithms for solving MIP-based UC problem [11].

Table 1 Types of MIP [16]

Problem Type	**Has integer variables**	**No quadratic terms in the objective Function**	**Has quadratic terms in the objective Function**	**Has quadratic terms in constraints**
Mixed integer linear programming (MILP)	X	X		
Mixed integer quadratic programming (MIQP)	X		X	
Mixed integer quadratically programming (MIQCP)	X		Possibly	X

2.4 Wind Power Generation

Plentiful, environmentally friendly renewable generations such as wind and solar energies are rapidly deployed, because environmental impacts of the electricity section become more significant [17]. Nowadays 2.5 % of global electricity supplied by wind power and it is expected that this percentage will be increased to 12% in 2020 [18]. Total installed wind power capacity in world has reached to approximately 370.000 MW at the end of 2014 and it is also expected that this capacity will reach to 600.000 MW in 2018 [18]. Historical development of installed capacity can be seen in Figure 1 [19].

Basically when wind blows, wind energy is available, and power level depends on wind speed. Thus, variations of wind speed cause to frequent and random power fluctuation and therefore security and reliability of the existing power system is affected negatively at high penetration levels of wind units. Planning, operation and control of power system turns to more challenging issue for wind resources integrated power system. It is because of natural characteristic of wind power plants, which differ from conventional unit [20].

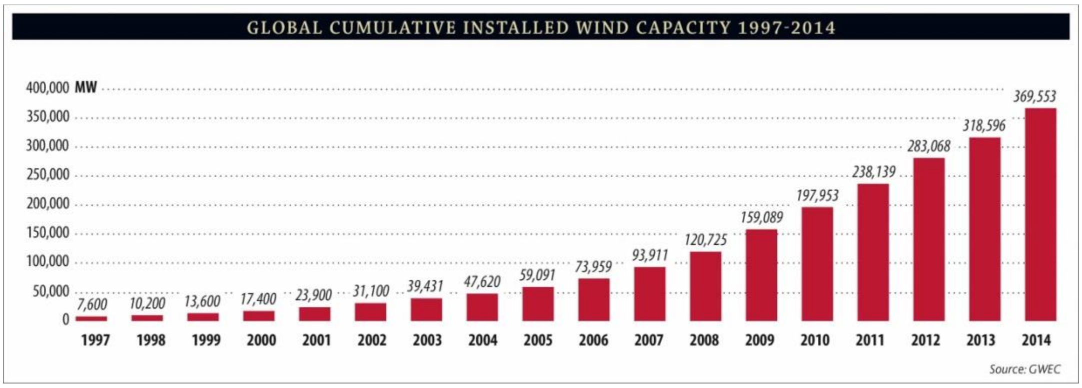

Figure 1 Historical development of installed wind capacity 1997-2014 [19]

The technical operation of the system and its expansion planning have been affected by integration of intermittent wind power into existing power system. Unit commitment and dispatch turns to more problematic issue when integrating more wind power into power systems. To guarantee operational reliability and improve system security, additional reserves must be allocated. Because of wind’s intermittency, other power units have to be operated more flexibly to maintain system reliability.

One of the solutions being proposed to improve the reliability and performance of these systems is to integrate energy storage systems into the power system network. Reliability and flexibility of power system can be increased with the usage of energy storage system.

2.5 Energy Storage Technologies

Although power system can operate effectively without storage, more efficient and reliable grid can be obtained by integrating cost-effective energy storage systems. Also having energy storage system may be a solution for mitigating volatility and intermittency of wind energy. Because electrical energy cannot be stored directly, it could be stored in others forms such as potential, chemical, magnetic or kinetic [21]. Energy storage system can be categorized according to methods they use. These categories are as follows;

- Electromechanical energy storage systems
  - ✓ Pumped storage hydro (PSH)
  - ✓ Compressed air energy storage (CAES)
  - ✓ Flywheel energy storage
- Electrochemical battery energy storage
  - ✓ Lead-acid battery
  - ✓ Sodium-Sulfur (NaS) and Sodium-Nickel –Chloride batteries
  - ✓ Nickel-cadmium battery (Ni-Cd)
  - ✓ Flow batteries
- Electric and magnetic energy storage
  - ✓ Capacitors and super capacitors
  - ✓ Superconducting magnetic energy storage (SMES)
- Power to gas energy storage
  - ✓ Hydrogen storage
  - ✓ Methane synthesis and storage [22]

- Thermal storage methods
    - ✓ Chilled Water Thermal Storage
    - ✓ Heat Thermal Storage
    - ✓ Ice Thermal Storage
    - ✓ Molten Thermal Storage [23].

Although, many forms are available to store electrical energy, mechanical energy storage systems, especially PHS, are by far the most widely used one. 142 GW pumped hydro system capacity is in service in 2015 [23]. Figure 2 shows the worldwide installed and operational storage capacity for electrical energy in 2010. As it can be seen from the chart, PSH is the dominant storage method. This method is kept out scope in Figure 3 in order to shows details of other storage methods. Figure 3 also show that there will not be any significant improvement of installed capacity of other types of storage methods up to 2020. In this graph, only CAES and flywheel are classified as electromechanical types. Figure 4 shows the chronological improvement of installed capacity of global energy storage. Installed PSH capacity will reach to 147 GW in 2020.

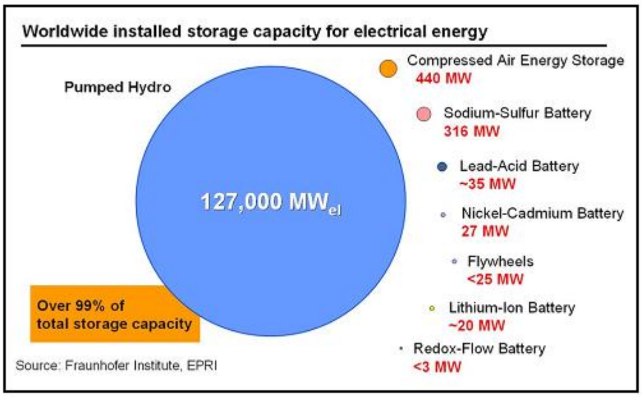

Figure 2 Worldwide installed storage capacity for electrical energy in 2010 [22]

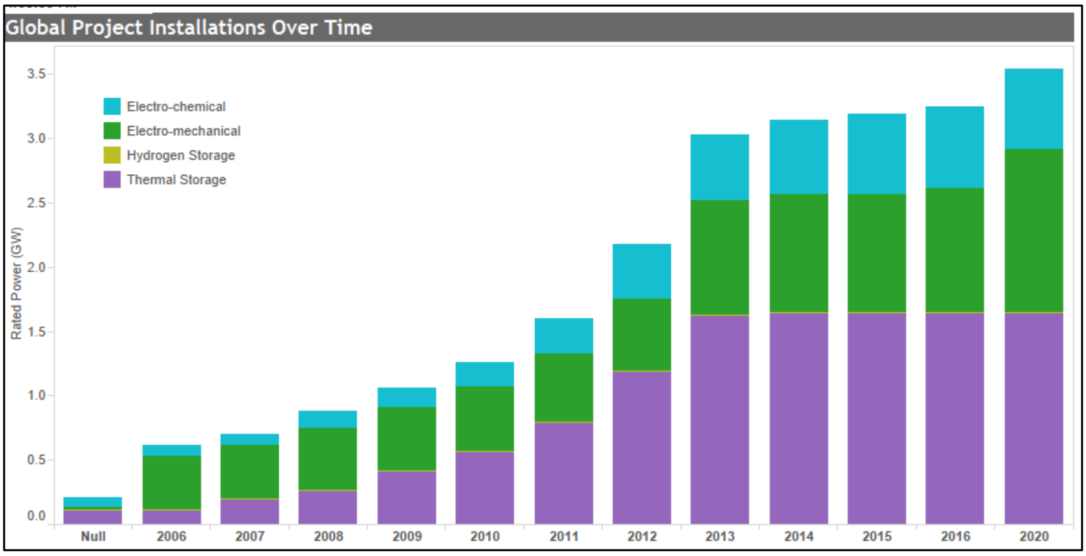

Figure 3 Cumulative worldwide installed and announced energy storage capacity for all methods except PSH since 2005 up to 2020 [23]

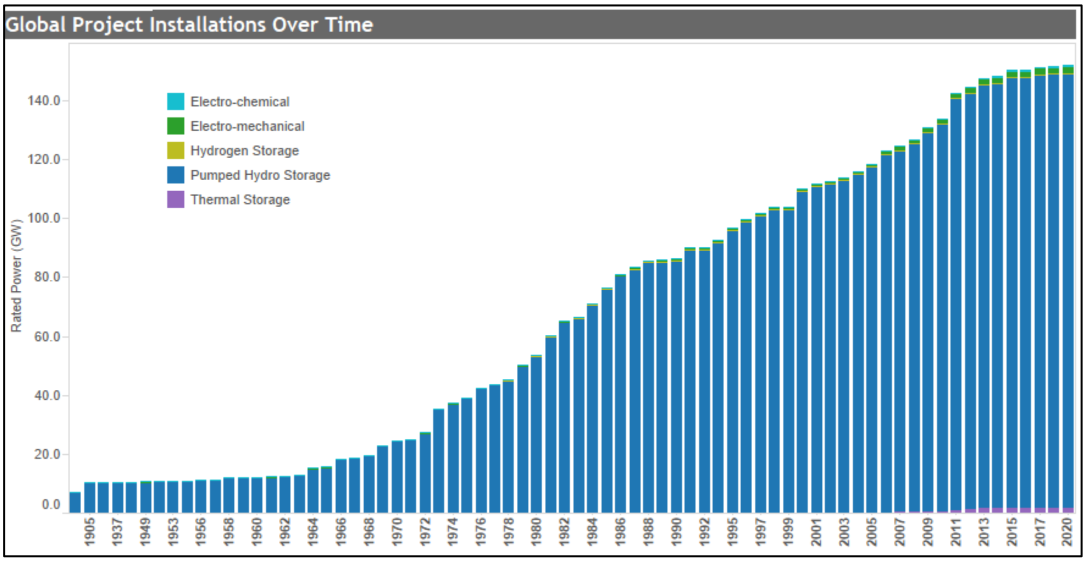

Figure 4 Cumulative worldwide installed and announced energy storage capacity since 1905 up to 2020 [23]

Although generation and system level application are considered and examined in this thesis, a lot of different energy storage applications are available for whole scale of storage size. These applications are summarized at Table 2.

Wholesale energy services and renewable integration application are highly related with SCUC problem for ESS integrated power system. Requirements of energy storage for these applications are listed in Table 3 [24].

Although most of the electrical energy storage methods are not suitable for large-scale grid application; PSH, CAES and lead-acid ESS technologies are possible alternatives for large scale applications. Summarized technical characteristic of ESS system are tabulated at Table 4 [22]. Power ranges of ESS technologies, which are given in table, are theoretical ones. Largest power rated ESSs in the world, which are in services or under construction, are tabulated at Table 5.

Table 2 Summarized definition of energy storage applications [22]

Value Chain	**Application**		**Description**
Generation & System Level Application	1	Wholesale Energy Services	Utility-scale storage systems for bidding into energy, capacity and ancillary services markets
	2	Renewables Integration	Utility-scale storage providing renewables time shifting, load and ancillary services for grid integration
	3	Stationary Storage for T&D Support	Systems for T&D system support, improving T&D system utilization factor and T&D capital deferral
T&D System Applications	4	Transportable Storage for T&D support	Transportable storage system for T&D system support and T&D deferral at multiple sites as needed
	5	Distributed Energy Storage	Centrally managed modular system providing increased customer reliability, grid T&D support and potentially ancilary services
	6	ESCO Aggregated Systems	Residential-customer-sited storage aggregated and centrally managed to provide distribution system benefits
	7	C&I Power Quality and Reliability	System to provide power quality and reliability to commercial and industrial customer
T&D : Transmission and Distribution; C&I : Commercial and Industrial ; ESCO : Energy Services Company			

Capital cost of ESS depends on many different factors for each individual type. PSH is chosen to give an example of ESS's cost items. The construction and installation cost of PSH can be estimated as twice as conventional hydropower plants with similar capacity. Besides, geological and topographical characteristics of examined site have also great effects of PSH system Total Capital Cost (TCC). Cost items that have effect on capital cost of PSH are listed in Table 6 [22].

Although capital cost of ESS technologies depend on many factors, authors of reference [22] make detailed literature search to find out capital cost of ESS technologies. Tabulated search results can be examined in Table 7 for all possible alternative ESS system.

Table 3 Requirement of ES application [24]

Application	Description	Size	Duration	Cycles	Desired Lifetime
Wholesale Energy Services	Arbitrage	10-300 MW	2-10 Hr	300-400/y	15-20 yr
	Ancillary Services	See note 2	See note 2	See note 2	See note 2
	Frequency regulation	1-100 MW	15 min.	>8000 / y	15 yr
	Spinning Reserve	10-100 MW	1-5 Hr		20 yr
Renewables Integration	Wind integration ramp & Voltage support	1-10 MW distributed 100-400 MW centralized	15 min.	5000/y 1000 full energy cycles	20 yr
	Wind integration off-peak storage	100-400 MW	5-10 Hr	300-500/ yr	20 yr
	Photovoltaic integration time shift, voltage sag, rapid demand support	1-2 MW	15 min-4 Hr	>8000 /yr	15 yr
1. Size, duration and cycle assumptions are based on Electrical Power Research Institute's (EPRI) generalized performance specification and requirements for each application, and are for the purposes of broad compression only, Data may vary greatly based on specific situations, applications, site selection, business environment etc. 2. Ancillary services encompass many market functions, such as black start capability and ramping services, that have a wide range characteristics and requirements					

Table 4 Technical characteristic of electrical energy storage systems [22]

ESS Technology	Power Range (MW)	Discharge Time (ms-h)	Overall efficiency	Storage Durability	Self-discharge (per-day)	Life-time (y)	Life Cycles (Cycles)
PSH	10-5000	1-24 h	0.70 - 0.82	h - months	Negligible	50 - 60	20,000 - 50,000
CAES Underground	5-400	1-24 h	0.70 - 0.89	h - months	Small	20 - 40	>13,000
CAES Aboveground	3 - 15	2-4 h	0.70 - 0.90	h - days	Small	20 - 40	>13,000
Lead-acid	Up to 20	s-h	0.70 - 0.90	min - days	0.1 - 0.3 %	5 - 15	2,000 - 4,500
NANiCl2 (ZEBRA)	50	s-h	0.86 - 0.88	s - h	15 %	15	2,500 - 3,000
Ni-Cd	Up to 40	2-5 h	0.60 - 0.73	min - days	0.2 - 0.6 %	10 - 20	2,000 - 2,500
Fe-Cr	1-100	4-8 h	0.72 - 0.75	-	-	10 - 15	>10,000
PSB	15	s-10 h	0.65 - 0.85	h - months	Small	10 - 15	2,000 - 4,500

Table 5 Largest power rated ESS in world [23]

Status	Type	Name	Country	Rated power (MW)	Duration (hh:mm)
Operational	PSH	Bath County Pumped Storage Station	US	3030	10:18
	CAES	Kraftwerk Huntorf	Germany	321	2:00
	BESS	Duke Energy Notrees Wind Storage Demonstration Project	US	36	0:40
Under construction	PSH	Hongping Pumped Storage Power Station	China	2400	n/a
	CAES	Adele CAES Project	Germany	200	5:00
	BESS	Sendai Substation Lithium Ion Battery Pilot Project	Japan	40	0:30

Table 6 Cost items of PSH [22]

Direct Costs	**Indirect Costs**	**Other Costs**
Civil works (storage section)	Planning and investigation	Transmission interconnections
✓ Power station costs	Environmental studies	Infrastructure upgrade
✓ Dams, spillways, water diversion, and embankments	Licensing and permitting	Initial charging energy (filling)
✓ Intakes	Preliminary and final design	Pumping
✓ Surface penstocks	Quality assurance	Life cycle operation and maintenance
✓ Vertical shaft	Construction management	Time cost of money
✓ Horizontal power tunnels	Administration	Escalations
Steel-lined tunnel		Interest during construction
Electromechanical works (PCS)		Bank fees
Transmission works		Depreciation
Switchyard		

Table 7 TCC of different ESS systems [22]

EES Technology	**Configuration**	**Total capital cost [a] (TCC) per unit of power rating (€ / kW)**			**Total capital cost [a] (TCC) per unit of storage capacity [b] (€ / kWh)**		
		Min.	**Average**	**Max**	**Min.**	**Average**	**Max**
PSH	Conventional	1030	1406	1675	96	137	181
CAES	Underground	774	893	914	48	92	106
	-	1286	1315	1388	210	263	278
Lead-acid	-	1388	2140	3254	346	437	721
NANiCl2 (ZEBRA)	-	874	1160	1786	973	1095	1211
Ni-Cd	-	2279	3376	4182	596	699	808
Fe-Cr	-	1376	1400	1425	527	569	611
PSB	-	927	1093	1308	1071	1147	1153
a: It should be noted that the capital costs are calculated based on typical discharge time (storage size) for each technology, which is not necessarily the same among different ESS systems. Minimum and maximum values are the bands of interquartile range (middle- fifty likelihood) and the average value is the median of whole sample, excluding outliers. It should be noted that the costs of grid interconnections and infrastructure requirements are not included in this estimation.							
b : For the batteries, the storage capacity is equivalent to the rated depth of discharge.							

2.6 Literature Review on the SCUC Problem

Many approaches and programming methods are utilized and evaluated in literature for UC problem. Reference [4] is a bibliographical survey study of UC, which is published in 2004. It includes explanations of approaches which have range from simple rule of thumb methods to theoretically complicated ones. Reference [5] is also about the collected UC methodologies from literature. Methods are classified in three groups, which are deterministic techniques, metaheuristic approaches and hybrid approaches in that paper. As it is stated in [25], that formulation and solution methods are evolved and developed from early ones based on priority list and dynamic programming to the most commonly used ones based on mixed integer programming. UC problem turns to SCUC problem with the incorporate with the transmission security constraints and bus voltage constraints. Modelling and solution of the SCUC is also studied in several works such as [26, 12, 9, 11].

In literature, UC and SCUC problems can be solved by using deterministic and stochastic approaches. Stochastic approach becomes more attractive than deterministic one, since uncertainty of power system operations is increased due to the large-scale integration of renewable energy resources and demand. Methods and applications are reviewed in [27] for stochastic optimization of UC.

Short term operation planning should be made by considering volatility and intermittency of renewable sources in power system which has high penetration level of renewable sources. The unexpected failures of transmission lines and generating units, and “Wind Power Generation (WPG) and demand forecast errors” are two kind of uncertainty factors considered in stochastic approach. In [27], both of them are taken into account in stochastic (SCUC) problem solution algorithm. On the other hand, WPG and demand forecast errors are only taken into account as uncertainty sources in [28].

In stochastic approach, scenario generation and reduction techniques should be applied to obtain computationally manageable problem and adequate simulation precision. Monte Carlo simulation with Latin hypercube sampling is utilized to generate scenarios in [27]. On the other hand, roulette wheel mechanism and lattice Monte Carlo simulation are used to generate scenarios in [29].On the other hand, four different scenario reduction techniques are also available in literature to reduce number of scenarios for stochastic UC. K-means scenario reduction, backward scenario reduction, fast forward scenario reduction and importance-sampling scenario reduction, are four different methods which are compared in [30].

With increase of penetration levels of renewables, energy storage systems are accepted as one of the possible alternative solutions for mitigating volatility and intermittency of them. Following papers are related with UC problem for ESS integrated systems.

In [20], CAES is chosen as alternative solution to deal with intermittency in wind generation in SCUC problem. Formulation of CAES in SCUC problem is defined in that study. Deterministic SCUC problem is solved for simple eight bus system. Sensitivity analysis of CAES size is also made for that system. Similarly, same authors examine deterministic SCUC problem results for CAES integrated sample power system at [31] in terms of local marginal price (LMP), peak-shaving and wind curtailment. IEEE 118 bus system is used as sample system in addition to eight bus simple system in [31].

In [21], SCUC problem is examined at ESS integrated simple 8-bus system for different level of wind penetration. Battery Energy Storage System (BESS) is considered as an alternative system to store energy. Formulation of BESS is also proposed at that study. Deterministic SCUC problem is solved for simple eight bus system. The effects of ESS on wind curtailment, peak generation system operational cost and local marginal price are examined.

In [32], the effects of BESS on peak generation and operation cost are examined in deterministic SCUC problem for IEEE 24 bus system. BESS are also used to support operating reserve requirement of the system at this study. Annual benefit is also determined for BESS integrated system by using different typical load scenarios in a year.

In order to overcome the volatility of wind power generation, wind unit generation is coordinated with PSH. Coordination methodology for wind and PSH units in the day-ahead operation planning of power system is proposed at [33]. Intrahour modelling of wind energy is used in hourly coordination of wind-PSH in that study. Deterministic SCUC problem is examined in simple six bus system.

Two different strategies is proposed to coordinate PSH with wind unit in [34]. Decomposition of scenarios based stochastic SCUC problem into master and subproblems is preferred as a solution method. Day ahead forecast error of hourly load and wind speed, and random outages of generators and transmission lines are considered as the sources of uncertainty in stochastic scenarios. In that study, integration of ESS to power system defined as system level-coordination. However, the effects of ESS location and ESS storage size on production cost is not examined at that study. ESSs are located at same buses with wind units at modified IEEE 118 bus system. Hourly commitment and dispatch of conventional unit, expected operational cost and expected wind energy curtailment are investigated from stochastic SCUC results at different cases.

Finally, the effect of ESS on stochastic UC problem is examined in [35]. In order words, transmission security constraints are not considered in algorithm. Energy arbitrage, primary reserve and secondary reserve services of ESS are evaluated in different cases. Wind and solar generation forecast error are considered by generating stochastic scenarios. However, outages of lines and generators are not taken into account in that study. Economic effects of ESS are obtained from the result of consecutive stochastic UC simulation in full year operation. Sensitivity analysis is also performed to understand impacts of ESS under different circumstances

CHAPTER 3

MODELLING AND APPROACHES

The objective of the UC algorithm is to schedule commitment of units in the most economical manner. So the main goal in commitment problem is minimization of the objective function. This function is actually summation of cost functions (or bidding) of all units or which are commited to satisfy load demand. This problem has also some system and unit constraints. To derive a solution that satisfies security and reliability criteria of power system and minimizes total system cost, SCUC algorithm uses information submitted by market participants (characteristics of generating units), as well as system constraints (load balance & network constraints). Since SCUC is an optimization problem, a MATLAB code is constructed to obtain an input file of MILP optimization program. Actually the MATLAB code generates all variables and constraints which are necessary inputs of optimization tool IBM CPLEX 12.6. CPLEX is a tool for solving linear optimization problems, commonly referred to as LP problems. MIP problems are also be solved by CPLEX.

