MODELING COMPRESSED AIR ENERGY STORAGE FOR RELIABILITY STUDIES OF SUSTAINABLE POWER SYSTEMS

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By

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ABSTRACT

Environmental concerns arising from the conventional generating sources have resulted in extensive growth of renewable energy sources (RES) such as wind and solar. The inherent variability and uncertainty of RES introduce major concerns in power system planning and operation to maintain an acceptable level of supply reliability and system efficiency. Energy storage systems (ESS) are considered as a potential option to mitigate the challenges associated with large scale RES integration. Bulk-scale ESS such as compressed air energy storage (CAES) are expected to take a prominent role in the future sustainable power system with high penetration of RES. This thesis investigates the reliability benefits of CAES in a wind integrated power system.

The reliability contribution of a CAES depends on the operating strategy as well as the technical characteristics. The operating strategy of a CAES is dependent on the number of factors such as the existing market structure, objective of the owner and the intended application. Such factors need to be accurately accounted while developing a reliability model for CAES. This work develops a novel reliability assessment framework for a power system consisting of wind and CAES. The component reliability model of CAES is also developed and incorporated in the overall framework. The applications of CAES to seasonally and diurnally time shift energy are explored. The reliability benefit of CAES, as well as the capacity value increment of wind due to CAES, are quantified. The environmental benefits of CAES from its support to wind power and the financial benefits for a CAES from the existing electricity markets are evaluated. The impact of CAES operation on its potential benefits is analyzed.

Furthermore, appropriate models and methodologies are developed in this work in order to quantify to the overall societal benefits of CAES considering the reliability impact, economic aspects, and environmental objectives. The feasible applications of CAES in wind integrated power systems are formulated and the potential benefits of CAES are assessed. The assessment of CAES benefits provide insights to utilities and policy makers in formulating effective policies and regulatory structures that can attract ESS participation, sustain the growth of RES and ensure acceptable supply reliability. In general, the models and analyses in the work can be valuable for stakeholders regarding cost effective and reliable transition of power system towards sustainable solutions.

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Finally, I want to thank my parents and my brother for their love and support.

DEDICATION

To,

My wonderful parents, Harihar and Laxmi

For their love

And To my awesome brother, Kushal

For his support

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AESO	Alberta Electric System Operator
ARMA	Auto Regressive and Moving Average
BES	Battery Energy Storage
CAES	Compressed Air Energy Storage
CCS	Customer Outage Cost Saving
CEA	Canadian Electric Association
CIC	Customer Interruption Cost
COPT	Capacity Outage Probability Table
CRM	Capacity Reserve Margin
CV	Capacity Value
ECOST	Expected Cost of Interruption
EESW	Expected Energy Supplied from Wind
ELCC	Effective Load Carrying Capability
ERIS	Equipment Reliability Information System
ESS	Energy Storage System
FES	Flywheel Energy Storage
FOR	Forced Outage Rate
HL	Hierarchical Level
HLI	Hierarchical Level I
HLII	Hierarchical Level II
HLIII	Hierarchical Level III
HR	Heat Rate
IEEE	Institute of Electrical and Electronics Engineers
IWEU	Incremental Wind Energy Utilization
kJ	Kilojoule
kWh	Kilowatt Hour
LDC	Load Duration Curve
LLU	Loss of Largest Unit

LOEE	Loss of Energy Expectation
LOLE	Loss of Load Expectation
MCS	Monte Carlo Simulation
MW	Megawatt
MWh	Megawatt Hour
NB	Net Economic Benefit
NERC	North American Reliability Corporation
PDF	Probability Density Function
PHES	Pump Hydro Energy Storage
PJM	Pennsylvania Jersey Maryland
PTC	Production Tax Credit
RES	Renewable Energy Source
RPS	Renewable Portfolio Standard
RTS	Reliability Test System
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
TC	Total societal Cost
UC	Utility Cost
UPM	Units Per Million

CHAPTER 1: INTRODUCTION

1.1. Power System Reliability

Power system reliability can be defined as the ability of the electric power system to deliver electricity to customers with acceptable quality and continuity. Power outages can result in significant adverse economic and social impacts to the end users as well as the utility supplying the power. Therefore, power utilities must provide reasonable assurance of system reliability to their customers. The reliability of supply can be improved by increasing redundancies and reserves during system planning and operation. However, this increases the overall system cost, which should be justified by the achieved reliability worth. With growing worldwide concerns regarding the adverse environmental impacts of energy generation from conventional sources, the goal of meeting environmental regulations is considered as an important aspect in power system planning and operation. The primary purpose of the modern sustainable electric power system is to provide its customers with electric power as economically as possible with an acceptable level of reliability while complying with environmental obligations.

Power system reliability evaluation is an essential task in system planning and operation. System reliability can be generally divided into two fundamental aspects of adequacy and security, which are represented in Figure 1.1.

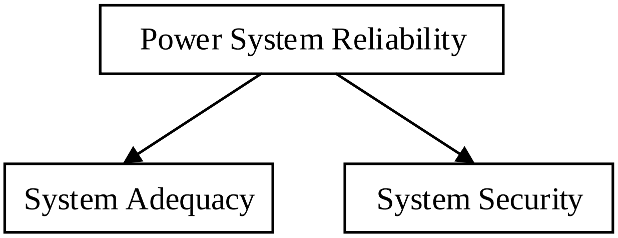


Figure 1.1. Fundamental aspects of power system reliability.

The North American Electric Reliability Corporation (NERC) [2] defines system adequacy as the ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements. System security is defined as the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components. The scope of this thesis is within the area of system adequacy.

1.1.1. Functional Zone and Hierarchical Level

The overall power system can be divided into three major functional zones of generation, transmission and distribution. Power system reliability assessment can be performed by creating different hierarchical levels (HL) from the combination of these functional zones [3] as shown in Figure 1.2.

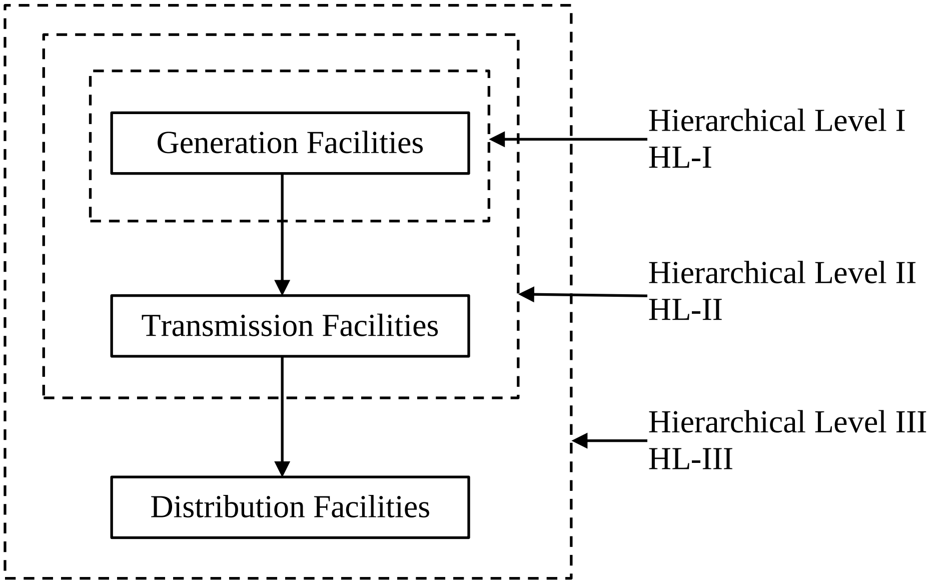


Figure 1.2. Hierarchical levels in reliability assessment.

Reliability assessment at HL-I is concerned with the ability of the total system generation to satisfy the total system demand. HL-I studies are also termed as generating capacity reliability evaluation. HL-II studies, also called bulk or composite system reliability analysis, considers both the generation and transmission system, and determines their combined ability to generate and deliver power to bulk supply points. Reliability assessments at HL-III includes all of the generation, transmission and distribution systems and evaluates the ability of the complete system to meet the demands of the individual consumer. Predictive HL-III studies are not conducted in practical power systems due to the complexity and scale of problem and are mainly limited to past performance analysis. Instead, the reliability analysis is performed independently in distribution facilities often using the results of upstream HL-II evaluation.

The research work presented in this thesis is focused on HL-I adequacy analysis. The basic representation of the system model for HL-I studies is shown in Figure 1.3.

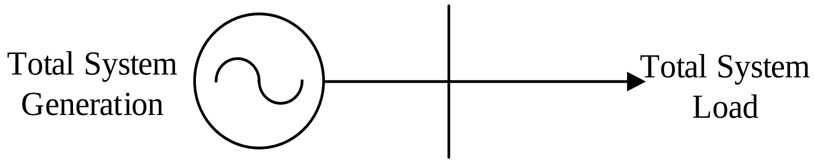


Figure 1.3. System representation at HL-I.

HL-I studies involve the development of a generation model and a load model for the entire power system, and the convolution of these two models to obtain the risk model as represented in Figure 1.4. Limited transmission system models can also be incorporated under HL-I studies [1]. The work presented in this thesis also includes transmission lines connecting wind farms to the power grid.

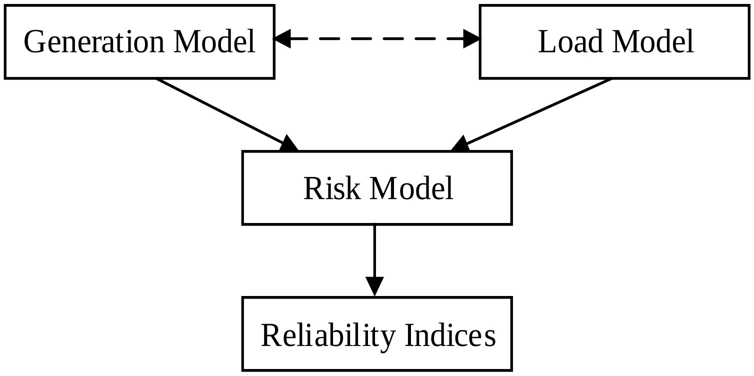


Figure 1.4. Conceptual task for HL-I adequacy evaluation.

1.1.2. Reliability Assessment Techniques

Reliability assessment of a power system can be performed using either deterministic or probabilistic techniques. Deterministic techniques are simple and easy to apply and have been widely used in the past. The common deterministic approach include the loss of the largest unit (LLU) or ‘N-1’ method, capacity reserve margin (CRM) method, and a combination of the two methods [4]. The major drawback of a deterministic technique is that it cannot represent the inherent stochastic behavior of a power system arising from component failures, or load and generation variations. On the other hand, probabilistic techniques are capable of representing the actual random factors existing in the power system that influence the system reliability. Probabilistic techniques can provide quantitative reliability indices that can be interpreted to compare alternative operation, planning or upgrade options against their associated costs to make prudent decisions. With increasing uncertainties and changing scenarios in emerging power systems, probabilistic techniques are preferred for power system reliability assessment. This thesis explores probabilistic techniques for reliability assessment of power systems incorporating wind power and energy storage.

Probabilistic reliability assessment can be conducted using either analytical methods or Monte Carlo simulation (MCS) techniques [5], [6].

An analytical method involves the formulation of mathematical models to represent the system components and characteristics, and the evaluation of the reliability indices from the developed models using direct numerical solutions [1]. These methods take relatively short computation time and generally provide the expected value of the reliability indices. The demerit of an analytical method is that it cannot easily provide the distribution of indices around the expected value. In addition, it often requires many assumptions in the model development to represent complex systems with dependencies and sequential events. The accuracy of results is therefore compromised to obtain solvable mathematical models to represent such systems. These difficulties can be mitigated by the use of simulation techniques.

A MCS technique estimates the reliability indices by simulating the actual process and stochastic behavior of the system. This technique utilizes random numbers to represent the system states. In this technique, a particular problem is treated as a repeated series of experiments conducted until the convergence criteria is met, and, subsequently, the reliability indices are calculated. MCS techniques used in power system reliability evaluation can be broadly classified into two categories: random simulation and sequential simulation. Power system operating states are simulated without considering the chronology of events in the random MCS approach. The sequential MCS approach incorporates the sequence of events in time chronology. The main advantage of a sequential MCS technique is that it can easily incorporate complex system operating conditions and can recognize the inherent correlations and dependencies existing in the system. This technique can also be used to easily obtain the distribution of reliability indices including the frequency and duration indices along with the expected values. The main drawback of an MCS technique is its high computational requirement to conduct large simulation samples. This is becoming less of a concern as computational power has been rapidly increasing with technological advances. The convergence of the simulation process depends on the random number seed, and different seeds do not usually converge at the same value when high precision is desired. A key problem in the application of this technique is that a customized computer program needs to be developed for a particular type of system evaluation, and it is extremely difficult to obtain a general tool that can be used for any system or that can consider new scenarios and operating philosophies.

The research work presented in this thesis utilizes both the analytical method and the sequential MCS technique for reliability assessment. A hybrid approach combining the two methods has also been developed in this work.

1.1.3. Reliability Cost/Worth Concepts

Reliability cost refers to the cost needed to achieve a certain level of reliability. This is the capital investment, operation and maintenance cost incurred by the utility, and is also referred to as the utility cost (UC). Reliability worth refers to the benefit obtained due to the improvement in supply reliability. The direct evaluation of reliability worth is difficult, and therefore, it is generally estimated from customer interruption costs (CIC). This is the cost of unserved energy to the customers caused due to the unreliability of the supply. In general, CIC depends on the types of customer and the duration and magnitude of supply interruptions. Both the UC and CIC are eventually transferred to the customers. The total societal cost is the sum of the UC and CIC as shown in (1.1).

$$Total\ Societal\ Cost (TC) = Utility\ Cost\ (UC) + Customer\ Interruption\ Cost\ (CIC) \quad (1.1)$$

Reliability cost/worth assessment also termed as value based reliability assessment, considers generating and delivering reliable power to the customers at the lowest societal cost. Figure 1.5 illustrates the concept of reliability cost/worth assessment. It can be observed from the figure that, the utility cost increases while CIC decreases with the increase in system reliability level. The optimum reliability level occurs at the point where the sum of UC and CIC is the lowest. Reliability cost/worth analysis is performed to find such optimal reliability point.

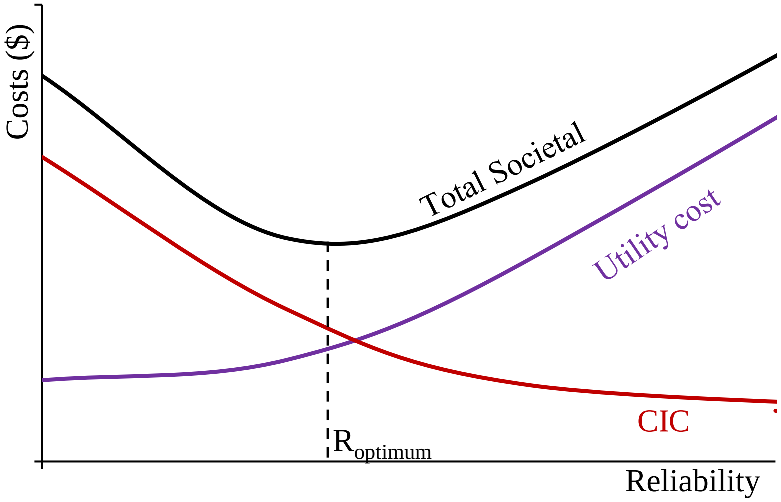


Figure 1.5. Total societal cost and system reliability.

1.1.4. Basic Reliability Indices Used in HL-I Reliability Studies

Different reliability indices are used to quantify system adequacy at HL-I. The evaluation of reliability indices require performance and reliability data of different system components. In Canada, the Canadian Electric Association (CEA) Equipment Reliability Information System (ERIS) [7] collects power system equipment outage data from participating electric utilities and compiles them to provide annual reliability data reports.

The definitions of the basic reliability indices used in Hl-I adequacy studies are presented below. The detailed methodologies and procedures to obtain these indices can be found in [1], [6].

- Loss of Load Expectation (LOLE): LOLE is the expected amount of time during which loss of load occurs in the system. It is expressed in hours/year or days/year. Many North American electric utilities use the NERC recommended reliability planning criterion of 0.1days/year. However, with the growth of variable generations such as wind and solar, LOLE in hours/year and energy related indices are also used in adequacy planning studies.

- Loss of Energy Expectations (LOEE): LOEE is the expected amount of energy not supplied when needed due to the supply interruptions. It is expressed in MWh/year.

- Units Per Million (UPM): UPM is obtained by normalizing the LOEE index with the annual energy demand and multiplying the resulting number by one million.

- Effective Load Carrying Capability (ELCC): ELCC is the maximum peak load that a system can serve while meeting a specified reliability criterion. It is measured in MW.

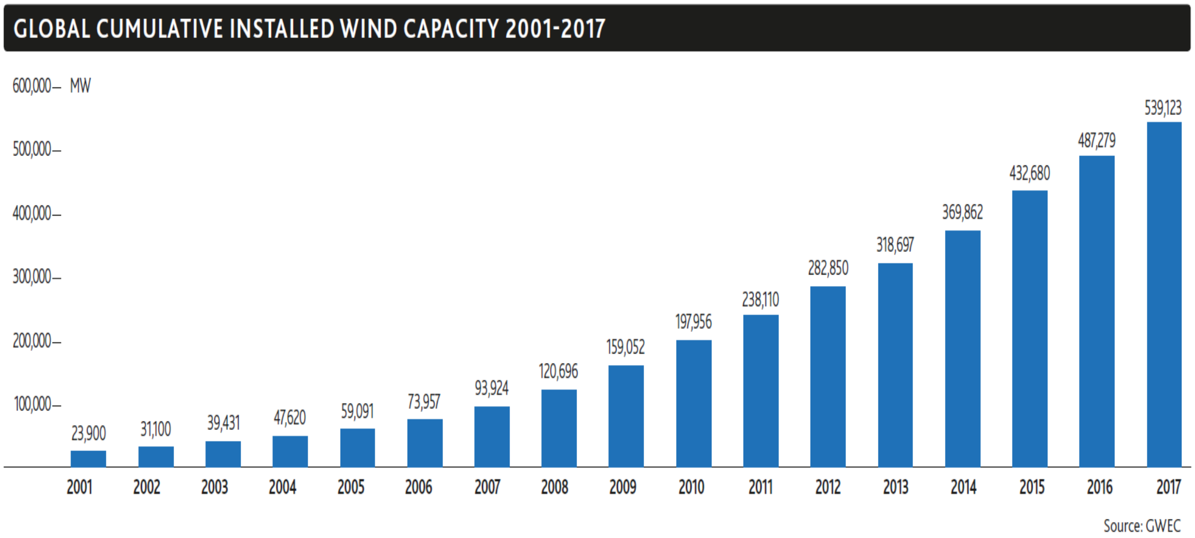
- Capacity Value (CV): CV of any generating resource is the increase in ELCC due to the addition of the generating resource in the system while maintaining the original level of system reliability. It is measured in MW or as a percentage of the rated value of the added generation.

- Expected Cost of Interruptions (ECOST): ECOST is the expected cost of unserved energy which is measured in $/year. It is also called as customer interruption cost or expected damage cost.

1.2. Wind Power and Energy Storage Systems

1.2.1. Growth of Wind and Energy Storage Systems in Power Systems

The conventional fossil fuel based generating sources are considered as the prominent factor causing adverse effect to the environment. Therefore, tremendous effort has been applied for the development and utilization of clean renewable energy sources (RES) such as wind and solar. Many jurisdictions around the world have adopted renewable portfolio standards (RPS) that require electric utilities to produce a certain percentage of their generation from RES [8]. Wind energy is perceived as a promising alternative to the conventional generating sources and has a great potential to be one of the major power source in the future. The addition of wind power in power systems has been increasing continuously for the past few decades, and the trend is expected to continue in the future. Figure 1.6 shows the global installed capacity of wind power from the year 2001 to 2017 [9]. In Canada, the current installed capacity of wind is 12,252 MW, which is around 6% of Canada's electricity demand. The annual growth rate of wind energy from 2012 to 2017 was about 15% in Canada [10]. In Saskatchewan, the present installed wind capacity is 221 MW, which is about 5% wind penetration. By 2030, the wind capacity in Saskatchewan is expected to grow to 2100 MW, which will be 30% penetration in the system [11]. These statistics clearly indicate that high levels of wind penetration can be expected in the future to achieve a sustainable power supply.


GLOBAL CUMULATIVE INSTALLED WIND CAPACITY 2001-2017

Source: GWEC

Figure 1.6. Global cumulative installed wind capacity [11].

Wind energy sources are variable and uncertain in nature as their output is dependent on the wind characteristic of the geographic site. A site with high wind potential can have very low or even zero output for a significant portion of the time. With large scale integration of wind power, the associated variability and uncertainty gives rise to new challenges in power system planning and operation to continuously maintain a balance between electricity generation and demand and ensure system reliability and efficiency (minimizing cost of resources) [12],[13]. Furthermore, the transmission upgrade required to accommodate a large amount of wind can also be a major concern [14].

The accommodation of a large amount of wind energy in the electric grid requires greater grid flexibility [12]. In this regard, energy storage systems (ESS) are emerging as potential technologies that can mitigate the challenges of wind integration [15], [16]. ESS can absorb the variability and compensate for the uncertainty of the wind generation with the management of stored energy and thus can open up the opportunity for large scale wind power growth. By mid-2017, there existed approximately 176 GW of total installed capacity of different types of ESS. Pumped hydro energy storage (PHES) currently dominates installed capacity with around 96% of the total capacity [17]. The rapid growth of RES can be considered as the primary factor for increasing integration of ESS in the electricity grid [18]. Furthermore, with technological improvement and decreasing capital cost, different types of ESS technologies are expected to grow in power systems [17].

1.2.2. Different Types of ESS

This section provides a general overview of different ESS technologies. They have diverse technical characteristics, and accordingly, provide different power system applications. ESS technologies can be classified in different ways. Figure 1.7 shows the classification of major ESS technologies based on the form of energy stored [19], [20]. A general comparison of the characteristics of different ESS technologies is shown in Figure 1.8 [21].

