# Study of Electrical Grid Profile & Behavior and its Impact on Design and Operation of Adiabatic Compressed Air Energy Storage (A-CAES) Systems

by

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# EXAMINING COMMITTEE MEMBERSHIP

The following served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

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# AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

# STATEMENT OF CONTRIBUTIONS

Chapters 3, 5 and part of chapter 2 of this thesis have been incorporated within a paper co-authored by myself, Dr. Ehsan Samadani, and Prof. Roydon Fraser (my supervisor) which has been submitted for publication. The model development and simulation work have been conducted by myself and Dr. Ehsan Samadani.

Chapter 6 has been embedded within a paper to be submitted for publication. The paper is co-authored by myself, Dr. Samadani, and Prof. Fraser. I collected and analyzed the data, developed the methodology, wrote the majority of the content, and created the data visualization figures. The model was developed and enhanced in association with Dr. Samadani.

The balance of the research is my own work.

# ABSTRACT

Integration of intermittent renewable energy, such as wind and solar, into the electrical grid results in risk of instability, increased cost (due to higher reserve and ancillary requirements), and inefficiency. In Ontario, integration of wind energy has been a significant contributor to increased energy prices. In addition to that, a lack of storage capacity has resulted in 7.6 terawatt-hours (TWh) of curtailment of clean energy at a value of more than one billion dollars [1]. These issues can be mitigated by using Electrical Energy Storage (EES) technologies (multiple studies have shown this). Compressed Air Energy Storage (CAES) is a proven EES technology with more than 40 years of operating history. In the recent years, there has been a renewed interest in developing CAES technology; however, the research has primarily focused on improving existing technology and its individual components, which creates a gap in research from a whole system design perspective. Furthermore, the studies of the role of CAES system in the electrical power grid has been mainly based on the sizing and performance of the existing systems, which does not take into account the potential capabilities of CAES, if it is designed and sized for specific applications and requirements. This research studies the impact of performance requirements on the design and operation of any potential CAES system using one full year worth of real operating data from the Ontario grid for analysis. The objective is to introduce a new approach to designing CAES systems based on specific grid requirements. In addition, a model is developed to identify the thermodynamic performance requirements of the system under real operating conditions.

# ACKNOWLEDGEMENTS

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***“For my beloved parents, brother, and sister…”***

Thank you for your eternal love and support, you have my deepest gratitude.

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# Nomenclature

| Symbol | Property | Units |
|---|---|---|
| $C_p$ | $Specific\ heat\ capacity\ (constant\ pressure)$ | $J/(kg \cdot K)$ |
| $C_v$ | $Specific\ heat\ capacity\ (constant\ volume)$ | $J/(kg \cdot K)$ |
| $h$ | $Specific\ enthalpy$ | $J/kg$ |
| $k$ | $Thermal\ conductivity$ | $W/(m \cdot K)$ |
| $m$ | $Mass$ | kg |
| $\dot{m}$ | $Mass\ flow\ rate$ | $kg/s$ |
| $P$ | $Pressure$ | $Pa$ |
| $\dot{q}$ | $Heat\ rate$ | $kJ/s$ |
| $R$ | $Gas\ constant$: 8.314 | $J/(mol.K)$ |
| $T$ | $Temperature$ | $K$ |
| $u$ | $Specific\ internal\ energy$ | $J/kg$ |
| $V$ | $Volume$ | $m^3$ |

Greek letters

| | | |
|---|---|---|
| $\gamma$ | $Specific\ heat\ ratio$: 1.4 ($for\ air$) | dimensionless |
| $\rho$ | $Density$ | $kg/m^3$ |

Abbreviations

| | |
|---|---|
| $CAES$ | $compressed\ air\ energy\ storage\ system$ |
| $A - CAES$ | $Adiabatic\ CAES$ |
| $I - CAES$ | $Isothermal\ CAES$ |
| $D - CAES$ | $Diabatic\ CAES$ |
| $Cav$ | $cavern$ |
| $Comp$ | $compressor$ |

| | |
|---|---|
| DDAM | Data − Driven Analysis Method |
| EDA | Exploratory Data Analysis |
| EES | Electrical Energy Storage |
| OOAD | Object − Oriented Analysis and Design |
| SOC | state of charge |
| TER | thermal energy reservoir |
| TES | thermal energy storage |
| Turb | turbine |
| UCD | User − Centered Design |

# Chapter 1

# Introduction

Compressed Air Energy Storage (CAES) is a very promising energy storage technology that can help with adding flexibility and capacity to the electrical grid that is required for increasing the share of renewable energy sources while reducing the environmental impact of the whole system. However, in order to ensure feasibility and maximizing the value, design considerations and operating requirements of the system needs to be first identified and assessed. The present study is concerned with understanding the required operational characteristics of the electrical grid and the potential effect it has on the design, sizing, and operation of CAES systems. This chapter introduces this thesis in three sections: research motivations, objectives, and the thesis outline.

The electrical grid infrastructure in use today was designed based on the concept of large centralized generators and steady and predictable demand profiles. Therefore, it lacks the flexibility and capacity required to operate reliably in a changing environment [2–6]. While, the electrical power system is composed of three parts, energy generation, transmission, and distribution, for the purpose of this study and for the remainder of this thesis the term “grid” refers to the whole system rather than only the transmission part of the power system unless specifically mentioned. Electrical energy storage (EES) technologies are one of the most promising technologies that can alleviate the grid reliability issues and the mismatch between supply and demand [7]. They can be used to store energy when there is excess supply in the grid, and then give it back to the grid when demand increases, while at the same time, there is a shortage of generation power [8]. There are many types of EES technologies and based on their operational characteristics, each type is better suited for a specific range of applications in the electrical grid [9]. Compressed Air Energy Storage (CAES) is a type of electromechanical energy storage system that has been in operation since early 1970s. In the past few years, the technology has gained a lot of interest in Canada. For example, a recent study of energy storage in Alberta identified CAES as a leading candidate for grid-scale storage in that province [10]. In fact, at the time of preparating this thesis, the only operational large-scale Adiabatic CAES (A-CAES) system in the world is in Toronto, Ontario, while a second facility is currently under construction in Goderich [11].

## 1.1 Motivation

Decarbonization of the electrical grid is an essential part of the global movement toward mitigating the causes of climate change [12,13]. In order to achieve this, the grid of future will have to be able to integrate energy generated from multiple renewable sources, with the majority coming from intermittent sources such as wind and solar. This requires a much higher operational flexibility by the grid while maintaining the same service quality and stability [14]. In such an operating environment, Electrical Energy Storage (EES) technologies are essential for stable operation of the electrical grid [15]. Although there have been significant developments in “distributed” energy storage systems, which are local and relatively small, the only commercially credible options for large grid energy storage are pumped hydro and CAES [16–19]. Compressed Air Energy Storage (CAES) is a promising EES technology that if designed right, can provide an extensive amount of ancillary and arbitrage services that are required by the grid for stable operation. Existing and proposed CAES plants have been primarily designed and utilized for arbitrage applications, and limited attention has been paid to the other potential applications (such as high revenue grid services). In this research, the motivation is to understand how a CAES design would be impacted based on the electrical power system expected service requirements. There have been multiple studies on the operation [20–22], cost analysis [20,23,24], and thermodynamic design and modeling of CAES systems [25–34]. However, a thorough understanding of the overall system, including the cavern, conversion, and the electrical grid component of the CAES is still lacking. This is due to the fact that the above studies were based on the operational data and design characteristics of the two existing CAES plants, Huntorf and McIntosh [24–27], and also the traditional design approach that emphasizes on improving system components rather than the overall system. Therefore, applying a new high-level system design approach to CAES design and operation, that would expand its applicability and use within the electrical power system, would be of high interest. Furthermore, customized design means that the new CAES will be able to provide a variety of applications with dissimilar performance requirements at an optimal cost and higher operational flexibility.