Methods proposed in [21] and [7] are used as a guide to determine functions, variables and contraints of SCUC algorithm.

The proposed MILP-based solution minimizes the production cost. The generated algorithm is tested using modified IEEE 24 bus sample system. All IEEE 24 Bus system data are obtained from [36], some modifications are made on that system. These modifications are integration of three wind units and dividing whole system into two zones by reducing some transmission line capacities. Properties of modified IEEE 24 bus system are declared in Appendix A part of thesis.

3.1 Modelling of constraints

All constraints of SCUC problem should be obtained in a suitable form of MILP. A MATLAB code is constructed to obtain following constraints, which are suitable format in order to be used by optimization tool.

3.2 Objective Function

The objective function of SCUC optimization problem is overall cost function of power generation which is composed of three basic terms. These are generation cost, start up and shutdown costs of thermal units for all scenarios. Wind power generation has no direct effect on overall cost. It assumed that wind farms have minute operation cost. As it can be seen from objective function, main objective of algorithm is minimization of expected operation cost of system for all scenarios. Since in deterministic approach, there is only one certain scenario, result of algorithm is obtained as day-ahead operation cost of that system.

$$\boldsymbol{Minimize}[\sum_{\boldsymbol{s=1}}^{\boldsymbol{S}} \boldsymbol{\rho_s} * \sum_{\boldsymbol{i=1}}^{\boldsymbol{I}} \sum_{\boldsymbol{t=1}}^{\boldsymbol{NT}} [\boldsymbol{C_{i,t,s}} + \boldsymbol{y_{i,t}} * \boldsymbol{ST_{i,t}} + \boldsymbol{z_{i,t}} * \boldsymbol{SD_{i,t}}\ ]$$

subject to all unit and system constraints. All considered constraints are defined as follows.

3.3 Thermal Unit Constraints

3.3.1 Cost Function

Below equations can be used to express unit’s convex piecewise linearized cost function, the cost function involves the no-load cost and incremental costs terms.

$$C_{i,t,s} = C_{i0}\ * u_{i,t,s} + \sum_{m}^{M} IC_{im} * px_{i,m,t,s}$$

$$p_{i,t,s} = \sum_{m}^{M} px_{i,m,t,s}$$

$$0 \leq px_{i,m,t,s} \leq MW_{i,m} \quad , \forall\, t, \forall\, m, \forall\, s \tag{1}$$

where $px_{i,m,t,s}$: utilized power amount in segment m of unit i at hour t in scenario s

For non-convex cost function, formulation is modified a little. For first and last piece of cost function, a sigma variable added to formulation. This variable is inserted to algorithm in order to make sure all previous power segments (from 1 to m-1) are fully utilized before using any power in segment ‘m’.

$$MW_{i,1} * \delta_{i,1,t,s} \leq px_{i,1,t,s} \leq MW_{i,1} * u_{i,t}\text{, m=1 (the first piece)}$$

$$MW_{i,m} * \delta_{i,m,t,s} \leq px_{i,m,t,s} \leq MW_{i,m} * \delta_{i,m-1,t,s} \quad ,2 \leq m \leq M-1$$

$$0 \leq px_{i,m,t,s} \leq MW_{im} * \delta_{i,m-1,t,s} \text{ , m=M (the last piece)} \tag{2}$$

3.3.2 Capacity

All units have some generation capacity which has minimum and maximum limits. So below constraint (3) is added to formulation to keep unit’s generation in their operation range.

$$u_{i,t} * PMIN_i \leq p_{i,t,s} \leq u_{i,t} * PMAX_i \tag{3}$$

3.3.3 Startup-Shutdown Indicator

If a unit changes its status from offline to online, startup indicator is used to indicate this status changes. Shutdown indicator also indicates transition of units from on state to off state. Both of these binary indicators cannot be equal to one simultaneously. Startup and shutdown constraints of conventional units can be defined by using equations (4).

$$y_{i,t} + z_{i,t} \leq 1$$

$$y_{i,t} - z_{i,t} = u_{i,t} - u_{i,t-1} \tag{4}$$

3.3.4 Ramp-Up/Down Limits

From one time period to the next one, generation of a unit cannot be increased more than its maximum increment (called as ramping up limit) limit. Similarly, a unit cannot decrease its output between two consecutive hours more than decrement limit, called as ramping down limit. Indeed, unit generations can only be $\mathrm{PMIN_i}$ both rights after start up and just before shut down. Therefore, these constraints can be included to algorithm by inserting equation (5) and (6).

For $\forall\ \mathrm{t} = 1, \dots, NT$

$$p_{i,t,s} - p_{i,t-1,s} \leq y_{i,1} * PMIN_i + (1 - y_{i,t}) * RU_i \tag{5}$$

$$p_{i,t-1,s} - p_{i,t,s} \leq z_{i,1} * PMIN_i + (1 - z_{i,t}) * RD_i \tag{6}$$

3.3.5 Reserve Limits

The summation of power generation and spinning reserve support of unit cannot be more than its maximum generation capacity (7). The 10-minute spinning reserve of a unit is the unloaded synchronized generation that can ramp up in 10 minutes. Spinning reserve support of unit is determined by the maximum sustained rate of unit (8) Operating reserve is the unloaded synchronized/unsynchronized generating capacity that can ramp up in 10 minutes. When unit is in operation, its operating reserve is the same as spinning reserve. For down units, operating reserve is limited by units quick start capability. Relation between spinning and operating reserve support of units is defined in equation (9).

$$p_{i,t,s} + sr_{i,t,s} \leq PMAX_i \tag{7}$$

$$0 \leq sr_{i,t,s} \leq 10 * MSR_i * u_{i,t} \tag{8}$$

$$or_{i,t,s} \leq sr_{i,t,s} + \left(1 - u_{i,t}\right) * QSC_i \tag{9}$$

3.3.6 Minimum Up Time Constraints

When a unit is started at any time, this unit must stay in on mode for at least specific time (minimum up time) duration before it shutdowns again. So this requirement can be implemented by using the following constraints in optimization problem.

$$UT_i \leq max\{0, min[NT, (MU_i - TU_{i0}) * u_{i0}]\}$$

$$\sum_{t=1}^{UT_i}(1 - u_{i,t}) = 0$$

$$\sum_{m=t}^{t+MU_i-1} u_{i,m} \geq MU_i * y_{i,t} \qquad \forall\, t = UT_i + 1, \ldots., NT - MU_i + 1$$

$$\sum_{m=t}^{\mathrm{NT}}(u_{i,m} - y_{i,t}) \geq 0 \qquad \forall\, \mathrm{t} = NT - MU_i + 2, \ldots, NT \tag{10}$$

3.3.7 Minimum Down Time Constraints

When it is stopped at any time, this unit must stay in off mode for at least specific time (minimum down time) duration before it starts up again. So this requirement can be implemented by using the following constraints in optimization problem.

$$DT_i \leq max\{0, min[NT, (MD_i - TD_{i0}) * (1 - u_{i0})]\}$$

$$\sum_{t=1}^{DT_i} u_{it} = 0$$

$$\sum_{m=t}^{\mathrm{t}+MD_i-1}(1 - u_{i,m}) \geq MD_{\mathrm{i}} * \mathrm{z}_{\mathrm{i,t}} \;, \forall\, \mathrm{t} = DT_i + 1, .., NT - MD_i + 1$$

$$\sum_{m=t}^{\mathrm{NT}}(1 - u_{i,m} - z_{i,t}) \geq 0 \qquad \forall\, \mathrm{t} = NT - MD_i + 2, \ldots, NT \tag{11}$$

3.4 Wind Power Constraints

Both deterministic approach and stochastic approach, forecasted values of wind power generation is supplied as an input to SCUC algorithm. Since wind power curtailment is allowed in proposed algorithm like in [34], dispatched wind power is limited by the hourly forecast. The relationship between the forecasted and utilized wind power is expressed using the following equation (12).

$$0 \leq pw_{w,t,s} \leq \ FWP_{w,t,s} \qquad \forall\, w, \forall\, t, \forall\, s \tag{12}$$

3.5 Constraints of ESS

Although power system can be operated effectively without storage, cost effective ways of storing electrical energy can help to make the grid more efficient and reliable. In this study, ESS is included to power system to observe the impact on SCUC. Firstly, constraints of BESS are explained. Secondly, pumped-storage hydro plant's constraints are stated.

3.5.1 Constraints of BESS

For BESS, there are some physical and technological limitations such as minimum/ maximum energy storage capacity, charge and discharge limits. Following BESS related constraints are inserted into algorithm. Reference [31] is used as a guide to construct these constraints of BESS.

3.5.1.1. Mode Constraints

A BESS has three operating modes; which are charging, discharging and idle modes. In charging mode, batteries are charged with utility power. On that mode, BESS behaves like a load and store energy. In discharging mode, batteries behave as generation unit, and they discharge stored energy to the grid. In idle mode, neither charging nor discharging process is active. Possibilities of mode variables of BESS are tabulated at Table 8 and stated as an equation (13).

Table 8 Mode variables of BESS

Variable	Charging mode	Discharging mode	Idle mode
$\boldsymbol{u_{k,t,s}}$	0	1	0
$\boldsymbol{uc_{k,t,s}}$	1	0	0

$$u_{k,t,s} + uc_{k,t,s} \leq 1 \quad \forall\, t, \forall\, k, \forall\, s \tag{13}$$

3.5.1.2. Energy Constraints

For BESS, charging efficiency (η_k) is defined as a ratio of rate of change in stored energy in battery to consumed power from grid in charging mode. (1/ η_k) can be defined as discharging efficiency of batteries. So energy balance equation can be obtained as given in eq. (14). The stored energy ($\boldsymbol{A_{k,t,s}}$) in batteries should also be kept in allowed range as given in eq. (15). And at the end of commitment period, BESS should have same amount of stored energy with beginning of commitment period as given in equation (16).

$$A_{k,t,s} = A_{k,t-1,s} + P^{ch}_{k,t,s} * \eta_k - P^{dch}_{k,t,s} * \left(\frac{1}{\eta_k}\right) \quad \forall\, t, \forall\, k, \forall\, s \tag{14}$$

$$A_{k,min} \leq A_{k,t,s} \leq A_{k,max} \quad \forall\, t, \forall\, k, \forall\, s \tag{15}$$

$$A_{k,t,s} = A_{k,0,s} \quad t = NT, \forall\, k, \forall\, s \tag{16}$$

3.5.1.3. Power Constraints

There are some physical and chemical limitations for charging and discharging speed of batteries. Therefore two constraints are inserted to algorithm in order to limit charging power ($\boldsymbol{P^{ch}_{k,t,s}}$) and discharging power ($\boldsymbol{P^{dch}_{k,t,s}}$) of BESS as given in eq. (17) and (18) respectively.

$$0 \leq P_{k,t,s}^{ch} \leq P_{k,max}^{ch} * uc_{kt} \quad , \forall\, t, \forall\, k, \forall\, s \tag{17}$$

$$0 \leq P_{k,t,s}^{dch} \leq P_{k,max}^{dch} * u_{kt} \quad , \forall\, t, \forall\, k, \forall\, s \tag{18}$$

3.5.2 Constraints of PSH

Pumped-storage hydro plant constraints can be listed as mode, minimum and maximum water storage capacities and flow constraints. Following PSH related constraints are inserted into to algorithm. [12] is used as a guide to construct these constraints of PSH.

3.5.2.1. Mode Constraints

A PSH unit has three operating modes; these are pumping, generating and idle modes. In pumping mode, water is pumped from lower reservoir to upper one by using the electrical energy which is supplied from grid. In power generation mode, turbine of PSH is used to generate energy from stored mechanical energy at upper reservoir. In idle mode, neither power generation nor power consumption process is active. These modes can be stated by using following mode variables and equation (19). Possible sets of these variables are tabulated in Table 9.

$$u_{h,t,s} + up_{h,t,s} \leq 1 \quad , \forall\, t, \forall\, h, \forall\, s \tag{19}$$

Table 9 Mode variables of PSH

Variable	Pumping mode	Generation mode	Idle mode
$\boldsymbol{u_{h,t,s}}$	0	1	0
$\boldsymbol{up_{h,t,s}}$	1	0	0

3.5.2.2. Capacity Constraints

Mechanically stored energy can be measured with stored water volume in upper reservoir. Minimum and maximum levels of upper reservoir determine storing capacity and operational storing range of PSH.

The relation between water and power of PSH is expressed using two different curves. Slopes (μp_h and μg_h) of these curves are used to insert pumping power and generating power into water capacity constraint of PSH. Pumping efficiency and power generating efficiency are expressed by using these constants. So water balance equation (20) can be obtained as follows. The stored water ($\boldsymbol{Vol_{h,t,s}}$) in upper reservoir should also be kept in allowed range (21). And at the end of commitment period, PSH should have same amount of stored energy (water) with beginning of commitment period as it is stated in equation (22).

$$Vol_{h,t,s} = Vol_{h,t-1,s} + P_{h,t,s}^{pump} * \mu p_h - P_{h,t,s}^{gen} * \mu g_h \quad \forall\, t, \forall\, h, \forall\, s \tag{20}$$

$$Vol_{h,min} \leq Vol_{h,t,s} \leq Vol_{h,max} \quad \forall\, t, \forall\, h, \forall\, s \tag{21}$$

$$Vol_{h,t,s} = Vol_{h,0,s} \quad t = NT, \forall\, h, \forall\, s \tag{22}$$

3.5.2.3. Power Constraints

There are some physical limitations for pumping and generating flow and power of PSH. Thus, following two constraints are used to limit pumping power ($\boldsymbol{P_{h,t,s}^{pump}}$) and generating power ($\boldsymbol{P_{h,t,s}^{gen}}$) of PSH as given in eq. (23) and (24) respectively.

$$P_{h,min}^{pump} * up_{h,t} \leq P_{h,t,s}^{pump} \leq P_{h,max}^{pump} * up_{h,t} \quad \text{for } \forall\, t, \forall\, h, \forall\, s \tag{23}$$

$$P_{h,min}^{gen} * u_{h,t} \leq P_{h,t,s}^{gen} \leq P_{h,max}^{gen} * u_{h,t} \quad \text{for } \forall\, t, \forall\, h, \forall\, s \tag{24}$$

Since storage capacity and cycle efficiency of BESS can be explained easier than volume capacity and pumping and generating mode' water-power curves, BESS is chosen as ESS in rest of this thesis. On the hand, BESS, which has a specific storage capacity and efficiency values, can be easily replaced with PSH counterpart in algorithm by adjusting storage volume and generating and pumping mode water-power curve' slope values.

3.6 System Constraints

3.6.1 Line Flow Constraints

Power flow through a line is obtained with DC power flow calculation for dispatched units. As a criteria of system security, obtained power flow of all transmission lines in SCUC problem should not violate the thermal limits of them. So above constraint should be inserted to algorithm as an inequality (25).

$$0 \leq | FL_{l,t,s} | \leq FL_{l,max} \quad , \forall\, t, \forall\, l, \forall\, s \tag{25}$$

3.6.2 System Power Balance and Reserve Constraints

In addition to system demand requirement, reserve capacity is also required for secure and reliable operation of power system. As a rule of thumb, operating and spinning reserve can be defined as a ratio of demand amount**.** As can be seen from equation (26), system demand is supplied from generation of conventional units, wind units and ESS. On the other hand, spinning and operating reserve requirement of the system are only supplied from conventional unit's reserve support (27, 28).

$$D_{t,s} = \sum_{i=1}^{I} p_{i,t,s} + \sum_{k=1}^{K} (P_{k,t,s}^{dch} - P_{k,t,s}^{ch}) + \sum_{w=1}^{W} pw_{w,t,s} \quad , \forall\, t, \forall\, s \tag{26}$$

$$\sum_{i=0}^{I} sr_{i,t,s} + \geq SR_{t,s} \quad , \forall\, t, \forall\, s \tag{27}$$

$$\sum_{i=0}^{I} or_{i,t,s} \geq OR_{t,s} \quad , \forall\, t, \forall\, s \tag{28}$$

$$SR_{t,s} \quad = 5\,\% \;\; Dt,s$$

$$OR_{t,s} \quad = 7\% \;\; Dt,s$$

Since all of the constraints should be stated in a suitable format of MILP problem, an input file is generated in MATLAB. System power demand, system reserve requirements, unit’ generation limits and characteristics, unit’ linearized cost curves, line properties of system, system’ load distribution on buses and wind generations should be supplied to MATLAB code to obtain MILP input file. Modified IEEE 24 bus is used as sample system to apply SCUC problem. Relevant properties of that system are used as an input to constructed MATLAB code.

Formed input file is used by CPLEX optimization tool. Optimization problem is solved by CPLEX. Since result file of CPLEX is obtained in a text file format, another MATLAB code is generated to get all variable values.

3.7 Deterministic and Stochastic Approaches for SCUC Problem

In deterministic approach, wind generation and load are assumed that they will accrue exactly the same as forecasted values. However, the inherent variability and unpredictability of wind power are the main characteristics that should be accounted in SCUC problem, so deterministic approach is not a sufficient approach to SCUC problem. In order to consider uncertainty of wind power generation and forecasted load, stochastic approach is applied in some studies which are focused on SCUC problem for wind power integrated power system. In order to construct stochastic SCUC problem, probabilistic scenarios should be generated from hourly forecasted wind generation, and load.

For deterministic case, objective of SCUC algorithm is minimization of overall operation cost by using forecasted values for a specific deterministic scenario. On the other hand, for scenario based stochastic approach, units should be committed in order to minimize the expected operation cost for all possible scenarios’ wind generation and load values. The expected operation cost of all scenarios is calculated by considering load and wind power generation forecast errors.

In stochastic approach, scenarios are obtained from forecasted values. The Monte Carlo simulation is adopted in this study to generate scenarios for representing day-ahead forecast errors of hourly load and wind power generation. For this thesis, normal distribution function is used to take into account errors of forecasted load and wind power generation. In order to consider volatility of wind generation and load, it is assumed wind generation and load are subject to a normal distribution **$(N(\mu,\sigma^2))$** with forecasted powers as its expected value μ and a percentage of μ as its volatility σ. Total 1000 stochastic Monte Carlo scenario is formed from forecasted values, which is normally distributed with 5% and 3% standard deviation for forecasted wind power generation and forecasted load, respectively. A MATLAB code is constructed to generate scenarios of both wind generations and load values.

Scenario reduction should be applied to generated scenarios, to reduce calculation burden requirement of stochastic approach. In literature, three kinds of reduction method, k-means clustering, backward scenario reduction and forward scenario selection, are generally applied in stochastic approach of UC problem. In this thesis, k-means clustering is chosen as scenario reduction method. Statistical computing program ‘R’ is utilized to obtain clusters from all generated scenarios by using k-means clustering method. In order to consider all independent variables simultaneously, a matrix (1000 rows, 24*4=96 columns), composed all scenarios of wind generators and load, is given as an input to R program. Input matrix formation is illustrated in Figure 5. All hourly values of all of four independent variables are considered in clustering progress by ‘R’ program.

In result of ‘R’ program execution, ten Monte-Carlo stochastic scenarios and their probabilities are obtained. Each stochastic scenario contains hourly based daily wind power generation curves for each wind units and hourly based daily load curves. Stochastic scenarios’ values of wind power generation and load are given as tables at

APPENDIX B. Stochastic scenarios, which are the results of reduction process, are used as inputs to scenario based stochastic SCUC problems in following chapters.

When generated Monte Carlo scenarios of “hour 1 load” are examined with MATLAB statistic tool as an example, generated scenarios are fitted with a normal distribution. Probability distribution function of hourly load Monte Carlo scenarios can be examined in Figure 6. Similarly, probability distribution function of reduced scenarios of hourly load 1 and distribution fit of it also can be seen in Figure 7. Fitted curves of all generated scenarios and reduced scenarios have **1599,66** and **1599,63** mean values and **3%** and **0.6 %** standard deviations, respectively.

In rest of the thesis, some deterministic and Monte-Carlo scenario based stochastic cases for SCUC problem are formed and examined.