ESS can be deployed for providing a wide range of applications in power generation, transmission and distribution. Such applications include renewable energy support, time shift of energy, transmission support, ancillary services, power quality, and reliability, etc. Compressed air energy storage (CAES) and PHES are typically suitable for large scale deployment and can store energy for a long duration. Therefore, they are applicable for bulk power system applications such as time shifting of electrical energy, transmission congestion management, providing a seasonal reserve, etc. However, CAES and PHES can only be installed in suitable geographical locations. Flywheel energy storage (FES), superconducting magnetic energy storage (SMES) and supercapacitors have rapid response capability and are generally applicable for providing ancillary services such as frequency regulations, power quality, and renewable smoothing. These ESS technologies can only retain energy for a relatively short duration. Battery energy storage (BES) technologies also have fast response capability and can support the power system by providing frequency regulation services, peak shaving, and renewable capacity firming [22]- [24].

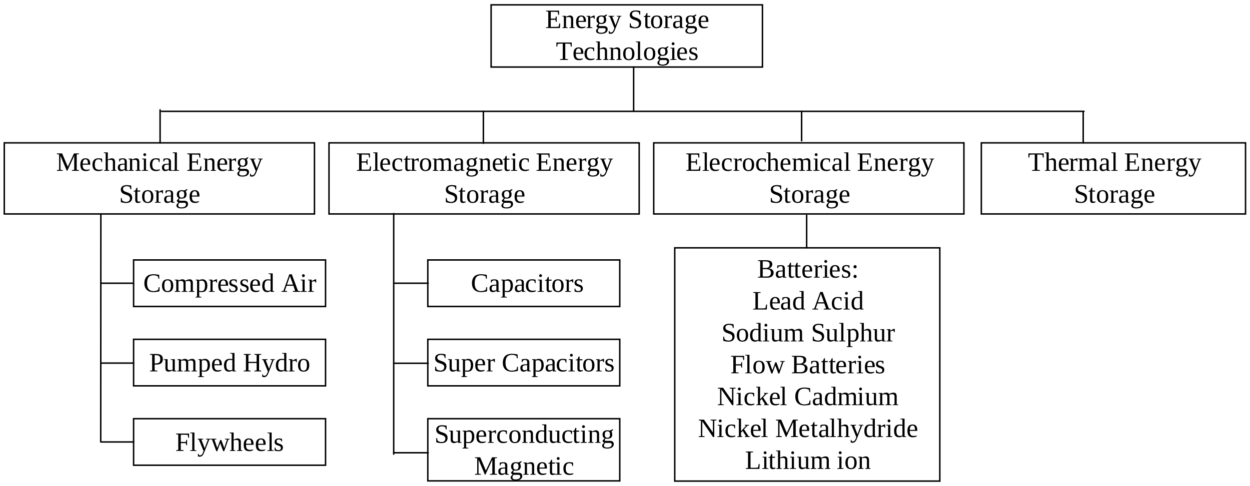


Figure 1.7. Classifications of different energy storage.

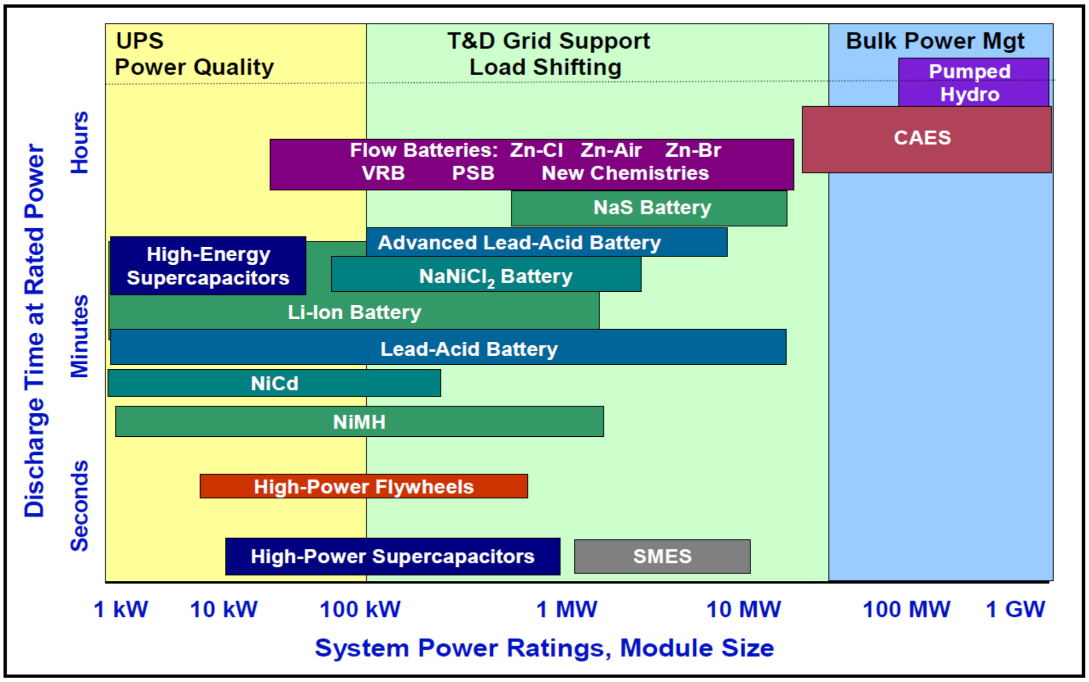


Figure 1.8. Comparison of characteristics of different energy storage technologies [23].

The applications of ESS in a power system are dependent on their technical characteristics as well as on the ownership, objective and the existing market and regulatory structures. ESS needs to respond to the market in order to gain financial advantage from its application. Basically, ESS can obtain revenue by participating in the capacity market, energy market (day ahead and real time) and ancillary service market [25].

1.3. Compressed Air Energy Storage

1.3.1. Operation of CAES

CAES is one of the mature, bulk scale energy storage technology that can store energy for a long duration [22]. CAES stores energy in the form of high pressure compressed air. The schematic diagram of a CAES is shown in Figure 1.9. The major parts includes: a motor/generator set that can be used as a motor during charging and generator during discharging using a clutch mechanism, a multistage compressor with intercoolers and after-coolers, a turbine train consisting both high pressure and low pressure turbine, and one or more caverns for storing high pressure air [26], [27].

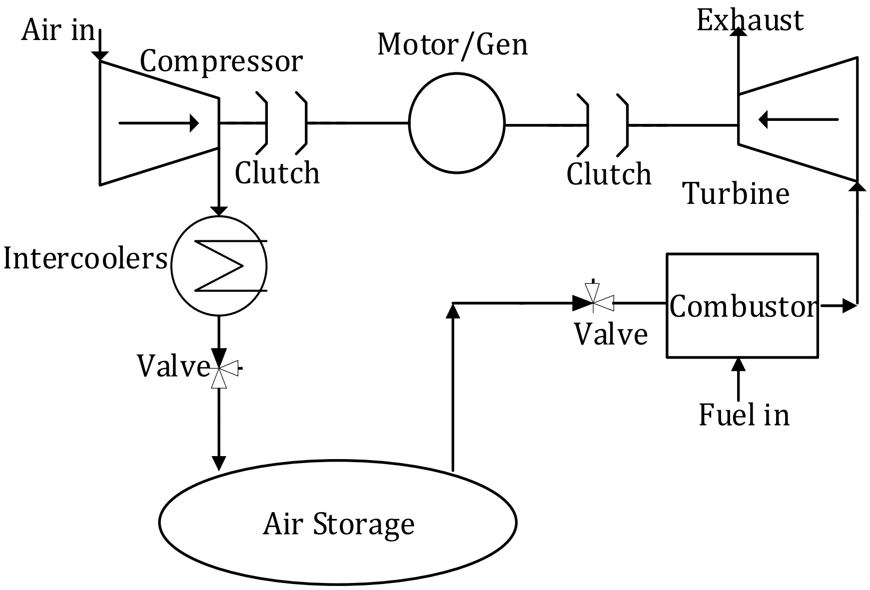


Figure 1.9. Schematic diagram of CAES.

During the charging or compression mode, ambient air is compressed using a chain of compressors, which are driven by an electric motor. The surplus power in the power system can be used to run the CAES motor and store energy during the period of low electricity demand. The compression process uses intercoolers and after-coolers to reduce the temperature of the air and improve compression efficiency. The high pressure air is stored in a cavern, usually an underground salt cavern. During the expansion or discharging mode, the stored high-pressure air is released, combusted in the combustion chamber and finally expanded through the gas turbine. The gas turbine runs the electric generator to generate electricity. The combustion process in a CAES uses the pre compressed air as well as a portion of natural gas [27], [28]. The state of charge (SOC) or the energy level in CAES is indicated by the mass/pressure of air inside the cavern [29]. The discharging process of CAES is similar to that of a conventional gas turbine. In a conventional gas turbine, the compression and expansion process takes place simultaneously and around two third of the turbine output is used to run the compressor. However, in a CAES, the compression and expansion process are completely decoupled and the full output of the turbine can be used to generate electricity [29]. The fuel consumption in a CAES during expansion is significantly lower compared to that of a traditional gas turbine. In general, a CAES plant can produce the same power output as a conventional gas plant using approximately 60% less natural gas [30].

The performance of CAES can be characterized using different parameters such as heat rate, energy ratio, round trip efficiency. The heat rate of a CAES is measured in kJ/kWh and indicates the amount of fuel consumed per kWh output of electricity generated [31]. The energy ratio is defined as the amount of compression energy required to produce one unit of energy output. The energy ratio of a conventional CAES is less than one, which implies more energy is generated than stored because of the use of natural gas during generation [31]. Similarly, the round trip efficiency of a CAES is defined as the ratio of total energy output to the energy input. The total energy output is the output power of the electric generator, and the total energy input is the sum of energy consumed by the compressor and the energy consumed from natural gas/fuel [27].

The siting of CAES requires a feasible geographical structure for storage of compressed air. The possible geological structures suitable for large scale CAES include underground salt cavern, aquifers, depleted oil and gas reservoirs and rock mines [32],[33]. Underwater balloon vessels and air accumulators can also be used for storing compressed air [34].

CAES is not an independent storage technology as it requires fuel during discharging. CAES that use a portion of fuel (natural gas) is called diabatic CAES. With the advancement of technology, many improvements in CAES technology is proposed and being researched. An advanced adiabatic CAES (AA CAES) is such technology in which the heat released during the compression stage is stored using thermal energy storage and is reused during the expansion stage. This can eliminate or reduce the requirement of natural gas combustion during the expansion process and improve CAES efficiency [33].

The CAES models used in this thesis are based on diabatic CAES. The operating parameters are taken from an existing operational CAES plant for the studies presented in this thesis.

1.3.2. Existing and Proposed CAES

At present, there are two large-scale operational CAES plants. The world's first CAES plant was built in 1978 and is located in Huntorf, Germany. This plant is operated to reduce the price of electricity during peak periods and provide black start power to nuclear units located near the North Sea. The Huntorf CAES has two underground salt caverns with a total volume of 310,000 m^3. The rated charging power of the Huntorf plant is 60 MW and the rated discharging power is 290 MW. The charging duration at the rated power is 8 hours and the discharging duration at the rated power is 2 hours. The operating range of pressure is between 46 bars to 66 bars. The heat rate of the plant is around 5800 kJ/kWh and the energy ratio is around 0.82. The round trip efficiency of the plant is around 42% [27], [28], [35], [36].

The other existing CAES plant is located in McIntosh, Alabama and was built in 1991. This plant is used to provide spinning reserve and store off peak power. The McIntosh CAES has a single underground salt cavern with a volume of 538,000 m^3. The rated charging power of the McIntosh plant is 50 MW and rated discharging power is 110MW. The charging duration at the rated power is 40 hours and the discharging duration at the rated power is 26 hours. The operating range of pressure is between 45 bars to 74 bars. This plant uses heat recuperator to reuse the heat from the exhaust of the gas turbine. The heat rate of the plant is around 4300 kJ/kWh and the energy ratio is around 0.7. The round trip efficiency of the plant is around 54% [27], [28], [35], [36].

Many other CAES plants have been planned and proposed. An 800 MW CAES facility with provision to expand to 2700 MW (9 x 300 MW) was proposed to be constructed in Norton, Ohio, US which would use abandoned limestone mine for air storage. Similarly, a 268 MW CAES plant coupled with 75 MW to 100 MW of wind was proposed to be constructed in Iowa, US. Ridge Energy Storage and Grid Service have announced the construction of 540 MW (4 x 135MW) CAES plant in Matagorda County, Texas [29], [32].

A pilot project for underwater CAES with 660 kW capacity is developed in Toronto Island, Ontario, Canada by Hydrostor, which uses underwater accumulators to store pressurized air [34]. A 135 MW - 160 MW CAES facility is proposed near Lloydminster Canada. The project is called Alberta Saskatchewan Intertie Storage Project (ASISt) [37]. The province of Saskatchewan also has other several potential locations for CAES siting. The area of Yorkton, Saskatoon, and North Battleford show high potential for CAES construction [38].

1.3.3. Application of CAES in Power System

CAES provides a range of benefits in operation and planning of wind integrated power systems. CAES supports wind integration, helps in managing peak demand, improves system reliability, and provides transmission value. Some of the major applications of CAES in power system are discussed below [23], [24], [27], [32]:

- Time shifting of electrical energy: CAES can shift energy from the low load period to the peak load period to benefit from peak shaving. Since the price of electricity is closely correlated with the demand, the CAES owner can make a profit from energy arbitrage by buying at a low price period and selling at high price period.
- Seasonal energy storage: Large scale CAES can store and accumulate energy for months, and can shift energy from one season to another. Such application is useful in a power system having large seasonal variation in power generation and consumption.
- Improving capacity value of intermittent wind power: Wind generation acts as an energy resource rather than a capacity resource. Wind energy may not significantly contribute to the peak load carrying capability of the system. CAES can store the off peak wind energy and discharge during the peak load period. Such operation improves the system reliability and increases the capacity value of wind power.

- Ancillary services: CAES can provide ancillary services such as frequency regulation, operating reserve, black start etc.
- Transmission support: Strategic location of CAES can be utilized to relieve transmission line congestion. CAES can also be used to defer transmission upgrades in the system.
- Wind curtailment reduction: CAES can store wind energy when there is excess wind generation that cannot be absorbed by the system, and would otherwise be spilled.

1.4. Research Motivations and Objectives

The transition of the modern power industry towards sustainable solutions requires large scale expansion of renewable energy such as wind. The increased variability and uncertainty in power generation due to renewables creates considerable challenges in power system operation and planning to maintain an acceptable level of reliability to consumers. ESS technologies are emerging as a potential solution that can mitigate the concerns of RES integration. Therefore, bulk scale ESS such as CAES are expected to take a prominent role in future sustainable power systems with high penetration of renewables [39]. CAES is a grid scale storage that can have significant implications on power system operation and long term planning. The planning and operation of CAES should consider the system reliability implications in addition to the economic aspect and environmental benefits from its support to renewable energy.

In order to analyze the impact of CAES on power system reliability, appropriate models techniques and frameworks need to be developed. The reliability impact of CAES is dependent on its characteristics as well as the operation strategy. The operation strategy depends on a number of factors such as the location of CAES, objective of the owner, intended application, electricity market structure and the regulatory policies. CAES can be operated for energy arbitrage, seasonal energy management, wind curtailment reduction, transmission congestion management, etc. The operation of CAES is also contingent upon the availability of different components responsible for charging and discharging process. The operating strategies of CAES along with the technical characteristics and the component unavailability should be accurately accounted in the reliability assessment models. The stochastic nature of power system arising from variable RES, CAES operation, random component outages as well as the other sources needs to be considered while developing probabilistic reliability assessment techniques and tools. Furthermore, it is important that the developed techniques are relatively easy to apply in practice.

Considerable research has been conducted to assess the reliability level of the power system with ESS [14], [40]-[52]. These works have considered a generic ESS model without detailed modeling of the specific type of ESS. There is a need to develop specific reliability models for CAES considering its characteristics as well as the failures of the components present in CAES and their effect in the charging/discharging process. Both the MCS methods [40], [41], [43] and the analytical methods [51], [52] have been explored to analyze the reliability impact of ESS in power systems. A MCS based method can incorporate the correlations and dependencies between the system variable such as the state of charge (SOC) in ESS, load, wind etc. However, these methods are computationally cumbersome and cannot provide a generic model to provide a direct solution to the reliability planning problem. On the other hand, analytical methods are computationally efficient and provide general mathematical models for reliability assessment. However, these methods require many assumptions to represent the system complexities and cannot accurately model the dependencies in the system. It is necessary to develop a reliability assessment framework that can utilize the advantage of both analytical method and the MCS method in order to produce generic, comprehensive and computationally efficient methods. Moreover, it is necessary to quantify the adequacy benefit of CAES in a system with large scale renewable penetration as well as the increment in capacity value of renewables due to CAES.

The operation strategy of a CAES is dictated by the existing market and regulatory structure which in turn impacts the overall system performance. The works in [40], [46] have modeled operating strategies of ESS and their impact on system reliability. However, different feasible applications and operating scenarios of CAES that can have significantly different impacts on system reliability have not been modeled in these works. Therefore, there is a need to explore CAES applications and operations and study their impacts on system reliability.

In addition to providing the reliability benefit to the system, CAES can play a crucial role to meet the environmental objective by supporting wind integration as well as to ensure system efficiency in wind integrated power system. An extensive assessment of the reliability value, environmental benefits and economic impacts of CAES are essential for developing effective regulatory structures that can integrate bulk scale ESS efficiently in power system. Existing works [40], [48] have explored the environmental benefits obtained from ESS through renewable support as well as the economic aspect [53] - [56] of ESS in the wind integrated power system. However, specific characteristics and applications of bulk scale ESS have not been explored while quantifying the potential benefits. New models are required to quantify the overall societal impact of CAES considering reliability, environmental objective, and CAES economics. Therefore, there is a need to develop models and methodologies that incorporates CAES attributes, and, systematically analyzes different aspects of the potential benefits obtained from different CAES operations. Such models and methodologies are crucial to providing insights for formulating effective regulatory structures to integrate bulk-scale storage efficiently and support the imminent growth of renewable energy while maintaining reliable supply to electricity consumers.

Based on the research motivations presented, this thesis aims to develop reliability assessment models and quantify the reliability contribution of CAES in a wind integrated power system. The specific objective of this research work are summarized below:

- To develop a component reliability model of CAES considering the failure of major system components and their effect on the charging/discharging process.
- To develop a power system adequacy assessment framework considering CAES characteristics, diurnal and seasonal energy management, market scenarios, intermittent wind power and other system variables.
- To quantify the reliability benefit and capacity contribution obtained from CAES for power system adequacy planning.
- To develop a methodology to assess the overall societal benefit obtained from different CAES applications and provide insights for formulating regulatory structures that can integrate CAES efficiently.

1.5. Thesis Organization

This manuscript based thesis contains five chapters. The three main chapters of this thesis are based on the papers submitted or published. Each chapter contains necessary details and can be read on its own. References are presented separately for each chapter. All the chapters are closely linked with each other and contribute to meet the overall objective of the thesis. The thesis is organized as follows:

Chapter 1 introduces the basic concepts of power system reliability and reliability assessment methods. A brief description of the wind power and ESS growth in the power system is presented in this chapter. CAES operation mechanisms and the applications are discussed. Preliminary work done to investigate the impacts of CAES operation on the reliability of wind integrated bulk power system was reported on the paper entitled "Reliability Evaluation of Bulk Power System Considering Compressed Air Energy Storage", which is published in the *IEEE Electrical Power and Energy Conference (EPEC),* Saskatoon, 2017 [57]. This work provided the basis for developing reliability models and methodologies presented in the thesis. The research motivation, objective and the thesis organization is also presented in Chapter 1.

Chapter 2 is the paper titled "Reliability Modeling of CAES for Adequacy Assessment of Wind Integrated Power System" which is submitted to *IET Generation, Transmission and Distribution* journal. This chapter presents a novel hybrid framework for adequacy assessment of a power system with wind and CAES. A detailed Markov model for CAES component reliability is also presented. The case studies were conducted to quantify the reliability benefit of CAES operated for diurnal and seasonal energy management.

Chapter 3 is the paper titled "Reliability and Environmental Benefits with Market Operation of CAES in Wind Integrated Power System" [58]. This paper is published in the proceedings of *2018 IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS),* Boise, ID. This chapter focuses on studying the impact of operating scenarios on the potential reliability benefit of CAES. Different operating scenarios including maximum profit scenario are modeled for a merchant owned CAES and the reliability benefit is quantified.

Chapter 4 is a paper titled "Reliability and Economic Assessment of CAES in Transmission Constrained Wind Integrated Power System" which is submitted to *Journal of Energy Storage, Elsevier*. This chapter presents a comprehensive methodology to quantify the overall societal benefit of CAES considering the reliability impacts, economic aspects, and environmental objectives. The methodology incorporates transmission constrained wind farm models and different operational modes for CAES. The assessment of CAES benefits provide insights into the development of new policy and regulatory structures that can efficiently integrate bulk scale ESS in the power system.

Finally, Chapter 5 presents the summary and conclusion of the work.

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CHAPTER 2: RELIABILITY MODELING OF COMPRESSED AIR ENERGY STORAGE FOR ADEQUACY ASSESSMENT OF WIND INTEGRATED POWER SYSTEM [1]

2.1. Abstract

The integration of Energy Storage System (ESS) is gradually accelerating in existing power systems as they are considered as potential means to mitigate the challenges arising from the extensive renewable energy growth. This paper considers the impact of bulk scale Compressed Air Energy Storage (CAES) on power system reliability. A hybrid approach for power system adequacy assessment is proposed and a detailed Markov model for CAES component reliability is developed. The proposed approach uses a sequential Monte Carlo Simulation method to model the state of charge incorporating the important dependent variables and a probabilistic analytical framework to assess the system adequacy. An equivalent average model that can reflect the effect of energy accumulation is developed based on this hybrid framework for adequacy assessment considering seasonal energy management using large scale ESS. The potentiality of bulk-scale CAES for diurnal and seasonal energy management is explored. The proposed framework is applied to a test system to quantify the reliability, environmental and financial benefits of CAES.