The purpose of this thesis is not to improve the design of specific components of existing CAES systems, but rather to introduce a new approach to designing CAES systems, that focuses on sizing, performance, and its application within the electrical power system, in order to improve their usability and effectiveness. Improving how a system is designed can significantly reduce the design cycle time and the number of required revisions [35,36]. It is proposed that a User-Centered Design (UCD) [37] approach will achieve this goal by measuring, understanding, and focusing on the needs and requirements of the grid operator (User) to define the boundaries of the designed system, prior to improving the design of individual components [38,39]. Another benefit of this approach is the ability to create a uniform process for analyzing the feasibility and design limitations of customized CAES systems. Finally, utilizing UCD results in enhanced design adaptability, which is the flexibility of a system design to be altered, allowing it to incorporate new requirements once introduced [40–42]. UCD methodology has been extensively used in many areas of system design; however, at the time of writing this document, this method has not been applied explicitly to designing grid-scale energy storage systems.

To identify the technical, economical and policy issues and operating challenges of the Ontario grid and CAES, and to validate the identified gaps in the current research which this study intends to address, the following individuals were consulted and/or interviewed:

- Honourable Glenn Thibeault, Minister of Energy (Ontario)
- Honourable Glen R. Murray, Minister of the Environment and Climate Change (Ontario)
- Tim Christie, Director of Electricity Policy, Economics and System Planning Branch (Energy), Ministry of energy (Ontario)
- Terry Young, Vice-President of Conservation and Corporate Relations at IESO
- Todd Ramsey, Vice President of Business Development at Whitby Hydro
- Jayesh Shah, Interim Vice President of Engineering and Operations at Oshawa Power
- Paul Grod President & CEO, Rodan
- Janos Rajda, Senior Technical Advisor, Microgrid/Energy Storage at Canadian Solar
- Oliver Winkler, Business Leader, Strategy and Innovation at Siemens Canada

## 1.2 Objectives

The objectives of this research are as follow:

### 1.2.1 To identify potential opportunities to utilize the CAES EES system in order to provide high-value grid services to the electrical grid

Increased level of renewable energy penetration in the electrical power grid has caused stability challenges for system operators. To mitigate this issue, a higher level of operating flexibility is required. Energy storage is an effective and proven way of increasing flexibility. In that context, Although CAES technology has been successfully used for more than forty years, its capability for providing high-value services has largely been overlooked. Therefore, this research aims to identify how CAES systems can be utilized to provide these services to the electrical grid.

### 1.2.2 To develop a method for preliminary CAES system and component sizing based on a specific electrical power system grid profiles and operating requirements

CAES is a complex multi-physics system consisting of multiple interacting mechanical, electrical, and geomechanical elements. Therefore, CAES performance is affected by numerous operating and design parameters. A thorough review of the current literature indicates the lack of a comprehensive and system-level approach to the design and operation of CAES system within the electrical power grid. In this research, a user-centered design approach is employed to develop a high-level design method for sizing the CAES system and its operating capabilities (such as response time) that encompasses all the inter-related elements, especially the service requirements for improved operation of the grid.

### 1.2.3 Apply the developed method to analyze the impacts on the design and constraints of different components from thermodynamics and geomechanical perspective as well as electric grid operation viewpoint

Efficiency, cost, and capacity of a CAES are highly sensitive to the sizing and dynamic characteristics of its components. By applying the method mentioned above to a specific grid, the potential constraints of each element in the CAES system operating in that grid can be identified.

These include geomechanical parameters (e.g., cavern state of charge, temperature and pressure limits), thermodynamic parameters (e.g., heat exchangers sizing and efficiency, compressor and turbine power rating, etc.).

## 1.3 Thesis Layout

In accordance with the research objectives stated above, this thesis encompasses the following general sections: a broad overview of the electrical grid operation and challenges with emphasis on Ontario electricity system, introduction and explanation of the methodology and approach developed for this study, the analysis of long-term Ontario grid data, and the discussion of results and design implications for CAES systems. These sections are organized into the following chapters:

Chapter 1 includes an overview of the issues and motivation for the research presented in this thesis, followed by the research objectives, and explanation of the structure of the thesis.

Chapter 2 provides background information on the electrical power system (grid), including its operation and challenges, Electrical Energy Storage (EES) systems, Compressed Air Energy Storage (CAES) system, and Ontario’s electrical grid. This is followed by a comprehensive review of the published literature related to CAES.

Chapter 3 describes the CAES thermodynamic model and its scientific foundation. This includes the development of the conceptual, system, and operational models. The assumptions and boundaries applied to the system are also covered.

Chapter 4 focuses on the methodologies used in this study. The User-centered Design (UCD), Object Oriented Design and Modelling (OODM), and Data-driven Analysis Method (DDAM) methodologies and approaches are described. After that, the data collection process is explained.

Chapter 5 introduces the CAES-by-Design approach. A detailed description of the process is given. The results of analysis and thermodynamic simulation of a sample grid data are then discussed.

Chapter 6 begins with the analysis and visualization of the long-term grid data. The significant patterns are highlighted and discussed. This is followed by the result and discussion of the thermodynamic simulations.

Chapter 7 covers the concluding remarks and highlights the potential subjects for future work.

# Chapter 2

# Background and Literature Review

In this chapter, the operation, infrastructure, and challenges of the electrical power system/grid, and the role of electrical energy storage (EES) system in alleviating some of those challenges are reviewed in detail. The discussions are focused on North America, and more specifically, Ontario-Canada electrical power grid. Then a comprehensive overview of CAES technology is presented. The chapter concludes with highlights of relevant research and the identification of gaps in the literature. The literature review revealed that while there are many studies on the different aspects of CAES systems, a thorough understanding of the overall system, including the cavern, conversion, and the electrical grid component of the CAES is still lacking.

## 2.1 Background

In the following section, some background information about the electrical power grid operation and services, as well as CAES system design, operation, and applications are presented. After that, a critical review of major published research on different aspects of this technology is discussed.

## 2.2 Electrical Power System (Grid)

The electrical power system is composed of three parts, energy generation, transmission, and distribution as shown in Figure 1[43].