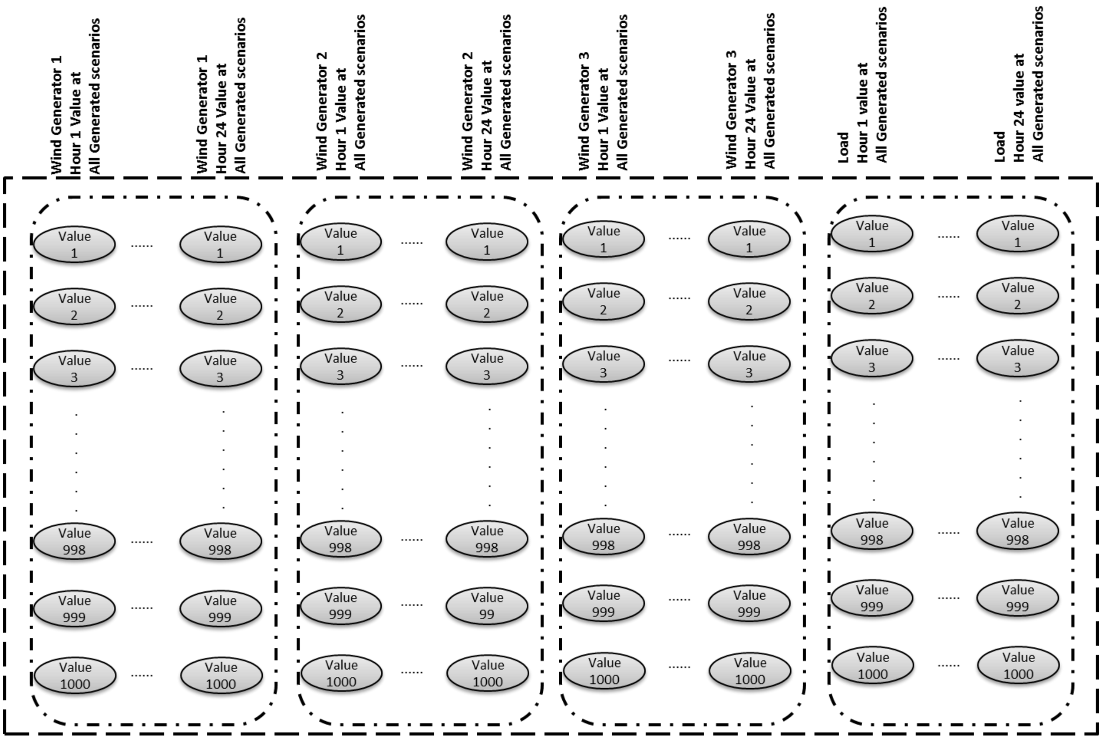

Figure 5 Input matrix formation of R program

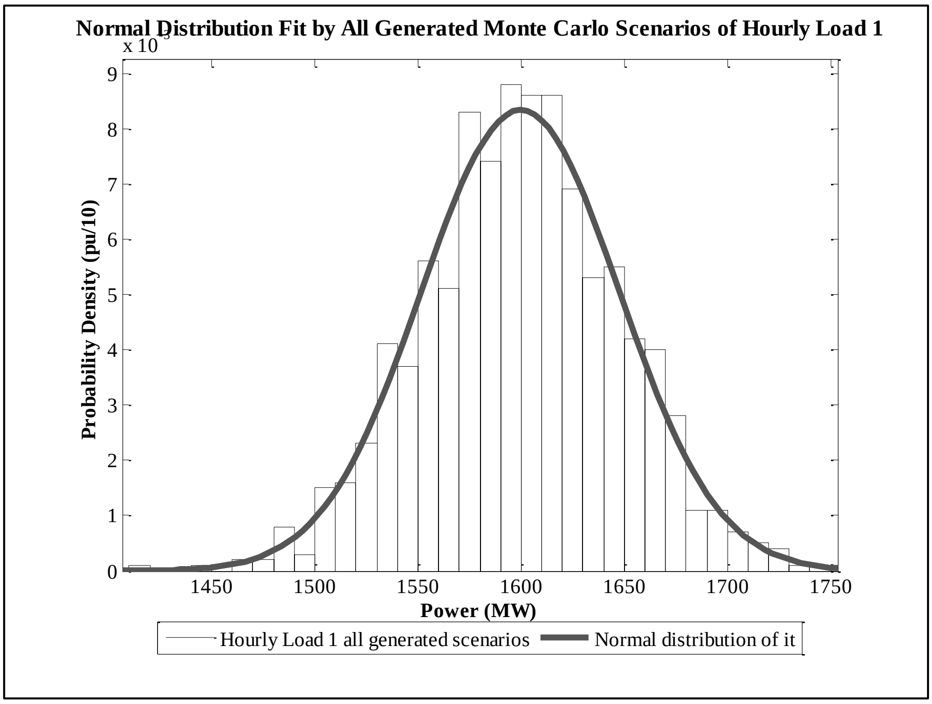

Figure 6 Normal distribution fit by generated Monte Carlo scenarios of hourly load 1

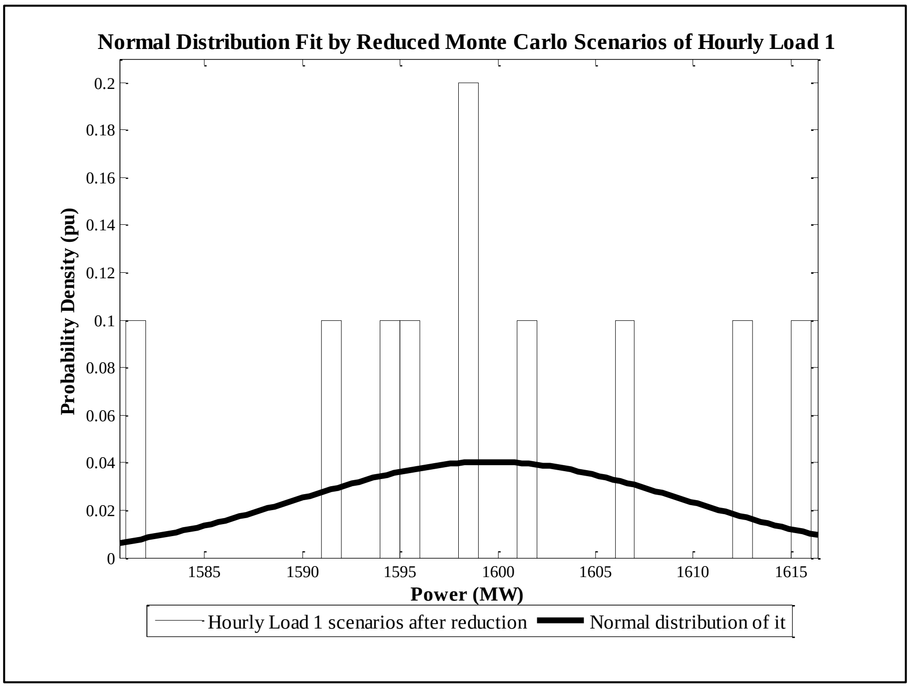

Figure 7 Normal distribution fit by reduced Monte Carlo scenarios of hourly load 1

CHAPTER 4

SIMULATION AND RESULTS

4.1 Optimization Tool CPLEX

In this thesis, SCUC problem is solved by using IBM ILOG CPLEX 12.6. It provides high-performance mathematical programming solvers for linear programming, mixed integer programming, quadratic programming, and quadratically constrained programming problems. CPLEX uses branch and cut algorithm to solve the problems. This algorithm actually combination of branch and bound algorithm and cutting plane algorithm.

In branch and cut algorithm, CPLEX solves a series of continuous subproblems. CPLEX builds a tree, in which each subproblem is a node, in order to manage those subproblems efficiently. The root of the tree is the continuous relaxation of the original MIP problem.

Applied cuts method is described in manual of CPLEX [16] as “if the solution to the relaxation has one or more fractional variables, CPLEX will try to find cuts. Cuts are constraints that cut away areas of the feasible region of the relaxation that contain fractional solutions.If the solution to the relaxation still has one or more fractional valued integer variables after CPLEX tries to add cuts, then CPLEX branches on a fractional variable to generate two new subproblems, each with more restrictive bounds on the branching variable. For example, with binary variables, one node will fix the variable at 0 (zero), the other, at 1 (one).”

The result of subproblems may be an all-integer solution, an infeasible solution, another fractional solution. If the solution is fractional, CPLEX repeats the process.

4.2 Case Study and Scenarios

In modified IEEE 24-bus system, three wind power units 1, 2 and 3 are located at buses 23, 14, 13, respectively. Conventional unit's properties, piecewise cost curves, system properties, load forecast and wind generation forecast should be supplied to SCUC algorithm as input. Detailed properties of that system and units are given in Appendix A part of this thesis. For this thesis, SCUC problem is solved for modified IEEE 24-bus system at two cases.

In case 1, the existence of ESS, size and location of ESS is examined in deterministic approach in different scenarios. In case 2, deterministic approach for SCUC problem is replaced with scenario based stochastic approach. At that case, the effect of integration of ESS on system operation cost and wind power curtailment in scenario based stochastic SCUC problem is examined . Cases are listed as follows;

- Case 1: Deterministic case
- Case 2: Scenario based stochastic case

4.2.1 Case 1: Deterministic Case

For deterministic case, it is assumed that load and wind power generation is forecasted completely true without any error. Therefore, load will occur exactly same as forecasted in commitment problem. On the other hand, partly utilization of forecasted wind power generation is allowed in SCUC algorithm.

In case 1, scenarios are constructed to examine and evaluate the effects of storage plant/s size and location on production cost result and wind power curtailment result of SCUC in deterministic approach. Listed scenarios are examined in following sections;

- Scenario 1 : Deterministic case without ESS
- Scenario 2 : Deterministic case with 200 MWh ESS at bus 14
- Scenario 3 : Deterministic case with 200 MWh ESS at bus 10

- Scenario 4 : Deterministic case with 40 MWh ESSs at buses 6, 7, 8, 10, 12
- Scenario 5-13: Deterministic case with various ESS storage sizes

4.2.1.1. Case 1, Scenario 1

For this scenario, SCUC problem is solved for wind unit integrated modified IEEE 24 bus system. Since there is no ESS on power system, this deterministic scenario is base scenario for deterministic approach. Obtained operation cost of this scenario is used as a reference to other scenarios of deterministic approach.

Following results are obtained from results of deterministic SCUC problem for case 1, scenario 1. Unit commitment result of this scenario and results of case 1 scenario 2 are combined and given in next scenario part. Daily system operation cost is obtained as **490,726 $** for this scenario.

Power generations of unit types are shown in Figure 8 for all hours. As it can be seen from figure, hydro units (P50s) are fully utilized with help of zero generation cost. Nuclear power unit (P400) is utilized more than %80 of its capacity for all hours. Different types of coal units (P350, P155 and P76) is started up and shut down in commitment period. On the other hand, some type of units, which have petroleum based fuel, (P12, P20, P100 and P197) are never committed during day.

Forecasted wind power generation is accepted as maximum limit for wind units' generation. Algorithm is free to curtail wind unit's power by considering whole constraints. As it is previously stated, curtailment of wind energy is allowed in some other works in literature such as [21] and [33]. No penalty factor of wind energy curtailment is included to objective function. Because of congested lines and technical constraint, some amount of available wind power generation may be curtailed by algorithm. Figure 9 contains utilized and forecasted wind generation curves of WUs in whole day. Although WPG 1 and 3 are completely utilized; WPG 2 is curtailed at some hours in commitment period. Daily total wind energy curtailment of WU 2 is found as **111 MWh**. This is because of congested interzonal lines, these lines capacities are intentionally reduced in order to show the effects of ESS on SCUC results for a system, which has congested lines.

When algorithm is constructed to allow wind power generation curtailment, lower production cost can be obtained by utilize WPG partly rather than fully by considering all constraints of SCUC problem. In order to verify this fact, SCUC algorithm is modified to force fully utilization of forecasted wind power generation. At that circumstance, operation cost is obtained as **491,468 $**. Contribution to power generation of unit type P76 increases while generated power of unit types P155, P350 and P400 decreased; when fully utilization of wind energy is forced in algorithm. Since production cost of P76 is higher than the other units (P155, P350 and P400), cost reduction can be obtained even if wind generation is curtailed. In other words, since energy requirement of loads on are more economically supplied from other sources instead of supplying from wind unit, less day-ahead production cost can be obtained by utilizing less wind power generation.

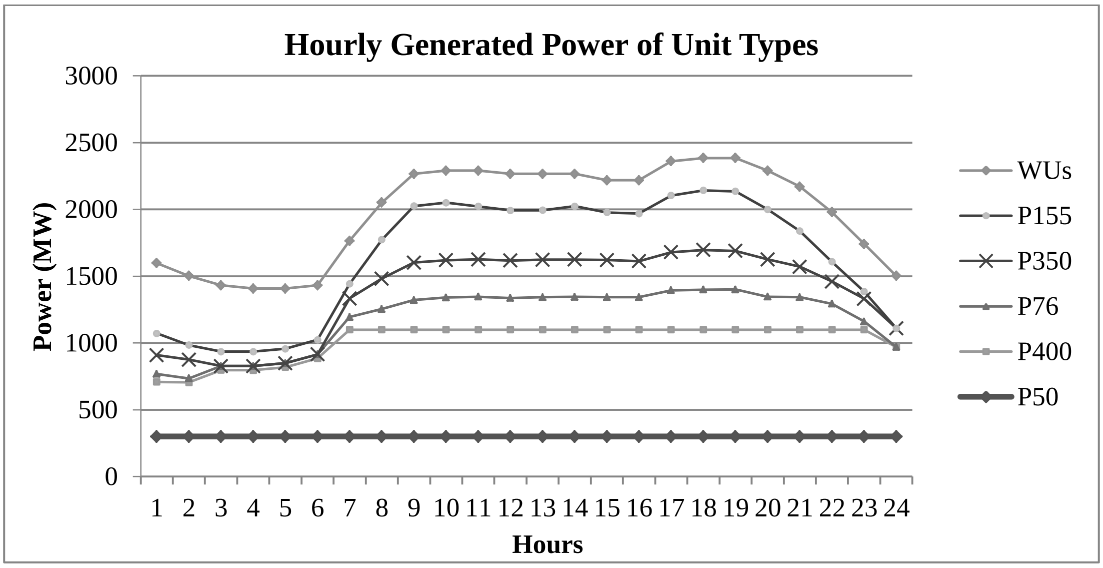

Figure 8 Hourly power generation of committed unit types for case 1- scenario 1

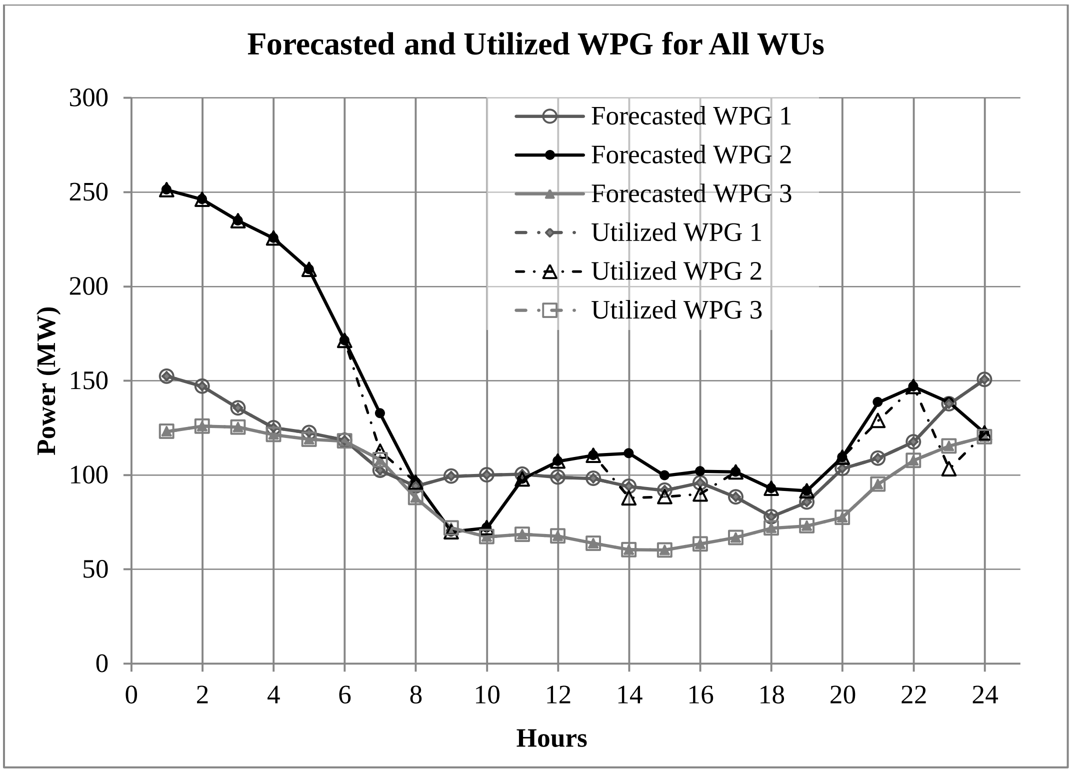

Figure 9 Forecasted and utilized WPG for all WUs for case 1- scenario 1

4.2.1.2. Case 1, Scenario 2

In case 1-scenario 2, an ESS is integrated to 24 bus system at bus 14, properties of it are tabulated at Table 10. System operation cost is reduced to **486,287 $** with the contribution of ESS. When two costs of scenarios are compared, **0.904** % of first scenario cost is achieved as a cost reduction, which mainly obtained from energy arbitrage ability of ESS and fully utilization of WPG of WU 2.

Unit commitment result of this scenario and results of case 1 scenario 1 are combined and tabulated at Table 11 and Table 12. Gray shaded cells indicate that commitment results of two scenarios are different at that hour. At that shaded cells, first number indicate the result of scenario 1 and separated number with symbol “/” indicates the commitment result of scenario 2. As it can be seen from Table 12, commitment result for the coal unit (U21) is changed.by integration of ESS to the system. It is stayed at off status in whole day instead of being committed at hours from 14 to 21. On the other, one of the petroleum based unit (U18) is committed at peak load hours.

Table 10 Properties of bulk ESS

ESS Name	Max. Charging Limit (MW)	Max. Discharging Limit (MW)	Max Energy (MWh)	Min Energy (MWh)	Cycle Efficiency (%)	Initial Charge (MWh)
1	50	50	200	20	0.9	60

Power generations of unit types are shown in Figure 10 for all hours for case 1-scenario 2. As it can be seen from Figure 11, contribution of wind units and nuclear units on power generation increases with the help of ESS while contribution of coal units decreases. Figure 12 shows the peak-shaving effects of ESS. In this graph, generated power means that summation of conventional and wind units generations on an hourly base. Since an ESS is integrated to system; as it can be seen from figure, peak power generation is reduced from 2385 MW to 2361 MW. Peak-shaving amount is highly dependent on size and location of ESS. In next scenarios, size and location dependency of peak-shaving advantage of ESS will be examined.

Summation of generated power (conventional and wind units generations) and ESS power should be equal to load requirement of system instantly. This relation can be easily seen from Figure 12. In order to use same notation with conventional unit, positive ESS power means that it is in generating mode. Negative one states that it is in storing mode. Zero power of ESS means that it is in the idle mode.

Table 11 Unit commitment result of units 1-16 in case 1- scenario 1, 2

Unit Name	U 1	U 2	U 3	U 4	U 5	U 6	U 7	U 8	U 9	U 10	U 11	G 12	G 13	G 14	G 15	G 16
h=1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=2	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
h=3	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
h=4	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
h=5	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
h=6	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
h=7	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=8	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=9	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=10	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=11	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=12	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=13	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=14	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=15	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=16	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=17	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=18	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=19	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=20	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=21	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=22	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=23	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
h=24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 12 Unit commitment result of units 17-32 in case 1- scenario 1, 2

Unit Name	U 17	U 18	U 19	U 20	U 21	U 22	U 23	U 24	U 25	U 26	U 27	U 28	U 29	U 30	U 31	U 32
h=1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
h=2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
h=3	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0
h=4	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0
h=5	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0
h=6	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0
h=7	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
h=8	0	0	0	1/0	0	1	1	1	1	1	1	1	1	1	1	1
h=9	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1
h=10	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1
h=11	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1
h=12	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1
h=13	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1
h=14	0	0	0	1	1/0	1	1	1	1	1	1	1	1	1	1	1
h=15	0	0	0	1	1/0	1	1	1	1	1	1	1	1	1	1	1
h=16	0	0	0	1	1/0	1	1	1	1	1	1	1	1	1	1	1
h=17	0	0/1	0	1	1/0	1	1	1	1	1	1	1	1	1	1	1
h=18	0	0/1	0	1	1/0	1	1	1	1	1	1	1	1	1	1	1
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h=21	0	0	0	0	1/0	1	1	1	1	1	1	1	1	1	1	1
h=22	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
h=23	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1
h=24	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	1

Since an ESS is located at same bus with a WU2, WPG 2 is completely utilized like the other WUs at this scenario. Utilization of WPGs can be seen in Figure 13.