2.2. Introduction

Global environmental pollution has become a major concern regarding electricity generation from conventional fossil fuel based sources. Renewable energy sources such as wind and solar are being perceived as alternatives for sustainable energy supply.

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[1] **S. Bhattarai, R. Karki, and P. Piya, "Reliability Modeling of Compressed Air Energy Storage for Adequacy Assessment of Wind Integrated Power System ," submitted to *IET Generation, Transmission and Distribution journal* (Under review).**

The variability and uncertainty associated with power generation from large-scale wind energy resources integrated in a power system create significant challenges in system planning and operation. These challenges can be mitigated by an Energy Storage System (ESS), which facilitates high penetration of wind generation in the power grid by absorbing the variability and managing the usage of the stored energy. Compressed Air Energy Storage (CAES) is one of the mature bulk energy storage technology [1]. With increasing renewables, the deployment of bulk-scale ESS technologies such as CAES is expected to increase significantly in the power grid.

The planning and operation of ESS should consider the system reliability implication in addition to the environmental benefit from its support to renewable energy, and the financial benefit from the electricity market. The operation of ESS is dependent on a number of factors such as the existing electricity market structure, the objective of the owner, and the regulations for incentives/penalties on its performance. ESS can be operated for different applications, such as electric energy time shifting, improving supply reliability, providing ancillary services, renewable capacity firming, congestion relief, transmission and distribution upgrade deferral [1], [2]. Depending on the application of ESS, it can participate in the day ahead and/or real time energy markets, installed capacity market and ancillary services market [3]. The economic aspect of ESS integration along with the different potential mechanism to gain financial benefits considering various kinds of electricity market have been studied in [4]-[7]. Several studies have explored the possible environmental benefit of ESS obtained by facilitating wind integration and increasing wind utilization [8]-[10].

The reliability benefit of ESS in the power system has been evaluated in past research work using analytical or Monte Carlo Simulation (MCS) based methods [11]. References [12] - [16] use a sequential MCS framework to quantify the reliability contribution of ESS. Though MCS based method can incorporate the correlations and dependencies between the system variables, these methods are computationally cumbersome and cannot provide a generic model to provide a direct solution to the reliability planning problem. Analytical methods have also been explored for the reliability assessment of power system with ESS. Reference [17] uses the load profile modification technique to model the ESS operation and evaluates the reliability using an analytical framework. This technique cannot account for the scenarios where ESS has to discharge in a different way than its pre-scheduled operation because of randomly occurring loss of load events. Also, the dependencies of state of charge (SOC) on component reliability, intermittent renewable generations, and variability in available power for charging cannot be easily incorporated in the load modification technique. In [18], researchers incorporate the effect of component failure on its SOC by introducing a certain constant and evaluate the reliability index at each time step. This method cannot accurately model the effect of failure/repair process and other system variables during charging on the SOC level of ESS. The modeling of SOC due to stochastic ESS operation is performed in every time step based on all possible system scenarios in [19]. Such SOC modeling is computationally burdensome for practical systems with a large number of system states. Reference [20] combines similar SOC modeling technique with load modification technique as in [17] to model reliability based and economical operation of ESS. However, the model cannot accurately emulate the feasible ESS applications and the dependencies of SOC with system variables.

The technical and economical characteristics determine the application of the ESS in the power system [21]. A CAES is applicable to time shift energy within a daily cycle as well as to accumulate and shift energy from one season to another [2], [21]. Such seasonal energy transfer can have significant importance in terms of capacity available for the reliability requirement, which provides a different perspective for a long term power system adequacy planning. In addition, the capacity uncertainty problem caused by variable renewable integration can be mitigated with CAES. This application makes CAES suitable for participating in the capacity as well as the energy market. The reliability evaluation method for a system consisting of CAES should accurately model its typical applications and technical characteristics. However, in the existing literature, applications and technical characteristics specific to CAES reliability modeling have not yet been explored. A generic ESS model has been used in [12]-[15], [17], [18]. The CAES reliability model used in [16] lacks accurate modeling of the charging/discharging process and the components involved. The feasibility of CAES for seasonal energy transfer has been studied in [21], [22], but, the existing works have not explored the adequacy benefit obtained from such operation.

This paper develops a hybrid framework for the adequacy evaluation of power systems consisting of CAES. The framework uses sequential MCS to model SOC during charging process incorporating dependent variables such as component failure, available charging power, and variable renewable generations. The SOC model obtained using MCS is integrated with the wind, load, and conventional generator models for reliability evaluation using an analytical approach.

An equivalent average model to quantify the adequacy benefit of CAES operated to seasonally accumulate and transfer energy is developed within the hybrid framework. This hybrid framework brings together the advantages of both MCS and analytical method in the reliability evaluation resulting in a comprehensive and computationally efficient framework. Moreover, the component reliability model of CAES used in the hybrid framework, considering the failures of the components and their effect in the charging/discharging process, has been developed in this paper.

2.3. Markov Model for CAES Component Reliability

A schematic diagram of CAES with its major components is shown in Figure 2.1. The major components of a CAES system can be divided into three main subsystems:

1) Compression subsystem
2) Turbine/expansion subsystem
3) Motor/generator subsystem.

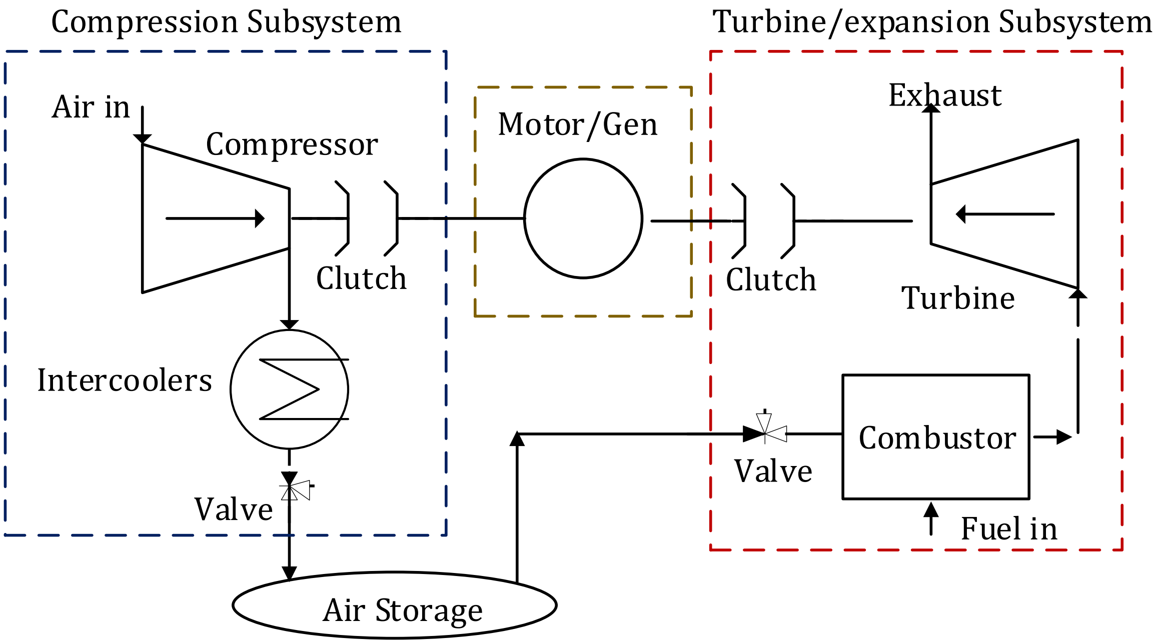
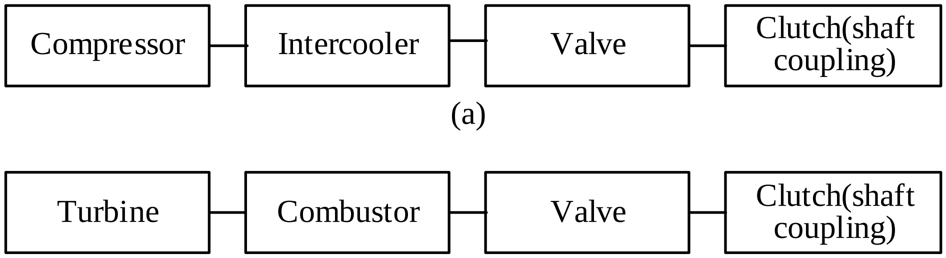


Figure 2.1. Schematic diagram of CAES showing different subsystems.

The compression subsystem consists of compressors, intercooler or heat exchanger, control valve and a clutch for shaft coupling. Similarly, the expansion subsystem consists of the turbine, combustor, control valve and clutch. The reliability network diagrams for the two sub-systems are shown in Figure 2.2.



(a)

(b)

Figure 2.2. Reliability block diagram for different subsystems (a) compression subsystem (b) turbine subsystem.

The motor/generator set in a single shaft can act a motor during charging and generator during discharging [23]. During charging, the air at ambient condition is compressed using multi-stage compressors and is stored in the cavern at high pressure. The stored air is released from the cavern, combusted with natural gas, and, expanded in the turbines during discharging. Underground caverns are generally used to store high pressure compressed air. The SOC of a CAES can be represented by the mass or pressure of the air in the cavern. The detail thermodynamic modeling of CAES charging and discharging process is presented in [24].

A reliability model of CAES representing its actual process of operation, possible failure/repair mechanism and their effect in the charging/discharging process has been developed here. Approximate series equations [11] are applied to obtain the failure and repair rates of the three sub-systems using the component data provided in [25], [26]. A Markov state space model as shown in Figure 2.3 is developed [11] considering the 3 subsystems and their random failure mechanism. Figure 2.3 shows the 7 operating states assuming no further component failure occurs when the CAES in the down state. Operating states resulting in the similar functional state are merged into 2 cumulative states of CAES being available and unavailable for operation. Figure 2.4 and Figure 2.5 shows the 2 cumulative states for charging and discharging operating modes respectively. The unavailability of CAES for charging and discharging process can be mathematically represented by their forced outage rates, FOR_{ch} and FOR_{di}, respectively. The developed reliability model of CAES can be utilized for adequacy studies in both the analytical and MCS methods.

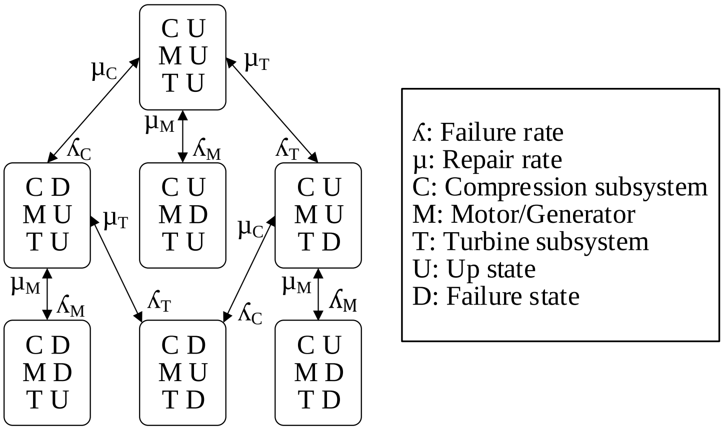


Figure 2.3. Markov model for CAES component reliability.

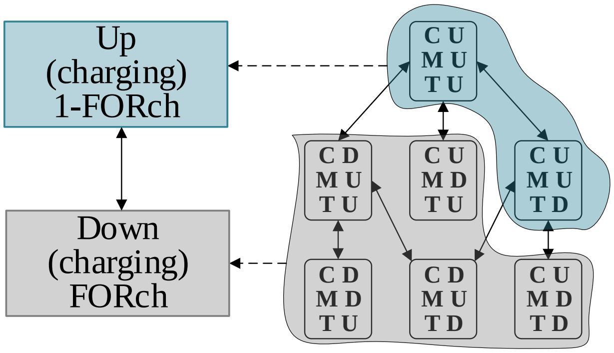


Figure 2.4. Cumulative up and down states for charging mode.

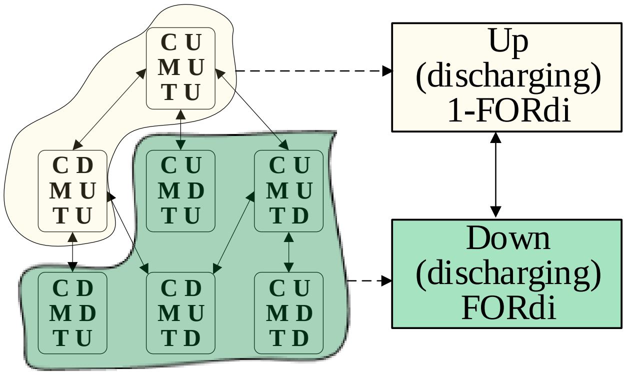


Figure 2.5. Cumulative up and down states for discharging mode.

2.4. Proposed Hybrid Approach for Adequacy Assessment

Power system adequacy indices are generally calculated on an annual basis and used in system planning. Reliability assessment using a period analysis helps to capture the correlations between dependent variables such as wind, load, as well as the CAES operational pattern in a power system structure. Seasonal de-ratings and scheduled maintenance of generating units can also be incorporated in a period analysis. In the proposed approach a year is strategically divided into a number of seasonal periods such that each day within a season has a similar diurnal characteristic. Each day is further divided into 3 diurnal sub-periods (charging, discharging, and idle) to recognize the distinct operational modes of CAES in a diurnal cycle that are primarily dictated by the load profile, electricity price and the availability of renewable energy. Reliability indices are calculated for each diurnal sub-period of each season and are aggregated to obtain the annual reliability index (R) as shown in (2.1).

$$R = \sum_{p=1}^{Ns} (R_p^{ch} + R_p^{di} + R_p^{id}) \tag{2.1}$$

Where, N_s is the number of seasonal periods and R_p^{ch} R_p^{di}, R_p^{id} represents the reliability indices for the charging, discharging and idle sub period for the p^{th} seasonal period respectively. The overall framework to obtain these indices is shown in Figure 2.6.

Modeling the stochastic operating behavior of CAES that is influenced by system uncertainties is the major challenge while developing the reliability evaluation framework. A sequential MCS approach is utilized in the proposed hybrid method to simulate the system behavior when CAES is in the charging mode and acts as a load. The MCS based approach develops a SOC model of CAES in the form of discrete probability density function (PDF) while accurately incorporating the correlations and dependencies of SOC with the inherent system variables such as failure/repair of components, wind power, load, and the available charging power. In order to make the overall framework simple and efficient, the MCS approach is only limited to model the SOC of CAES during charging, where the analytical method cannot accurately and easily model the dependent system variables. The SOC model is then integrated with the generating unit model represented by capacity outage probability table (COPT), load model and wind model in order to evaluate system reliability using an analytical approach as described in Figure 2.6. The use of analytical approach substantially reduces computational burden and provides a generic framework to obtain the system reliability indices. The detailed elaboration of the proposed approach is presented in the following subsections.

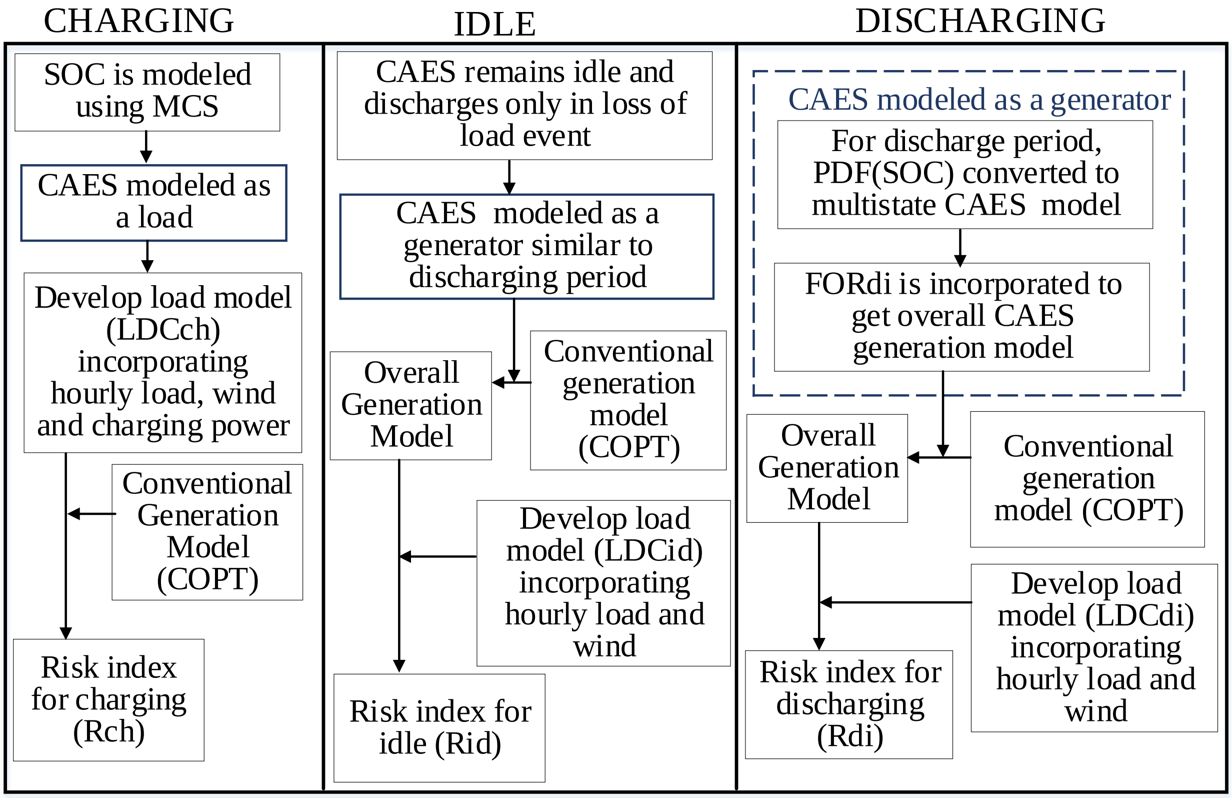


Figure 2.6. Overall framework for the proposed hybrid approach.

2.4.1. Probabilistic SOC Model for CAES

The SOC of a CAES during the charging sub-period is sequentially modeled at each hour considering the major system variables and their dependencies using MCS based algorithm shown in Figure 2.7.

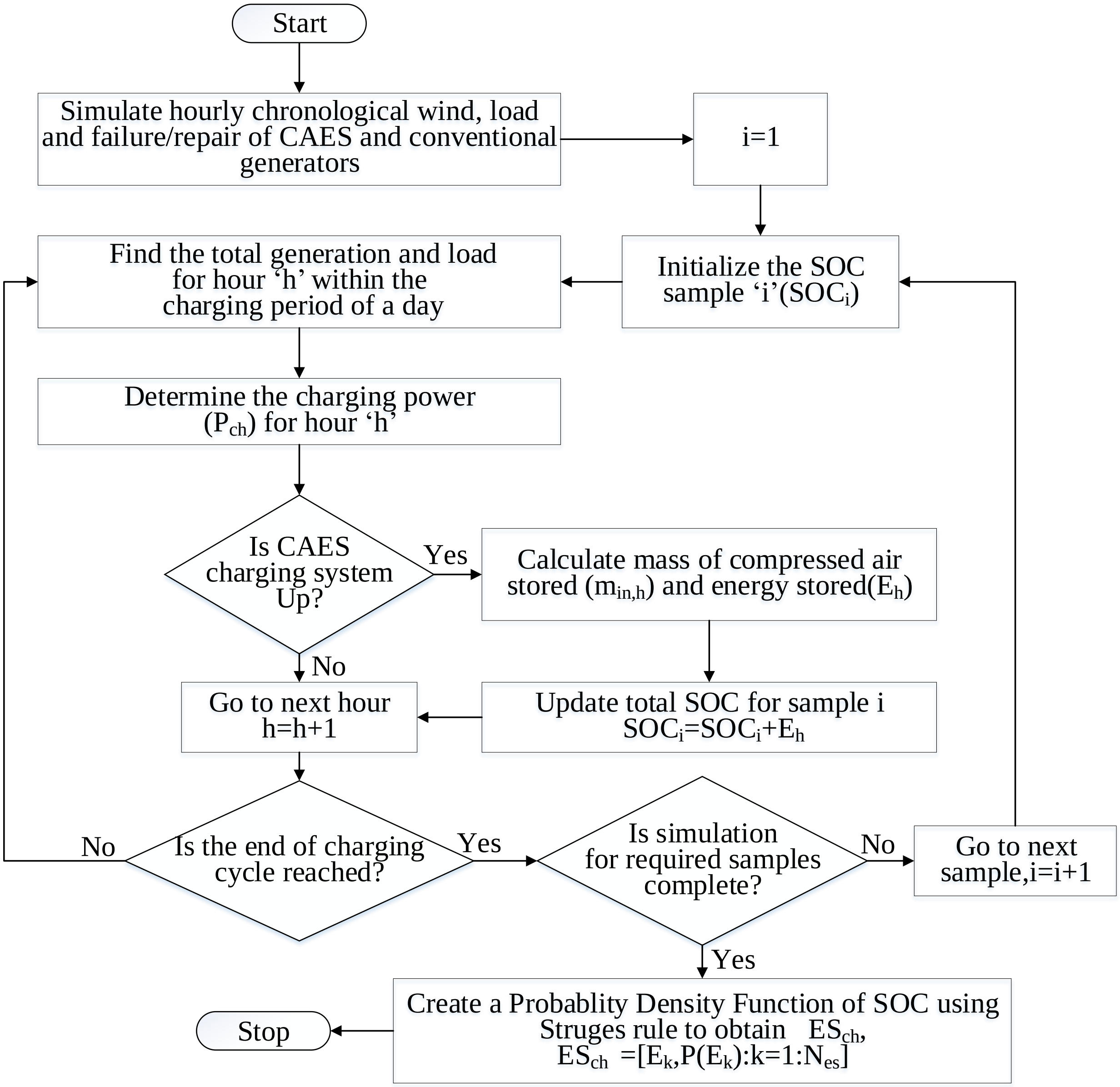


Figure 2.7. SOC modeling during charging.