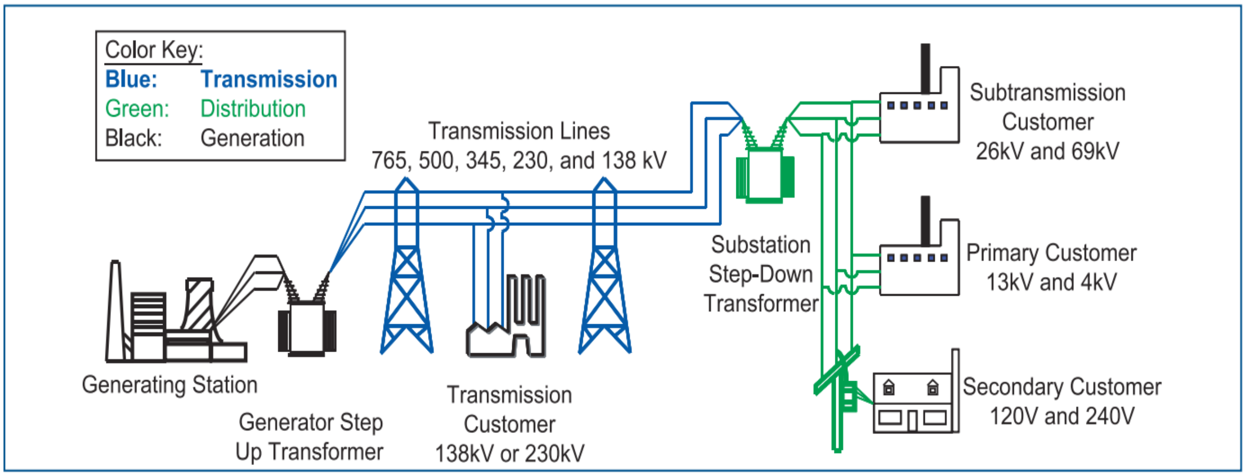


**Figure 1 - Schematics of Electrics Power System** [44]

In North America, the electrical power system is divided into multiple smaller regional interconnected electricity markets. At the highest level, the North America electric power system is divided into eastern interconnection, western interconnection, and the electric reliability council of Texas (ERCOT) [45]. While these interconnections are all independent, they synchronize at the high level, and as shown in Figure 2, are all connected through a small number of low capacity direct current (DC) lines [44,45]. To ensure the reliability of the electrical grid, all the generators within each of the three major interconnections are tightly synchronized to provide fault tolerance in the system [46].

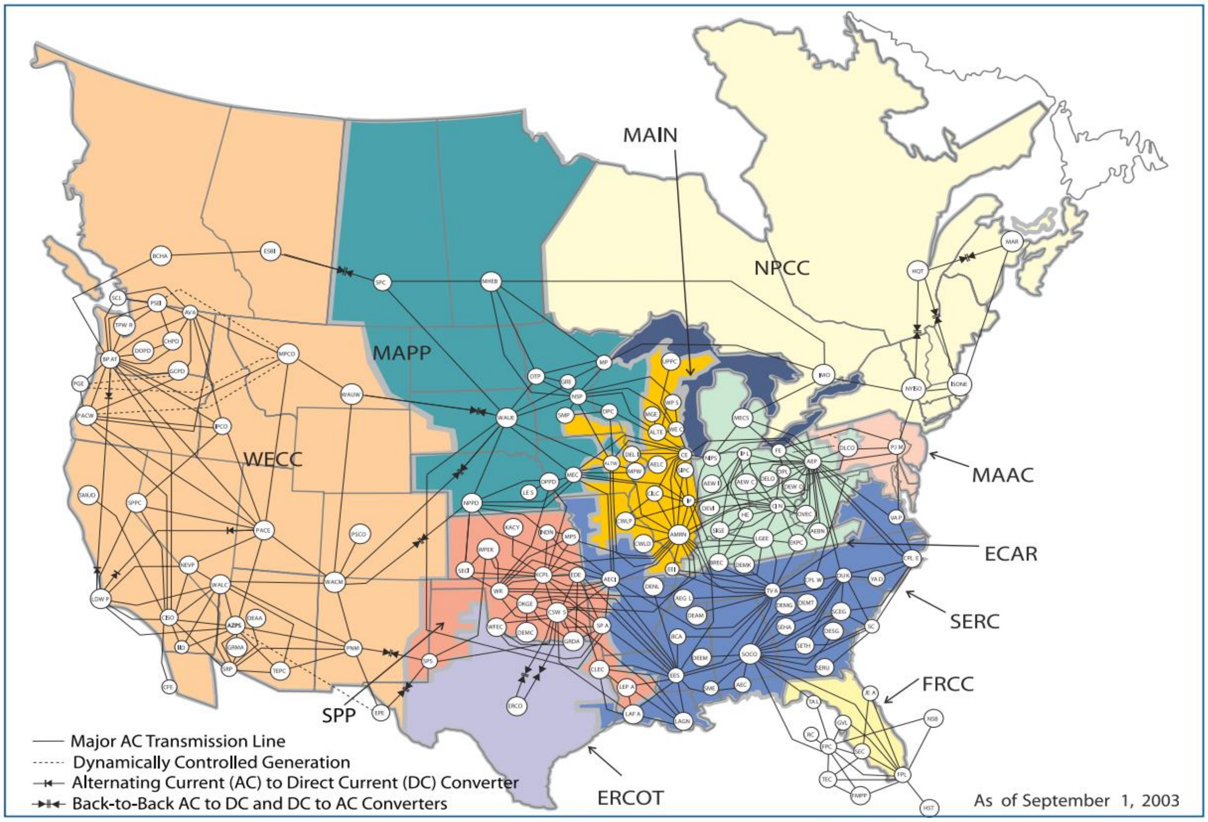


**Figure 2 - North America Regional Divisions and Interconnections** [44]

The North America electric reliability cooperation oversees and sets the reliability standards for the North America grid, however, each of these responsibilities is passed down to multiple regulatory bodies that function at a more regional level [43]. Canadian electricity power system falls under the North American Electric Reliability Corporation (NERC) regulatory umbrella and each province will also belong to one of the regional balancing authorities; for example, Ontario is a part of Northeast Power Coordinating Council (NPCC).

### 2.2.1 Challenges

As previously mentioned, the grid of future will have to be able to integrate the energy generated from multiple renewable sources, including intermittent sources such as wind and solar in order to reduce its carbon footprint [12,13]. This means that the operational flexibility of the grid has to be increased significantly without any losses in service quality and stability [14][14]. Achieving such requirements will introduce new challenges to the grid systems, which are summarized in Table 1.