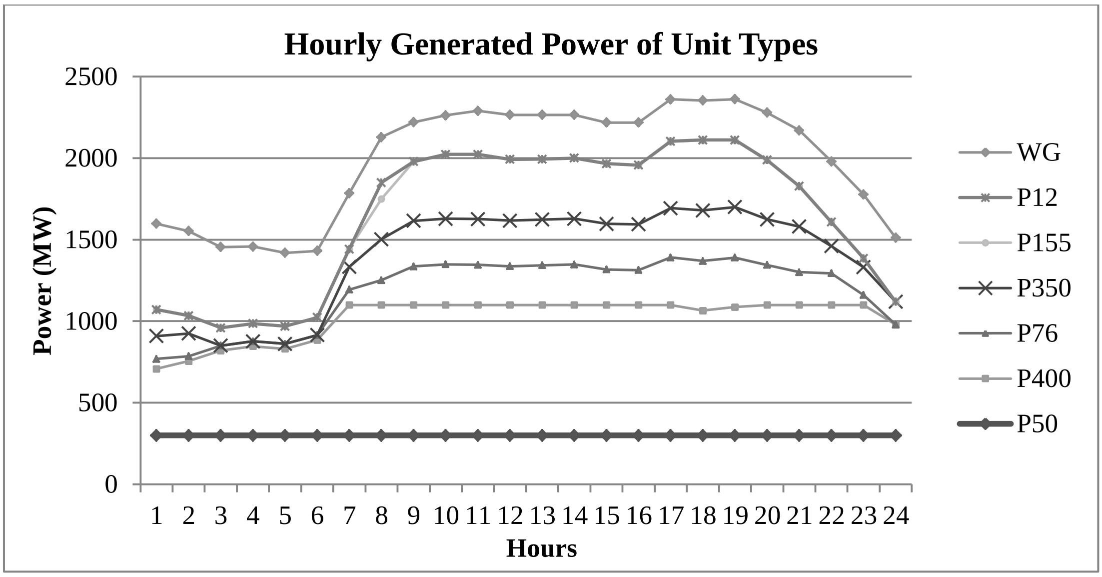

Figure 10 Hourly power generation of committed unit types for case 1- scenario 2

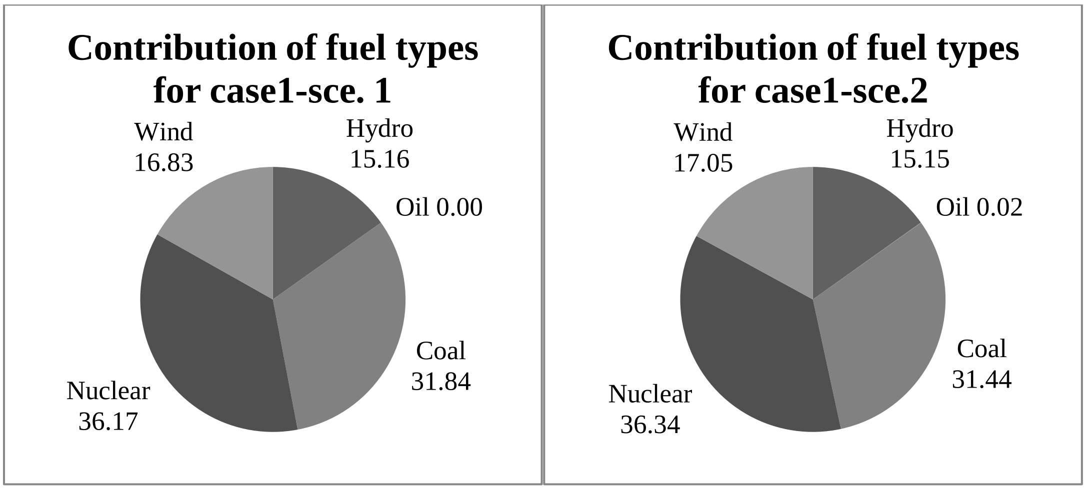

Figure 11 Contribution of fuel types units for case 1- scenario 1, 2

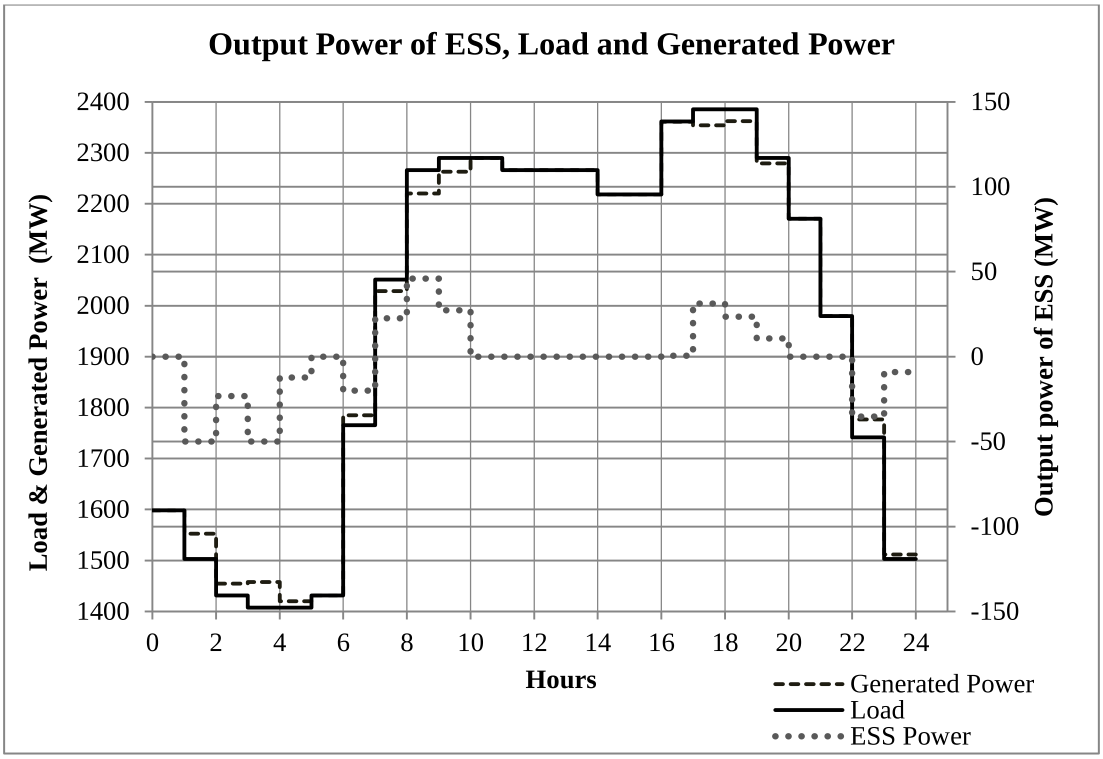

Figure 12 Output power of ESS, load and generated power for case 1- scenario 2

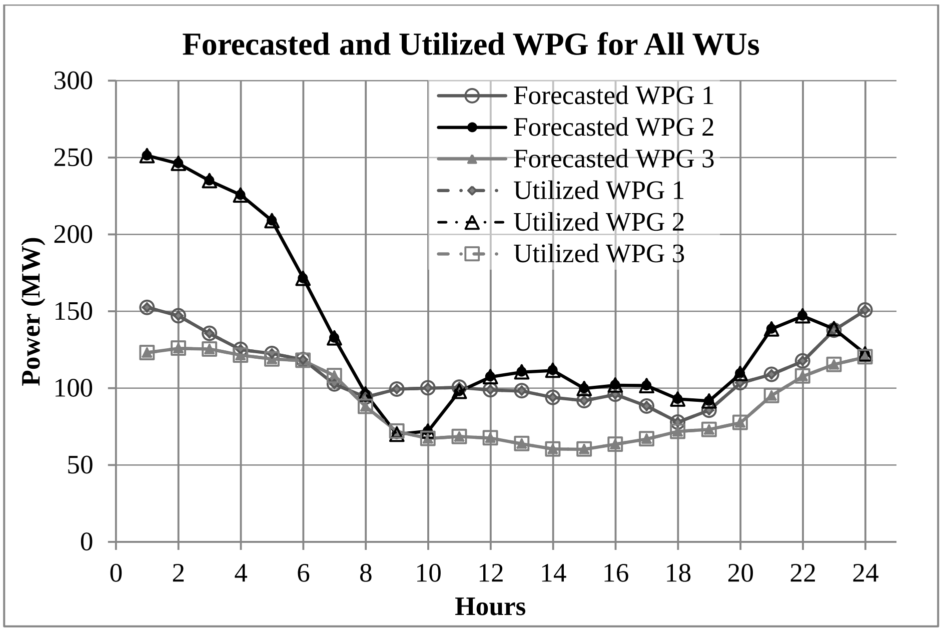

Figure 13 Forecasted and utilized WPG for all WUs for case 1- scenario 2

4.2.1.1. Case 1, Scenario 3

In Case 1 scenario 3, same size bulk ESS is moved from bus 14 to zone 2, to diminish the negative effect of congested interzonal lines on operation cost. Power flow on three of the interzonal lines (lines 19, 21 and 22) reach maximum power capacities at some of the peak hours at previous scenario whereas line 27 is less loaded line among interzonal lines. However, since there is no direct indicator to select most suitable location to ESS at zone 2, all buses of zone 2 should be evaluated in terms of system operation cost. At this scenario, system operation costs are obtained and compared to each other, when ESS is located at all buses of zone 2. Table 13 contains obtained operation costs of the repeated SCUC problem algorithm execution for all zone 2 buses as ESS bus.

Table 13 Operation costs of bulk ESS located at different buses at zone 2

ESS Bus	Operation Cost $
1	482,127
2	482,119
3	482,536
4	482,097
5	482,076
6	482,050
7	482,054
8	482,054
9	482,078
10	**482,032**
11	482,054
12	482,048
13	482,181
24	482,254

As it can be seen from table, least production cost is obtained, if bus 10 is chosen as ESS bus. If ESS is located at bus 10, generation cost is reduced to **482,032 $**. Although size of ESS is same with previous scenario, less generation cost value is achieved at this scenario. Limited transfer capacity between two zones is one of the reasons of this reduction. Another reason is the distribution of load and installed generation capacity between two zones. As it can be seen from tabulation of distribution of load and generation capacity in Table 14. As it can be seen from table, most of the generation capacity is located at zone 1. Indeed, loads are mostly located at zone 2. In addition to this, the cheaper units (hydro, nuclear units and cheap coal unit (P155, P350)) are located at zone 1, congested line causes generation shift from zone 1 to zone 2 (cheaper side to expensive side).

Power generations of unit types are shown in Figure 14 for all hours. Although same types of units are committed as it is expected, different dispatch of unit types' results are obtained from previous scenario. While daily contribution of coal units (P350 and 76) and WU 2 on power generation decrease, nuclear unit and other coal unit (P155) have increased contribution on power generation. Changing of contribution of units, which are using different type of fuel, on power generation from previous scenario to this scenario can be seen in Figure 15. Although contribution of wind units decreases, cost reduction can be obtained by generating more power from nuclear unit and cheap coal unit (P155) instead of P350 and eliminating startup cost of oil unit in previous scenario. Peak-shaving effect of ESS and ESS power can be seen in Figure 16. Peak generation amount is not so different than base case as it is in previous scenario. For this scenario, Figure 17 shows wind power curtailment result. Since ESS and curtailed wind power unit are located at different buses for this scenario whereas it is located same bus in previous scenario, more wind curtailment occurs at case 1, scenario 2. SCUC algorithm obtains minimum operation cost with **81 MWh** wind energy curtailment of WU 2. Consequently, the moving of ESS from Zone 1 to Zone 2 increases the wind power curtailment while the operation cost decreases. For this specific network, an ISO could use the algorithm to evaluate the tradeoff between wind curtailment and total cost. Details of wind generation curtailments can be examined in Figure 17. As it can be seen from figure, wind energy is curtailed at three hours in a day.

Table 15 shows hourly energy transfer between zones and power generation amounts of two zones. As it can be seen from table, transferred power amount is increased by moving the ESS from bus 14 to bus 10. Gray shaded cells indicate that transferred power from zone 1 to zone 2 increases at that hours. ESS on zone 2 can stores excess energy from zone 1 at off peak-load hours. Stored energy is used to supply energy to loads on zone 2 at peak-load hours. **1.77 %** cost reduction is obtained when it compared with the base scenario. Cost reduction is calculated as **0.875 %** when it compared with case 1 scenario 2.

Table 14 Loads distribution, units installed capacity distribution over zones

	Conventional Units Installed Power (MW)	Wind Units Installed Power (MW)	Load Percent. (%)	Conventional Gen. Percent. (%)	Wind Units Percent. (%)	Total Gen. Percent. (%)
Zone 1	2130	385	44	62.56	71.30	63.75
Zone 2	1275	155	56	37.44	28.70	36.25

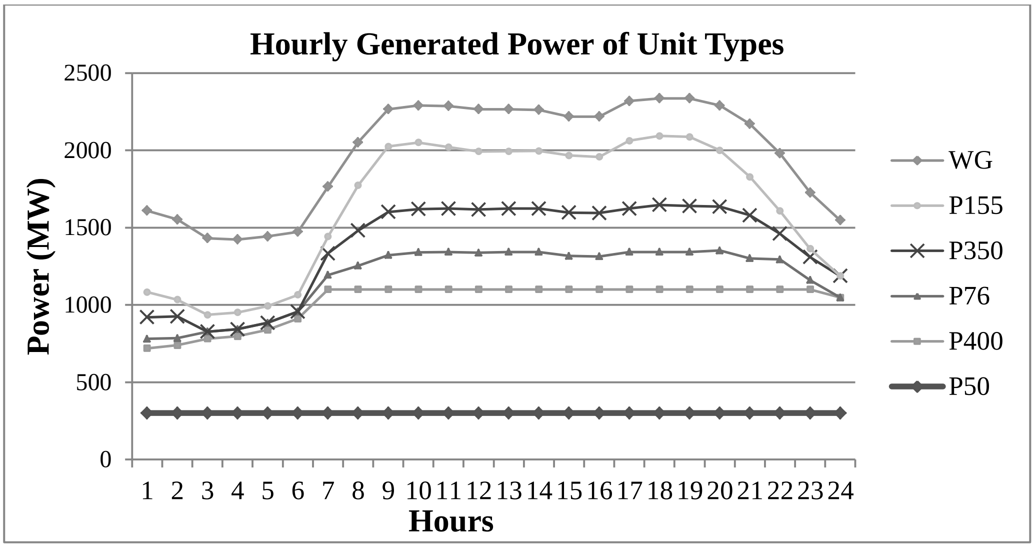

Figure 14 Hourly power generation of committed unit types for case 1- scenario 3.

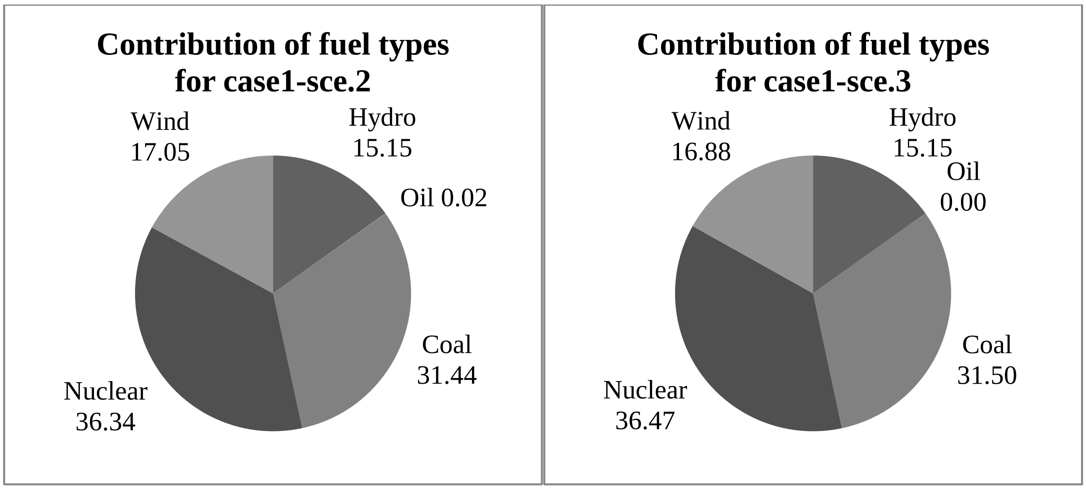

Figure 15 Contribution of fuel types units for case 1- scenario 2, 3

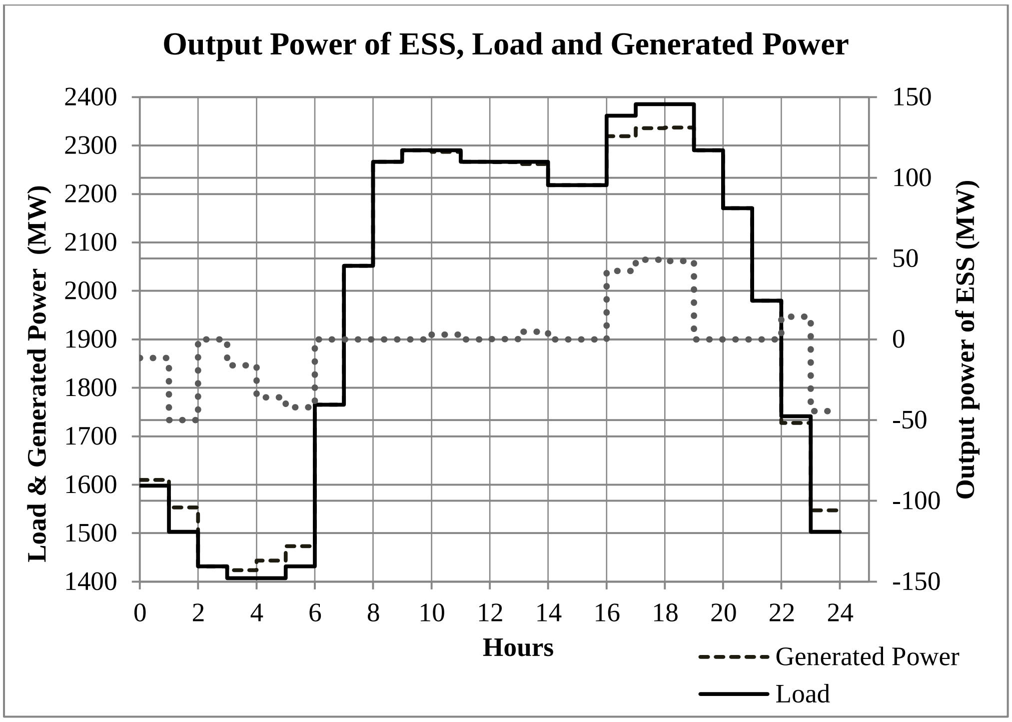

Figure 16 Output power of ESS, load and generated power for case 1- scenario 3

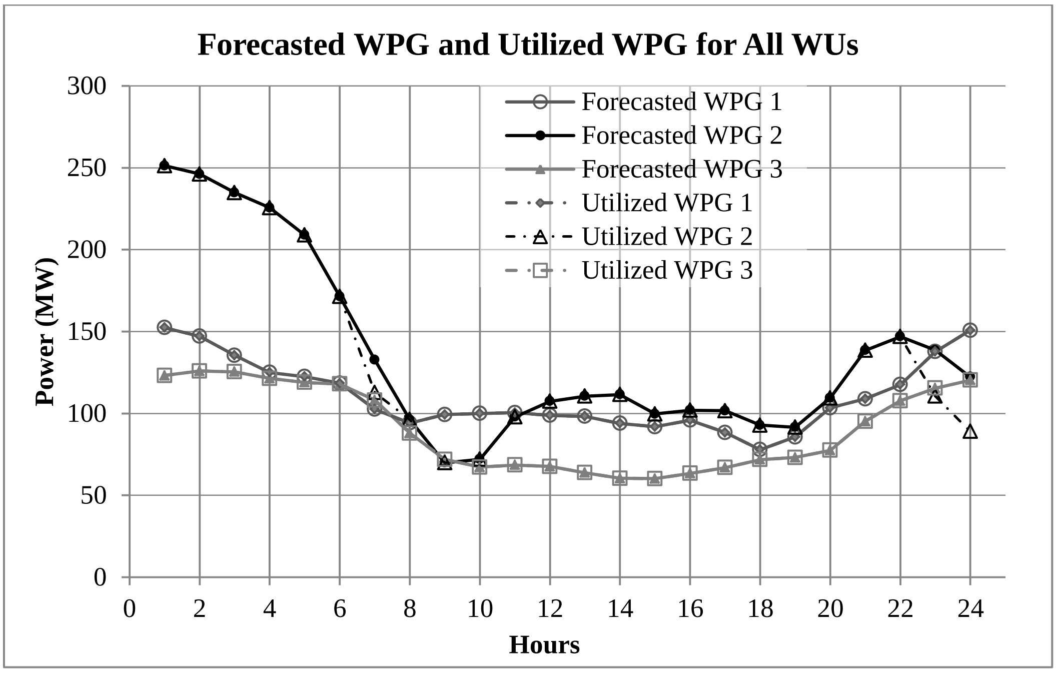

Figure 17 Utilized wind power for all wind units, for case 1- scenario 3

Table 15 Power transfer between zones and power generations of two zones at case 1-scenario 2, 3

Hour	Power transfer from zone 1 to zone 2 at C1-S 2 (MW)	Power transfer from zone 1 to zone 2 at C1-S 3 (MW)	Generation at zone 1, C1-S 2 (MWh)	Generation at zone 1, C1-S 3 (MWh)	Generation at zone 2, C1-S 2 (MWh)	Generation at zone 2, C1-S 3 (MWh)
1	711.68	723.24	1414.91	1426.47	183.34	171.78
2	685.82	720.62	1347.07	1381.87	155.76	120.96
3	646.27	631.07	1276.03	1260.83	155.24	170.44
4	636.83	637.78	1256.09	1257.05	151.33	150.37
5	639.32	659.94	1258.59	1279.20	148.83	128.21
6	653.62	680.44	1283.38	1310.20	147.89	121.07
7	787.53	787.53	1564.23	1564.23	201.00	201.00
8	909.60	907.69	1812.25	1810.34	239.24	241.14
9	962.14	976.41	1959.26	1973.52	306.92	292.65
10	967.26	975.70	1974.88	1983.31	315.15	306.72
11	968.26	968.64	1975.88	1976.25	314.15	313.78
12	965.02	965.02	1962.14	1962.14	304.04	304.04
13	962.78	962.79	1959.90	1959.91	306.28	306.27
14	961.07	961.67	1958.19	1958.79	307.99	307.39
15	965.62	965.62	1941.74	1941.74	276.73	276.73
16	965.79	965.79	1941.91	1941.91	276.56	276.56
17	964.99	970.84	2004.09	2009.94	357.51	351.65
18	960.85	972.31	2010.45	2021.91	375.00	363.54
19	959.62	971.93	2009.22	2021.53	376.23	363.92
20	961.09	953.23	1968.70	1960.85	321.33	329.19
21	920.24	920.24	1875.38	1875.38	295.38	295.38
22	807.48	807.48	1678.64	1678.64	301.28	301.28
23	799.61	785.49	1565.82	1551.70	175.56	189.68
24	721.86	766.30	1383.11	1427.55	119.73	75.28
Total	20,484.36	20,637.77	41,381.86	41,535.28	6,112.46	5,959.04

4.2.1.2. Case 1, Scenario 4

In Case 1 scenario 4, same storage size with previous two scenarios is distributed to five ESSs which have 40 MWh energy storage capacity. The locations of these distributed ESSs are chosen as the best five location of bulk ESS in terms of production cost from Table 13. These ESS's buses are determined as 6, 7, 8, 10 and 12. Tabulated properties of distributed ESS's can be seen in Table 16.

Operation cost is obtained as **482,020 $** for this scenario. Although total size of ESS is same with previous scenario; operation cost is less than previous two scenarios. **1.774 %** cost reduction is obtained when it is compared with the base scenario. Reduction amount is calculated as **0.002 %** when it is compared with case 1 scenario 3. Using distributed storage plants instead of bulk one has no meaningful improvement on cost for these scenarios. However, if the location of WU and distributed ESS location and size chosen properly, cost reduction might be slightly increased by reducing wind power curtailment. Power generations of units are shown in Figure 18 for case 1- scenario 4. Contribution of units changes slightly from case 1-scenario 3 to case 1-scenario 4 which is given in Figure 19. While contribution of zone 1 coal unit (P76) and nuclear unit slightly decreases, same amount of generation is obtained from zone 1 coal units (P155). Peak-shaving effect of ESS and ESS power can be seen in Figure 20. During night hours(off peak hours) all storage plants are charged and these are discharged between 5-8 pm. Figure 21 contains energy levels of ESSs and daily load curve for this scenario. **82 MWh** wind energy of WU 2 is curtailed in schedule results of SCUC algorithm. Details of wind generation curtailments can be examined in Figure 22. Curtailment amount of wind energy is nearly same with case 1- scenario 3.