The SOC in CAES can be expressed in terms of the compressed mass of air or the energy stored in the cavern. The CAES consumes charging power(P_{ch}) to compress a mass of air ($m_{in,h}$) and store in the cavern at each hour 'h'. The corresponding energy stored in the hour (E_h) is obtained using the CAES thermodynamic model described in [24]. P_{ch} can be constant or can vary depending on the CAES objective and available charging power at the time. A large number of SOC samples are generated at the end of the charging cycle and are grouped using Struges rule

[27] to obtain a probability density function (PDF). The discrete PDF represents a multi-state SOC model denoted by ES_{ch}, which consists 'N_{es}' number of states, where, each state 'k' corresponds to certain energy level 'E_k' and its associated probability '$P(E_k)$' as expressed in (2.2).

$$ES_{ch} = [E_k, P(E_k): k = 1: N_{es}] \tag{2.2}$$

The SOC is represented as a multi-state model during the idle and discharge period as illustrated in Figure 2.6. In the idle sub-period, CAES will discharge only in case of loss of load event, which results in the change of its energy level. The probabilistic SOC model at the beginning of the idle period and the end of the idle period, therefore, will be different. The stochastic behavior of storage due to the probable loss of load scenario and the change in the energy level during the idle period is modeled using a probabilistic model as explained in the following steps:

Step 1: Let ES_{id}^{b} represent the multi-state SOC model at the beginning of the idle period with N_{es} number of states, each state with the energy level of E_k and probability $P(E_k)$. Let LM_{id} represent the discrete probability distribution of load during the idle period with N_{lm} number of states, each state with load level of L_q and probability $P(L_q)$. Let CG_{id} represent COPT of conventional units with N_{cg} number of states, each state with a capacity of C_r and the probability of $P(C_r)$ [12]. These models can be expressed in (2.3), (2.4) and (2.5). The SOC model at the end of the idle period (ES_{id}^{e}) is the function of ES_{id}^{b}, LM_{id}, CG_{id}, as expressed in (2.6).

$$ES_{id}^{b} = [E_k, P(E_k): k = 1: N_{es}] \tag{2.3}$$

$$LM_{id} = \left[L_q, P\left(L_q\right): q = 1: N_{lm}\right] \tag{2.4}$$

$$CG_{id} = \left[C_r, P(C_r): r = 1: N_{cg}\right] \tag{2.5}$$

$$ES_{id}^{e} = f\left(ES_{id}^{b}, LM_{id}, CG_{id}\right) \tag{2.6}$$

Step 2: The CAES will supply the deficit energy when the conventional units and wind fail to meet the load. The power discharged from the CAES ($D_{k,q,r}$) for the k^{th} state in the SOC model, q^{th} state in load model and r^{th} state in conventional generation model is given by (2.7), where P_{di} is the rated discharging power.

$$D_{k,q,r} = \begin{cases} 0 & \text{if } L_q \leq C_r \\ L_q - C_r & \text{if } L_q > C_r \text{ and } \left(L_q - C_r\right) \leq P_{di} \\ P_{di} & \text{if } L_q > C_r \text{ and } \left(L_q - C_r\right) > P_{di} \end{cases} \tag{2.7}$$

Step 3: The new state in the SOC model (E_s) and its probability $P(E_s)$ is obtained using (2.8) and (2.9) where id_h represents the duration of the idle period. It should be noted that the maximum discharge energy during idle period is limited by the SOC state at the beginning of the idle period.

$$E_s = \max\left[\left(E_k - D_{k,q,r} \times id_h\right), 0\right] \tag{2.8}$$

$$P(E_s) = P(E_k) \times P\left(L_q\right) \times P(C_r) \tag{2.9}$$

Step 4: The SOC model at the end of the idle period (ES_{id}^{e}) with (N'_{es}) number of states is expressed in (2.10) where each state has the energy level of E_s and probability $P(E_s)$.

$$ES_{id}^{e} = [E_s, P(E_s): s = 1: N'_{es}] \tag{2.10}$$

Apportioning method can be used to reduce the number of states in the SOC model [11]. The SOC during discharge sub-period can also be represented by a multi-state model (E_{di}) with N''_{es} number of states, each state with the energy level of E_t and probability $P(E_t)$ as expressed in (2.11).

$$E_{di} = [E_t, P(E_t): t = 1: N''_{es}] \tag{2.11}$$

The SOC model for different diurnal sub periods for a day within a season is obtained using the above procedure. As mentioned earlier, the diurnal operation of the CAES is assumed to be the same for a particular season. The procedure is repeated for each seasonal period.

2.4.2. Wind Power and Load Model

An autoregressive and moving average (ARMA) model [28] is used to obtain chronological wind speeds at hourly intervals, which are converted into wind power output using wind turbine generator characteristics [29]. In a system with a high penetration of wind, the system wide wind power absorption capability is restricted to a certain level in order to maintain system stability

[12]. Such a restriction is obtained considering the ramping constraints of the scheduled generators and is expressed in terms of a certain percentage of the hourly load values [30]. The chronological wind power that is absorbed by the system is incorporated in a chronological load data to get a wind integrated modified load model. For the proposed adequacy assessment approach, the load models are obtained for each diurnal sub period in a season and are represented by their respective Load Duration Curve (LDC). Since CAES acts as a load during the charging sub period, the charging power of CAES is sequentially added into the system load during the MCS process. However, in discharging and idle sub-period, CAES is incorporated with the system generation model as shown in Figure 2.6.

It should be noted that the restrictions in wind power absorption capability of the system can cause a significant amount of wind energy spillage. The CAES can help to reduce the amount of spilled wind energy. The additional amount of wind energy (MWh) utilized due to the presence of CAES can be quantified using an index, designated as the Increase in Wind Energy Utilization (IWEU) expressed in (2.12), where WES_{ESS} and $WES_{no\ ESS}$ are the expected value of wind spilled with and without storage respectively.

$$IWEU(Mwh) = WES_{ESS} - WES_{no\ ESS} \tag{2.12}$$

2.4.3. Seasonal Energy Management Model

CAES can accumulate and facilitate diurnal and/or seasonal transfer of stored energy to meet financial or reliability objectives of its operation. This application can be particularly significant from adequacy perspective in a power system where system capacity is in surplus in a season, and in deficit in another. It should be noted that most system plan system capacity requirements based on the established loss of load expectation (LOLE) criterion, which is primarily influenced by the load peaking season of the year. The accumulated energy in the CAES can provide significant capacity value in terms of reliability requirements.

In this work, energy accumulation season is a period of the year when the system capacity is in excess and energy dissipation season is a period of the year when system capacity is inadequate to meet the reliability requirements. Consider a day in the energy accumulation season consisting of diurnal sub periods as shown in Figure 2.6. Let ES_0 represent the corresponding SOC model with N_0 number of states where each state 'u' has energy level E_u and probability $P(E_u)$. ES_0 can be expressed by (2.13) and is obtained using the algorithm described in Figure 2.7.

$$ES_0 = [E_u, P(E_u): u = 1: N_0] \tag{2.13}$$

Let 'ρ' be the portion of energy that is being retained for the seasonal transfer and (1- ρ) be the portion of energy that is used on the same day. Then, the SOC model for a d^{th} day in a season (ES_d) can be obtained using (2.14).

$$ES_d = [col_1(ES_0) + (d-1).\rho.\overline{E}\ , col_2(ES_0)]\ ,\quad \forall d \in [1,2 \ldots\ldots..m] \tag{2.14}$$

Where, $\overline{E}$ is the expected value of energy stored each day, 'm' is the total number of days in the season, and col_1(γ) represents the first column of any array γ.

The generation model and the load model can be assumed to be identical for adjacent days in a season whereas the SOC model varies due to daily energy accumulation. The reliability index calculated each day varies with the SOC model. The daily variation in SOC throughout a season and the reliability index, LOLE, calculated for the corresponding SOC models is shown in Figure 2.8. In the figure, from Day '1' to Day 'v' the reliability index varies almost exponentially.

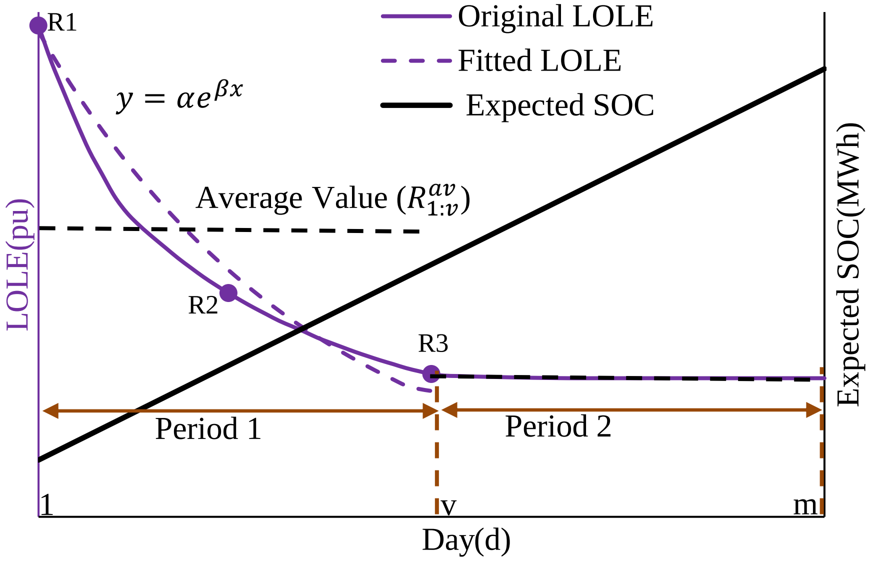


Figure 2.8. Variation of LOLE with accumulation of energy.

The system LOLE remains constant after Day 'v' when the CAES has accumulated sufficient energy to produce its rated discharging power and the increase in the accumulated energy will not further change the SOC model of CAES. Day ‘v’ can be expressed mathematically in (2.15) which takes a positive integer value from 1 to m, where Day ‘m’ is the last day of a season where the energy is gradually accumulated.

$$v = \frac{P_{di} \times di_h - \overline{E}}{\rho \times \overline{E}}, \qquad v \in \mathbb{Z}: v \in [1, m] \tag{2.15}$$

where, di_h is the total discharge period in a day, P_{di} is the rated discharge power.

Reference [31] has approximated the variation of reliability with peak load to be exponential. A similar exponentially decaying characteristic is observed for the case of energy accumulation from Day 1 to Day v as shown in Figure 2.8. This paper proposes a simplified approach to evaluate the system adequacy recognizing the varying SOC model of the CAES between Day 1 and Day v. The mid and end points of the exponential function in Figure 2.8 were evaluated subjected to the single term exponential regression represented by (2.16).

$$y = \alpha e^{\beta x} \tag{2.16}$$

Here, y represents the reliability index and x represents the linearly increasing capacity or the corresponding days, α and β are the coefficients obtained from regression.

The average value of the curve (16) on any interval [δ_1,δ_2] can be calculated using (2.17).

$$y_{avg} = \frac{1}{\delta_2 - \delta_1} \int_{\delta_1}^{\delta_2} \alpha e^{\beta x} dx = \frac{\alpha}{\beta\,(\delta_2 - \delta_1)} \quad [e^{\,\beta.\delta_2} - e^{\,\beta.\delta_1}] \tag{2.17}$$

The calculated average value from Day 1 to Day v gives the reliability index that will reflect the accumulation of energy or the increase in capacity. The reliability index from Day (v +1) to Day m can be calculated using a single SOC model, since the storage model remains constant due to the discharging constraint despite the continuous increase in the accumulated stored energy. The overall reliability index (R_{sp}) for a seasonal period which has ‘m’ number of days is the weighted sum of reliability index at Period 1 and 2 which is given by (2.18).

$$R_{sp} = z_1 * R_{1:v}^{av} + z_2 * R_{v+1:m}^{av} \tag{2.18}$$

Here, $R_{1:v}^{av}$ is the average reliability index in pu for the period of Day 1 to Day v (Period 1), $R_{v+1:m}^{av}$ is the reliability index for the period of Day (v +1) to Day m (Period 2), z_1 and z_2 are the weighing factor for Period 1 and 2 respectively and depends on the entire duration of the respective periods.

The methodology described above is for the case of gradual increase of energy in the cavern during energy accumulation seasons. In the case of the energy dissipation season, where the accumulated energy is gradually discharged, (2.14) can be modified to represent the decrease in energy as given by (2.19).

$$ES_d = [col_1(ES_0) - (d-1).\sigma.E_{acc}\ ,\ col_2(ES_0)]\ \forall d \in [1{,}2\ldots n] \tag{2.19}$$

Here, E_{acc} is the total accumulated energy, ES_0 is the initial SOC model for the first day of energy dissipation season, ES_d is the SOC model for d^{th} day, 'σ' is the portion of energy discharged each day, and 'n' is the number of days in energy dissipation season. The CAES can discharge at its rated power until Day 'w' given by (2.20).

$$w = \frac{E_{acc} - P_{di} \times di_h + \overline{E}}{\sigma \times E_{acc}},\quad w\ \in \mathbb{Z}: w \in [1, n] \tag{2.20}$$

The CAES SOC models are identical form Day 1 to Day w, and the corresponding system LOLE remain constant as shown in Figure 2.9 even though there is a gradual decrease in stored energy. The reliability index will increase exponentially from Day '$w+1$' to Day 'n', and similar exponential regression procedures are followed to obtain the LOLE of the entire season.

The proposed technique derives an equivalent average model that can approximately reflect the effect of seasonal energy management using CAES on system adequacy. The developed methodology is computationally simple and reasonably accurate and is generic to any type of storage and any duration of storage.

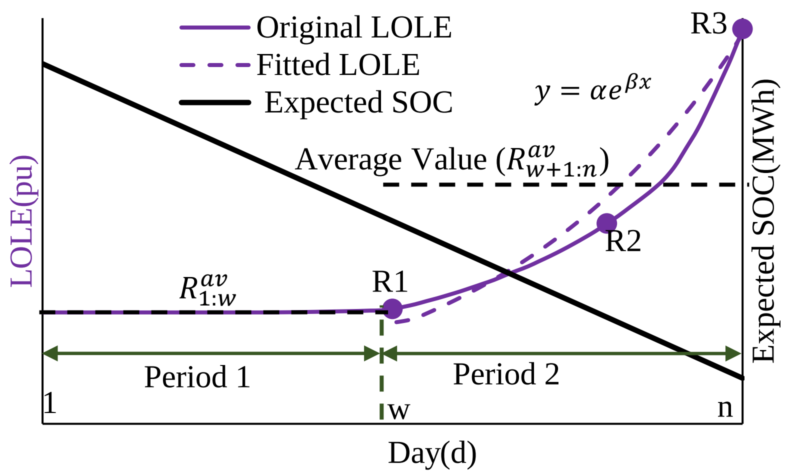


Figure 2.9. Variation of LOLE with gradual discharge of accumulated energy.

2.5. Validating the Proposed Model Using MCS

The proposed algorithms are applied to the IEEE RTS system [32] which has an installed capacity of 3405 MW. A 5% wind penetration to the RTS system is considered with wind farm represented by Swift current wind profile [28]. A CAES with 60MW rated charging and 290MW rated discharging power and characterized by Huntorf CAES parameters [24] is assumed to be connected to the system which operates in a diurnal operation cycle consisting of 10 hours charging, 4 hours idle, and 10 hours discharging. A seasonal period analysis is performed with four seasons as described in [32]. The winter season contributes about 80% of the annual LOLE, and is considered as energy dissipation season. The remaining 3 seasons are considered as energy accumulation seasons.

The accuracy of the proposed algorithms is verified by comparing the results with the results obtained from the MCS approach. A computer program based on sequential MCS approach was developed. The program was run until convergence [33] and repeated with different random number seeds. The MCS based program and the proposed algorithm were run for different scenarios of system peak loads and percentage energy accumulations in CAES for seasonal transfer. It should be noted that the percentage accumulation indicates the portion of energy retained each day of the energy accumulation season. The accumulated energy is transferred to the energy dissipation season, where it is discharged uniformly each day. The LOLE values obtained are shown in Table 2.1 for comparison. It can be seen that the proposed algorithms provide reasonably close results to that of the MCS for all the scenarios.

Table 2.1. LOLE (hours/year) obtained with different methods

Method used Scenario	Proposed Approach	MCS Seed1	MCS Seed2	MCS Seed3
Peak Load= 2750MW 0% accumulation	1.7919	1.7694	1.8203	1.8142
Peak Load= 2950MW 0% accumulation	7.2481	7.2851	7.2583	7.3248
Peak Load= 2950MW 5% accumulation	2.3249	2.3967	2.4263	2.3654
Peak Load= 2950MW 7.5% accumulation	2.1782	2.1839	2.1674	2.1267
Peak Load= 2950MW 20% accumulation	1.9996	1.9692	1.9656	1.9393
Peak Load= 3150MW 20% accumulation	7.6701	7.5473	7.5625	7.6461

Although MCS method can incorporate the system complexity and dependencies, an analytical method with appropriate modeling of the system is more preferable for reliability planning. The developed algorithms can produce small errors, but the benefit of less computation and the use of a generic model that uses an analytical framework for reliability evaluation outbalances the use of detailed MCS methods. The results in the table validate the diurnal hybrid approach as well as the model to incorporate seasonal energy transfer.

2.6. Results and Analysis

The proposed framework is implemented to quantify the adequacy benefit associated with the integration of CAES in the system. The wind and CAES parameters as explained in Section 2.5 are considered. Three different cases as described below are implemented in the proposed framework and the LOLE values are obtained for the system peak load of 3050 MW with varying wind penetration level which are shown in Table 2.2.

Case 1: RTS system with the wind but no CAES.

Case 2: RTS system with the wind and CAES operated in a diurnal cycle with no seasonal energy transfer.

Case 3: RTS system with the wind and CAES operated in a diurnal cycle with 10% retention of stored energy in each day of energy accumulation seasons.

The results for all 3 cases show that the system reliability increases as wind penetration are increased. The addition of wind power increases the total system capacity, and therefore, improves the system reliability. The incremental reliability benefit, however, decreases. Table 2.2 shows that there is further improvement in system reliability in Case 2 and 3 when CAES is added to the system and operated in a diurnal cycle. This is due to the shift of energy by the CAES from the off-peak hours to the peak hours of the day. Besides, the stored energy can also be discharged to avoid loss of load event during the idle period if the electricity market offers financial incentives for such action. A comparison of Case 2 and 3 results in Table 2.2 shows that the system reliability can be significantly improved by the transfer of energy from the energy surplus seasons to the energy deficit season. Since the annual LOLE is mainly attributed to the deficit or the load peaking season, the seasonal transfer has considerable impact in lowering the LOLE.

Table 2.2. System LOLE with different wind penetration for 3 cases

Wind Penetration (%)	LOLE (hours/year)		
	Case 1	Case 2	Case 3
0	31.20	18.14	5.79
5	23.63	13.54	4.19
10	18.82	10.75	3.28
15	15.76	8.99	2.72
20	13.63	7.76	2.34
25	12.06	6.83	2.06

CAES can provide a significant capacity contribution and defer other capacity investments due to its ability to transfer bulk amount of energy diurnally as well as seasonally to the load peaking period where the capacity requirement to meet reliability criterion is most critical. The proposed framework identifies such CAES application and quantifies the capacity benefit of CAES using a novel, computationally simple, and generic approach. The capacity value (CV) is estimated using reliability based method [34] for a specified reliability criterion. The CVs of wind and CAES are computed with variation in wind penetration level for Case 1, 2 and 3 which are shown in Figure 2.10. The LOLE criterion of 5 hours/year is considered in order to estimate these CVs.

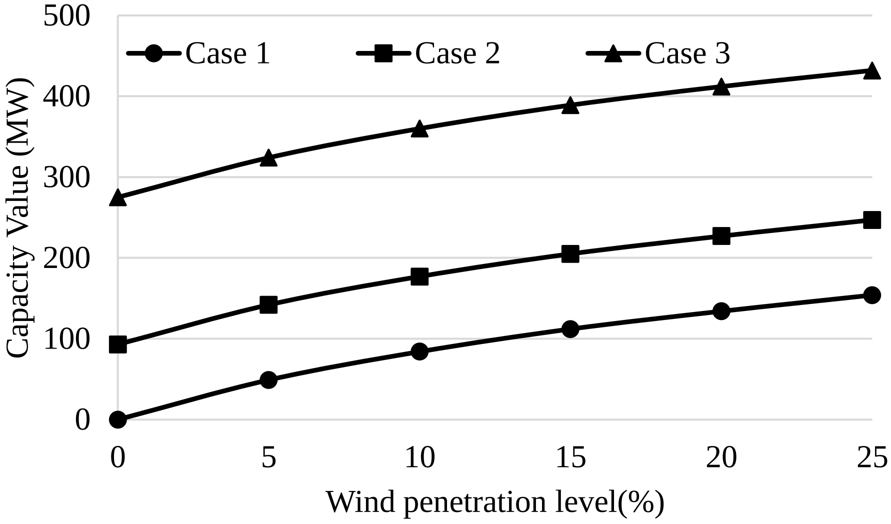


Figure 2.10. Capacity value of wind and CAES.

With the integration of CAES in the system, the effective CV increases due to the augmented reliability benefit obtained from the operation of CAES. Furthermore, in the case of seasonal energy management, the accumulated energy in CAES can contribute significantly in terms of capacity requirements during the load peaking season of a year. Therefore, the CV of CAES when operated for seasonal energy management is considerably higher than that when operated without seasonal management.

Along with the capacity benefit, a CAES can support wind integration in the system in order to meet the environmental compliance required for the planning of a sustainable power system. A proper coordination between CAES operation and wind generation can increase the amount of wind energy utilized by reducing wind power curtailment in a system with high wind penetration. The probability of wind energy spillage is increased at the off-peak hours of the day due to the limited ramping capability of base load generation. CAES can absorb the wind energy that would have been curtailed otherwise. Table 2.3 shows the IWEU indices, calculated using (2.12), for different wind penetration levels in the RTS system when the CAES is operated as in Case 2 with different charging rates. It can be seen that there is no wind energy spillage for low wind penetration of less than 5% as the wind generation is well within the absorption capability of the system. For higher wind penetration, it can be seen that the wind spillage decreases, or the IWEU increases, as the CAES power rating is increased. For 10% wind penetration case, the IWEU values tend to saturate as the rated charging power increases because the excess amount of wind energy that the storage can utilize is limited by the wind generation capacity.