**Table 1 - Electrical power grid challenges**

| Grid Challenges | Main Cause |
|---|---|
| **Decarbonization** | Generation from fossil fuel power plants are a major contributor to carbon and GHG emission, therefore, reducing dependence on fossil fuel is a challenge. [47,48] |
| **Renewable Integration** | Due to the intermittent and unpredictable nature of renewable sources, electrical power grids have difficulty with integrating these sources. This becomes especially significant as the share of renewable energy reaches 20-25% of the total generation capacity. [45,49] |
| **Lack of Flexibility** | The existing infrastructure of the power grid is based on the concept of large centralized generation and distribution. Therefore, the electrical power grid lacks the required flexibility for the era of ever-increasing localized distributed generation. [45,50] |
| **Increasing Energy Demand** | The demand for electrical energy is constantly increasing and is expected to reach 281 GW by 2025 in North America. Furthermore, electrification of the transportation system could significantly speed up this growth. Therefore, electrical grid systems have to constantly add new generation capacity, while being constrained by limited resources. [21,51] |
| **Efficiency & Reliability** | Oversizing and underutilization of the existing capacity result in lower overall efficiency of the electrical grid, leading to a high operation cost. [7,52] |

### 2.2.2 Services

In order to ensure the stability of the power grid, the independent system operators (ISO) and regional transmission organizations (RTO) need to continuously shift generation and load, balancing the inflow and outflow of energy to/from the system. Depending on the requirements and variations, this response needs to occur within seconds or extend over many hours. Stable operation of the grid is attained through the utilization of many numbers of services, such as frequency & voltage regulation, and spinning & operating reserve [53–55]. As such, the grid operator needs to allocate, or have on standby, flexible resources to ensure the quality and delivery of power [56]. The different types of services provided by these resources are known as ancillary services. The types and values of these services vary significantly in every electricity market [57]. Also, the definition and operating parameter of similar services can be different in each market. Since providing ancillary services requires much more flexibility, and faster reaction time, they have a much higher financial value. It should be noted that there is no unique definition of the number and nature of these services in the literature [54,58–62]. EES technologies are particularly well suited for providing ancillary services [55].

### 2.2.3 Electrical Grid Efficiency

As a result of using fossil fuels for generating power, the electrical grid has an enormous negative impact on the environment. Hence, cleaning the electrical grid has become one of the main priorities in tackling global climate change [58]. Increasing the share of renewable energy sources in the supply mix and improving the overall efficiency of the grid, including conservation, are the main strategies for creating a clean electrical power system. Integrating larger quantities of renewable energy and improving overall efficiency, both create new challenges for the grid [9,58,59,63]. The existing grid lacks the flexibility and capacity required to operate reliably in this new environment, since it was designed for more steady and predictable demand profiles, utilizing an infrastructure that consists of large centralized generators [9,59,63,64]. The move to distributed generation model, which includes a majority of renewable sources, changing consumption pattern as a result of changing economy, shifting of consumer behavior, and a move to a service economy means that the system requires transformation by the grid at every level.

Furthermore, it requires adopting new strategies to mitigate the impact of these factors while ensuring the overall stability and reliability of the electric power system [65]. At a technical level, this requires re-examining how we operate and design the electrical grid. In 2011, an interdisciplinary study by MIT found that modifications to how the power systems were designed and operated were necessary in order to efficiently increase the share of renewable energy in the grid while maintaining reliability [45]. The study further stated the need to reform the processes for planning transmission systems expansion allocating facilities cost and, especially, citing interstate transmission facilities.

Worldwide, one other obstacle to achieving a clean electrical grid is the constant increase in energy demand. Electricity generation is around 15,000 billion kWh per year, with North America accounting for nearly 30% of this amount [46]. By the year 2025 in order to meet this growing demand, it is estimated that North America will need 281 GW of new generating capacity and close to 80,000 km of new high voltage transmission lines [61].

Multiple studies have identified efficiently increasing capacity while maintaining system reliability as one of the main challenges of the electric grid in the coming years [45,46]. The constant change in demand and the difficulty in storing electrical energy results in the system having to continuously increase and decrease power generation. This matching of supply and demand in real time is achieved through central control systems, generally known as independent system operator (ISO) and is essential for the reliable operation of the grid. How a grid is designed and operated can have a significant impact on the overall efficiency of the system. The efficiency here refers to the total energy generated and used by the electrical grid to meet the end user's consumption energy demand. The less efficient a specific grid is, the higher its overall capacity requirement will be, which increases the overall cost of the electricity consumed in that system. Examples of elements that can impact the efficiency of the electric grid include [65–67]:

- Oversizing to meet peak loads
- Transmitting electricity over long distances
- Lower efficiency generation at thermal power plants due to partial loading
- Generation curtailment due to oversupply

Electrical grids need to be designed to provide enough capacity to meet the demand at its highest point or peak during any specific time cycle (daily, seasonal, and annual). Since the demand fluctuates over time, there is a difference between peak and average demand, which is known as peaking load requirement. Power plants that are used to meet the peaking load requirement have to shut down or sit idle during average load demand periods, resulting in under-utilization of the system. The larger the difference between the peak and the average demand, the higher the underutilization and oversizing of the system [52].

#### 2.2.3.1 Transmission Losses

One primary source of losses in the electric grid is the transmission line. When electricity flows through the cables, heat is generated as a result of the resistance in the transmitting medium (copper or other types of metal alloys). The total losses in transmission are a function of the amount of power (current), and the distance traveled. Transmission losses can amount to up to 7.5% of the total system capacity [46,68]. While using higher capacity rated cables can reduce the losses due to heat generation, it results in underutilization of a highly expensive infrastructure. To put this into context, the estimated cost of building a kilometer of a new transmission line is about $1M [68]. Another strategy is to increase voltage and reduce current, which is the most common practice. Still, this method also has its limitations, as the voltage rating for both distribution and transmission level is standardized. Another complexity and cost factor in this method is the need for numerous substations and transformers to step up and down the voltage. A better strategy will be proper placement of generators to be as close as possible to the demand centers, which minimizes the losses due to transmitting electricity over a long distance. Energy storage systems can also be utilized to reduce the losses that occur as a result of congestion on the line [69].

### 2.2.4 Generation Efficiency and Underutilization Losses

Electricity generation power plants are designed to operate at a specific load which is typically their rated or nameplate capacity. This optimal load is also where the generator achieves its highest efficiency. To match fluctuating demand requirement and also keep the grid stable, generators need to ramp up and ramp down their production during different time periods. Some power plants which are mainly used to provide baseload power, such as nuclear, have limited flexibility to increase or decrease their output and also have a slow response time; therefore, other types of power plants are used to meet the peaking demand requirement [68]. This is most commonly done by natural gas generation power plants [9,25,70,71]. However, operating as peaking power plants means that these generators spent most of their time working at part-load, which significantly decreases the overall efficiency. Lower generating efficiency at these plants impacts the grid by increasing the total cost of production and increasing its carbon intensity. Optimizing operational planning and dispatch to decrease the partial load periods can help to improve the overall efficiency of this type of generators. Deploying energy storage systems can also reduce the ramping requirement of peaking power plants [70,71].

#### 2.2.4.1 Curtailment

System operators use forecasting to predict the future demand to ensure enough capacity is available at any given point; however, forecasting is subject to normal errors. The margin of error increases with the introduction of higher levels of non-dispatchable variable generation, such as wind and solar, into the electrical grid [59]. This can result in oversupply in the electricity market, which has to be managed by the system operator for the grid to remain stable. Curtailment is the practice of requesting a committed, dispatched or available generation source to shut down or remove itself from the system, which results in a much higher cost to the system operator. Other than oversupply, transmission constraints can also result in curtailment. This results in increased inefficiencies in generation, which in turn, translates to a higher overall cost of electricity [45]. Improved forecasting and planning results in less curtailment, but there is always a margin of error. Energy storage systems can have a positive impact by absorbing the oversupply in the market and reducing congestion in the transmission lines [72], which will decrease the need for curtailment by the system operator.