Table 16 Properties of distributed ESSs

ESS Name	Max. Charging Limit	Max. Discharging Limit	Max Energy	Min Energy	Cycle Efficiency	Initial Charge	Location
	(MW)	(MW)	(MWh)	(MWh)	(%)	(MWh)	Bus
1	10	10	40	4	0.9	12	6
2	10	10	40	4	0.9	12	7
3	10	10	40	4	0.9	12	8
4	10	10	40	4	0.9	12	10
5	10	10	40	4	0.9	12	12

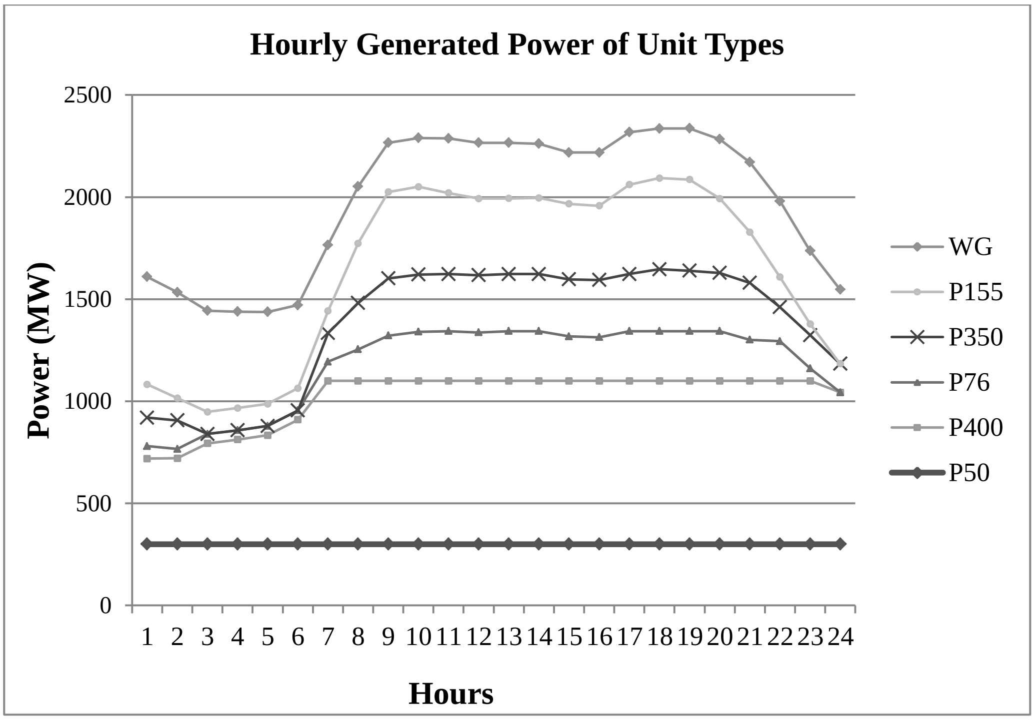

Figure 18 Hourly power generation of committed unit types for case 1- scenario 4

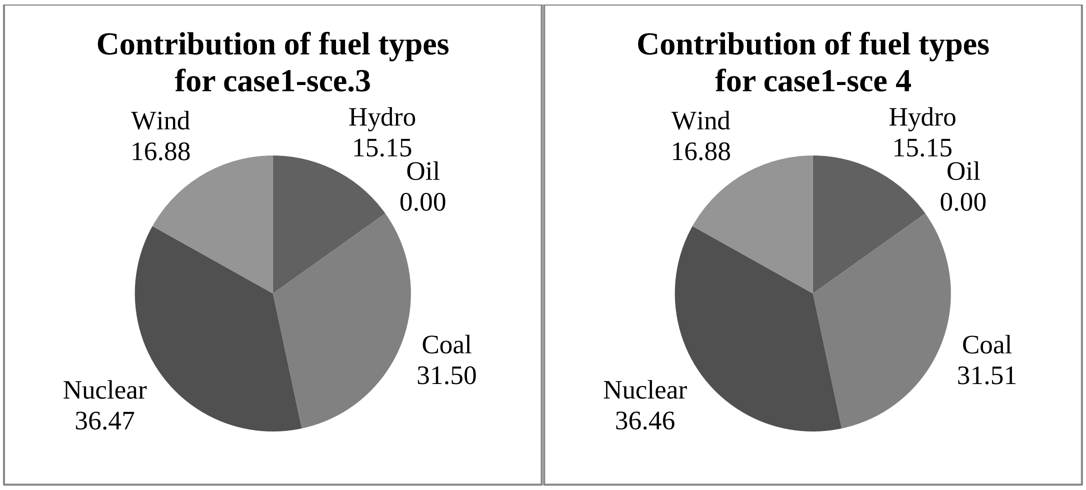

Figure 19 Contribution of fuel types units for case 1- scenario 3, 4

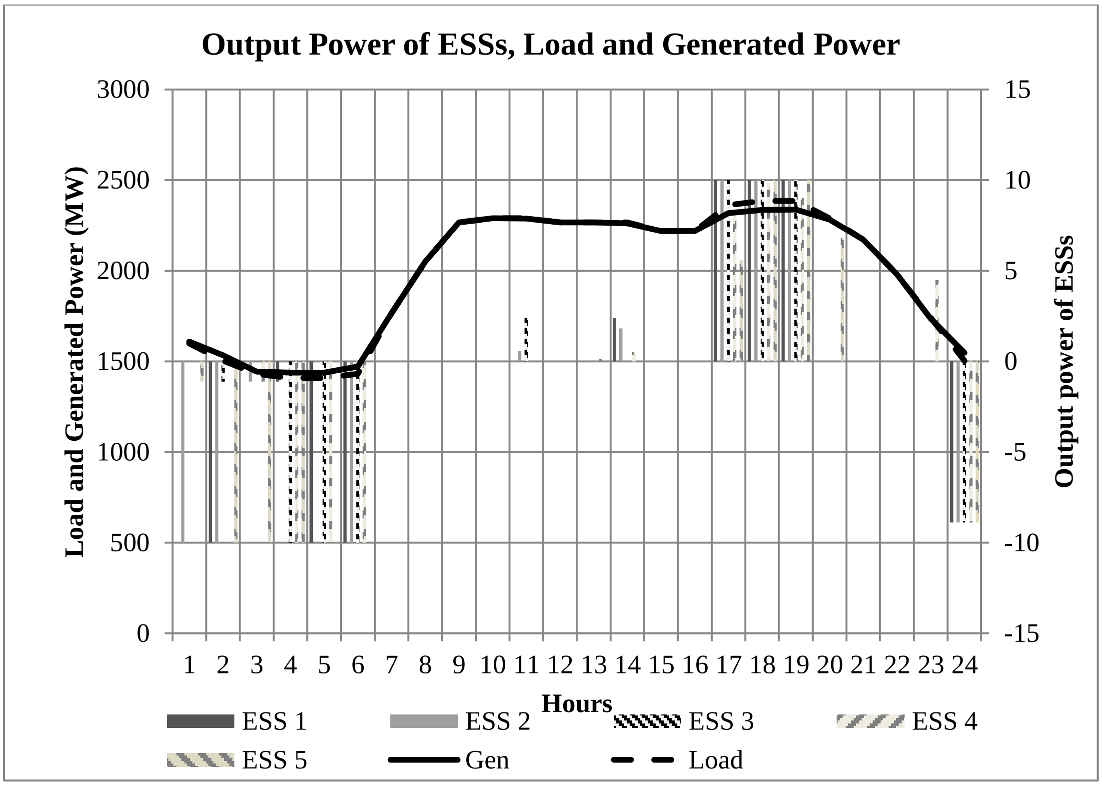

Figure 20 Power of ESSs, load and generated power for case 1- scenario 4

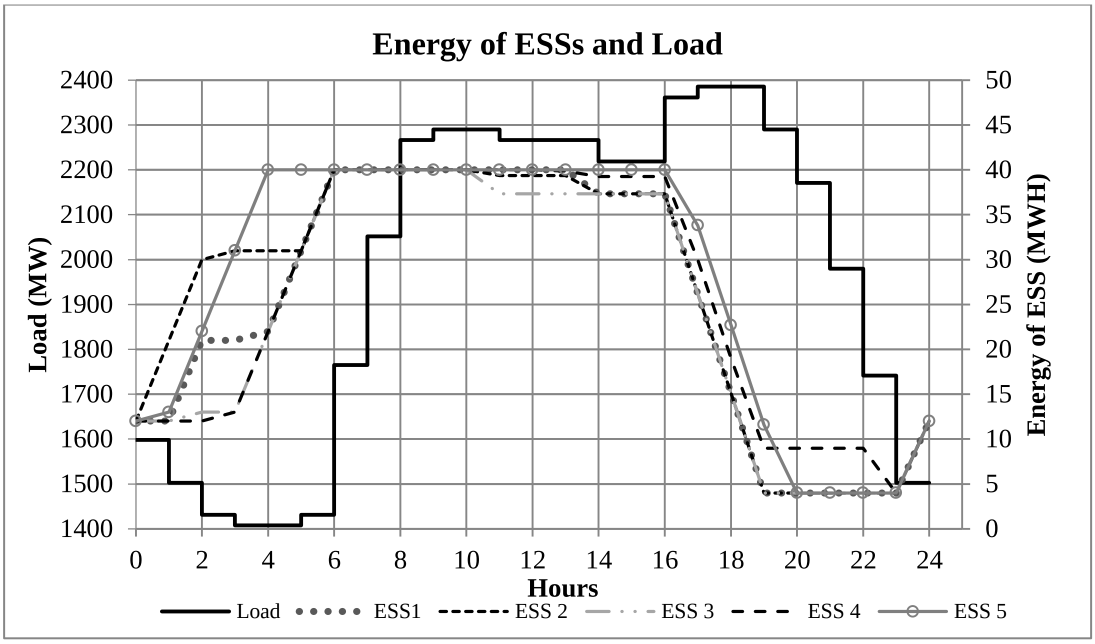

Figure 21 Energy levels of ESS and load curve for case 1- scenario 4

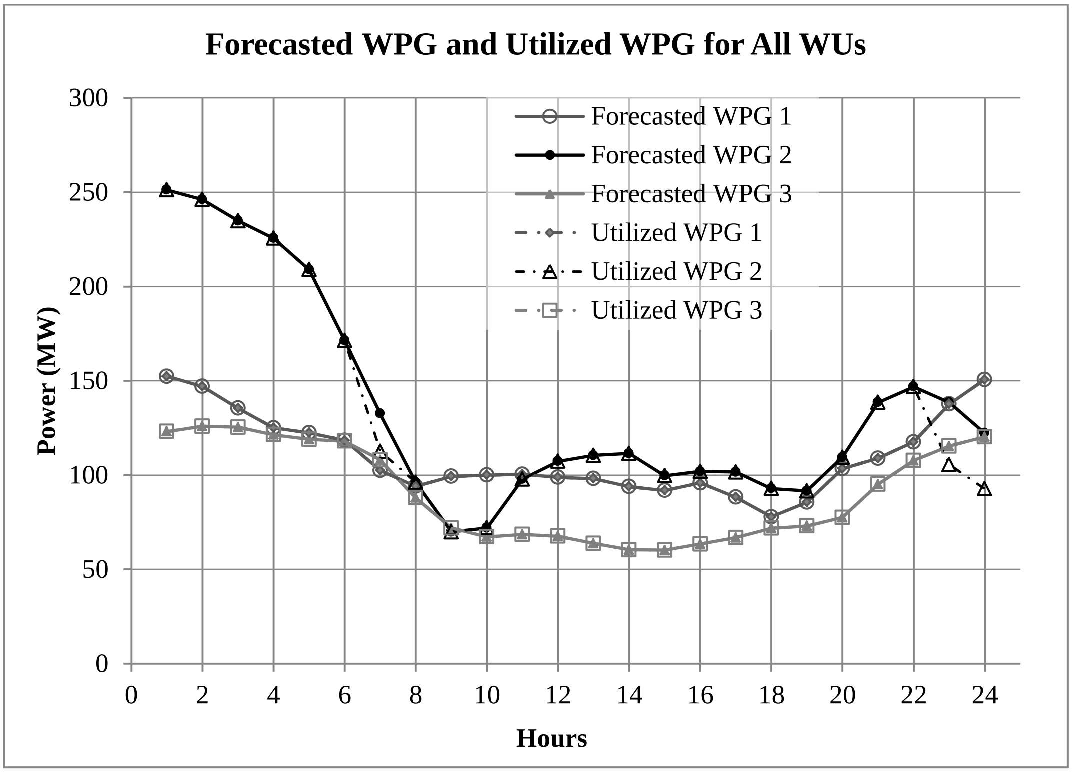

Figure 22 Utilized wind power for all WUs, for case 1- scenario 4

4.2.1.3. Case 1, Scenario 5-13

Up to this point, a few deterministic scenarios are examined for modified 24 bus system with and without ESS. Bulk ESS is located at two different buses and distributed ESS, has totally same storage capacity, are also integrated to power system. In order to examine the impact ESS capacity to overall system operation cost of SCUC problem, extra scenarios are also examined by executing SCUC algorithm repetitively. Total ESS storage size is increased from 200 MWh to 500 MWh with 100MWh steps. Locations and number of ESS are kept same with previous three scenarios. Totally nine different scenarios are examined. Some results of these scenarios such as cost, cost reduction from base scenario and wind energy curtailment of WU 2, are tabulated in Table 17. As it can be seen from table, generation cost may reduce significantly by using large storing capacity ESS. To determine the size of storage at that point the cost reduction is saturated, SCUC problem should be solved for bigger sized ESS integrated system. However, this situation is not so realistic, because ratio of the size of storage plant over total installed capacity of units already reaches 8% with 500 MWh ESS capacity. For all examined sizes of ESS, consistent cost reduction is obtained.

On the other hand, wind energy curtailment is related with several factors at ESS integrated system such as location of WU, ESS, transfer capacity and loading levels of transmission lines. If ESS and curtailed WU was located at the same bus as was given in scenarios 2, 5 and 8; fully utilization of wind power generation is obtained. Separate WU and ESS have higher wind power curtailment than adjacent pair ones. On the other hand, ESS(s), located at zone 2, has weaker performance than ESS located at zone 1 in terms of wind energy curtailment. Although less wind power generation is utilized for these scenarios, smaller production costs can be obtained. This fact depends on power flow capacity limit between zones. Since fully utilization of wind energy of curtailed WU 2 causes shift generation from cheaper units to expensive one, less daily operation cost is obtained by utilizing less wind energy.

Although distributed ESS has better performance than bulk one in terms of cost reduction when the larger ESS capacity scenarios are considered, meaningful cost reductions are not obtained for all scenarios by preferring distributed ESS. On the other hand, more utilization of wind energy can be obtained by using distributed ESS instead of bulk ESSs in deterministic approach. Operation cost and cost reduction result of scenarios are given in Figure 23 and Figure 24, respectively.

Table 17 Results of case 1- scenarios 5-13

Scenario Name	ESS size (item * MWh)	ESS Buses	Expected Cost ($)	Expected Cost Reduction (%)	Expected Wind Energy Curtailment of WU 2
Scenario 5	1* 300MWh	14	485,350	1.096	0
Scenario 6	1* 300MWh	10	480,142	2.157	77
Scenario 7	5* 60MWh	6,7,8,10,12	480,137	2.158	72
Scenario 8	1* 400MWh	14	484,942	1.179	0
Scenario 9	1* 400MWh	10	478,847	2.421	187
Scenario 10	5* 80MWh	6,7,8,10,12	478,688	2.453	154
Scenario 11	1* 500MWh	14	484,935	1.180	0
Scenario 12	1* 500MWh	10	477,918	2.610	333
Scenario 13	5*100MWh	6,7,8,10,12	477,693	2.656	297

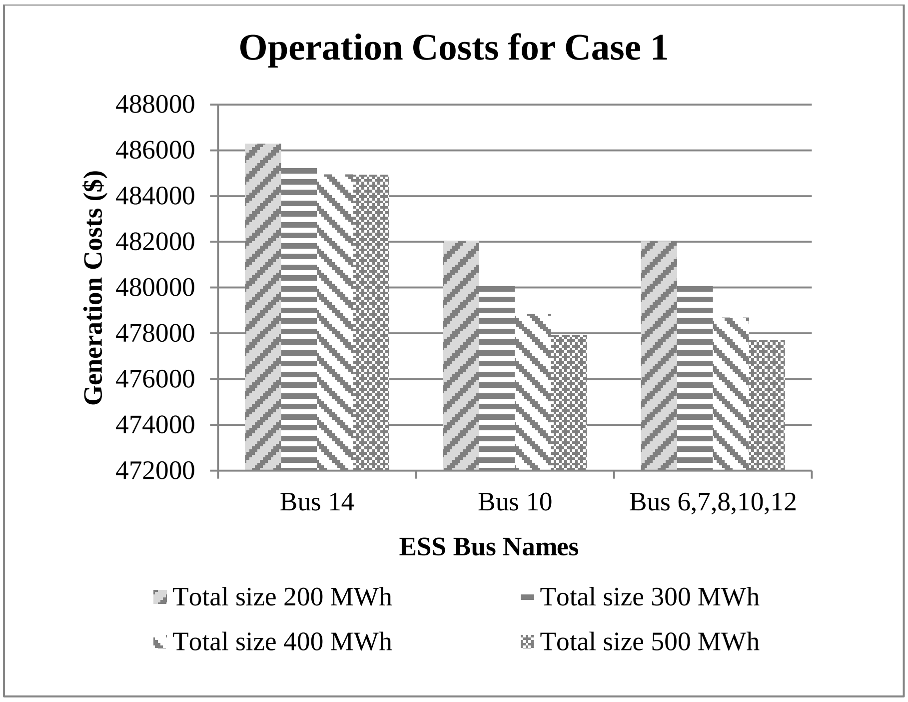

Figure 23 Operation costs for case 1

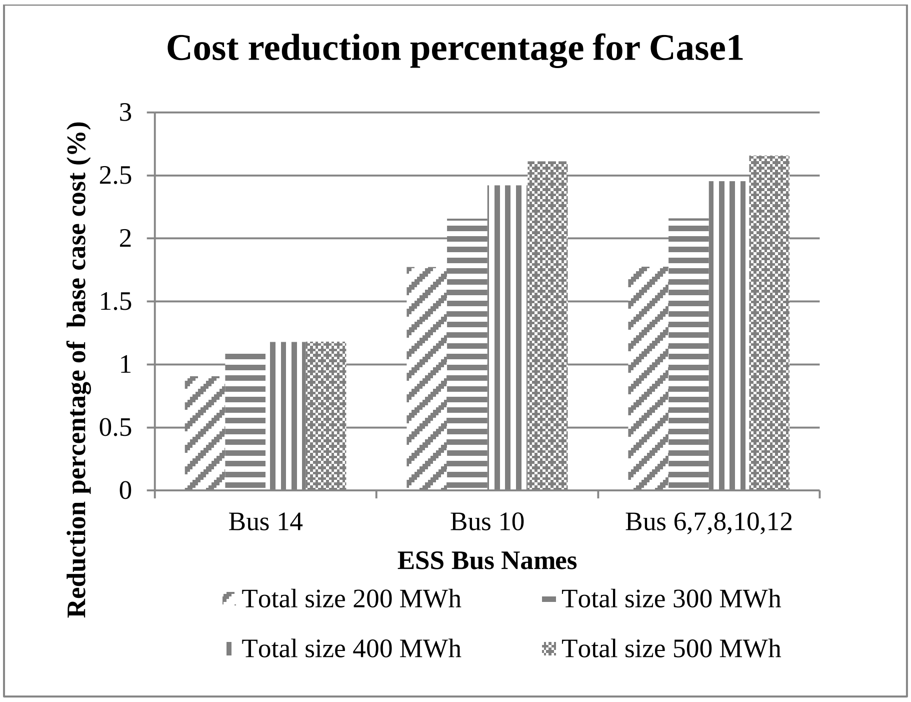

Figure 24 Cost reduction of case 1 in terms of base case cost percentage

4.2.2 Case 2 Monte-Carlo Scenarios Based Stochastic Case

In order to evaluate the effects of ESS on stochastic based SCUC problem results, generated stochastic scenarios are used as input to SCUC algorithm. Generation process of these scenarios were briefly explained in Chapter 3.2. At this case, SCUC problem is solved for modified 24 bus IEEE system in Monte-Carlo scenario based stochastic approach. Firstly, SCUC problem is solved for that system which does not has any ESS similar to deterministic case. Secondly, integration of bulk and distributed ESS is also examined in scenarios of case 2. Listed scenarios are examined in following section;

- Scenario 1 : Stochastic case without ESS
- Scenario 2 : Stochastic case with bulk ESS at bus 10
- Scenario 3 : Stochastic case with five distributed ESSs at buses 6,7,8,10,12
- Scenario 4-9: Stochastic case with various ESS storage sizes

4.2.2.1. Case 2, Scenario 1

As it was stated before, one commitment result and different dispatch results of stochastic scenarios are obtained in scenario based stochastic SCUC problem solution. Obtained operation cost value is not a specific cost result of any stochastic scenarios which are considered by algorithm. It is expected cost of commitment and dispatches which satisfies all scenarios necessities. Expected operation cost is defined as weighted averages of all stochastic scenarios’ operation costs by considering probability of them.

For this scenario, expected operation cost is determined as **498,010 $. C**omparing the deterministic (case 1- scenario 1) and stochastic scenarios (case 2- scenario 1), operation cost increased from **490,726 $** to **498,010 $** in response to represented uncertainty of load and wind power generation. This increment is the value of the perfect information. The expected operation cost is larger than to the deterministic ones to eliminate the uncertainty of wind power generation and load in all Monte

Carlo scenarios. In order to reflect the reason of this increment, if the commitment result of deterministic case 1-scenario 1 is forced in stochastic case 2- scenario 1, algorithm is resulted with an infeasible solution because of line capacity violation. This shows that possible variation of load and wind power may cause line capacity violation. Utilizing the balancing mechanism of the market to deal with the violation on congested lines causes extra cost to ISO. If uncertainty nature of the wind generation and system load is ignored by the ISO in day-ahead market, this additional correction actions should be provided from real time market.

Graphical representation of results seems problematic in stochastic approach, unlikely to previous approach. Although giving all detailed graphics of all scenarios separately is unnecessary, abstract form of them and some sample ones are adequate and beneficial to understand stochastic solution. Dispatch results of different types of units are given in Figure 25 for Monte Carlo stochastic scenario 1. This is a sample scenario result among all stochastic scenarios. For all stochastic scenarios, power generations of units are dispatched differently to satisfy load requirement for each individual Monte-Carlo scenario. On the other hand, load-generated power balance is satisfied instantly for all individual stochastic scenarios, because no storage system is integrated to system. This equality can be seen in Figure 26 for three sample stochastic scenarios (1-3) of case 2-scenario 1. Figure 27 shows that wind power curtailment of WU 2, which has slightly different characteristics through all stochastic scenarios. Wind energy curtailment values of stochastic scenarios are tabulated at Table 18. Expected wind energy curtailment is calculated as **159 MWh** by using energy curtailment values and probability of each scenario.