Table 2.3. Incremental wind energy utilized (IWEU) in MWh

Rated Charging Power (MW)	Wind Penetration level (%)					
	0%	5%	10%	15%	20%	25%
60	0	0	3888	14384	26635	39022
90	0	0	4639	19946	37605	55525
120	0	0	4878	24669	47287	70809
150	0	0	4913	28699	55843	84727

The operation of CAES is dictated by the existing electricity market structure. Therefore, the existing market needs to assure certain financial benefit to the CAES owner. A merchant owned CAES with parameters as in Section 2.5 is considered that can participate in the energy and capacity market. The owner can operate CAES with or without seasonal energy transfer. The CAES operation cost data are obtained from [35] and the historical natural gas price data are obtained for Alberta [36]. Similarly, historical hourly electricity price value is obtained for the AESO market [37] and the capacity market price is obtained from PJM reliability price modeling for 2020/21 [38]. The results in Table 2.4 show the financial benefit to a CAES owner through the wholesale energy market and a capacity market.

Table 2.4. Financial benefit in $M (CAD$)

Revenue Stream	ESS Operation / Period	No seasonal transfer	10% Seasonal transfer
Energy market	Spring	1.08	0.84
	Summer	3.96	3.42
	Fall	3.15	2.68
	Winter	2.77	3.84
	Total energy revenue	10.96	10.78
Capacity market	Total capacity revenue	3.22	9.52
Total Revenue	**Annual revenue($M/year)**	**14.18**	**20.30**

The capacity payments are made based on the obtained CVs of CAES. When CAES is operated for seasonal energy management, the capacity revenue is significantly higher while the energy revenue is slightly lower than for the case where it is operated without seasonal transfer. The capacity revenue is increased for the seasonal energy management case because the capacity value of CAES is significantly higher due to energy accumulation. However, the energy market revenue is slightly reduced because the energy market price profile used has the higher difference between the electricity prices within the diurnal hours in a season where the energy is accumulated than that for the energy dissipation season.

2.7. Conclusion

This paper developed a hybrid framework for adequacy assessment of a power system with CAES. The hybrid framework combines MCS technique with the analytical approach in order to produce a computationally efficient and reasonably accurate adequacy evaluation model. The MCS technique is used to model the stochastic CAES operation during charging considering the system dependencies, while the analytical framework is used for overall adequacy evaluation. Furthermore, the seasonal energy management model is built upon this hybrid framework using an equivalent average model. The component reliability model of CAES used in the hybrid framework, considering the failures of the components and their effect in the charging/discharging process, has also been developed and integrated. The developed adequacy assessment framework is generic to any type of bulk-scale storage. The accuracy and effectiveness of the proposed technique are validated by comparing the results with the results obtained from the MCS method. The case studies show the impact of CAES on system adequacy and provide new insights into the capacity planning of the power system with CAES. The models and studies presented in this work can provide valuable input to utilities and policymakers for reliability planning of modern power system with wind and storage.

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CHAPTER 3: RELIABILITY AND ENVIRONMENTAL BENEFITS WITH MARKET OPERATION OF COMPRESSED AIR ENERGY STORAGE IN A WIND INTEGRATED POWER SYSTEM [1]

3.1. Abstract

Energy storage systems are receiving considerable attention as potential means to exploit the benefits from extensive renewable energy growth in electric power systems by absorbing the variability of these intermittent generation sources. This paper focuses on the compressed air energy storage (CAES) which has high potential for grid-scale application. A hybrid approach is proposed which embeds a Monte-Carlo simulation (MCS) method in an analytical technique to develop a suitable reliability model of the CAES. The MCS technique is used to sequentially model the state of charge incorporating the important dependent variables. The analytical technique employs a period analysis utilizing suitable sub-periods to maintain the diurnal and seasonal correlation of the renewable resource, system load and the state of charge of the CAES and quantitatively assess the system adequacy and wind energy usage. The CAES model incorporates diurnal energy arbitrage for profit making. The proposed model is applied to a test system to investigate the economic and reliability benefits of CAES as well as its contribution in facilitating wind integration during different operating scenarios. The conclusions drawn from the study results provide valuable information to help utilities and policy makers in arriving at effective and efficient policies for planning and operation of large-scale energy storage, such as the CAES.

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3.2. Introduction

There is a strong public sentiment to promote renewable energy sources (RES) to reduce the adverse environmental effect caused by greenhouse gas emissions from conventional method of electricity generation. In this regard, renewable portfolio standards (RPS) have been adopted in different jurisdictions that bounds electric utilities to produce a certain percentage of their generation from RES [1].Wind energy is the most rapidly growing RES due to its potential for large scale power production. The variability and uncertainty in wind power generation creates significant challenges in system planning and operation to maintain acceptable level of reliability. Energy storage systems (ESS) are being perceived as potential solutions to these challenges in fully exploiting the benefits of renewable energy. ESSs can help in managing the peak demand, load leveling, preventing line congestion, reducing wind spillage and gaining financial advantage from energy arbitrage [2]. A proper planning and operation of ESS can maximize the benefits from large penetrations of RES while improving the system reliability.

Different ESSs technologies include battery, flywheel, pumped hydro energy storage (PHES), compressed air energy storage (CAES) etc. [2]. CAES is one of the large-scale energy storage technologies with relatively low capital and operational costs. Although there is a great potential for the development of CAES due to existence of natural air storage underground caverns in many parts of the world, only two systems are in operation: 290 MW CAES plant in Huntorf, Germany and 110 MW plant in Alabama, USA. The technical specifications of the two plants are presented in [3].

The impacts of ESSs on the system reliability, economics, and wind integration have been studied from different perspectives. The economic benefits of CAES as well as its contribution to integrate wind power by reducing wind curtailment is studied in [4]. Reference [5] presents a multi-objective optimization framework that considers PHES to reduce wind curtailment and total social cost, as well as to maximize storage units' revenue in a transmission-constrained power system. In [6], a bi-level optimization method is proposed to account for the benefit of both the system operator and owner of the energy storage. Reference [7] presents a Monte-Carlo simulation (MCS) based technique to assess the reliability benefits of ESSs considering different operating strategies and wind energy dispatch restrictions depending on the system load. In [8], a sequential MCS method is proposed to evaluate the reliability of bulk power system with CAES. A reliability assessment method for wind battery integrated system is proposed in [9]. In [10], reliability improvement of the bulk power system due to the presence of ESSs in local distribution systems has been quantified using a sequential MCS method.

CAES is a grid-scale resource with long term implications on planning and policy making of all other energy resources as well. Since the primary objective of integrating ESS in power systems is to facilitate higher RES penetration and yet maintain acceptable system reliability, it becomes very important to develop more comprehensive reliability models incorporating CAES characteristics as they are operated to gain profit from energy arbitrage. It is also important to provide techniques that are relatively easy to apply in practice. This paper proposes a hybrid approach which embeds a MCS method in an analytical technique to develop a suitable reliability model of the CAES. The MCS technique is used to sequentially model the state of charge (SOC) incorporating the important dependent variables. The analytical technique utilizes a period analysis consisting of suitable sub-periods to maintain the diurnal and seasonal correlation of the renewable resource, system load and the SOC of the CAES and quantitatively assess the system adequacy. The model considers a merchant owned CAES for profit making in diurnal energy arbitrage as well as its contribution to system reliability and wind energy utilization. The proposed model is applied to the IEEE Reliability Test System (RTS) to investigate the economic and reliability benefits during different operating scenarios [11].

3.3. Compressed Air Energy Storage (CAES)

3.3.1. Modeling CAES Operation Process

The operation cycle in CAES consists of charging, discharging and idle states. The main components of the CAES are shown in Figure 3.1.

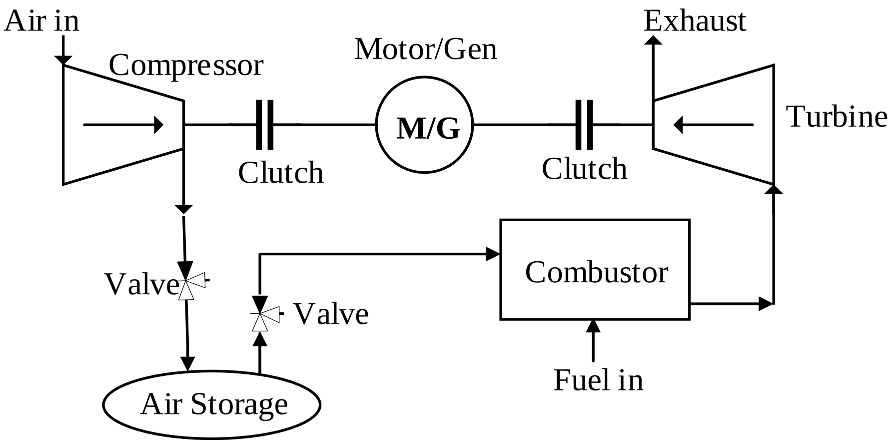

Figure 3.1. CAES system diagram.

During charging, the air at ambient conditions is compressed using multi-stage compressors and is stored in the cavern at high pressure. During discharging, the air from the cavern is released, combusted with natural gas and then expanded in the turbines. The discharging process is similar to the operation of a conventional gas turbine.

The models for the operation of constant volume CAES, with two stage compression and expansion process are obtained from [12]. The technical details for the models used are similar to that of Huntorf CAES. The SOC of the CAES is proportional to the mass of compressed air in the underground air storage cavern which depends on the mass flow rate of air into the cavern $\dot{m}_{in}$, that can be calculated in hourly intervals using (3.1).

$$\dot{m}_{in} = \frac{\eta_c P_c}{C_p T_1 \left[\left(\frac{P_2}{P_{in}} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right] + C_p T_2 \left[\left(\frac{P_{out}}{P_2} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]} \tag{3.1}$$

where, P_c is the input power to the compressor, η_c is overall efficiency of compressor, P_{in} is an atmospheric pressure, P_2 is the pressure at outlet of compressor for first stage and inlet for second stage compression, P_{out} is the pressure at outlet of second stage which equals to the pressure in the reservoir, C_p and C_v are specific heat capacity of air at constant pressure and volume respectively, γ is specific heat ratio of air, T_1 and T_2 are temperature of air at inlet of first and second stage compressors respectively.

The increase in air mass inside the cavern during charging increases the pressure inside the reservoir and increases the SOC of CAES. For a constant volume configuration, such as underground caverns, a minimum pressure P_{min} must be maintained with a minimum mass of air m_{min} given by (3.2), and the usable mass of air available at a time T is given by (3.3).

$$m_{min} = \frac{P_{min} \times V_c}{R \times T_c} \tag{3.2}$$

$$m_{usable,T} = m_{stored,T} - m_{min} \tag{3.3}$$

where, V_c is the volume of the cavern, T_c is the temperature of the cavern and R is the gas constant, $m_{stored,T}$ is the total mass stored in time T.

The compressed air in the reservoir is fed to a two stage gas turbine during discharge. The mass outflow rate of air from the storage, $\dot{m}_o$ is calculated using (3.4).

$$\dot{m}_o = \frac{P_{gen}}{\eta_m \eta_G [1 + m_r] \left[C_p T_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \right] + C_p T_2 \left[1 - \left(\frac{P_b}{P_2}\right)^{\frac{\gamma-1}{\gamma}} \right] \right]} \tag{3.4}$$

where, P_{gen} is the power rating of the generator, η_m and η_G are the mechanical and electrical efficiencies, P_1 and P_2 are the pressure of air at inlet of the first and second stage respectively, P_b is the atmospheric pressure, T_1 and T_2 are the temperature at inlet of first and second stage, m_r is the ratio of mass of fuel flow to mass of air flow.

The mass outflow rate of air $\dot{m}_o$, can also be expressed in terms of the total discharge duration D_{dis} and is shown in (3.5). And finally, the stored energy E_{stored} corresponding to the amount of stored mass is calculated using (3.6). The values of different parameters are obtained from [12] .The stored energy during charging process and available energy for discharging process can be calculated using (3.1) - (3.6).

$$\dot{m}_o = \frac{m_{usable,T}}{D_{dis}} \tag{3.5}$$

$$E_{stored} = P_{gen} \times D_{dis} \tag{3.6}$$

3.3.2. CAES Operating Strategy and Objective

The charging and discharging operation of CAES largely depends upon factors, such as objective of the owner, existing power system structure, energy market and any reward/penalty mechanism imposed on its performance. Different operating schedule of CAES will have different effect on system reliability, benefit to the owner and its contribution to facilitate renewable energy integration.

From the reliability perspective, it is beneficial to charge the storage fully and act as a standby back up until there is a loss of load scenario and to discharge to avoid the loss of load. However, for a merchant operated CAES, its primary objective will be to maximize its profit through the difference on electricity price in an electricity market. Therefore a merchant is likely to schedule its operation to gain maximum profit through diurnal energy arbitrage. So, a merchant owned CAES will tend to charge during low price and discharge during high price period. In a day ahead energy market the optimum scheduling will depend on various uncertainties on load, electricity prices, natural gas price and amount of renewable energy generation. The detailed modeling of such market mechanism is beyond the scope of this paper. This paper does not attempt to predict future electricity prices. This paper considers historical electricity prices to determine CAES operating schedule. The optimum scheduling that gives maximum profit in a diurnal arbitrage to a merchant can be obtained using (3.7) – (3.12).

$$\text{Max profit} = \sum_{t=1}^{24} (Pd(t) - Pc(t)) * p(t) - O(t) \tag{3.7}$$

$$\textit{Subject to,} \qquad O(t) = VC \times \big(Pd(t) + Pc(t)\big) + HR \times Pd(t) \times \pi_{\mathrm{N}} \tag{3.8}$$

$$0 \le Pc(t) \le Pc_{rated} \tag{3.9}$$

$$0 \le Pd(t) \le Pd_{rated} \tag{3.10}$$

$$E_{min} \le E_t \le E_{max} \tag{3.11}$$

$$E_{t+1} = E_t + Pc(t) - Pd(t) \times ER \tag{3.12}$$

where, $Pd(t), Pc(t)$ are discharging or charging power respectively, $p(\mathrm{t})$ is the electricity price, $O(t)$ is the total operating cost at hour t that consists of variable operation and maintenance cost VC and cost of natural gas consumed π_{N} . HR is the heat rate of CAES plant, Pc_{rated} , Pd_{rated} are rated charging and discharging power, E_{min} and E_{max} is the minimum and maximum limit of the stored energy in the cavern and ER is the energy ratio of the CAES plant.

3.4. Proposed Hybrid Approach

This section presents the proposed method to evaluate the reliability contribution of CAES in a wind-integrated power system. Reliability indices used in power system planning are evaluated on an annual basis. A year is divided into an appropriate number of seasonal periods to capture the seasonal correlation between important variables, such as load, wind, and other resources constrained by seasonal limitations. The number of seasonal periods considered in the evaluation depends upon the characteristics of the system and should be assumed in such a way that each day within a season has a similar diurnal characteristics. As the diurnal operation of a CAES is mainly dictated by the market price, which in turn responds to the demand profile, a day is further divided into sub-periods of charging, idle and discharging periods as shown in Figure 3.2. The charging operation of the CAES usually occurs during the off-peak period when electricity prices are low, and the discharge occurs during the peak period when electricity prices are high. Discharge can also occur at other times to mitigate loss of load scenarios.

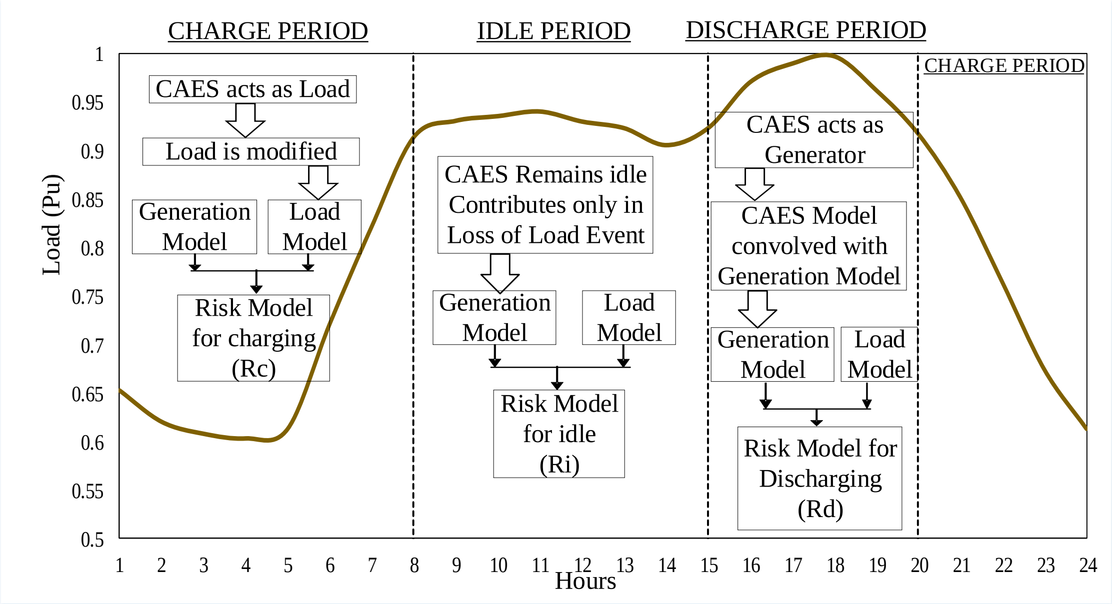

Figure 3.2. Diurnal adequacy evaluation technique.

The system adequacy represented by the annual risk index (R) is then evaluated analytically using the period analysis that can be represented by (3.13).

$$R = \sum_{n=1}^{ns} \sum (Rc + Ri + Rd) \tag{3.13}$$

where, ns is the number of seasonal periods, and Rc, Ri and Rd are the risk indices for the charging, idle and discharge diurnal sub-periods which are obtained by convolving the respective generation and load models as shown in Figure 3.2.

3.4.1. Wind Power Modeling

An auto-regressive moving average (ARMA) model developed using historical wind speed data is used to sequentially generate wind speed for the selected wind farm site for a large number of sample years [13]. The wind speeds are converted into wind power using the power curve of the wind turbines [14]. The chronological wind power is incorporated in a chronological load model to get a wind integrated modified load duration curve that can be used for reliability evaluation [15].

Normally, power systems have a limit on the amount of wind power it can absorb at different operating conditions. The wind energy that can be dispatched is restricted to a certain value to maintain system stability and reserves [7]. To follow the limit in the dispatch restriction, wind power is sometimes curtailed by the system operator. To get the exact value of the wind power dispatch restriction, detailed system analysis including factors such as stability, responding ability of conventional units, etc. should be performed. For this study, the dispatch of wind power is restricted to a certain percentage of the system load calculated based on the ramping constraints of generating units as in [15]. The absorbed wind power (AW) in hour t is calculated using (3.14), where, P_w is the wind power generated, L is the load, and β is the wind power absorption capability of the system expressed in percentage of the load at hour t. Wind power greater than AW is assumed to be curtailed by the system operator.

$$AW(t) = \begin{cases} Pw(t), & Pw(t) \leq \beta(t) \times L(t) \\ \beta(t) \times L(t), & Pw(t) \geq \beta(t) \times L(t) \end{cases} \tag{3.14}$$

3.4.2. Modeling of the Charge Period

A sequential MCS approach is used to simulate the charging operation of the CAES by sequentially assessing the SOC considering the time series of the wind power absorbed by the system, system demand, power available to compress the air into the cavern and the CAES component status.

The SOC of the CAES at each hour is obtained sequentially using (3.1) - (3.6) described in section 3.2 given that the CAES is available for the charging operation. The operating history of CAES components is obtained from the sequential simulation method considering the failure and repair rates of the components [16] . The SOC at the end of the charging cycle is obtained using (3.15), where, SOC_h is the stored energy at hour h and h∈y includes all the hourly intervals of the charging period in which the CAES is available.

$$SOC_{total} = \sum_{h \in y} SOC_h \tag{3.15}$$

The simulation is repeated until convergence, and the set of simulated SOC samples are converted into a discrete probability density function (PDF) represented by (3.16).

$$PDF(SOC) = \ [SOC_i, P\ (SOC_i) \colon i = 1 \colon s] \tag{3.16}$$

where, s is the number of SOC states determined by Sturge’s Rule [17], and $P(SOC_i)$ is the probability of the CAES having a state of charge equal to SOC_i at the end of the charging cycle.

The CAES behaves as a load during the charging sub-period. The hourly input power to the compressor (Pc) is sequentially added to the hourly load during the simulation to obtain the modified system load model for that period as shown in Figure 3.2. The risk index Rc in (3.13) for the charging sub-period is obtained by convolving the modified load model with the capacity outage probability table (COPT) of the conventional generation [18].

3.4.3. Modeling of the Discharge Period

The CAES SOC model obtained using (3.16) is transformed to a discrete probability distribution of CAES power capacity for a certain discharge duration. This distribution is then weighted by the forced outage rate (FOR) of the turbine/generator to obtain the CAES capacity model, F_{caes}. The total system generation model for the discharge period, F_{gen} is then obtained by convolving the COPT of conventional generators, F_{conv} with the CAES capacity model, F_{caes} as shown in (3.17).

$$F_{gen} = F_{conv} * F_{caes} \tag{3.17}$$

The generation model, F_{gen} is then convolved with the wind integrated load model of discharge period as shown in Figure 3.2 to obtain risk index *Rd* in (3.13) for the discharge sub-period.

3.4.4. Modeling of the Idle Period

The CAES will only discharge to avoid a loss of load event during the idle sub-period. Since the probability of loss of load events occurring during intermediate load and pricing period (idle period) are extremely low, it is assumed that the long term expected SOC values will remain the same. This approximation greatly simplifies the adequacy evaluation. The system generation model, F_{gen} for the idle period is therefore assumed to be the same as that of the discharge period, which is convolved with the wind integrated load model of idle period as shown in Figure 3.2 to obtain risk index *Ri* used in (3.13).