### 2.2.5 Grid Operation and Services

Electricity grid by its nature requires maintaining a constant balance between the power generated and the power consumed at any point in time. This is the primary challenge of operating a stable power system grid and is the reason for having multiple regulatory and control organization with the dedicated task of operating the grid in a balanced and stable way. To achieve this, the independent system operators (ISO) and regional transmission organizations (RTO) need to continuously shift generation and load to ensure the stability of the grid operation. Depending on the requirement and variation, this response needs to occur within seconds or extend over many hours. This balancing act can be managed particularly well by using energy storage technologies [73].

### 2.2.6 Ancillary and Arbitrage Services

The federal energy regulatory commission (FERC) defines ancillary services as those "necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system." [74]

As mentioned above, balancing the inflow and outflow of power to and from the grid is the main responsibility of the ISO. Achieving a stable operation will require many numbers of services provided through different technologies, system planning, and generators. While the number and nature of these services are different from paper to paper [58,59,62,64,75], there are some main services that are required in any electrical grid. These include:

- Power quality and regulation
- Spinning and non-spinning reserves
- Black start
- Load leveling
- Load following
- Transmission curtailment prevention
- Transmission loss reduction
- Unit commitment
- Voltage control
- Frequency regulation

Although every ISO uses many or all of the ancillary services mentioned in the list above the general definition and pricing of any of these services can be different in every region and based on that particular industry structure [75]. While "Energy Arbitrage" is part of grid services, it can generally be placed in a separate category, as both the required timescale (duration of charge/discharge) and the ramp speed (reaction time) are much longer and slower, respectively, compared to the other types of grid services. The difference in the performance requirements is also reflected in the lower price/value of arbitrage in comparison to ancillary services. For example between 2010 and 2011 in California, the price range for energy arbitrage was \$25-\$41 per kW, while the price range for regulation services was \$117-\$161 per kW [76].

Energy arbitrage, some of these ancillary services and CAES potential for providing them will be examined in Appendices A.

## 2.3 Electrical Energy Storage (EES)

As was discussed in the last section, ensuring the reliability of the electrical supply is the primary challenge of the electrical grid system. Electrical energy is different from other forms of energy, as it needs to be consumed as it is being generated and therefore the grid operator needs to constantly adjust the supply and demand to protect the system, guaranteeing power availability and quality. EES technologies are one of the most promising technologies that can alleviate the grid reliability issues and the mismatch between supply and demand [77]. They can be used to store energy when there is excess supply in the grid, and then give it back to the grid when demand increases, while at the same time, there is a shortage of available generation capacity [72].

### 2.3.1 EES Technologies

There are many types of EES technologies, and each type is better suited for a specific range of applications in the electrical grid. EES can generally be classified based on two main features:

- How the energy is converted and stored (Form of Energy Storage)
- What is its operating characteristics (Operating Parameters)

Each of these categories are explained in this section.

#### 2.3.1.1 Forms of Energy Storage

Energy can be stored in many forms such as heat, chemical (fuel), pressure, and so on. Depending on the type of energy conversion technology and in what form the energy is stored, the Energy Storage systems are categorized as:

- Mechanical - Electromechanical
- Chemical - Electrochemical
- Thermal

Below is a brief description of each category:

- **Mechanical – Electromechanical:** Energy can be stored by converting electricity to some form of kinetic or potential energy through mechanical conversion. Pumped-Hydro, Fly Wheels, and CAES are examples of Electromechanical EES technologies.

- **Chemical – Electrochemical:** Electrical energy can also be converted into a chemical form by creating higher energy content fuel or changing the chemical formation. Batteries are the best example of electrochemical EES technologies; another example is synthetic gas production (Power to Gas).
- **Thermal:** The thermal energy in a system (heat) can also be stored, retrieved, and used at a later time; this is known as thermal energy storage. Use of phase-change materials is the most common method for storing thermal energy.

### 2.3.2 Operational Characteristics of Different EES Technologies

The other main feature by which EES technologies are categorized is their operating characteristics as summarized in Table 2:

**Table 2 - EES operating characteristics** [8,77]

| Characteristics | Description |
|---|---|
| Response Time | How fast it can store/supply energy |
| Power rating – Power density | How much power it can provide/absorb at any point in time |
| Energy rating – Energy density | How much energy it can provide/store |
| Duration without discharge | How long it can store its energy for |

The relationship between these parameters and the suitability of EES technology for specific grid applications is shown in Figure 3 [9]:

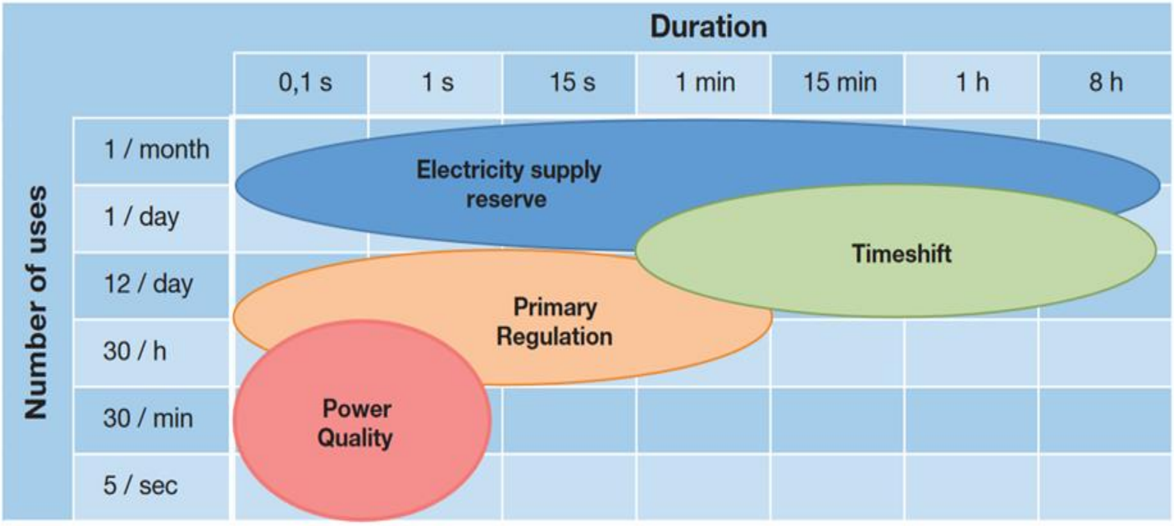


**Figure 3 - Relation between performance requirements and service provided by an EES [71]**

As can be observed, services such as power quality are frequently used, but only over a very short period, translating to a low energy capacity. On the other hand, timeshift services are used infrequently, but over a large period of time, i.e., high energy capacity required. These parameters determine the suitability of an EES technology for a specific application in the electrical grid [9]. Figure 4 shows the relationship between EES operating parameters and the type of services it can provide:

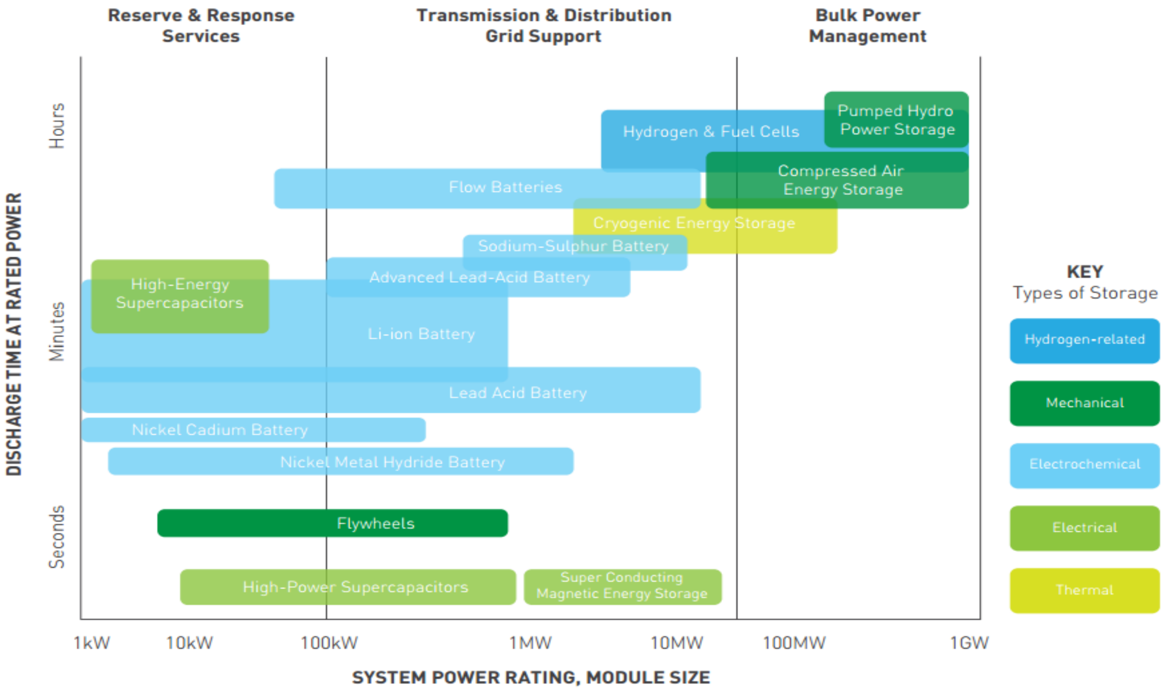


**Figure 4 - EES Operating Parameters and Its Services** [43]

### 2.3.3 EES Participation in the Electrical Grid

For any system (including EES systems) to provide services to the electrical grid, it needs to participate and trade in the electricity market.

Trading in energy/electricity markets generally happens in three ways [25]:

- Day-ahead market
- Intra-day market
- Ancillary services market

Of these three modes, the day-ahead market is the most predictable and the lowest cost, and it accounts for the major share of the overall trading. This is followed by the intra-day market, which is created to meet requirements for potential adjustment in capacity. Finally, ancillary services are the highest value components required to ensure grid stability, power quality, and smooth operation of the grid [9].

Depending on the capabilities and services that EES can provide, it can participate in one or all of the markets described above. However, due to the market structure and regulatory constraints, not all of these markets will be viable financially for storage systems to compete in [9]. Creating new market structures and adding value to the unique services that can be provided by EES systems such as CAES can make EES projects more attractive. An example of this type of approach is creating metrics for flexible capacity in the assessment of utility-scale energy storage systems, as was suggested by Cutter et al. [70].

## 2.4 CAES

Compressed Air Energy Storage (CAES), is an electromechanical energy storage system that has been continuously in operation since the 1970s in Europe and later in North America. In this section, CAES technical characteristics and its potential for integration in the electrical power grid will be discussed.

### 2.4.1 CAES Operation

The CAES system operates by running a compressor using the excess electricity supply in the grid to compress ambient air and pump it into a cavern or pressurize vessels and later on running the pressurized air through a turbine to generate electricity during demand periods. While there are many subcategories and proposed types of CAES systems, in general, they can be divided into two main categories: Conventional CAES (Also known as Diabatic or D-CAES) and fuel free CAES. The fuel-free CAES can be achieved through two different methods; isothermal process, and adiabatic process [23,78].

The main difference between the two systems is the management of the heat during the conversion process. In a D-CAES system, the heat generated during the compression of air is dissipated into the environment before pumping the air into the cavern. This is necessary to ensure the integrity of the cavern. When the pressurized air passes through the turbine and expands, it will result in a rapid drop of temperature that can cause freezing in the turbine [79]. Therefore heat needs to be added to the returning air upstream of the turbine to compensate for the heat dissipated into the environment during the compression process. Addition of heat is done by adding a conventional gas turbine in the expansion process. The two existing CAES systems in operation today in Germany and USA are D-CAES [52,79,80]. The main drawbacks of D-CAES are low roundtrip efficiency [47,81] and production of GHG emission. While the expansion process of D-CAES is much more efficient compared to a regular natural gas power plant [79,82], the heat loss in the compression process reduces the overall efficiency to around 50 or 55% [77,83]. Also, if D-CAES is used to store or integrate energy from clean renewable sources, these benefits are eliminated or reduced due to the combustion process during the expansion/generation cycle through the addition of natural gas.

The fuel-free CAES can be achieved through two different methods:

- Isothermal process
- Adiabatic process

## 2.4.2 Isothermal CAES

In this approach, the temperature of the pressurized gas is decreased in infinitely small steps during the compression process and then increased in the same way during the expansion process to eliminate/minimize thermodynamic losses of heat energy. Companies such as LightSail, SustainX, and General Compression have focused on this approach [84]. However, as of the time of this paper, none have been able to successfully demonstrate the technology [85]. Although theoretically isothermal CAES can have very high round trip efficiency (about 90%) in reality, there are many technical challenges and sizing constraints that will limit its operation to small scale applications (1-5 MW). In fact, LightSail ceased its operation in 2017 [86] and prior to that SustainX merged with General Compression [84] without deploying any commercial product.

## 2.4.3 Adiabatic CAES

In this method, the system operates similar to the D-CAES, but instead of releasing heat into the atmosphere the heat is stored in a heat storage medium and later used to reheat the air exiting the cavern before entering the turbine during the expansion process [47,87,88]. The ADELE project in Germany is an example of an adiabatic CAES project which is also known as advanced adiabatic CAES (AA-CAES) [89]. A-CAES has shown more potential for large scale storage applications. However, there are some technological challenges such as management of very high temperatures in the turbine inlet (around 600 degrees Celsius) [88,90]. There have been some studies on reducing the heat requirements in the system, such as a new low-temperature AA-CAES proposed by Wolf et al. [40]. The general consensus in literature identifies the overall efficiency of adiabatic CAES at or above 70% [82,88]. Figure 5 shows a comparison of the efficiency of different CAES types.