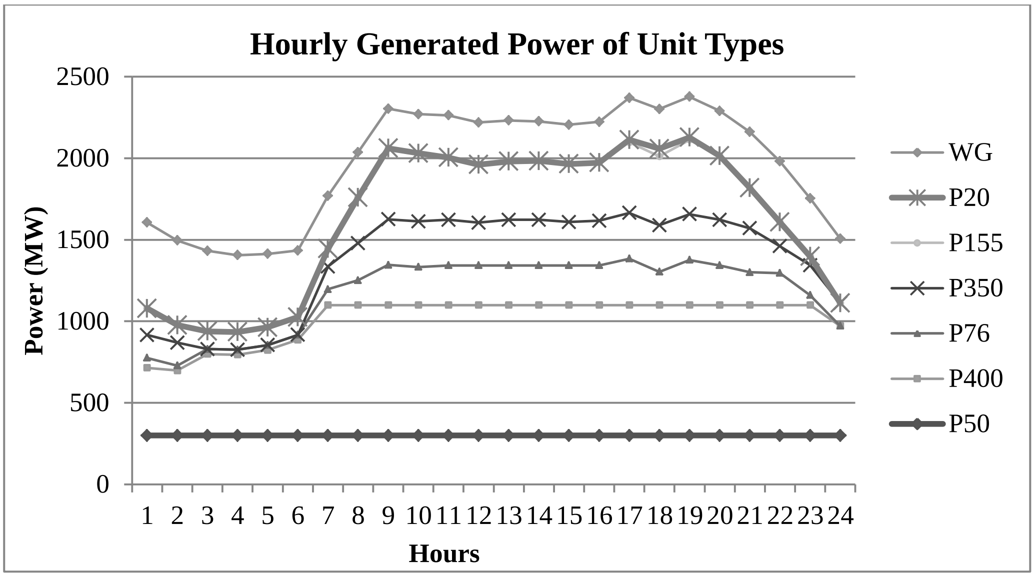

Figure 25 Hourly power generation of committed unit types for case 2- scenario 1- stochastic scenario 1

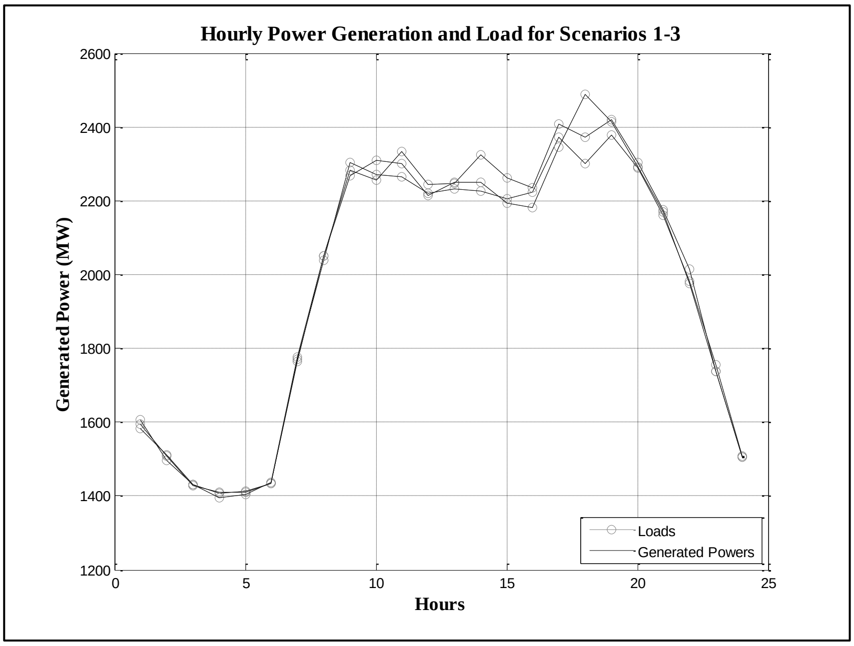

Figure 26 Hourly power generation and loads for case 2- scenario 1- stochastic scenarios 1-3

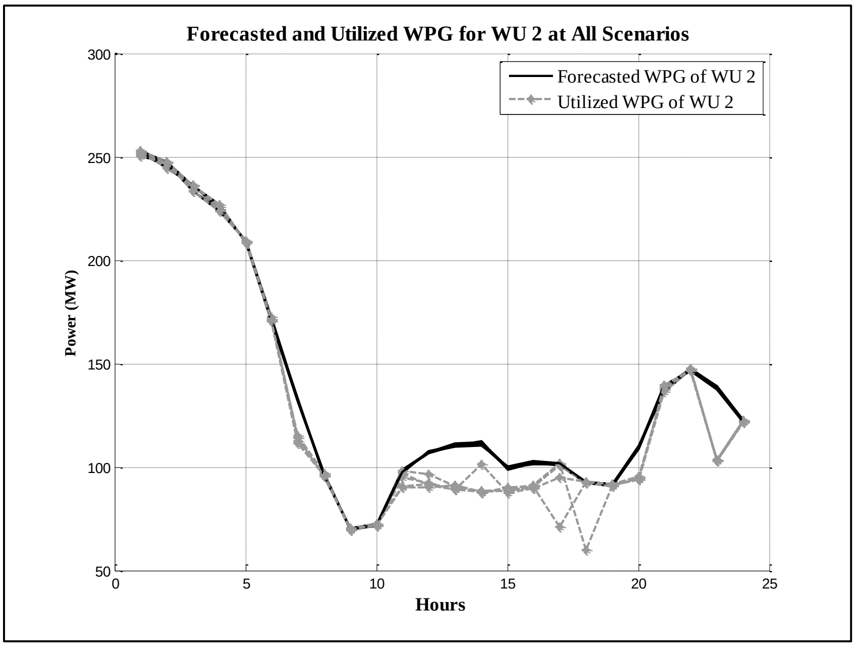

Figure 27 Forecasted and utilized wind generation for WU 2, for case 2- scenario 1- all stochastic scenarios

Table 18 Wind energy curtailment values of WU2 for all stochastic scenarios and expected wind curtailment value for case 2- scenario 1

	Sce. 1	**Sce. 2**	**Sce. 3**	**Sce. 4**	**Sce. 5**	**Sce. 6**	**Sce. 7**	**Sce. 8**	**Sce. 9**	**Sce. 10**
Probability (%)	9	12	9.3	9.4	10.6	7.5	10.3	10	10.7	11.2
Curtailed energy (MWh)	158	150	185	145	190	138	146	156	163	152
Expected Curt. energy (MWh)	159									

4.2.2.2. Case 2, Scenario 2

In this scenario, an ESS is integrated to system at bus 10 like deterministic case 1, scenario 3. Scenario based stochastic SCUC problem is solved for ten Monte Carlo stochastic scenarios. Expected operation cost is determined as **485.991 $** which is

12.019 $ lower than previous scenario. This cost reduction amount is equal to **2.413 %** of case 2- scenario 1 cost. Comparing the deterministic cost pair (case 1- scenario 2) and stochastic cost, operation cost increased from **482.032 $** to **486.991 $,** as expected.

As it can be seen from Figure 28, different unit types are committed during day hours at stochastic Monte Carlo scenario 1, while committed units satisfy whole load requirement of all hour with different economic dispatch decision due to differences of total load in each individual scenario. When commitment result of this scenario and previous scenario is compared, none of the P20 units is not committed at this scenario in contrast to previous one. Expected peak-shaving effect of ESS in stochastic approach can be seen in Figure 29. Peak load and generation values of all Monte Carlo stochastic scenarios are tabulated at Table 19. As it can be understood from that table, peak generation is reduced with ESS integration for all stochastic scenarios. Approximately peak load value can be reduced by **1 %** with the help of ESS. Table 20 contains curtailed wind energy amount of all stochastic scenarios of that scenario. Expected curtailed wind energy value is calculated as **105 MWh** for Case 2-scenario 2 which is lower than Case 2-scenario 1.

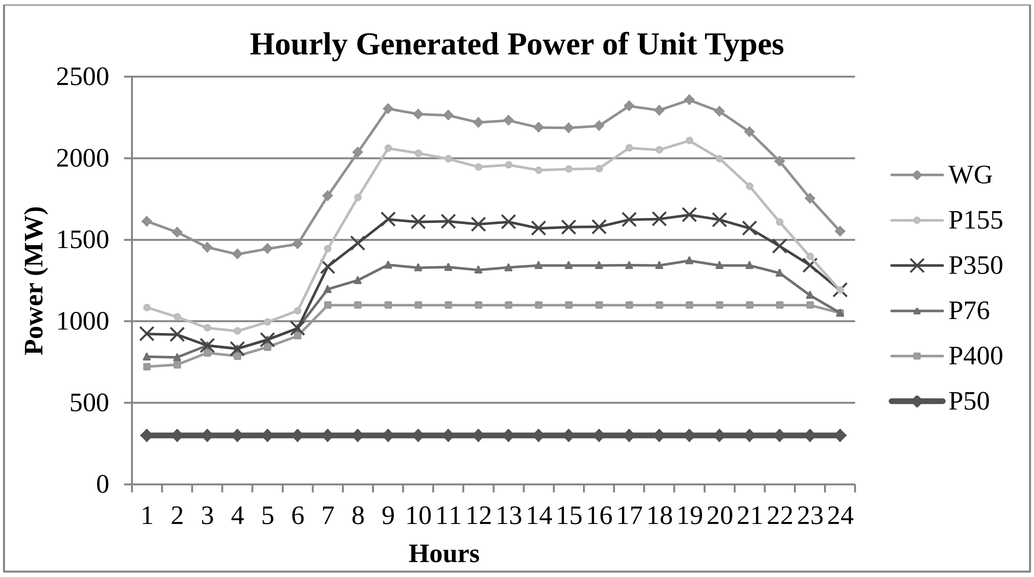

Figure 28 Hourly power generation of committed unit types for case 2- scenario 2-stochastic scenario 1

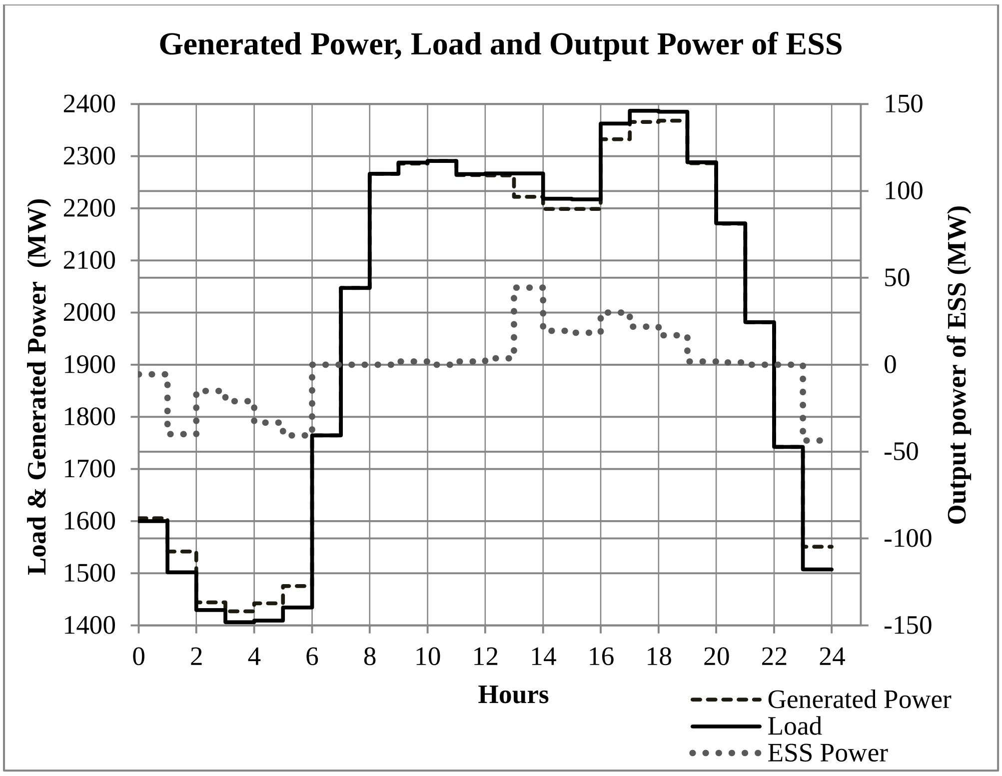

Figure 29 Expected hourly generated powers, expected loads and expected ESS power for case 2- scenario 2-all stochastic scenarios.

Table 19 Peak load and peak generation values for case 2- scenario 2- all stochastic scenarios.

	Sce. 1	Sce. 2	Sce. 3	Sce. 4	Sce. 5	Sce. 6	Sce. 7	Sce. 8	Sce. 9	Sce. 10
Peak Generation (MW)	2358	2392	2438	2347	2384	2398	2380	2383	2400	2363
Peak Load (MW)	2378	2418	2488	2365	2420	2430	2409	2413	2433	2387

Table 20 Wind energy curtailment values of WU2 for all stochastic scenarios of case 2-scenario 2 and expected wind energy curtailment

	Sce. 1	Sce. 2	Sce. 3	Sce. 4	Sce. 5	Sce. 6	Sce. 7	Sce. 8	Sce. 9	Sce. 10
Probability (%)	9	12	9.3	9.4	10.6	7.5	10.3	10	10.7	11.2
Curtailed energy (MWh)	102	101	105	105	107	106	106	101	109	104
Expected Curt. energy (MWh)	105									

4.2.2.3. Case 2, Scenario 3

In this case scenario, five distributed ESSs are used instead of bulk one at buses **6, 7, 8, 10** and **12**. Expected operation cost is obtained as **486.072 $** for case 2-scenario 3. When it is compared with the cost value of case 2- scenario 1, **2,397 %** cost reduction is obtained. This value is **4.052 $** higher than deterministic pair case 1-scenario 4. Obtained operation cost result is slightly higher than case 2- scenario 2. Although slightly reduction on cost can be obtained in deterministic approach by utilizing distributed ESS instead of bulk one, operation cost increases in stochastic approach with preferring distributed ESS instead of bulk ESS for this scenario.

Hourly generated power and loads can be seen in Figure 30. This graph belongs to stochastic Monte-Carlo scenario 1, given as an example result. The other Monte Carlo scenarios results have similar shape.

Expected peak-shaving effect of distributed ESS in stochastic approach can be seen in Figure 31. Peak load and generation values of Monte Carlo stochastic scenarios are also tabulated at Table 21. Although peak load and generation values are nearly same, obtained production cost for case 2- scenario 3 is higher than the case 2- scenario 2.

Power of ESSs, generated power and load curves are given in Figure 32. All of these are expected values. As it can be seen from figure, ESSs are charged at off-peak hours and discharged at peak hours. Energy level results of ESSs in case 2- scenario 3- stochastic scenario 1 is also given in Figure 33.

Curtailed wind energy amounts of all stochastic scenarios of that scenario are tabulated at Table 22. Expected curtailed wind energy is obtained as **116 MWh** for case 2- scenario 3. More wind energy is curtailed for distributed ESS than bulk ESS in stochastic approach.

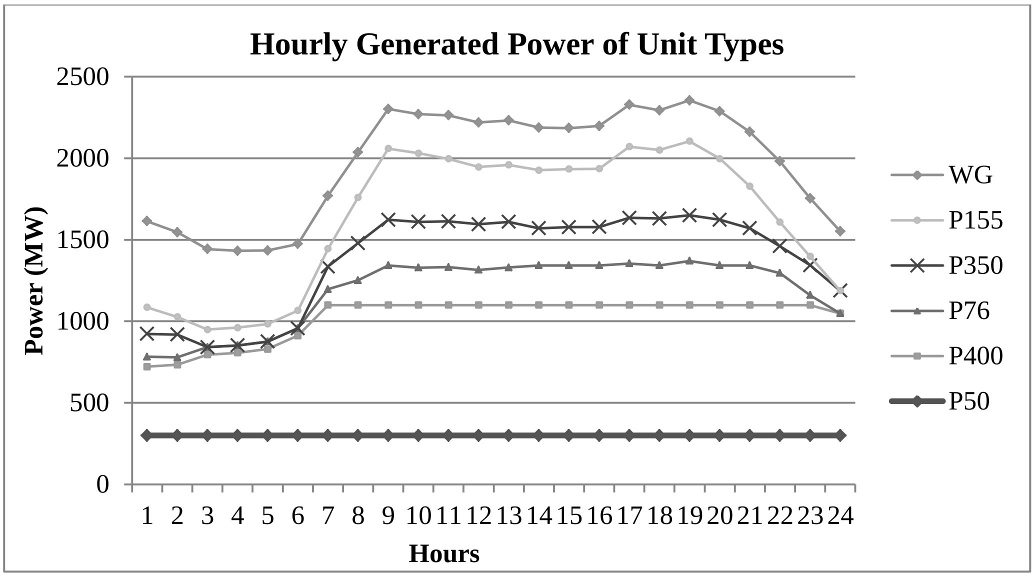

Figure 30 Hourly power generation of committed unit types for case 2- scenario 3- stochastic scenario 1

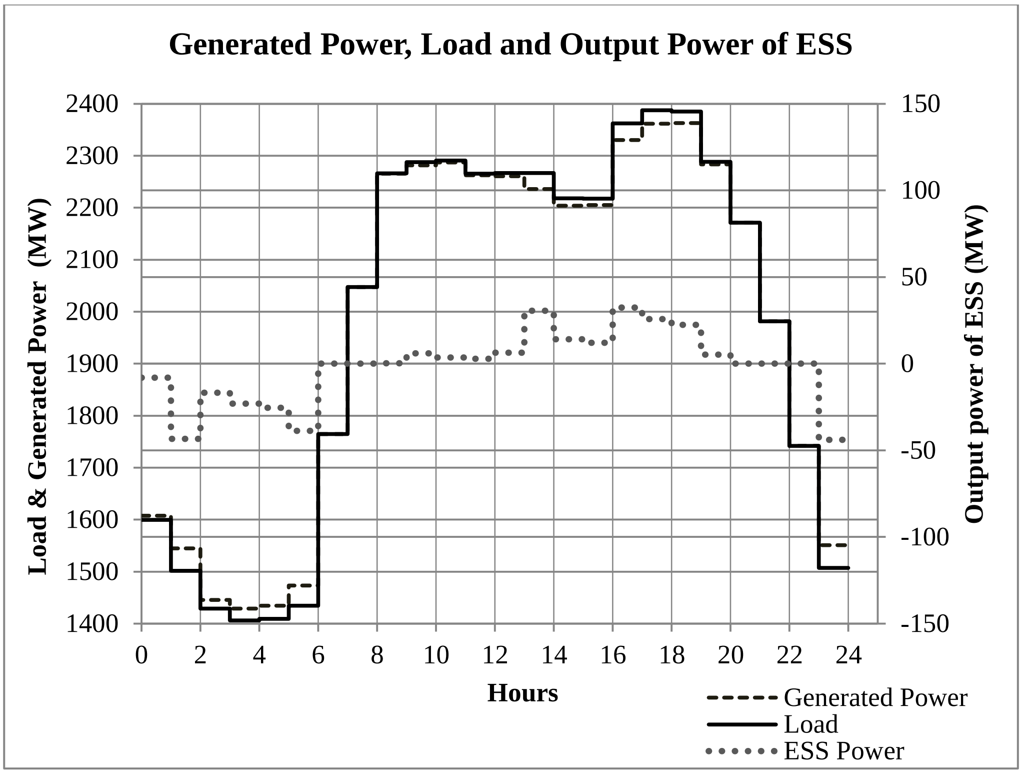

Figure 31 Expected hourly generated powers, expected loads and expected ESS power for case 2- scenario 3- all stochastic scenarios.

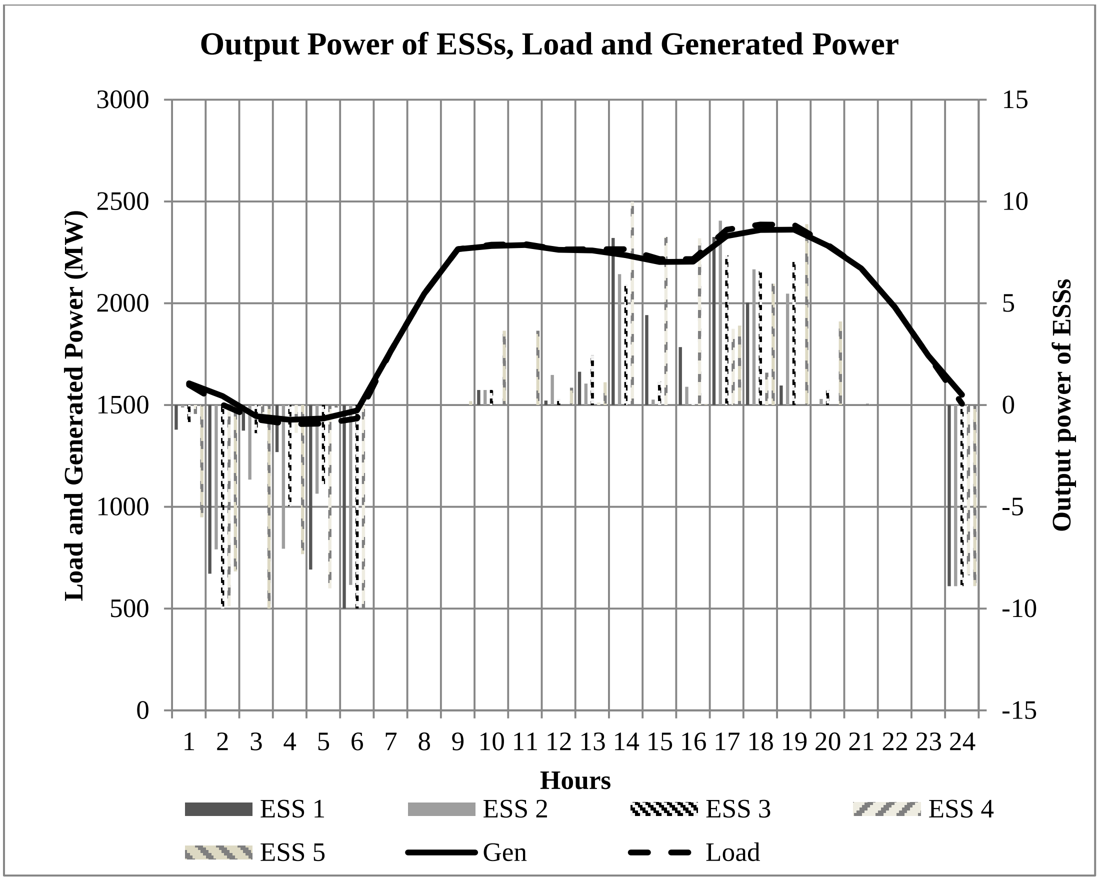

Figure 32 Expected power of ESSs, expected load and expected generated power for case 2- scenario 3- all stochastic scenarios

Table 21 Peak load and peak generation values for case 2- scenario 3- all stochastic scenarios

	Sce. 1	**Sce. 2**	**Sce. 3**	**Sce. 4**	**Sce. 5**	**Sce. 6**	**Sce. 7**	**Sce. 8**	**Sce. 9**	**Sce. 10**
Peak Generation (MW)	2355	2390	2438	2330	2380	2395	2377	2381	2397	2362
Peak Load (MW)	2378	2418	2488	2365	2420	2430	2409	2413	2433	2387

Table 22 Wind energy curtailment values of WU2 for all stochastic scenarios of case 2-scenario 3 and expected wind energy curtailment

	Sce. 1	Sce. 2	Sce. 3	Sce. 4	Sce. 5	Sce. 6	Sce. 7	Sce. 8	Sce. 9	Sce. 10
Probability (%)	9	12	9.3	9.4	10.6	7.5	10.3	10	10.7	11.2
Curtailed energy (MWh)	99	110	119	116	126	119	111	113	129	119
Expected curtailed energy (MWh)	116									

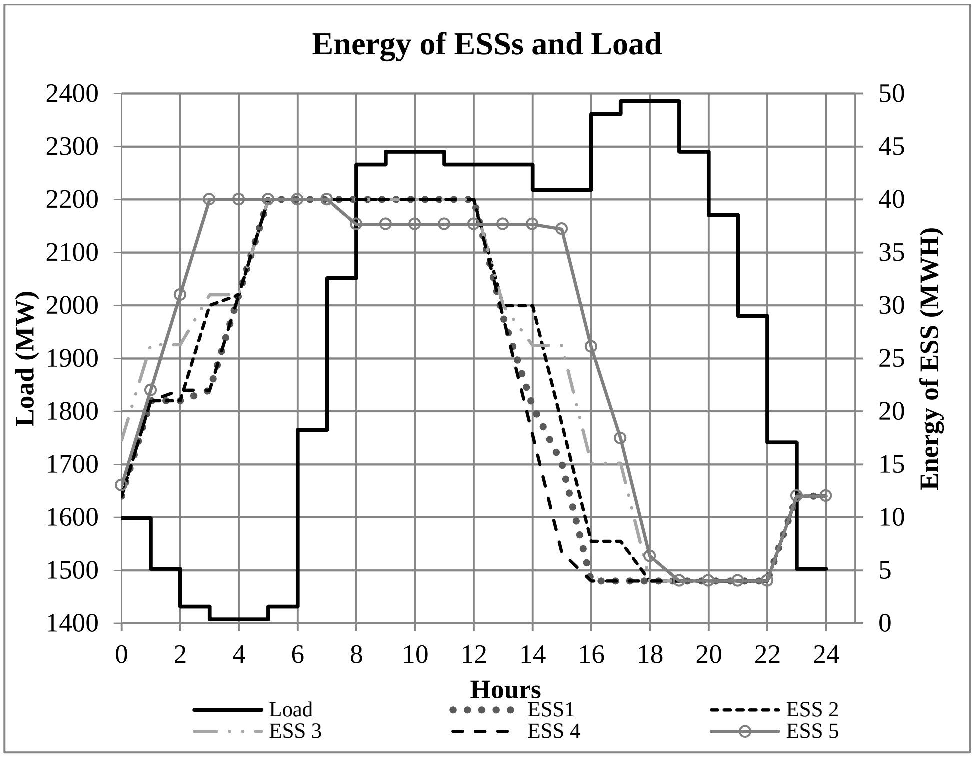

Figure 33 Energy levels of ESSs and load curve for case 2- scenario 3- stochastic scenario 1

4.2.2.4. Case 2, Scenario 4-9

Up to this point, a few stochastic scenarios are examined for modified 24 bus system with ESS. In order to examine the impact ESS capacity overall expected operation cost on SCUC problem, some extra scenario are also examined by repeating execution of SCUC algorithm. Total ESS size is increased from 200 MWh to 500 MWh with 100MWh steps. Locations and number of ESS are kept same as previously examined scenarios (case 2- scenario 2-3). Totally six additional scenario are examined. Some results of these scenarios such as expected production cost, cost reduction as percent of base scenario of this case and expected wind energy curtailment, are tabulated in Table 23.