3.5. Quantification of Reliability and Wind Utilization

The loss of load expectation (LOLE) is the reliability index of interest for this study which is given by (3.18), where, C_i is available capacity in hour *i*, L_i is the load in hour *i*. $P_i\ (C_i - L_i)$ is probability of loss of load in hour i [18].

$$LOLE = \sum_{i=1}^{n} P_i \,(C_i - L_i) \tag{3.18}$$

The presence of merchant owned CAES in an electric grid helps to reduce the amount of curtailed wind energy [4]. The incremental wind energy utilization (IWEU) due to ESS is calculated using (3.19), where, WES_{no_ESS} and WES_{ESS} are the expected wind energy spilled without and with storage in the system respectively [15].

$$IWEU = WES_{no\_ESS} - WES_{ESS} \tag{3.19}$$

3.6. Application to a Test System

The proposed approach is applied to the IEEE-RTS [11] which has an installed capacity of 3405 MW and annual peak load of 2850 MW. The profit from diurnal energy arbitrage operation of a CAES is calculated using historical electricity pool price from Alberta Electric System Operator (AESO) [19]. The variable operation and maintenance (O&M) costs are accounted using Huntorf CAES parameters [12], [20]. The natural gas price data from the Alberta market were used assuming the price remains the same for a season [21]. A wind farm characterized by the Swift Current wind speed data is used [13], [14]. The CAES connected to the system has a 60 MW motor/compressor with 16 hours rated charging duration and a 290 MW turbine/generator.

A seasonal period analysis is performed by dividing a year into 4 seasons and sub-dividing a day into charging, idle and discharge periods based on CAES operation. Each day the CAES was assumed to charge at rated power for 9 hours in off-peak period, stay idle for 9 hours in intermediate load period and discharge for 6 hours in peak period of the day. The system wind power absorption capability β for a response time of 15 minutes was found to be 21% during low load and 29% during high load considering ramping constraints as described in [15]. The low load and high load period are separated by the annual average load level.

Figure 3.3 shows the variation of the system LOLE with and without CAES for different wind penetration levels.

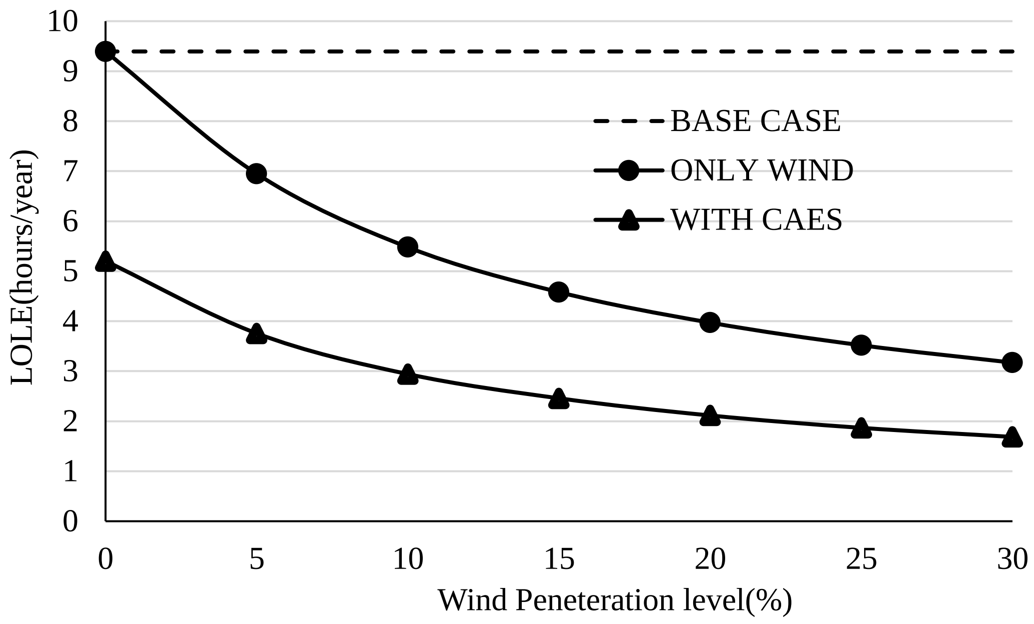

Figure 3.3. LOLE for a system with and without CAES.

It is apparent from Figure 3.3 that the system LOLE decreases with increase in wind penetration even without adding CAES to the system. The incremental benefit however decreases. With the addition of the CAES, it shows that the LOLE is reduced considerably. It should be noted that there is a reduction in LOLE due to CAES even for the case when the wind is not integrated in the system, i.e. for the 0% penetration case. The improvement in system reliability quantified by the reduction in LOLE and the increase in wind utilization quantified by IWEU index, due to the addition of CAES in the system is shown in Table 3.1. The last column shows the incremental wind energy utilization due to CAES. It can be seen that the IWEU is zero for the 5% penetration. This is because the wind power generated in this case is within the wind power absorption capability limit of the system and all the wind energy available can be utilized by the system even without CAES. But, for higher wind penetration the CAES utilizes the wind energy that would otherwise be spilled. The table shows that the IWEU increases as wind penetration is increased in the system.

Table 3.1. Benefits due to addition of CAES

Wind penetration level (%)	LOLE without CAES (hours/year)	LOLE with CAES (hours/year)	IWEU (MWh)
0	9.3942	5.2039	-
5	6.9491	3.7569	0
10	5.4796	2.9430	1,460
15	4.5816	2.4586	3,671
20	3.9714	2.1150	5,976
25	3.5193	1.8677	8,497
30	3.1722	1.6866	10,763

A high likelihood of wind energy spillage occurs during high wind speeds at low load periods. The CAES contributes to increasing the load at such periods and stores the wind energy. For instance, a wind absorption capability of 21% infers that, 21 MW of additional wind power would be spilled without CAES, for each 100 MW of increased demand due to CAES in the charging mode [4]. The presence of CAES can prevent wind spillage more significantly if the grid requirement of wind power absorption limit can somehow be circumvented. This can be done by using a hybrid wind farm and CAES facilities that share the same grid connection point such that the wind energy feeds the ESS before it is supplied to the grid [22]. Also, the fast ramping capability of CAES, its ability to provide reserve capacity and other applications further helps reduce wind spillage. But, these studies are out of the scope of this work, and therefore, the values of IWEU obtained are pessimistic.

The annual profit from energy arbitrage was calculated to be \$8.36M. This value only considers the profit due to energy arbitrage as described at the beginning of this section. It does not consider other costs and profits that could occur with other types of market participation of the CAES.

The above results were calculated for the described CAES operating schedule. If the charging and discharging periods were different, there will be changes in the profit, system reliability and wind utilization as well. The next section investigates these concerns.

3.6.1. Impacts of Operating Strategy

A sensitivity study was done to investigate the impact of varying the charging, idle and discharge periods of a CAES on the resulting profits from arbitrage, wind utilization and system reliability. Four different CAES operating scenarios were considered in the study, and are shown in Table 3.2. Scenario 4 is the operation resulting in a maximum profit to the CAES owner from diurnal arbitrage that is calculated using (3.7). A 20% wind penetration to the IEEE-RTS was considered in the study and the system LOLE without CAES was calculated to be 3.97 hours/year. A charging power rating of 60 MW with 16 hour charging capacity and 290 MW of discharge power rating was considered for the CAES integrated in the system. The system LOLE, wind energy utilization and the profit are computed for each season and aggregated to obtain the annual indices as shown in Table 3.3 for the four scenarios.

Table 3.2. Different operating scenarios

Operating scenarios	Charging period	Idle Period	Discharge Period
1	9 hours (11pm-7am)	9 hours (8am-4pm)	6 hours (5pm-10pm)
2	9 hours (11pm-7am)	8 hours (8am-3pm)	7 hours (4pm-10pm)
3	16 hours (9pm-12pm)	4 hours (1pm-4pm)	4 hours (5pm-8pm)
4	Optimize for maximum profit in diurnal arbitrage		

The results in Table 3.3 shows that the LOLE, IWEU and profit vary depending upon the CAES operating scenarios.

Table 3.3. System benefits for different operating scenarios

Operating scenarios	LOLE with CAES (hours/year)	IWEU (MWh)	PROFIT ($M/year)
1	2.1150	5,976	8.36
2	2.1381	5,976	8.91
3	2.2998	10,676	16.16
4	2.3393	18,663	25.10

Scenario 1 gives the lowest LOLE, because it avails the CAES the largest amount of time, i.e. 15 hours, to contribute to loss of load events. Although Scenario 2 also has 15 hours of idle and discharge period, its idle period is shorter than that of Scenario 1, and therefore the lower CAES SOC in the last 6 hours of the peak period causes the LOLE to be higher than that of Scenario 1. Scenario 1 and 2 have equal charging hours, and the opportunity to utilize wind energy. The IWEU for these scenarios are therefore equal. Scenario 3 and 4 has a higher value of IWEU compared to Scenario 1 and 2, because Scenario 3 and 4 get more opportunity to utilize wind energy due to longer charging hours. Although same amount of energy is stored in both Scenario 1 and 2, Scenario 2 still gives a slightly greater profit. This occurs because in Scenario 2, the energy is discharged for 7 hours while in Scenario 1 energy is discharged only for 6 hours. The additional discharge hour in Scenario 2 increases the profit. But, compared to Scenario 3 and 4, Scenario 1 and 2 has lower profit, because the total energy stored and discharged in Scenario 1 and 2 are lower than that of Scenario 3 and 4. The scenario that would be practical for a merchant is Scenario 4 as it gives maximum profit, but the system reliability is compromised. These results are specific to the load profile, wind profile and the pool price data used in the analysis. It is important that market policies be restructured to ensure that the system reliability and potential benefit to utilize wind energy is not adversely affected by the merchant objective of profit making.

3.6.2. Impacts of CAES Compressor/Motor Rating

A study was carried out to investigate the impact of the compressor motor rating, relative to the generator and storage capacity, on the contribution of CAES to the system LOLE, wind energy utilization and profit from energy arbitrage. A 20% wind penetration to the IEEE-RTS was considered in the study and the system LOLE for the base case, i.e. without CAES in the system, was calculated to be 3.97 hours/year. The storage capacity was limited such that, it could charge for a maximum of 16 hours with 60 MW power. A discharge rating of 290 MW was considered. The results for different motor ratings with Scenario 1 operating schedule are shown in Table 3.4.

It can be observed from Table 3.4 that the increase in the motor size from 40 MW up to 120 MW results in a reduction of the system LOLE and an increase in the profit and IWEU. A larger motor will store more energy, and therefore, more power will be available to reduce the loss of load probability during peak hours. Increasing the motor size will also help in capturing more wind energy, and therefore IWEU increases. In addition, increasing the motor size increases the profit from arbitrage due to higher energy sales during peak hours. The incremental benefits obtained with the increase in motor size are however reduced and eventually saturate at a certain point. This implies that the additional benefits come at increasing costs of installing a larger motor. Table 3.4 shows that the increase in the motor size from 120 MW to 140 MW does not provide any further benefit. This is due to the limitation on the storage capacity of the CAES cavern.

Table 3.4. Impact of motor rating

Motor size (MW)	LOLE with CAES (hours/year)	IWEU (Mwh)	Profit ($M/year)
40	2.5687	4,174	5.57
60	2.1150	5,976	8.36
80	1.7717	8,018	11.15
100	1.4243	10,171	13.94
120	1.4161	11,113	14.84
140	1.4161	11,113	14.84

3.7. Conclusion

This paper presents a probabilistic hybrid technique to assess the reliability of a wind integrated power system with a CAES. It uses an MCS approach to evaluate the SOC of the charging period and uses an analytical technique to evaluate the adequacy of the system. The results show the effect of the CAES operation on the profit from energy arbitrage, the overall system reliability and its contribution in utilizing wind energy. Different operating scenarios including the maximum profit scenario were considered in the studies. It was observed that the scenario that gave the best reliability improvement was not the same as the one that gave the highest profit from arbitrage. It indicates that one operating principle of the CAES may achieve a high reliability improvement to the system but may adversely affect the profit from energy arbitrage, while another operating practice may provide maximum profit for the merchant but with adverse impact to the overall system reliability or in wind energy utilization capability. The studies indicate the need to develop appropriate market policies or mechanism which should be structured in such a way that profit incentives to the merchant operating practices do not adversely affect the system reliability and utilization of renewable energy.

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CHAPTER 4: RELIABILITY AND ECONOMIC ASSESSMENT OF COMPRESSED AIR ENERGY STORAGE IN TRANSMISSION CONSTRAINED WIND INTEGRATED POWER SYSTEM [1]

4.1. Abstract

Bulk-scale energy storage systems (ESS) such as compressed air energy storage (CAES) are considered as viable options to alleviate the problems associated with the variability and uncertainty of wind power that is expected to meet a large share of global energy demand. The operation strategy of an ESS is dictated by the existing market and regulatory structure, which in turn impacts the overall system performance in terms of quality, reliability, efficiency and environmental commitments. A CAES can either be operated independently to maximize the profit in the existing market or can be operated in coordination with wind power resources to collectively benefit from the markets while maximizing the usage of renewable energy. This work explores feasible applications and benefits of CAES in a transmission constrained wind integrated power system. Comprehensive models for wind and CAES operating strategies are developed and the potential values of CAES to the systems are quantified in terms of their contributions to system reliability, efficiency, and environmental objectives. The results presented show the trade-off among different aspects of the potential benefits obtained from CAES. The method presented, and the results analyzed can provide valuable input to the utilities and policymakers for formulating effective regulatory structures to integrate bulk-scale storage to efficiently support the imminent growth of renewable energy while maintaining reliable supply to electricity consumers.

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4.2. Introduction

Wind energy sources are expected to provide a significant portion of the future energy mix as many jurisdictions around the world are embracing environmental commitments to phase out fossil-fired power plants within the next decade [1]. Large-scale wind integration in power systems will cause high variability and uncertainty in power generation and pose severe challenges in efficient and reliable system operation and planning. Energy storage systems (ESS) are perceived as viable solutions to mitigate these challenges. There are different ESS technologies with potential for diverse applications in different areas of a power system determined by their sizing, siting, and technical characteristics. For example, ESSs can be utilized for time shifting of electric energy, supporting renewable integration, managing transmission congestion, and providing ancillary services. An ESS can obtain financial revenue by participating in the existing electricity markets depending on its application, existing constraints and the end objective dictated by its ownership. The market should, therefore, be able to attract investment in the different ESS technologies that are essential in wind integrated power system to provide critical values through system reliability improvement and efficient utilization of wind energy. A compressed air energy storage (CAES) is a mature large-scale energy storage technology that can provide bulk energy services to a power system [2]. This work considers CAES and its applications and explores the potential values it can provide to the system.

Large scale wind power fluctuations cause power balancing problems due to the limitations in the scheduled generation response capability [3], and transmission line capability limitation cause frequent line congestions [4] leading to significant wind energy spillage. One potential measure to alleviate the problem is to diversify wind resources [5] by dispersing wind farm installations in multiple sites rather than installing at the same site. This reduces the variability of the overall wind power output, and therefore, provides increased reliability benefit as shown by the studies in [6]. Additional benefits obtained due to the reduction in transmission line congestions are evaluated in [7]. Wind power diversity can be achieved by new installations at a site that generally has poorer wind recourses than an existing site, or that is remotely located and is costly to integrate to the power grid. Wind power developers, however, will invest in sites that provide maximum profit from energy sales at minimum integration costs. Without additional financial incentives and infrastructure costs, the rapid growth of wind power will occur at a location with rich wind resources, thereby aggravating the wind fluctuations and line congestions. The deployment of ESS can act as a potential alternative to wind diversity and transmission upgrade requirement [8], [9], and hence support wind integration [10], [11]. The operation strategy of deployed ESS is dictated by the objective of the owner, location of ESS and the existing regulatory structure, which in turn impacts their potential benefits.

Existing works have analyzed different aspects of ESS in power system planning. The work in [12] has addressed the economic aspect of battery energy storage while [13], [14] has specifically considered bulk scale CAES and analyzed the CAES economics in a wind integrated power system. In [15], a trade-off between ESS installation and transmission upgrade in terms of the cost is presented considering a remote wind resource. Reference [16] presented a cost-benefit analysis for a CAES considering the revenue obtained from the market when a CAES is operated to regulate the wind output. In [17], optimal location and capacity of CAES to improve wind power production was investigated. The authors in [18] have assessed the potential financial benefits from energy market and wind utilization for bulk scale CAES in transmission constrained power system. Each of the above studies are focused on the financial benefit or the economic aspect of ESS and have not considered the potential reliability impacts. In terms of reliability assessment of the system with ESS, [4], [19]-[21] have examined the reliability value of ESS in a power system. However, specific CAES characteristics and feasible applications have not been explored in these works. Also, these works have not addressed the reliability worth in conjunction with the economic benefits from ESS. An extensive assessment of the reliability and economic impacts of ESS is essential for optimum planning of ESS in the power system.

Reference [22] has analyzed the reliability worth of ESS and presented the value based reliability planning framework for an ESS. In [23], sizing of ESS based on the reliability cost and worth method is presented. Although [22], [23] simultaneously analyze the reliability and economic perspective, feasible applications and possible operation strategy of bulk scale ESS have not been explored on those works. The quantifications of actual ESS impacts needs realistic modeling of the applications and operation strategies of ESS technologies. Furthermore, the modern power system has an additional objective of meeting environmental compliance along with economic and reliable power supply. Therefore, it is essential to quantify the environmental benefits of ESS along with the reliability and economic aspects. Such environmental benefits of ESS can be converted in to an economic value, considering the existing incentive mechanisms, while quantifying the net economic benefit of ESS. The work on [18], [24] have explored the environmental benefit of CAES obtained by mitigating wind curtailment, but, have not examined the reliability value of CAES. In [25] environmental and reliability benefit of ESS is presented. However, different feasible operating scenarios and revenues from the market for an ESS has not been considered. Researchers in [26], [27] focused on modeling the operating scenarios for a generic ESS and quantifying the reliability worth and the benefits from the market. However, they do not consider the environmental benefit of ESS obtained from wind integration support.

The development of new regulatory structures, that can efficiently integrate bulk scale ESS, needs to take into account the specific characteristics of ESS, and, their overall societal impact. The impact of utilizing ESS in terms of the reliability benefit, environmental benefit, and the cost aspects are collectively termed as the societal impact of ESS in this work. Literature survey of the existing works show that the individual models to analyze the reliability, economic and environmental aspects independently for a generic ESS are developed. The existing models cannot be simply combined to quantify the overall societal impact of CAES. Further research is needed to accurately emulate the operation of CAES by accounting its characteristics, objectives, potential applications and benefits. New models and methodologies are required to incorporate CAES attributes and quantify the contribution of CAES to fulfill the reliability, environmental and economic objectives in a power system.

In this regard, this paper develops a comprehensive methodology to quantify the overall societal benefits of CAES considering the reliability impact, economic aspects, and environmental objectives. The methodology integrates CAES characteristics and operational strategies, and, the accurate wind farm models considering transmission constraints and diversity. The comprehensive assessment of CAES benefits provides insights to utilities and policymakers for formulating effective incentive mechanisms and market structure that can attract CAES participation, sustain the growth of renewables and ensure acceptable supply reliability. The method presented and the case study results can contribute towards rational planning of CAES in order to exploit renewable energy in a sustainable power system.

4.3. Methodology

This section first presents the proposed probabilistic models for wind power and CAES considering the modes of operation. A sequential Monte Carlo simulation (MCS) based framework is then developed to analyze the contribution of CAES to system reliability. Finally, the potential values of CAES are quantified using appropriate indices. The overall methodology is shown in Figure 4.1.

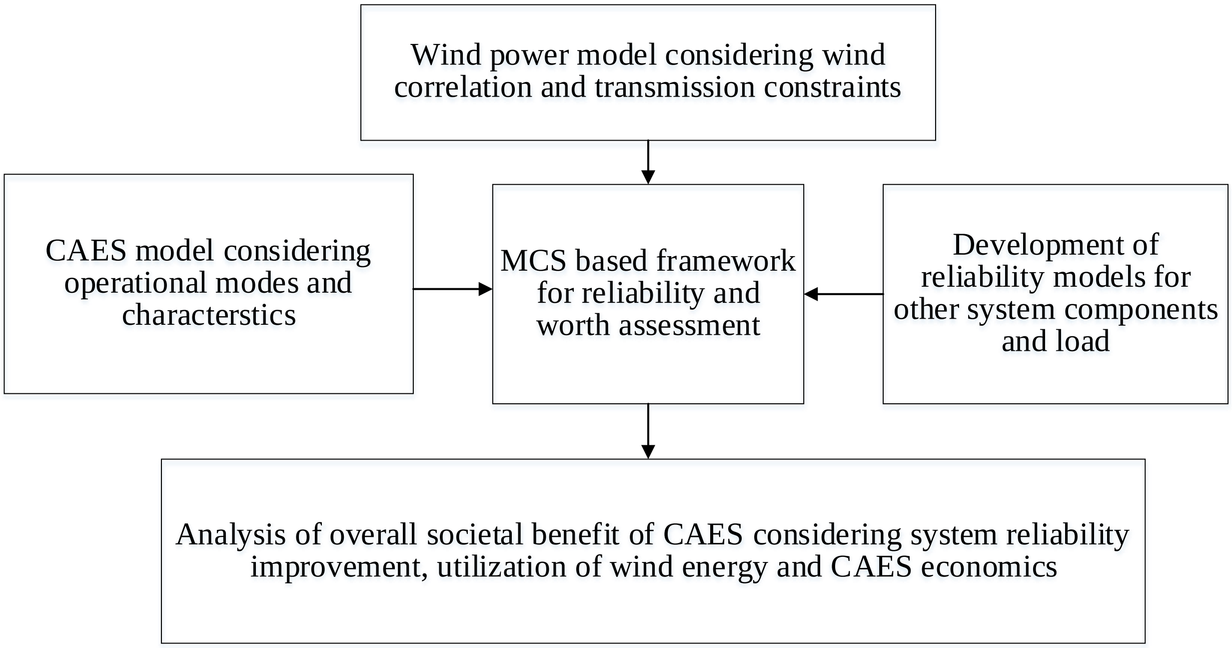

Figure 4.1. Proposed methodology.