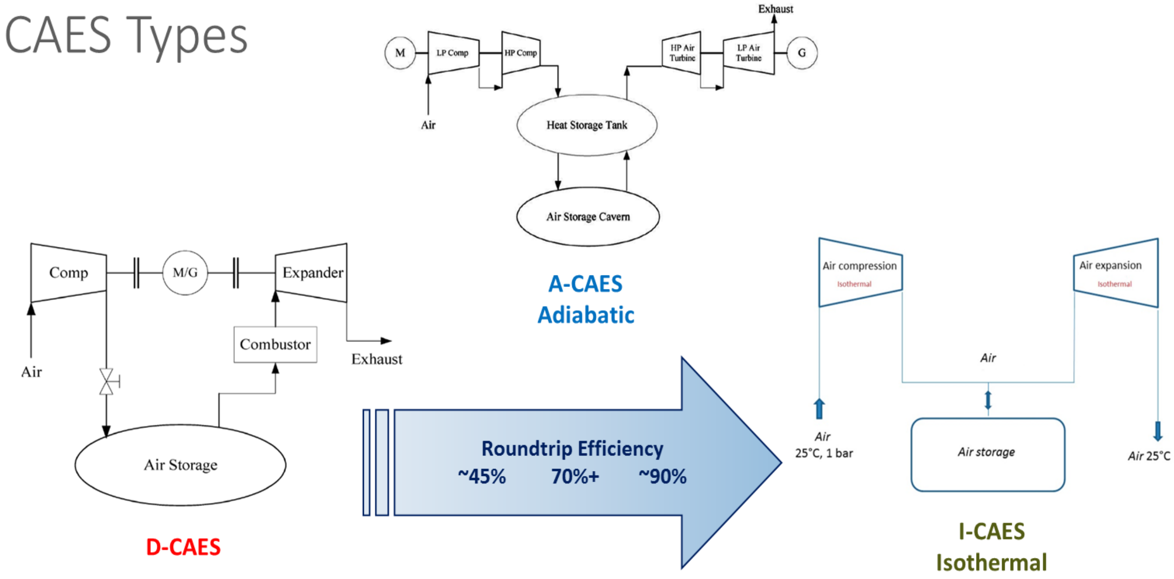


**Figure 5 - Efficiency Of Different CAES Technologies** [91]

### 2.4.4 Feasibility of CAES

The feasibility of the CAES system is affected by two main factors:

- System sizing
- Operational flexibility

In a fuel-free CAES system, the main cost is the capital cost (aka CAPEX) as the operating cost (aka OPEX) is limited to maintenance. Therefore, the principal method for reducing the cost of this type of ESS technology is by reducing the capital cost which includes the construction of the cavern, and energy conversion equipment such as compressors, turbines, heat exchangers and thermal storage system. As such, optimal sizing of the CAES components, i.e., cavern, energy conversion equipment (compressors, turbines, heat exchangers), and thermal storage system are crucial to its economic feasibility [77,79,92]. The operation parameters of the CAES are defined by the output and capacity of each of its components. The cavern volume and the minimum and maximum pressure determines the total energy (MWh) that can be stored, while, the energy conversion systems will set the input and output rates. The number and size of compressors determine how much and at what rate air can be compressed and stored in the cavern which determines the rate/speed that energy can be removed from the grid (stored). Conversely, the turbine will determine how much and at what rate/speed energy can be added to the grid (generated) [93].

The other key function that affects the feasibility of a CAES system is how it operates within the electrical grid and what kind of services it can provide. As a general rule, the more services an EES system can provide the higher its value [52]. Furthermore, the type of services that are provided by the system will greatly impact its financial viability [9,85]. Therefore, the design of the CAES system should be based on providing the highest value services required by the particular grid environment in which it will be operating. This could mean a trade-off between power rating versus energy rating, ramp up time, and thermal and round-trip efficiency.

In the current literature, CAES system technology is positioned for providing services that require a large energy capacity and low number of cycles with slow reaction time [43,94].

Depending on their performance characteristics, EES systems can participate and trade in the electricity market, which as previously mentioned is generally categorized into [25]: 1- Day-ahead market, 2- Intra-day market, 3- Ancillary services market. Of these three modes, ancillary services are the highest value components required to ensure grid stability, power quality, and smooth operation of the grid [9]. Subsequently, enhancing the CAES system design to provide ancillary services would be a key factor in improving its positioning in the market.