Figure 34 shows expected operation costs of case 2 scenarios 4-9. As it can be seen from figure, reduction on expected operation cost increases with increasing size of ESS. Preferring distributed ESS instead of bulk ESS, has different results for various size of ESS in terms of cost reduction. For 400 MWh ESS storage size, distributed ESS has better contribution to operation cost reduction than bulk one, while more operation cost reduction can be obtained by utilizing bulk ESS for other ESS storage sizes. Cost reduction result of scenarios are given in Figure 35.

As it can be seen from Table 23, expected generation cost is significantly reduced by integrating ESS, like as deterministic one. Although stochastic approach' expected generation costs are higher than the respective deterministic approach' operation cost, the integration of ESS has similar effects on operation cost. Besides, cost reduction percent of stochastic scenarios are larger than deterministic pairs for same storage size of ESS. The effect of the uncertainty comes from wind energy and load forecast on operation cost of SCUC problem is reduced efficiently by utilizing ESS.

When curtailed wind energy amounts are compared for different ESS capacities, larger storage ESS capacities cause to obtain more curtailed wind energy like in deterministic case. This result is related with the examined system's technical constraints. On the other hand, although slightly less curtailed wind energy can be obtained, when distributed ESSs are used instead of bulk one, lower operation cost are obtained for bulk ESS than distributed ESS. Since bulk ESS has better cost reduction performance for almost all scenarios, the ESS with 400 MWh storage capacity is exception in among the other capacities.

Table 23 Results of case 2- scenarios 4-9

Scenario Name	ESS size (item * MWh)	ESS Buses	Expected Cost ($)	Reduction on Expected Cost (%)	Expected Wind Energy Curtailment of WU 2 (MWh)
Scenario 4	1* 300MWh	10	483747	2.864	107
Scenario 5	5* 60MWh	6,7,8,10,12	483845	2.844	106
Scenario 6	1* 400MWh	10	482192	3.176	191
Scenario 7	5* 80MWh	6,7,8,10,12	482142	3.186	161
Scenario 8	1* 500MWh	10	480175	3.581	333
Scenario 9	5*100MWh	6,7,8,10,12	480467	3.523	297

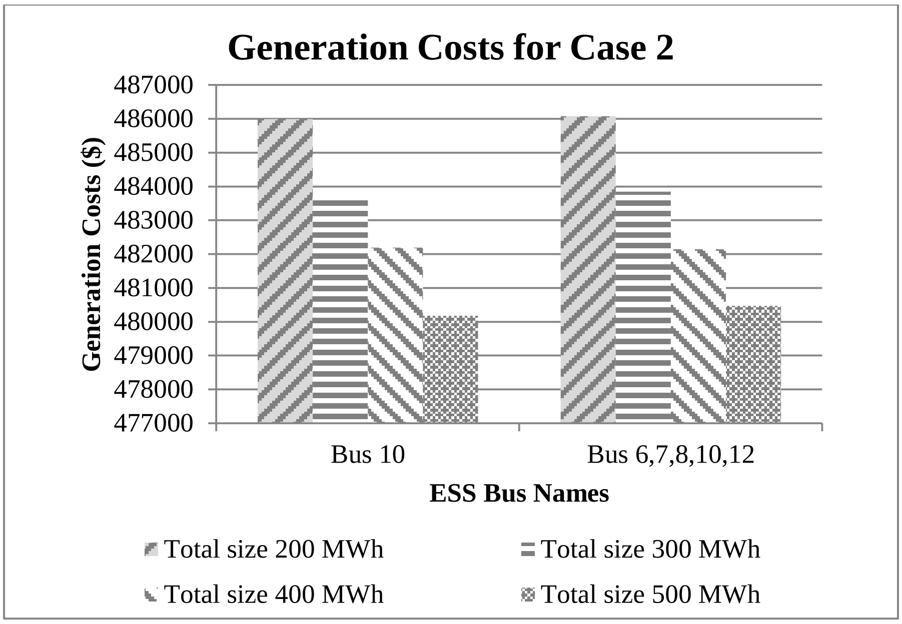

Figure 34 Expected operation costs for case 2

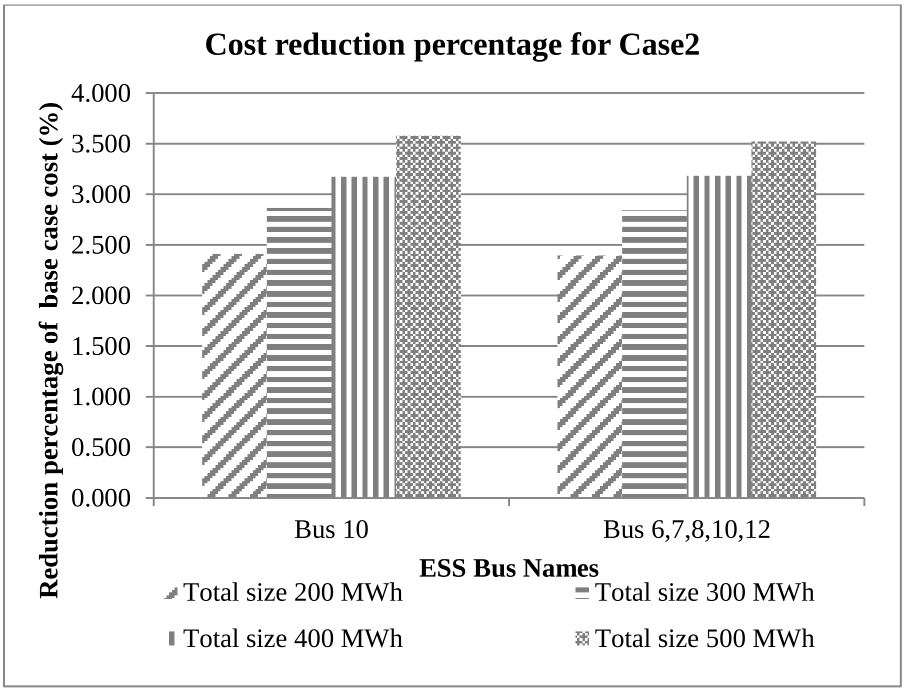

Figure 35 Cost reduction of case 2 in terms of base case cost percentage

CHAPTER 5

CONCLUSION

In this thesis, SCUC problem is solved for a sample power system in the existence of wind units and energy storage systems for both deterministic and Monte-Carlo Scenario based stochastic cases. The impacts of ESS on day-ahead operation cost and wind energy curtailment are examined in two cases. Firstly, the effects of ESS on SCUC problem is examined in deterministic approach. Secondly, same examination is repeated for Monte-Carlo Scenario based stochastic approach. Following observation and evaluations are obtained from results of these cases.

The impact of ESS on operation cost strongly depends on the examined system. Emphasized conclusions are obtained by considering the SCUC problem result of the modified IEEE system. Results may vary when different system constraints or different units cost curves are considered. On the other hand, wind power curtailment results of wind units strongly depend on technical constraints of the system and location of wind units. Consequently the impact of ESS on wind curtailment might be differing from system to system. The difference between effects of bulk ESS and distributed ESS on operation cost and wind power curtailment is also system dependent. Following conclusions are obtained by evaluating the result of SCUC test case which was run fir the modified IEEE 24 bus system. The mathematical model in this thesis provides a tool to which the user could feed the input data and assess the impact of the ESS.

As it is expected, lower production cost can be obtained by integrating ESS to system. Storage size of integrated ESS has an impact on amount of cost reduction. The obtained cost reduction increases with increasing ESS capacity. However obtained amount of cost reduction is not linearly proportional to integrated ESS storage sizes. Besides, larger size of ESS has also expensive capital and operational costs. Economical evaluation of ESS is subject of expansion planning of power system. In this thesis, only operational impact of ESS on power system day-ahead scheduling problem is considered.

Using distributed ESS instead of same size bulk one has similar reduction characteristic on operation cost. Both of them reduce production cost with nearly same amounts in deterministic approach. In stochastic approach, distributed ESS has worse reduction performance on operation cost than bulk ESS for all ESS storage sizes except 400 MWh one. Thus no significant cost reduction is obtained by utilizing distributed ESS instead of bulk one for both approaches. However this result is achieved by examination of the modified IEEE 24 bus system. Higher cost reduction can be obtained by integrating distributed ESS instead of bulk one in a different system.

There is limited transfer capacity between two zones of the IEEE modified 24 bus system. Interzonal lines are congested at some hours in daily operation of power system. Since the power flow of lines are considered as constrains of SCUC problem, ESS’s zonal location has effect on production cost reduction. Reduction amount is increased by shifting integrated ESS from zone 1 to zone 2 in examined cases. In addition to zonal locational, bus location of ESS also changes cost reduction. At some buses, storage ability of ESS is not utilized efficiently because of system constraints, when ESS is located at zone 1. When same storage size ESSs are located at different buses, different operation cost is obtained due to power flow capacity constraint of SCUC. Consequently, contribution of ESS on cost reduction is effected by the location of ESS due to the existence of the system constraints.

In examined power system, wind units are located at both zones. In proposed algorithm, curtailment of wind energy is possible to obtain minimum production cost by considering all constraints of SCUC. Indeed, some amount of wind power generation of wind unit is curtailed because of congested interzonal lines at no ESS scenario. Integration of ESS also has effect on curtailed wind energy amount for examined cases. If ESS is located at the same bus with curtailed wind unit, fully utilization of wind energy is obtained in deterministic approach. On the other hand, integration of ESS to any other buses, less operation cost can be achieved by curtail more wind energy than no ESS case. This result should be emphasized, although it is instinctively expected that minimum day-ahead operation cost is obtained by fully utilizing costless wind power, less operation cost is obtained by partly utilization of wind energy. In order to verify this result, the algorithm is modified to force utilization of the whole wind power and the operation cost increased with respect to the curtailment allowed version. This result shows that if system constraint is considered in day-ahead unit commitment problem, a different commitment decision might be generated than simple merit order method. In addition to this, integration of large ESS storage size resulted with a less operation cost in examined scenarios, even if more wind energy is curtailed.

When the results of deterministic and stochastic approaches are compared, larger operation costs are obtained for stochastic approach than deterministic one. This is caused from considered possible forecast errors of wind power and load. Stochastic approach is more realistic than deterministic since it can handle uncertainties in wind and system load forecasts. On the other hand, when deterministic SCUC approach is applied to day-ahead market, ISO may be faced with more expensive corrective action than afforded cost increment. When the contribution of ESS on operation cost reduction is compared for two approaches, more cost reduction in a percentage can be obtained with a same storage size ESS in stochastic approach than deterministic approach. This shows that the negative effect of uncertainty of load and wind power on power system operation can be diminished by integration of ESS to power system.

CHAPTER 6

DISCUSSION AND FUTURE WORK

In recent years, penetration level of wind energy has been increasing in power systems. The hourly commitment and dispatch of conventional units are affected with increased penetration of variable wind energy in power system. So wind units' existence and variability of wind energy should be taken into account in SCUC problem. Since energy storage systems are accepted as one of the possible alternative solution to negative effect of increased penetration level of wind energy to system security and reliability, the impact of energy storage system in SCUC problem is examined in both stochastic and deterministic approaches in this thesis. At this study, day-ahead forecast errors of hourly load and wind energy generation are considered to represent power system uncertainty. Random outages of generators and transmission lines will be inserted to SCUC algorithm as a source of uncertainty in future works on that subject. Execution time reduction and computational performance improvement of algorithm will be achieved by modification on constraints of SCUC algorithm in future works. Application of approved SCUC algorithm for large scale real power system will also be studied in future works. The contribution of ESS will be also examined in future works for different penetration level of wind power generation power system. Economical examination of investments of ESS will be done by considering the yearly saving of production cost and investment cost of ESS. In order to obtain yearly saving amount, hourly load and wind power forecast of whole year should be used in repetitive execution of day-ahead SCUC algorithm for all days of a year. Reserve support opportunity of ESS will be also examined by combining reserve market with day-ahead power market in day-ahead SCUC problem algorithm in future works.

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APPENDIX A

MODIFIED IEEE 24 BUS SYSTEM

IEEE 24 bus system is modified to sample power system in order to examine SCUC problem in presents of ESS and wind units. This power system has 32 conventional generators at 24 buses. Three wind units are also integrated to system in addition to conventional ones. All related information about system is obtained from reference [36]. Single line diagram of IEEE 24 bus system can be seen in Figure 36. Properties of the conventional units are tabulated at Table 24 and Table 25

All data are obtained from reference [36] except no load cost. No load cost is calculated by considering fuel costs and fixed running cost of conventional unit's values from reference [37].

Although piecewise incremental heat rates of conventional units types are given in ref [36], fuel cost of these types should be known to calculate the piecewise linearized cost curves. Current fuel cost of these fuel types are taken from reference [38] and ref [39] and tabulated at Table 26. Values of piecewise linear costs all conventional units are also tabulated at Table 27 and Table 28.

In this thesis, the effects of ESS on SCUC problem are examined. To emphasize the effects of ESS location, the modified IEEE 24-bus system is obtained by changing capacities of some lines of original system. Whole system is divided two zones which have 1000 MW transfer capacity between them, by reducing capacity of lines (19, 21, 22, 27) to 250 MW. Original line properties and modified values are tabulated at Table 29 for IEEE modified 24 Bus system.

In order to examine the effects of intermittent renewable generation to scheduling problem 3 extra additional wind units added to system at bus 13, 14 and 24. Wind power forecast corresponds to an estimate of the expected production of wind turbines in the near future. Several methods are used for short-term prediction of wind generation. The simplest ones are based on climatology or averages of past production values. But these methods are not related with main focus of this work. So forecasted wind generation is used as an input of SCUC algorithm. Daily forecasted wind generation is tabulated at Table 31. Forecasted wind generation daily trend are obtained from [40] and daily forecasted curves are scaled with installed capacities of three wind units. The installed capacities of them are determined as 160 MW, 260 MW 130 MW, respectively. Ratio of wind power generators installed capacity over total conventional generators capacity is equal to %16 in modified IEEE 24 Bus system.

Load forecast is also obtained from reference [36] spinning and operating reserve requirement of power system is assumed as %5 and %7 respectively of hourly load. All values of them are tabulated at Table 32.

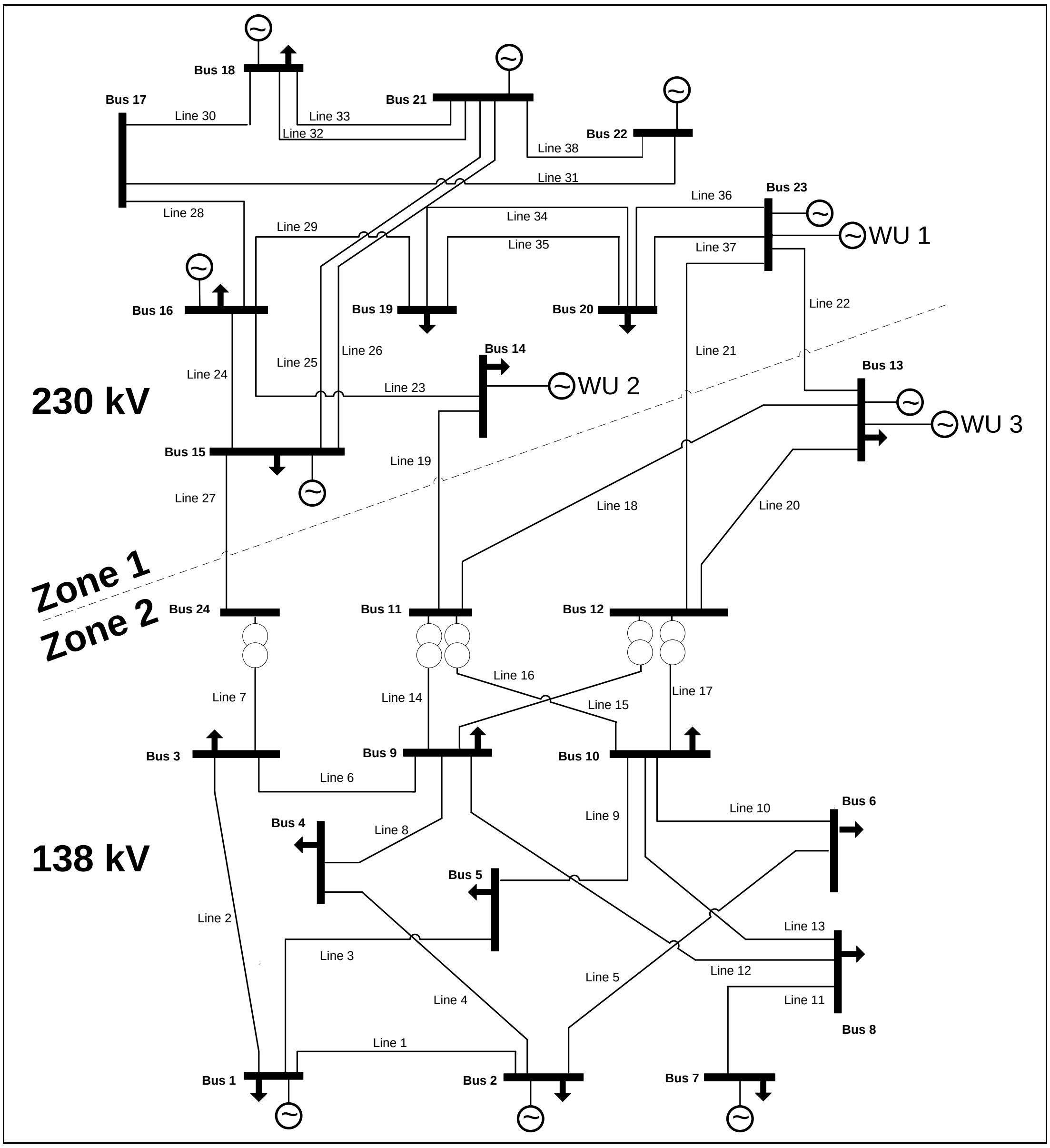

Figure 36 Single line diagram of IEEE modified 24 bus system

Table 24 Properties of conventional units part 1

Unit Name	Minimum Capacity (MW)	Maximum Capacity (MW)	No load Cost ($)	Shutdown Cost ($)	Min. Up time (h)	Min. Down Time (h)
1	15.8	20	19.28	0	1	1
2	15.8	20	19.28	0	1	1
3	15.2	76	17.31	0	8	4
4	15.2	76	17.31	0	8	4
5	15.8	20	19.28	0	1	1
6	15.8	20	19.28	0	1	1
7	15.2	76	17.31	0	8	4
8	15.2	76	17.31	0	8	4
9	25.0	100	32.78	0	8	8
10	25.0	100	32.78	0	8	8
11	25.0	100	32.78	0	8	8
12	69.0	197	57.85	0	12	10
13	69.0	197	57.85	0	12	10
14	69.0	197	57.85	0	12	10
15	2.4	12	20.25	0	4	2
16	2.4	12	20.25	0	4	2
17	2.4	12	20.25	0	4	2
18	2.4	12	20.25	0	4	2
19	2.4	12	20.25	0	4	2
20	54.3	155	14.43	0	8	8
21	54.3	155	14.43	0	8	8
22	100.0	400	0.00	0	24	24
23	100.0	400	0.00	0	24	24
24	10.0	50	0.00	0	1	1
25	10.0	50	0.00	0	1	1
26	10.0	50	0.00	0	1	1
27	10.0	50	0.00	0	1	1
28	10.0	50	0.00	0	1	1
29	10.0	50	0.00	0	1	1
30	54.3	155	14.43	0	8	8
31	54.3	155	14.43	0	8	8
32	140.0	350	46.17	0	24	24