4.3.1. Wind Power Model

The development of a probabilistic wind power model requires a large amount of wind power data, which is not usually available for new or potential installation sites. A time-series autoregressive and moving average (ARMA) model is utilized in this work to generate synthetic hourly wind speed data for a large number of yearly samples. An ARMA model for Swift Current [6], which is a site in the south-west region of the Saskatchewan province in Canada, is expressed in (4.1) using historical data obtained from Environment Canada.

$$\begin{aligned} y_t = \; & 1.1772y_{t-1} + 0.1001y_{t-2} - 0.3572y_{t-3} + 0.0379y_{t-4} \\ & +\alpha_t - 0.5030\alpha_{t-1} - 0.2924\alpha_{t-1} + 0.1317\alpha_{t-3} \\ & \alpha_t \in NID\,(0{,}0.524760^2) \end{aligned} \tag{4.1}$$

where, α_t is normally and independently distributed white noise process with zero mean and standard deviation of 0.5247602.

The simulated wind speed (SW_t) in the tth hour can be obtained from (4.2).

$$SW_t = \mu_t + \sigma_t y_t \tag{4.2}$$

where, μ_t and σ_t are historical hourly mean wind speed and standard deviation

The generated hourly wind speeds are scaled to the required wind turbine height using the logarithmic velocity profile as in [28] and are finally converted to hourly wind power output using the wind turbine generator characteristics given in [29]. The probability distribution of the wind power outputs thus obtained forms the wind power model for the particular wind site.

Figure 4.2 shows a bulk power system integrated with two wind sites. The cross co-relation in wind speeds at the two sites can be modeled using the Cholesky decomposition method described in [10]. The basic equation to generate two correlated random numbers in this method is shown in (4.3).

$$X_c = X_1.\Phi + X_2.\sqrt{1-\Phi^2} \tag{4.3}$$

where, X_1 and X_2 are series of uncorrelated random numbers, Φ is the desired amount of correlation coefficient between wind farm 1 (WF1) and wind farm 2 (WF2) which varies between 0 and 1, X_c is the series having a correlation coefficient of Φ with X_1.

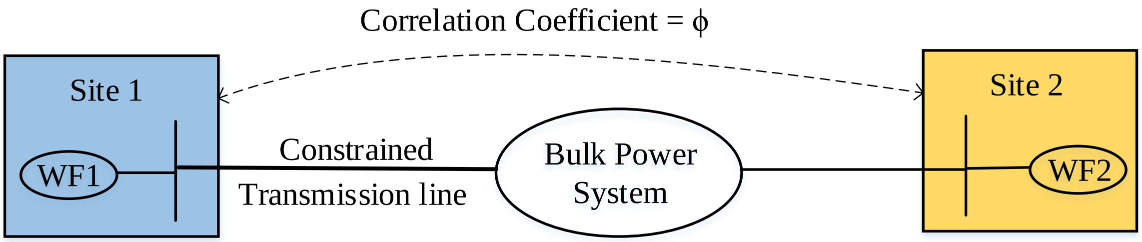

Figure 4.2. Two wind sites representing diversity and transmission constraints.

The wind power delivered to the load points depend on the location of wind farms and the connecting line capacity. The actual wind power delivered to the load considering the transmission constraint is modeled using (4.4).

$$WP_{l,t} = \begin{cases} WP_{g,t}, & WP_{g,t} < TC_t \\ TC_t, & WP_{g,t} \geq TC_t \end{cases} \tag{4.4}$$

where, $WP_{l,t}$ is the wind power delivered to the load at time t, $WP_{g,t}$ is the wind power generated and TC_t is the available transmission capacity at time ‘t’.

4.3.2. CAES Model Considering its Operational Modes

The operating strategy of a CAES integrated in a power system will dictate the benefits it can provide to the system. From the system reliability point of view, it is most appropriate to stay fully charged and discharge the stored energy only to avoid loss of load events. The CAES operation, however, depends on the objectives, location and existing market structures. A CAES can either be operated independently to maximize the profit in the existing market or can be operated in coordination with wind power resources to collectively benefit from the markets while maximizing the usage of renewable energy.

A CAES should be modeled to represent its multi-facet characteristics of demand, supply or an inactive component depending on its charging, discharging or idle operating modes. A CAES can be modeled by a probability distribution of its state of charge (SOC) that varies in time depending on several system variables, mainly wind power, load and market signals. The applications of CAES are broadly grouped into two operating scenarios in this work: Scenario 1 – Reference Power Flow Control, and Scenario 2 – Energy Arbitrage.

4.3.2.1 Reference Power Flow Control

In this scenario, CAES will charge when the wind generation exceeds a specified reference power level (P_{ref}) and discharge when the wind generation less than P_{ref}. The value of P_{ref} can be a constant, equal to the power limit of the transmission line, or can be updated in real time considering the system constraints and operating condition [4].

This operation strategy effectively models an onsite CAES co-located with a high quality wind farm that shares a common transmission line connecting to the main grid as shown in Figure 4.3. A CAES is operated in this scenario to alleviate wind induced transmission congestion and to reduce the variability of wind power injected to the grid system. The installation of CAES at a site with good wind resource, will therefore, open the opportunities for additional installation of new wind farms at the same site without the need to upgrade the existing transmission facilities, or to acquire additional balancing resources to absorb wind variability. The potentiality of CAES for this application is supported by the fact that many sites with high wind potential coincide with the feasible geological site for CAES installation [30].

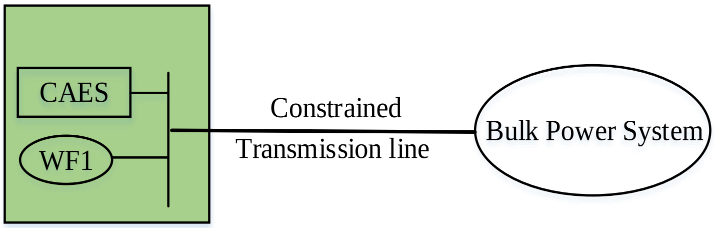

Figure 4.3. Co-located CAES operated to control power through the constrained transmission line.

A CAES in this operating scenario is charged with wind energy which would have been spilled due to line congestion if there was no CAES. The CAES gains from the revenue made by selling the energy in the existing market when the transmission constraint permits it to do so. This operating scenario maximizes the utilization of wind energy in the system. The utilized wind energy can be converted to an economic value in terms of existing renewable production credits and incentives [31],[32]. This operating strategy is mathematically expressed with (4.5) - (4.8).

$$\left.\begin{array}{r} P_t^c = \min\left(P_{max}^c\,,\, WP_{g,t} - P_{ref}\right) \\ P_t^d = 0 \end{array}\right\} if \qquad WP_{g,t} \geq P_{ref} \tag{4.5}$$

$$\left.\begin{array}{r} P_t^c = 0 \\ P_t^d = \min\left(P_{max}^d\,,\, P_{ref} - WP_{g,t}\right) \end{array}\right\} if \qquad WP_{g,t} < P_{ref} \tag{4.6}$$

$$E_{t+1} = E_t + P_t^c - P_t^d \times \xi \tag{4.7}$$

$$E_{min} \le E_t \le E_{max} \tag{4.8}$$

where, P_t^c, P_t^d, E_t are the charging power, discharging power and energy level at hour‘t’ respectively. $P_{max}^c, P_{max}^d, E_{max}$ are the maximum rated charging power, discharging power and energy level, ξ is the energy ratio of CAES.

4.3.2.2 Energy Arbitrage

In this operating scenario, a CAES is charged during the low price period, stays idle during intermediate pricing period and is discharged during the peak price period. A CAES located anywhere in the power system as shown in Figure 4.4 can be operated for energy arbitrage. Its operation is optimized for profit maximization from the market with no consideration for wind energy utilization or spillage from line congestions.

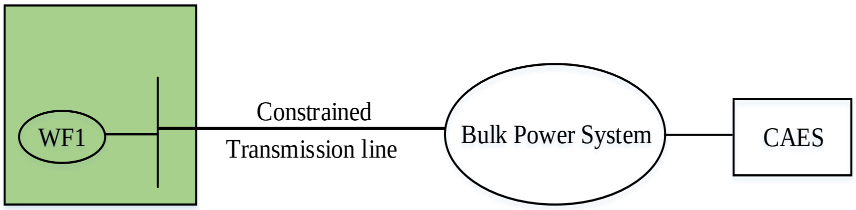

Figure 4.4. Independent CAES operated to maximize profit through the existing market.

This operating strategy is formulated considering the profit maximization from the energy market and is mathematically expressed in (4.9)-(4.15).

$$max \sum_{t=1}^{T} \left(P_t^d - P_t^c\right) \times \beta_t^e - OC_t \tag{4.9}$$

$$Subject\ to: \qquad OC_t = (P_t^d + P_t^c) \times V_c + H_r \times P_t^d \times \beta_t^g \tag{4.10}$$

$$0 \le P_t^c \le \delta_t^c P_{max}^c \tag{4.11}$$

$$0 \leq P_t^d \leq \delta_t^d P_{max}^d \tag{4.12}$$

$$\delta_t^c + \delta_t^d \leq 1 \tag{4.13}$$

$$E_{t+1} = E_t + P_t^c - P_t^d \times \xi \tag{4.14}$$

$$E_{min} \leq E_t \leq E_{max} \tag{4.15}$$

where, T is the number of hours in the optimization horizon, β_t^e is the electricity price, β_t^g is the natural gas cost, and OC_t is the total operating cost for hour t, V_c is the variable operating cost and H_r is the heat rate of CAES plant. δ_t^c and δ_t^d are binary variable indicating charging and discharging status of CAES respectively.

Normally a power system has a positive correlation between electricity price and load. Therefore, a CAES operating for energy arbitrage shifts energy to peak load period. As the peak load period has a high probability of loss of load, such CAES operation can improve the reliability of the system. Furthermore, this application of CAES can have a similar effect to peak shaving application and can displace peaking units by increasing the utilization of base load units [11].

4.3.3. Reliability Value Assessment Framework

This work utilizes a sequential MCS method to develop a reliability assessment framework. The advantage of using the MCS method over an analytical method is that the MCS method can provide the probability distribution of indices along with their expected values. The details regarding the actual nature of outages in the system (frequency and duration) can also be obtained from MCS techniques [33]. This allows for accurately estimating worth related reliability indices in addition to basic reliability indices. Moreover, MCS techniques are flexible to model the correlations and dependencies between different system variables such as wind, load, SOC in CAES, etc.

The developed wind model, CAES model along with the load and conventional generator models are integrated in a sequential MCS based framework to quantify the system reliability level. The detailed framework explaining the steps to obtain the reliability indices is shown in Figure 4.5.

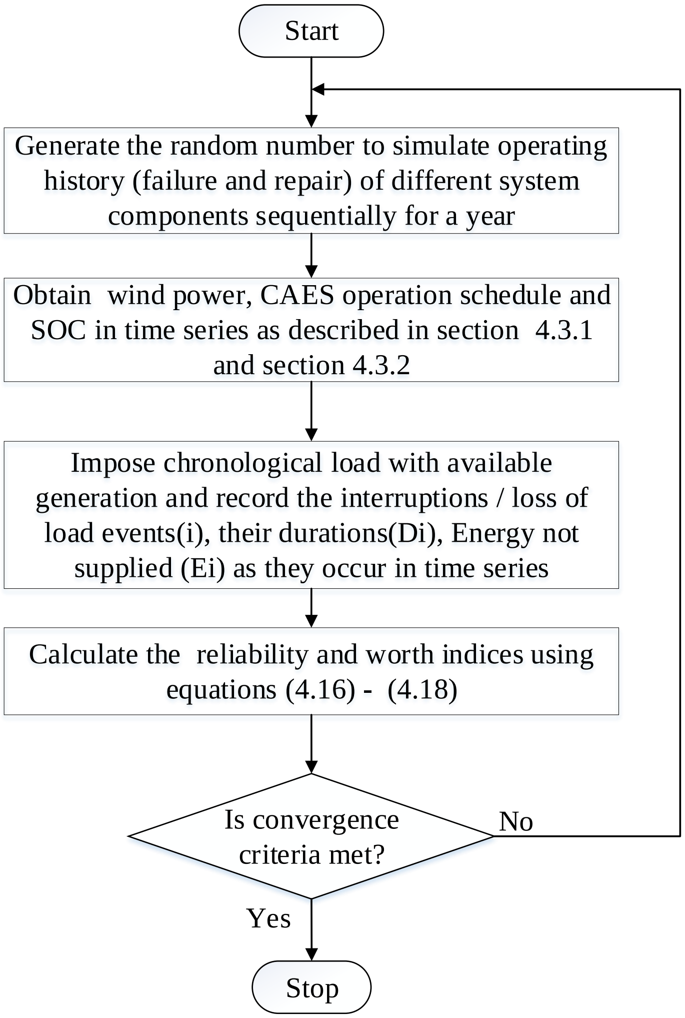

Figure 4.5. Framework for reliability assessment.

4.3.4. Assessment of Potential Benefits

The benefits obtained from the integration of CAES in power system are quantified using reliability, wind utilization, and the economic indices.

Proper planning and operation of CAES can improve the reliability of the system. The system reliability level before and after the integration of CAES is quantified using the loss of load expectation (LOLE) index in hours/ year which can be obtained using (4.16).

$$LOLE(hours/year) = \frac{1}{M}\sum_{i=1}^{N} D_i \tag{4.16}$$

where, D_i is the duration of i^{th} interruption, N is the total number of interruption and M is the total number of simulation year.

The reliability benefit obtained from the integration of wind/CAES in the system can be converted into a monetary value which is termed as ‘reliability worth’. The reliability worth can be evaluated considering the nature of outages and the possible financial loss to the customers in the system. The reliability worth is quantified using an index designated as the customer outage cost savings (CCS) in this work using (4.17).

$$CCS\ (\$/year) = ECOST_1 - ECOST_2 \tag{4.17}$$

where, $ECOST_1$ and $ECOST_2$ are the cost of unserved energy before and after the addition of wind/CAES in the system respectively. The cost of unserved energy (ECOST) can be obtained using (4.18)

$$ECOST(\$/year) = \frac{1}{M}\sum_{i=1}^{N} W(D_i)\ E_i/D_i \tag{4.18}$$

where, E_i is the energy not supplied of the i^{th} interruption, $W(D_i)$ is the composite customer damage function (CCDF). CCDF measures the unit interruption cost as a function of interruption duration. The CCDF values are usually obtained from customers’ survey [34].

The reliability benefit from wind/CAES can also be quantified in terms of their capacity value (CV). The CV is a widely used index to determine the capacity contribution of any generating resource to the system adequacy. CV represents the additional peak load carrying capability of the system when wind and CAES are added while maintaining the same reliability level. Wind resources have relatively low CV as they have little contribution to the meeting the system peak load. The integration of CAES can be operated to increase the CV of wind power. With large wind penetration, it will be important to accurately assess their CV considering CAES integration in order to determine appropriate investment in generation capacity in system adequacy planning. The CV of wind and CAES in MW is calculated using a probabilistic method [35] as shown in (4.19).

$$CV(MW) = ELCC_2 - ELCC_1 \tag{4.19}$$

where, $ELCC_1$ and $ELCC_2$ are the peak load carrying capability of the system for a certain LOLE criterion before and after the addition of wind/CAES in the system respectively.

The integration of CAES in a power system can provide environmental benefits due to the utilization of wind energy to offset fossil fuel. The expected energy supplied from wind (EESW) in MWh/year is calculated during the sequential simulation considering the hourly generated and curtailed wind power. The EESW index can be converted into a monetary value considering the environmental incentives such as renewable production tax credit (PTC). In Canada, the monetary incentives for wind energy are provided under an 'eco-energy for renewables' program [32]. This work considers PTC payment based on 'eco-energy for renewables' set as 10 $/MWh of wind energy utilized. The environmental benefit (EB) due to CAES is the incremental EESW converted to it monetary value.

Finally, the net economic benefit (NB) of a CAES is calculated in this work considering all the values that CAES can provide and the associated cost incurred. Equation (4.20) is used to obtain the NB value in $/year.

$$NB(\$/year) = CCS + BM + EB - CT \tag{4.20}$$

where, BM is the revenue obtained from participation in the existing electricity market, and CT is the total annualized capital cost, fixed and variable operation and maintenance cost of CAES.

4.4. Results and Discussions

The IEEE Reliability Test System (RTS) is selected as a test system which has a total installed capacity of 3405 MW and a peak load of 2850 MW [36]. The wind farms connected to the system is represented by Swift current wind speed profile [6]. The wind turbine generator considered in this work has cut in, rated and cut off speed of 15 km/h, 50 km/h and 90 km/h respectively. A CAES with 200 MW rated power, 26 h rated discharging duration and parameters as of McIntosh plant is assumed [37], [38]. The capital and operation cost data for CAES is obtained from [39] which is shown in Table 4.1. Historical electricity and natural gas price data were obtained from Alberta market [40], [41].

Table 4.1. Cost data for CAES

Power capital cost $/MW	Energy Capital cost $/MWh	Variable O&M cost $/MWh	Fixed O&M cost $/MW-year
520,000	2600	3.9	25,000

The CCDF shown in Table 4.2 was obtained from a recent customer survey in a practical power system. Logarithmic interpolation was used to obtain outage cost for the duration existing between the available survey data and linear extrapolation was used when the outage duration was longer than the maximum value from a survey [26].

Table 4.2. Composite customer damage function

Interruption Duration	1 min	20 min	1 hour	4 hour	8 hour	24 hour
Cost ($/kW)	1.53	3.35	9.31	41.21	70.34	144.46

The methodology described in section 4.3 was implemented for different study cases in order to compare the impact of wind diversity, transmission constraints, and CAES operation and locations. For line flow control operating scenario (Scenario 1), the reference power was set equal to the rating of the transmission line and the CAES was operated to maximize the wind utilization. For the energy arbitrage operating scenario (Scenario 2), the operation was optimized to maximize the revenue from the energy market for a period of a week in order to capture and exploit inter-day and intra-day price difference. Historical price data for 10 years were considered and the CAES operator is assumed to have perfect foresight of the price. All the economic values in the results are expressed in CAD$.

The cases considered are described below:

Case 1: Base case - RTS system with no wind power and no CAES connected

Case 2: RTS connected to two 300 MW wind farms located at different sites with wind speeds that have a correlation coefficient of 0.5

Case 3: RTS connected to a single 600 MW wind farm

Case 4: The transmission line connecting the wind farm in Case 3 to the bulk system is constrained to 300 MW

Case 5: A co-located CAES with wind farm operated as described by scenario 1 (reference power flow control) and connected in Case 4

Case 6: An independent CAES operated as in scenario 2 (energy arbitrage) is connected in Case 4

The reliability and wind energy utilization indices are obtained for all the cases and are summarized in Table 4.3.

Table 4.3. Reliability and wind utilization indices

Case	**1**	**2**	**3**	**4**	**5**	**6**
LOLE (hrs/yr)	9.431	4.106	4.582	4.707	3.993	3.731
ECOST (M$)	9.676	4.191	4.744	4.812	4.035	3.921
CV (MW)	-	127	113	107	132	146
EESW (GWh/yr)	-	1104	1104	909	1049	909

A comparison of Case 2 and Case 3 LOLE values in Table 4.3 shows that diversifying wind turbine installations to two sites provides higher reliability benefit compared to that when they are all installed at the same site. Since the study considers the same wind regime for the two sites with a correlation coefficient of 0.5, the EESW index is the same for Cases 2 and 3. With the transmission constraint in Case 4, the system LOLE is further increased and EESW is decreased because of the transmission induced wind curtailment. When CAES is co-located with wind farm and operated to control power flow through the line in Case 5, the CAES contributes to smoothing the wind output and also increases wind utilization. This results in a reduction of LOLE and an increment in EESW. The improvement in system reliability and environmental benefit justifies that such CAES can act as a potential alternative to wind diversity and transmission upgrade. The CAES does not improve system EESW when it is operated for energy arbitrage in Case 6, as it cannot mitigate transmission congestion. However, it can provide reliability benefit to the system as evidenced by a reduced LOLE. In this case, the operation of CAES is guided by market price and the positive correlation between the price and load results on CAES charging during low load and discharging during high load period which improves system reliability. It should be noted that the reliability contribution of such profit oriented operation is determined by the existing market structure and optimum CAES scheduling.

The ECOST index shown in Table 4.3 depends on the duration and frequency of outage in a system and therefore shows a similar variation as LOLE i.e. the case with a higher value of LOLE corresponds to higher ECOST. This indicates the system with poor reliability has a higher cost of unserved energy. Table 4.3 also shows the CV of the installed wind resources in Cases 2, 3 and 4, and the combined CV of wind and CAES in Cases 5 and 6, which are useful in long term capacity planning. It can be observed that the case with a higher reduction in LOLE provides a higher CV for wind/CAES. The results in Table 4.3 demonstrates that CAES can provide reliability and environmental benefits. However, the location and operational strategy largely affects the potential benefit from CAES and therefore needs to be considered while analyzing the overall benefits for CAES.

Further studies were performed on the RTS considering a gradual wind power growth at a single site with the transmission line capacity connecting the wind farm to the bulk system being constrained at 300 MW. Studies were carried out without considering CAES, and with CAES under the two operating scenarios to analyze the reliability and environmental impacts. Figure 4.6, 4.7 and 4.8 show the LOLE, CCS and EESW indices respectively.

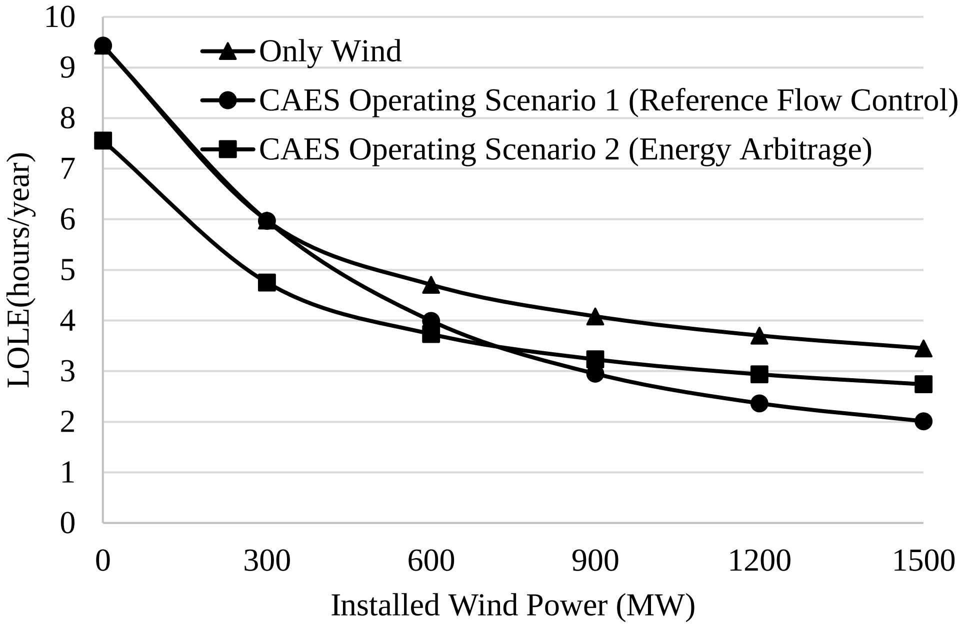

Figure 4.6. LOLE with and without CAES.

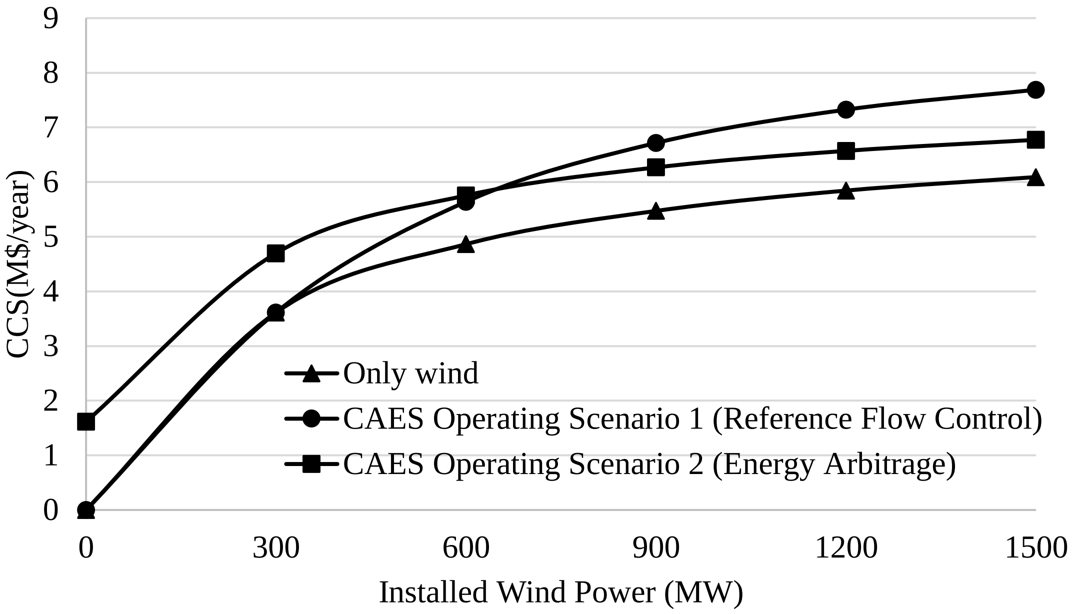

Figure 4.7. CCS with and without CAES.

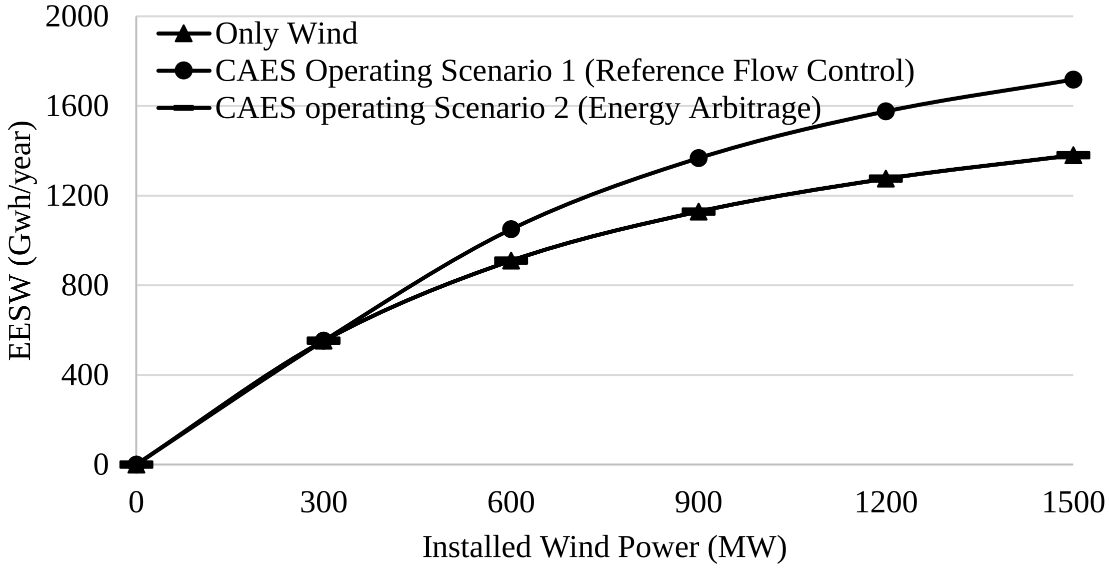

Figure 4.8. EESW with and without CAES.

It can be observed from Figure 4.6 that the system LOLE reduces with increasing wind installation. However, the incremental reliability benefit from wind power growth is reduced. Also, the existing constraint in the transmission line induces wind curtailment and limits the reliability contribution of wind power. With CAES operated for line flow control, system LOLE is further reduced because such operation smoothens wind output and also lowers wind curtailment. An independent CAES operated for energy arbitrage also reduces system LOLE due to time shifting of energy to peak load period. It should be noted that, for higher wind penetration case, the line flow control operating scenario can provide higher reliability benefit than that of energy arbitrage operating scenario. From the reliability perspective, the reduction of wind curtailment and smoothing wind output becomes more significant than time shifting energy for the system with higher wind penetration.

It can be observed from Figure 4.7 that the installation of CAES increases the CCS values. At lower wind penetration, energy arbitrage scenario has a higher contribution on improving system reliability than line flow control scenario, and, therefore results on higher reliability worth as shown by CCS values. However, for higher wind penetration the line flow control scenario provides greater reliability benefit and therefore results in higher CCS values.

The results in Figure 4.8 shows the EESW with wind power growth. The line flow control operating strategy reduces transmission induced wind curtailment and increases EESW values. With increasing wind penetration, the increase in EESW value due to such CAES operation is more significant because CAES has more opportunity to utilize otherwise spilled wind energy. On the other hand, the energy arbitrage scenario cannot mitigate the congestion induced curtailment and the operation is dependent on the market price signals, and not on the wind energy output. Therefore the EESW index is not changed for this scenario. However, such CAES is still potential in providing high value ancillary services required for the operation and planning of the system with high wind penetration. Benefits from voltage support, operating reserve, frequency regulation fall under such category and quantifications of those benefits are beyond the scope of this work.

The NB of CAES in \$/year is obtained considering the reliability worth, environmental incentive, market revenue and the associated CAES costs as expressed in (4.20). The cost data is shown in Table 4.1. The capital cost was annualized considering a discount rate of 4% and CAES operating life of 20 years [42]. Figure 4.9 shows the NB values for different operating scenarios obtained for varying wind penetration level. It can be observed that the energy arbitrage scenario provides higher net economic benefit than line flow control scenario. The revenue from the energy market consists a major portion of the NB. The energy arbitrage scenario optimizes the operation of CAES considering a weekly foresight of the market price and therefore results in higher revenue from the market. On the other hand, the line flow scenario operates depending upon the available transmission capacity and wind power generated in order to maximize wind utilization and may not discharge during higher price hours. Therefore the revenue from energy market is lower for line flow control scenario than energy arbitrage scenario. However, the energy arbitrage scenario cannot mitigate transmission congestion. Thus, the benefit from the reduction of transmission induced wind curtailment is zero and the net benefit is almost constant for all wind penetration level. The line flow control gains a significant portion of the benefit from wind utilization through environmental incentives. The NB values for line flow control scenario are dependent on the installed wind power and renewable PTC values as seen in Figure 4.9. Furthermore, the energy arbitrage scenario has lower values of reliability worth than line flow control scenario for higher wind penetration case. The studies from the two scenarios clearly show that the operation strategy of CAES impacts the resulting NB and the economic worth of reliability.

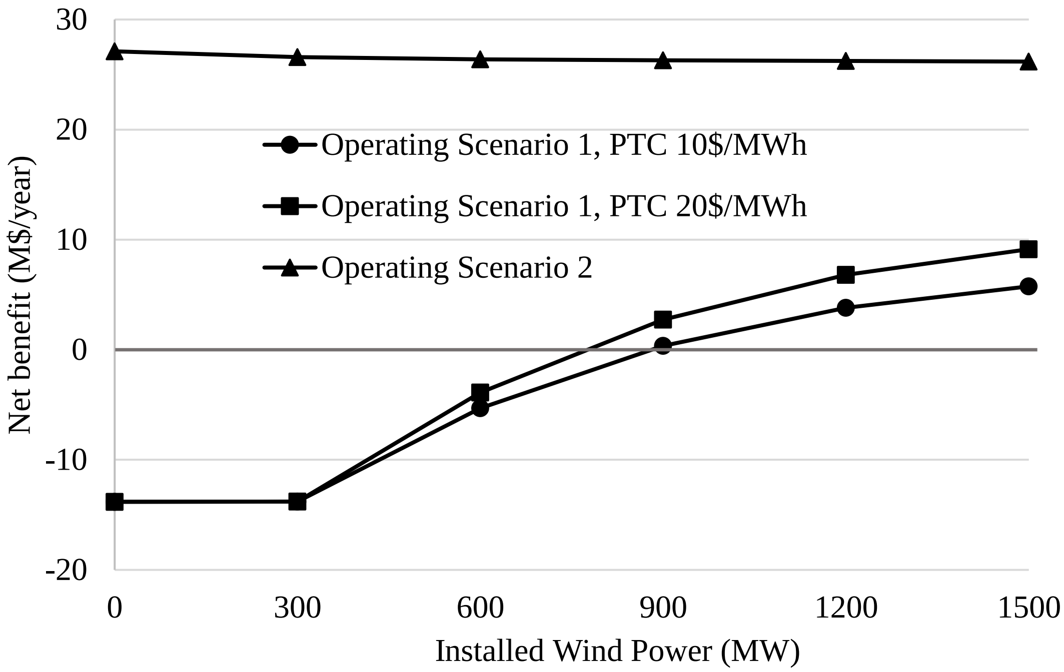

Figure 4.9. Net economic benefit for CAES.

The above benefits obtained are specific to the market structures, price data, load profile, wind profile, and the correlations between them, as well as the CAES cost parameters used in the assessment.

The analyses presented show that a CAES installed and operated for an objective of profit maximization from the market can have an inadequate contribution in improving system reliability and providing environmental benefits. It is important that the planning of CAES in a wind integrated power system should consider the potential reliability and environmental benefits along with the profits from the market.

A sensitivity study was carried where the CAES power rating was varied and the NB values were evaluated. Different scenarios of installed wind capacity were also considered. A co-located CAES operated for line flow control scenario was assumed. The transmission line was restricted to 300MW. Figure 4.10 shows the results of the study.

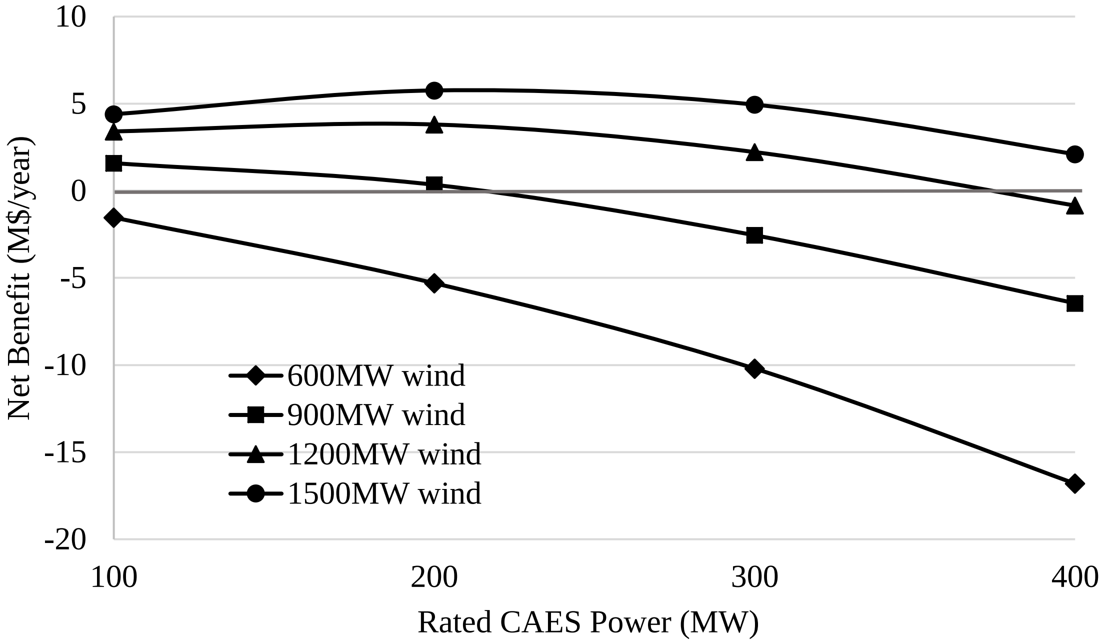

Figure 4.10. Variation in net economic benefit with CAES power for operating scenario 1.

It can be observed from the figure that, for the installed wind capacity of 600MW, each of the CAES rating results in negative NB values. This indicates that the CAES has lower opportunities to store and utilize wind energy and therefore provides low benefits form market, reliability improvement and wind utilization. The benefits obtained cannot offset the CAES cost even for the minimum CAES rating of 100MW. For wind penetration of 1200MW and 1500MW, increasing CAES power rating from 100MW to 200 MW increases the NB values because the CAES with higher ratings can utilize more wind energy and provide higher benefits. However, a further increase in CAES rating reduces NB values. The transmission capacity is restricted to 300MW which constraints the discharging operation of CAES. Therefore, the benefits tend to saturate while the cost increases with increase in CAES size. The optimum CAES ratings are dependent on the installed wind power, the transmission capacity, and also on the CAES operating scenarios.

4.5. Conclusion

This paper presents an overall methodology to quantify the societal benefits of CAES considering the reliability impact, economic aspects, and environmental objectives. Comprehensive models are developed for wind power and CAES taking into account its characteristics and operational modes. The models and methodology developed in this work can be utilized to quantitatively assess the overall societal impact of CAES and provide insights into the development of regulatory structures that can integrate CAES efficiently. The results from the case studies showed that the benefits CAES can provide to the system depend on the operating strategy of the CAES as well as the existing market and incentive mechanisms. The reliability and environmental benefits obtained from the CAES can often contradict with the objective of profit making. Therefore, the regulatory structures should drive the installation and operation of the CAES with the objective of supporting wind energy and reliability improvement through appropriate incentive and market mechanisms so that the CAES owners gain sufficient financial benefit

4.6. References

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CHAPTER 5: SUMMARY AND CONCLUSIONS

Fossil fuel based conventional generating sources are considered as a major factor for greenhouse gas emissions causing environmental hazards. With growing worldwide environmental concerns, the integration of renewable energy based sources such as wind and solar is gradually accelerating in the power system. Wind power is suitable for large scale installations, and therefore large penetration of wind energy is expected in the future sustainable power system. The stochastic nature of wind creates a significant challenge in power system operation and planning to ensure system reliability and efficiency (minimizing the cost of resources). The accommodation of a large portion of wind energy demands for greater flexibility of power grid. In this regard, energy storage systems (ESS) are emerging as a potential means that can mitigate the issues of wind integration. There are different ESS technologies with diverse applications in power system. Compressed Air Energy Storage (CAES) is one of the mature bulk scale ESS technology. CAES can have significant implications in the planning and operation of sustainable power systems. The reliability value of CAES is an important aspect that needs be assessed. This thesis explored the reliability impact of CAES in a wind integrated power system with the development of novel models, methodologies and frameworks. The case studies in the work demonstrated the reliability, economic and environmental aspects of the benefits obtained from CAES.

The reliability benefit obtained from the integration of CAES depends on the number of factors such as the operation strategy, objective of the owner, and the existing market and regulatory structure. These factors along with the technical characteristics and the component unavailability of CAES determines their actual reliability contribution. The reliability assessment framework for a system with CAES should properly incorporate the aforementioned factors. Besides, the framework should accurately model the chronological dependencies and correlations of the SOC in CAES with different system variables such as component failures, available renewable generation, charging and discharging power, etc. Modeling of CAES stochastic operating behavior that is influenced by system uncertainties is the major challenge for developing the reliability evaluation framework. In this regard, a novel probabilistic framework has been developed in this thesis to quantify the reliability value of CAES. The framework follows a hybrid approach and brings together the advantage of Monte Carlo simulation (MCS) method and analytical method to produce a comprehensive and computationally efficient framework. A sequential MCS method is utilized to model the state of charge (SOC) during charging process incorporating dependent variables while the analytical method is used for reliability evaluation. A period analysis consisting of seasonal periods and diurnal sub periods is proposed to evaluate the annual reliability indices. The Markov based component reliability model, considering the major components and their effect on charging discharging process, has also been developed and incorporated in the framework. The uncertainties in the wind power and the amount of wind power absorbed and curtailed in the system were also modeled and incorporated in the framework. The developed framework effectively models the feasible applications of CAES to diurnally and seasonally time shift energy. The framework presented can be applied to other bulk energy storage technologies too. The accuracy and effectiveness of the proposed models are validated with the results obtained from traditional MCS approach.

The proposed models and frameworks are utilized to quantify the reliability benefit of CAES in a wind integrated power system. The results indicate that the integration of CAES can significantly improve the system reliability because it can time shift of energy from off peak period to the peak lead period, where the probability of loss of load is higher. In addition, the stored energy in CAES can also be discharged to avoid other loss of load events occurring when CAES is in idle mode. From the case studies, it was deduced that the reliability contribution of CAES is mainly dependent on the operation scheduling of CAES. A CAES has to respond to the existing market, and, schedule its operation to gain financial revenue. The results show that the objective of profit making can compromise the potential reliability benefit of CAES. Therefore, the existing market and regulatory structures need to ensure that the CAES operating practices do not limit its reliability benefit. Furthermore, it is observed from the results that the seasonal energy management using CAES provided higher reliability benefit than the diurnal energy management strategy. The test system utilized in the work had a significant portion of the loss of load arising from the winter season. Therefore, time shifting energy from other seasons to winter season using CAES provided higher reliability value. The seasonal energy management application of CAES particularly significant from adequacy perspective in a power system where system capacity is in surplus in a season, and in deficit in another. Moreover, the results demonstrate that CAES can provide significant capacity contribution and defer other generation capacity expansion. The capacity values of wind and CAES are evaluated to analyze the role of CAES in capacity planning of wind integrated power systems. It is also revealed from the studies that, in addition to reliability benefit, the effective coordination between wind generation and CAES operation can contribute towards meeting the environmental compliance of sustainable power system by effectively utilizing the wind energy. Furthermore, a sensitivity study is performed to evaluate the impact of CAES rating on the reliability benefit. The financial benefits to a CAES owner from the energy market and capacity market are quantified. The studies indicate that the planning of CAES should consider its typical characteristic, feasible operations, potential reliability value as well as different revenue streams in the electricity market that an owner can use to get a financial benefit.

The regulatory market structures should be able to attract investment in the bulk scale ESS such as CAES that are essential in wind integrated power system to provide critical values through system reliability improvement and efficient utilization of wind energy. An extensive assessment of CAES applications and benefits is essential in order to provide insights to utilities and policymakers in formulating effective policy structures for integrating CAES efficiently. A comprehensive methodology is developed in this thesis to quantify the overall societal benefits of CAES in a wind integrated power system considering the reliability impacts, economic aspects and environmental objectives. The methodology incorporates wind power model considering wind diversity and transmission constraints. Moreover, feasible CAES operation strategies are formulated in the work considering CAES characteristics and objectives. A MCS based framework is utilized to evaluate the reliability impact. The benefits are quantified in terms of the reliability worth, incentive through wind support and revenue from the existing market. The net societal impact of CAES is then evaluated considering the benefit and cost models.

The results from the case studies indicate that a CAES can act as an alternative to wind diversity and transmission upgrade. A co-located CAES with a remote and high quality site can open up the opportunity for new wind farm installation at such site. However, depending on the objective and application, the potential CAES values to system differ significantly. It is observed from the results that a CAES installed and operated for an objective of profit maximization from the market can have a limited contribution in improving system reliability and providing environmental benefits. It is important that the regulatory structures that dictate the installation and operation of CAES in a wind integrated power system should recognize the primary objective of CAES to promote renewable energy and improve system reliability while assuring that the CAES owner gains sufficient financial benefit from electricity market and incentive mechanism.

In conclusion, this thesis modeled CAES characteristics, applications and operations, and, developed novel frameworks and methodologies in order to quantify the reliability value of CAES in a wind integrated power system. In addition to the reliability value, potential environmental benefit and the economic aspect of CAES were also analyzed. The models and methodologies developed, and the results and discussions presented in the work can be valuable to system planners, utilities and policymakers for rational planning and operation of CAES in future sustainable power systems.