Table 25 Properties of conventional units part 2

Unit Name	Ramp Up/Down Rate (MW/hour)	MSR (MW/min)	QSC (MW)	Initial Status	Initial Hour	Initial MW	Bus Name
1	180	3	15.8	0	10	0	1
2	180	3	15.8	0	10	0	1
3	120	2	15.2	1	22	50	1
4	120	2	15.2	1	22	50	1
5	180	3	15.8	0	10	0	2
6	180	3	15.8	0	10	0	2
7	120	2	15.2	1	22	50	2
8	120	2	15.2	1	22	50	2
9	420	7	25.0	0	2	0	7
10	420	7	25.0	0	2	0	7
11	420	7	25.0	0	2	0	7
12	180	3	69.0	0	1	0	13
13	180	3	69.0	0	1	0	13
14	180	3	69.0	0	1	0	13
15	60	1	2.4	0	1	0	15
16	60	1	2.4	0	1	0	15
17	60	1	2.4	0	1	0	15
18	60	1	2.4	0	1	0	15
19	60	1	2.4	0	1	0	15
20	180	3	54.3	0	10	0	15
21	180	3	54.3	1	10	100	16
22	1200	20	100.0	1	50	200	18
23	1200	20	100.0	1	16	200	21
24	120	2	0.0	1	24	30	22
25	120	2	0.0	1	24	30	22
26	120	2	0.0	1	24	30	22
27	120	2	0.0	1	24	30	22
28	120	2	0.0	1	24	30	22
29	120	2	0.0	1	24	30	22
30	180	3	54.3	1	10	100	23
31	180	3	54.3	1	10	100	23
32	240	4	140.0	1	50	200	23

Table 26 Fuel cost of fuel types

Fuel Type	Fuel Cost (Dollars per MMBtu)	Fuel Type	Fuel Cost (Dollars per MMBtu)
#6 oil	11.57	Coal	2.77
#2 oil	8.87	Nuclear	0.6
Water	0		

Table 27 Piecewise linear cost curve values of conventional units part 1

Unit Name	First segment length (MW)	First Segment Price ($/MW)	Second segment length (MW)	Second segment Price ($/MW)
1	15.8	114.08	0.2	117.32
2	15.8	114.08	0.2	117.32
3	15.2	26.45	22.8	27.61
4	15.2	26.45	22.8	27.61
5	15.8	114.08	0.2	117.32
6	15.8	114.08	0.2	117.32
7	15.2	26.45	22.8	27.61
8	15.2	26.45	22.8	27.61
9	25.0	71.73	25.0	77.25
10	25.0	71.73	25.0	77.25
11	25.0	71.73	25.0	77.25
12	69.0	74.05	49.3	78.37
13	69.0	74.05	49.3	78.37
14	69.0	74.05	49.3	78.37
15	2.4	90.28	3.6	91.71
16	2.4	90.28	3.6	91.71
17	2.4	90.28	3.6	91.71
18	2.4	90.28	3.6	91.71
19	2.4	90.28	3.6	91.71
20	54.3	22.90	38.8	23.66
21	54.3	22.90	38.8	23.66
22	100.0	5.31	100.0	5.38
23	100.0	5.31	100.0	5.38
24	10.0	0.00	13.3	0.00
25	10.0	0.00	13.3	0.00
26	10.0	0.00	13.3	0.00
27	10.0	0.00	13.3	0.00
28	10.0	0.00	13.3	0.00
29	10.0	0.00	13.3	0.00
30	54.3	22.90	38.8	23.66
31	54.3	22.90	38.8	23.66
32	140.0	23.27	87.5	24.61

Table 28 Piecewise linear cost curve values of conventional units part 2

Unit Name	Third segment length (MW)	Third Segment Price ($/MW)	Fourth segment length (MW)	Fourth segment Price ($/MW)
1	3.8	165.14	0.2	166.92
2	3.8	165.14	0.2	166.92
3	22.8	32.06	15.2	36.86
4	22.8	32.06	15.2	36.86
5	3.8	165.14	0.2	166.92
6	3.8	165.14	0.2	166.92
7	22.8	32.06	15.2	36.86
8	22.8	32.06	15.2	36.86
9	30.0	84.73	20.0	87.62
10	30.0	84.73	20.0	87.62
11	30.0	84.73	20.0	87.62
12	39.4	81.84	39.4	85.35
13	39.4	81.84	39.4	85.35
14	39.4	81.84	39.4	85.35
15	3.6	103.51	2.4	117.24
16	3.6	103.51	2.4	117.24
17	3.6	103.51	2.4	117.24
18	3.6	103.51	2.4	117.24
19	3.6	103.51	2.4	117.24
20	31.0	24.65	31.0	25.99
21	31.0	24.65	31.0	25.99
22	120.0	5.53	80.0	5.66
23	120.0	5.53	80.0	5.66
24	13.3	0.00	13.3	0.00
25	13.3	0.00	13.3	0.00
26	13.3	0.00	13.3	0.00
27	13.3	0.00	13.3	0.00
28	13.3	0.00	13.3	0.00
29	13.3	0.00	13.3	0.00
30	31.0	24.65	31.0	25.99
31	31.0	24.65	31.0	25.99
32	52.5	25.60	70.0	27.05

Table 29 Lines properties of IEEE modified 24 bus system

Line No	From Bus	To Bus	X (pu)	Original Line Limit (MW)	Modified Line Limit (MW)
1	1	2	0.01	175.00	175.00
2	1	3	0.21	175.00	175.00
3	1	5	0.08	175.00	175.00
4	2	4	0.13	175.00	175.00
5	2	6	0.19	175.00	175.00
6	3	9	0.12	175.00	175.00
7	3	24	0.08	400.00	400.00
8	4	9	0.10	175.00	175.00
9	5	10	0.09	175.00	175.00
10	6	10	0.06	175.00	175.00
11	7	8	0.06	175.00	175.00
12	8	9	0.17	175.00	175.00
13	8	10	0.17	175.00	175.00
14	9	11	0.08	400.00	400.00
15	9	12	0.08	400.00	400.00
16	10	11	0.08	400.00	400.00
17	10	12	0.08	400.00	400.00
18	11	13	0.05	500.00	500.00
19	11	14	0.04	500.00	250.00
20	12	13	0.05	500.00	500.00
21	12	23	0.10	500.00	250.00
22	13	23	0.09	500.00	250.00
23	14	16	0.04	500.00	500.00
24	15	16	0.02	500.00	500.00
25	15	21	0.05	500.00	500.00
26	15	21	0.05	500.00	500.00
27	15	24	0.05	500.00	250.00
28	16	17	0.03	500.00	500.00
29	16	19	0.02	500.00	500.00
30	17	18	0.01	500.00	500.00
31	17	22	0.11	500.00	500.00
32	18	21	0.03	500.00	500.00
33	18	21	0.03	500.00	500.00
34	19	20	0.04	500.00	500.00
35	19	20	0.04	500.00	500.00
36	20	23	0.02	500.00	500.00
37	20	23	0.02	500.00	500.00
38	21	22	0.07	500.00	500.00

Table 30 Bus properties of IEEE modified 24 bus system

Bus name	Bus type	Load Percentage (%)
1	Reference bus	3.8
2	PQ	3.4
3	PV	6.3
4	PQ	2.6
5	PV	2.5
6	PQ	4.8
7	PQ	4.4
8	PQ	6
9	PV	6.1
10	PV	6.8
11	PV	0
12	PV	0
13	PQ	9.3
14	PQ	6.8
15	PQ	11.1
16	PQ	3.5
17	PV	0
18	PQ	11.7
19	PV	6.4
20	PV	4.5
21	PQ	0
22	PQ	0
23	PQ	0
24	PV	0

Table 31 Forecasted wind generation for three wind units

Hour	**Forecasted Wind Generation (MW)**		
	Wind Unit 1 at bus 23	**Wind Unit 2 at bus 14**	**Wind Unit 3 at bus 13**
1	152.40	251.20	123.10
2	147.05	246.13	125.89
3	135.49	234.82	125.34
4	125.04	225.63	121.42
5	122.44	208.93	118.93
6	118.45	171.40	117.99
7	102.49	132.57	108.06
8	94.11	96.21	87.96
9	99.32	69.89	71.90
10	100.00	72.03	67.23
11	100.42	97.85	68.51
12	98.78	107.35	67.57
13	98.17	110.49	63.74
14	93.90	111.49	60.35
15	91.84	99.70	60.21
16	95.85	101.95	63.43
17	88.30	101.63	66.87
18	77.85	92.85	71.84
19	85.59	91.57	73.07
20	103.42	109.42	77.49
21	108.89	138.50	95.18
22	117.54	146.89	107.73
23	137.70	138.58	115.37
24	150.66	122.22	120.25

Table 32 Hourly load, spinning and operating reserve requirements of the system

Hour	Forecasted Load (MW)	Spinning Reserve (MW) %5 of load	Operating Reserve (MW) %7 of load
1	1598.25	79.91	111.88
2	1502.83	75.14	105.20
3	1431.27	71.56	100.19
4	1407.42	70.37	98.52
5	1407.42	70.37	98.52
6	1431.27	71.56	100.19
7	1765.23	88.26	123.57
8	2051.49	102.57	143.60
9	2266.18	113.31	158.63
10	2290.03	114.50	160.30
11	2290.03	114.50	160.30
12	2266.18	113.31	158.63
13	2266.18	113.31	158.63
14	2266.18	113.31	158.63
15	2218.47	110.92	155.29
16	2218.47	110.92	155.29
17	2361.60	118.08	165.31
18	2385.45	119.27	166.98
19	2385.45	119.27	166.98
20	2290.03	114.50	160.30
21	2170.76	108.54	151.95
22	1979.92	99.00	138.59
23	1741.38	87.07	121.90
24	1502.83	75.14	105.20

APPENDIX B-

10 STOCHASTIC SCENARIOS

Forecasted hourly load for all Monte Carlo stochastic scenarios are tabulated at Table 33. Similarly forecasted wind power generations of three wind units for all stochastic scenarios are tabulated at Table 34, Table 35 and Table 36.

Table 33 Load values (pu) for stochastic 10 scenarios

Hour	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
1	1.00523	0.99833	0.98960	1.00862	1.01056	0.99743	1.00038	1.00218	1.00044	0.99588
2	0.99577	1.00265	1.00534	1.00321	0.98950	0.99837	1.00077	0.99312	1.00165	1.00126
3	1.00066	0.99730	1.00013	0.99578	0.99755	1.00728	0.99807	0.99404	0.99848	0.99885
4	0.99914	1.00193	0.99199	0.99276	1.00252	1.00362	1.00347	0.99477	1.00259	0.99593
5	1.00418	1.00196	0.99655	1.00046	1.00144	1.00531	1.00406	1.00390	1.00027	0.99641
6	1.00247	1.00132	1.00395	0.99713	1.00104	1.00780	1.00315	0.99756	1.01127	0.99766
7	1.00262	0.99995	1.00563	0.99771	1.00345	1.00310	0.98995	1.00052	1.00213	0.99355
8	0.99305	0.99950	1.00018	1.00386	0.98837	0.99045	1.00840	0.98874	1.00081	1.00335
9	1.01661	1.00732	1.00118	0.99165	0.96812	1.00287	1.01006	1.00450	1.00743	0.99174
10	0.99158	0.98460	1.00895	1.01288	0.99096	1.02987	1.00816	0.98566	0.99995	0.98957
11	0.98843	1.01882	1.00500	1.01909	0.99588	1.00536	0.98688	0.96922	1.00654	1.00633
12	0.97965	0.98963	0.97724	1.01844	1.00198	1.00960	1.02603	1.01997	0.99485	0.98257
13	0.98506	0.99179	0.99237	0.97173	1.00751	1.02173	1.00748	0.98363	1.02542	1.01594
14	0.98257	1.02581	0.99257	0.99198	0.98456	0.99115	1.00615	1.00724	1.00573	1.00389
15	0.99449	1.01953	0.98918	0.97450	0.99814	0.99370	1.02829	0.99147	0.99950	1.00058
16	1.00237	1.00794	0.98347	0.98721	0.99249	0.99153	0.99268	1.01821	1.00482	1.00768
17	1.00390	1.01953	0.99362	1.00146	1.02483	1.00808	1.01166	0.97340	0.97323	0.99268
18	0.96491	0.99458	1.04294	0.98729	1.00921	0.99274	1.00989	1.01140	0.99170	1.00061
19	0.99694	1.01379	1.01239	0.98572	1.00118	1.01849	0.98680	1.00530	1.02009	0.96255
20	1.00006	1.00552	1.00068	0.98600	0.99921	1.03236	0.98625	1.00625	0.98027	1.00449
21	0.99578	1.00192	0.99985	0.99552	1.01928	0.98640	0.99499	0.99294	1.01990	0.99059
22	1.00073	1.01811	0.99779	0.99663	0.99712	1.00011	0.99144	0.99848	0.99425	1.00800
23	1.00770	0.99870	0.99710	0.99185	1.00496	0.99560	1.00244	0.99583	1.00522	1.00332
24	1.00303	1.00109	1.00173	0.99434	1.01146	0.99854	1.00011	1.00181	1.00985	1.00318
Scenario Probability (%)	9	12	9.3	9.4	10.6	7.5	10.3	10	10.7	11.2

Table 34 Wind power generation of WU 1 values (pu) for stochastic 10 scenarios in terms of deterministic values

Hour	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
1	0.99404	0.99978	0.99691	0.98712	1.00340	0.99941	0.99513	0.99944	1.00156	0.99964
2	0.99373	0.99602	1.01362	1.00146	1.00422	0.98892	0.99829	0.99624	1.00822	1.00091
3	0.99740	0.99982	0.98784	0.99281	0.99688	1.00262	1.00056	0.99729	1.00792	1.00537
4	1.00121	1.00663	0.99826	1.00111	1.00274	0.99736	0.98980	0.99853	0.99660	1.00449
5	0.99448	0.99616	1.00461	0.99869	0.99760	1.00370	1.00166	0.99895	0.99754	1.00952
6	0.99940	0.99519	1.00588	1.00130	1.00495	0.99993	1.00081	1.00990	0.99415	1.00403
7	0.99718	1.00646	0.99765	0.99515	0.99773	0.99647	1.00190	1.01067	1.00380	0.99739
8	0.99653	0.98855	0.99637	0.99847	1.00440	1.00259	0.99547	1.00489	1.00463	1.00103
9	1.00564	0.99369	0.99505	1.00290	1.00176	0.99661	0.99864	0.99939	0.99808	0.99026
10	1.00117	0.99874	0.99948	1.01017	1.00002	0.99728	0.99849	0.98949	0.99679	0.99520
11	0.99963	1.00013	1.00598	1.00212	0.99314	1.00949	1.00029	0.99521	0.99300	0.99910
12	1.00133	1.00064	1.00158	0.99957	1.00086	1.01068	0.99845	0.99712	1.00155	1.00554
13	1.00010	1.00671	0.99155	1.01107	0.99321	0.99795	1.00119	1.00037	0.99750	0.99575
14	0.99916	1.00282	1.00255	0.99588	1.00509	0.99860	1.00591	1.00370	1.00260	1.00420
15	1.00459	0.99901	0.99964	1.00865	1.00002	1.00444	1.00076	1.00487	1.00473	1.00070
16	1.00767	0.99603	1.00345	1.00101	0.99878	0.99346	1.00364	0.99711	0.99606	1.00314
17	1.01122	0.99737	0.99618	0.99628	1.00117	1.00632	1.00266	1.00430	0.99551	0.99713
18	1.00308	0.98748	1.01063	0.99810	0.99352	0.99614	0.99826	0.99593	0.99811	0.99818
19	0.99822	0.99595	0.99174	0.99883	1.00099	1.00303	1.00045	0.99953	1.00222	1.00297
20	0.99857	0.99731	1.00047	0.99824	1.00347	0.99942	0.99095	0.99472	1.00718	0.99539
21	1.00234	1.00338	1.00453	1.00419	1.00271	0.99780	1.00125	0.99806	0.99560	1.00324
22	1.00326	1.00323	1.00553	0.98559	1.00250	0.99544	1.00265	1.00730	1.00070	1.00699
23	1.00390	0.99603	0.99867	1.00633	0.99049	0.99685	0.99929	0.99552	0.98975	0.99727
24	1.01092	0.99818	0.99516	1.00431	1.00546	0.99275	1.00262	0.99817	0.99905	1.00449
Scenario Probability (%)	9	12	9.3	9.4	10.6	7.5	10.3	10	10.7	11.2

Table 35 Wind power generation of WU 2 pu values for stochastic 10 scenarios in terms of deterministic values

Hour	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
1	1.00629	1.00613	1.00073	1.00214	0.99718	0.99886	1.00151	0.99934	0.99730	1.00043
2	1.00631	0.99272	1.00500	0.99505	1.00290	0.99814	1.00193	0.99885	0.99606	1.00435
3	0.99422	1.00697	1.00394	1.00351	0.99311	1.00366	0.99775	1.00156	0.99423	0.99955
4	0.99657	0.99462	1.00185	1.00591	0.99243	0.98972	1.00897	0.99885	0.99671	1.00290
5	1.00256	1.00077	0.99973	0.99593	1.00236	1.01014	0.99306	0.99755	1.00052	0.99549
6	1.00629	1.00093	0.99578	0.99480	0.99748	0.98463	1.00717	0.99588	1.00038	0.99776
7	1.00022	1.00056	0.99817	0.99241	1.00418	0.99995	0.99729	1.00143	1.00556	1.00188
8	0.99372	1.00231	1.00692	0.99870	0.99322	0.99145	0.99971	0.99984	0.99808	1.00249
9	1.00659	0.99604	0.99985	0.99866	0.99821	0.99804	0.99854	0.99692	1.00611	1.00139
10	1.00959	1.00086	0.99608	0.99311	1.00314	0.99866	1.00245	1.00144	1.00072	1.00255
11	1.00576	0.99161	1.00483	1.00104	1.00000	0.99680	1.00773	0.99816	1.00097	0.99824
12	0.99835	1.00128	0.99518	0.99900	0.99878	1.01009	0.99486	1.00398	0.99868	1.00454
13	1.00574	0.99966	1.00058	1.01010	0.99188	1.00053	0.99753	1.00390	1.00595	0.99942
14	0.99586	1.00558	1.01023	1.00667	0.99163	0.99061	1.00473	0.99505	1.00676	1.00570
15	0.99570	1.00073	0.99212	0.99994	1.00808	1.00111	0.98842	1.00503	1.00267	0.99775
16	1.00527	0.99286	0.99788	0.99679	1.00922	1.00370	0.99228	0.99676	0.99249	1.00601
17	0.99667	0.99822	1.00347	0.98985	1.00333	1.00456	0.99659	0.99583	1.00250	0.99719
18	1.00248	1.00038	0.99258	0.99456	0.99988	0.99116	1.00269	0.99318	1.00100	0.99842
19	0.99640	1.00200	0.99895	0.98977	0.99987	0.99831	0.99552	1.00130	0.99634	1.00076
20	0.99305	1.00708	1.00322	0.99730	1.00432	0.99796	1.00020	1.00962	1.00290	0.99760
21	1.00196	0.99194	0.98414	0.99570	1.00877	0.99089	1.00491	0.99405	1.01002	0.99882
22	1.00585	1.00520	1.00145	0.99676	0.99870	0.99963	1.00456	1.00269	1.00608	1.00313
23	0.99452	1.00342	1.00407	0.99352	0.99404	1.00240	1.00743	1.00341	1.00071	1.00115
24	1.00054	1.00285	1.00362	0.99724	0.99480	1.00158	0.99880	1.00186	0.99778	0.99510
Scenario Probability (%)	9	12	9.3	9.4	10.6	7.5	10.3	10	10.7	11.2

Table 36 Wind power generation of WU 3 pu values for stochastic 10 scenarios in terms of deterministic values

Hour	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
1	1.00480	0.99501	0.98495	1.00820	1.00146	0.99225	0.99738	1.00395	1.00204	1.00362
2	0.99526	0.99374	1.00277	0.99759	0.99502	0.99682	0.99496	0.99338	0.99999	0.99693
3	0.99897	1.00131	0.99898	1.00353	0.99824	1.00123	0.99195	0.98725	0.99536	1.01208
4	1.00032	0.99239	0.99755	1.00172	1.00780	0.99345	0.99429	0.98710	1.00484	1.00230
5	1.00068	1.00231	1.00703	1.00620	1.00452	0.98932	1.01002	1.00301	1.00293	1.00078
6	1.00000	1.00148	1.00117	1.00582	1.00499	0.99932	0.99927	1.00141	1.00048	0.99578
7	1.00532	1.00205	1.00237	0.99281	0.99327	0.99693	0.99871	1.00560	1.00173	0.99254
8	0.99833	1.00332	0.99623	0.99946	0.98683	0.99306	0.99562	1.00688	1.00688	0.99113
9	0.99791	1.00372	0.99531	0.99480	0.99939	1.00180	1.01186	0.99954	1.00218	1.00705
10	0.99704	1.00236	1.00197	1.00430	0.99495	0.99932	1.00025	0.99857	0.99233	0.99228
11	0.99328	0.99802	1.00176	1.00023	0.99773	1.00590	1.00424	1.00163	1.00447	0.99227
12	0.99972	1.00950	1.00616	1.00621	0.99350	0.99946	0.99547	0.99738	1.00551	0.99692
13	1.00098	0.99610	0.99605	1.00344	1.00014	0.99805	1.00823	0.99819	1.00110	0.99201
14	1.00226	1.00169	1.01062	0.99262	1.00118	1.00634	0.99410	0.99940	0.99139	1.00200
15	0.99749	1.00113	1.00666	0.99867	0.99958	0.99829	0.99637	1.00160	0.99600	1.00198
16	1.00639	1.00037	1.00186	0.99193	1.00069	0.98902	0.99722	1.00343	0.99972	1.00272
17	0.99491	0.99724	0.99481	0.99838	0.99925	0.99548	1.00210	0.99867	1.00501	1.00162
18	0.99680	0.99883	1.00187	0.99826	0.99903	0.99690	0.99575	0.99878	1.00991	0.99698
19	0.99951	1.00161	0.99642	1.00193	0.99763	1.00292	0.99559	0.99775	1.00304	0.99541
20	1.00673	1.00502	0.99792	1.00327	0.99833	1.00638	1.00451	0.99696	1.00117	1.00299
21	0.99987	1.00610	0.99561	1.00579	0.99769	0.99983	1.00149	0.99952	1.00692	1.00080
22	1.00293	0.99555	1.00369	1.00354	0.99913	0.99071	0.99377	1.00298	1.00420	1.00555
23	1.00009	1.00038	1.00207	0.99682	0.99681	0.99649	0.99967	0.99321	0.99763	1.00021
24	1.00338	0.99510	1.00936	0.99121	1.01452	0.99465	1.00207	1.00241	1.00103	0.99907
Scenario Probability (%)	9	12	9.3	9.4	10.6	7.5	10.3	10	10.7	11.2