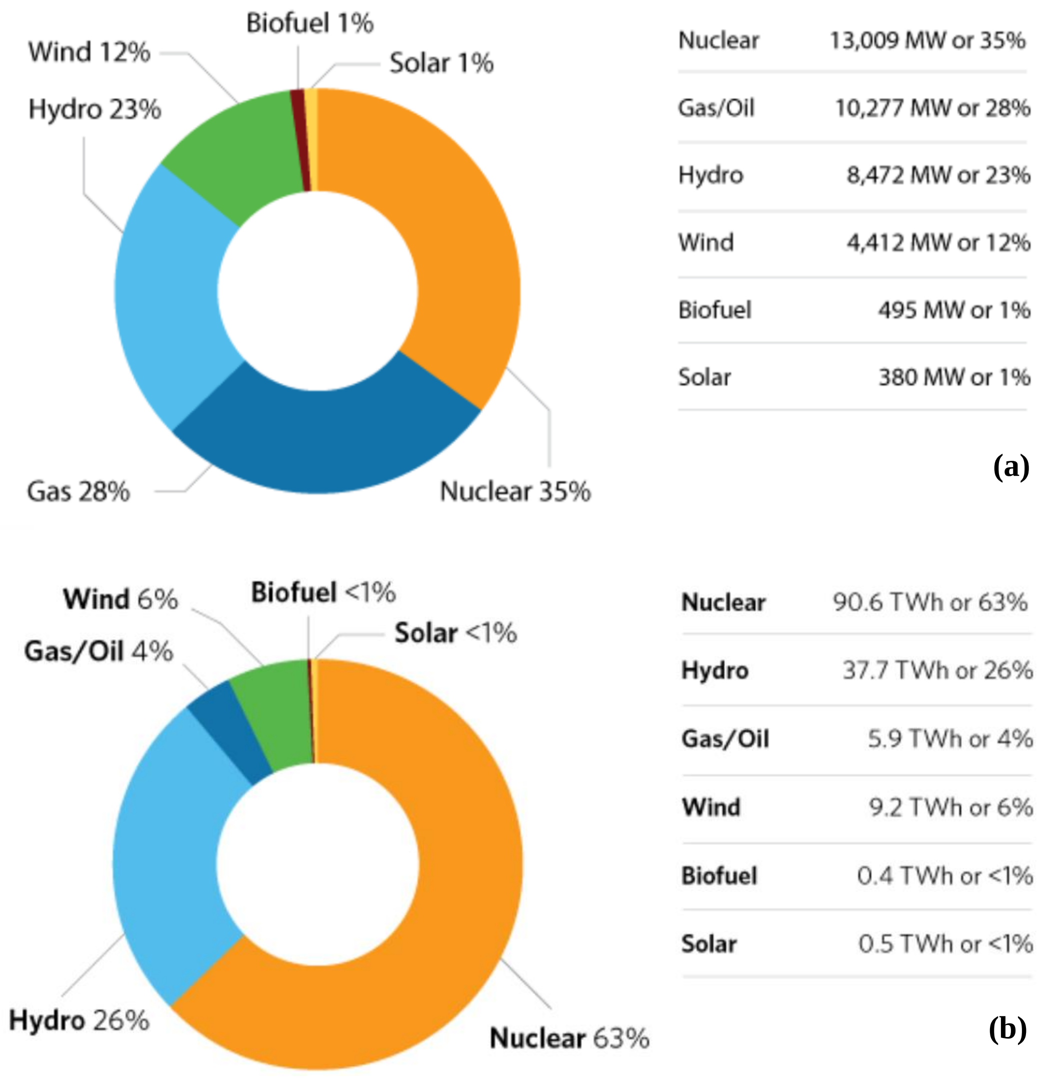
### 2.4.5 CAES versus batteries

Unlike batteries, CAES technology is uniquely qualified for simultaneously providing both load and supply (discharge and charge) at any point in time due to its design [82] and therefore can have higher values for the grid operator. This type of ramping capabilities are essential to the suitability of the storage technology for replacing or utilizing the natural gas generation that is currently used in markets such as Ontario, to manage peaking demand which can reach up to 10,000 MW on some days [95].

Another difference between the two systems is their average operating lifecycle. While CAES systems are designed to operate for 20+ years, batteries have a much shorter lifecycle [96] and are also affected by degradation within their operating lifespan.

## 2.5 Ontario Electrical Grid

The independent electricity system operator (IESO) is in charge of grid management and stability in Ontario. As of 2018, IESO has a total installed generation capacity of 37045 MW under its control in Ontario. As shown in Figure 6, Ontario has a diverse energy generation mix, that includes nuclear, gas, hydro, wind, biofuel, and solar.



| | |
|---|---|
| Nuclear | 13,009 MW or 35% |
| Gas/Oil | 10,277 MW or 28% |
| Hydro | 8,472 MW or 23% |
| Wind | 4,412 MW or 12% |
| Biofuel | 495 MW or 1% |
| Solar | 380 MW or 1% |

| | |
|---|---|
| **Nuclear** | 90.6 TWh or 63% |
| **Hydro** | 37.7 TWh or 26% |
| **Gas/Oil** | 5.9 TWh or 4% |
| **Wind** | 9.2 TWh or 6% |
| **Biofuel** | 0.4 TWh or <1% |
| **Solar** | 0.5 TWh or <1% |

**Figure 6 - Ontario power generation data by fuel: (a) installed generation capacity and (b) energy output** [97]

It is observed that there is a mismatch between the installed capacity and annual energy output of these resources. In Ontario, the energy cost is composed of the actual cost of production and the costs of inefficiencies and infrastructure improvements referred to as global adjustment (GA).

Underutilization, in fact, has a direct impact on these inefficiencies [98]. Since, wind and gas have the highest amount underutilization in the grid, measuring ~50% and ~14% respectively, there is a tremendous potential for improving the system efficiency and reducing the costs by focusing on these two resources.

Other major factors behind the cost of energy in Ontario, include outstanding capacity and reliability issues associated with integrating renewable generators, cost of constraint output (e.g., curtailment), and conservation (e.g., demand management) [99]. In addition to their effect on the grid underutilization, wind and gas disproportionally contribute to the overall cost ($/MWh) compared to other generating resources.

### 2.5.1 Ontario grid services performance requirements

The type and performance requirements of the IESO mandated ancillary services in Ontario are summarized in Table 3. It is observed that the majority of services have a response time of five to fifteen minutes.

**Table 3 - Ontario required ancillary services and performance (IESO)** [100][101]

| **Type of Service** | **Response time** | | |
|---|---|---|---|
| | *Seconds-5 minute* | *5-15 minutes* | *15 minutes or longer* |
| Power quality and regulation | × | | |
| Reactive Support and Voltage Control | × | × | |
| Black start | | × | × |
| Reliability Must-Run | | × | |
| Spinning and non-spinning reserves | | × | × |

### 2.5.2 Ontario Peak Management Challenges

There is a significant difference between the average and peak demand in Ontario. In 2014, the peak demand was 22,774 MW, while the average demand was only 15,959 MW [102]. The peak demand has a significant impact on the capacity requirements and infrastructure of Ontario's power system and cost. Therefore, one of the main challenges and opportunities for improving the system and reducing cost is by reducing peak demand. This can be achieved through multiple strategies. The current focus has been on demand-side management through conservation [103], but there is a great potential for supply-side optimization, where EES systems and particularly CAES can play a vital role.

### 2.5.3 The Role of Natural Gas

In Ontario, the difference between the base and the peak demands is mainly provided by natural gas power plants. This is also true for the shortcomings of the wind and solar energy sources at any point in time. Conventional natural gas plants are particularly suited for peaking applications due to their operational flexibility and dispatchability as they can be turned on and off and ramped up and down quickly. This also makes them suitable for spinning and operating reserve applications. The downside of gas power plants is their cost of operation and low efficiency [104].

### 2.5.3.1 Operating Cost and Efficiency of Natural Gas Power Plants

The cost of operation of a gas power plant is affected by two factors: the initial cost to build the plant and the ongoing operating cost, which includes the cost of fuel, maintenance, and personnel. Since peaking power plants sit idle for a long time, they need to recuperate their cost during the short period of time when they are generating power to be financially viable. This significantly increases their cost of operation, and therefore the price of a unit of energy produced by a gas power plant during the peaking hours is much higher than the average wholesale price in the energy market. The operating cost of a gas turbine power plant is also directly related to the price of natural gas and therefore subjected to the risks of fluctuating prices. This is now of special importance in Ontario, where the price of natural gas will be increasing as part of the plans by the governments to reduce carbon emissions, which in return increases the cost of energy production at these plants [105,106]. The maintenance cost of gas turbine peaking plants is higher than regular plants operating at baseload due to their high number of ramp up and ramp down cycling, which increases fatigue and increases downtime [106]. Furthermore, since these plants most often operate at partial load, the actual operating efficiency ($\eta_{Generator} = \frac{E_{Output,Electricity}}{E_{Input,Fuel}}$) of these units is much lower than their rated efficiency; resulting in a higher fuel consumption and carbon intensity per generation unit than a similar plant operating at full load.

## 2.6 Ontario Electricity Market

IESO allows for three types of market participation in the Ontario electricity market: 10 minutes spinning, 10 minutes non-spinning, and 30 minutes non-spinning [107]. Looking at Ontario's market structure, it can be understood that from a generator's perspective, the highest opportunity for maximizing income will be in the ability to increase their participation in the 10 minutes spinning reserve market, while reducing their operating cost. From the technology perspective, natural gas turbine peaking power plants currently provide a large share of the service in Ontario due to their ability for fast response and suitable capacity.

### 2.6.1 CAES for Ontario Grid

Adding CAES facilities to the Ontario grid designed to operate for fast responses in place of the conventional natural gas turbines is a good example of how this technology can be successfully implemented. In such a configuration, gas power plants can frequently operate at full load (Rated Power), which has much higher throughput efficiency, and lower cost of operation, while enabling them to participate in the energy market in a different way. This means that many of these plants will provide energy at the market wholesale price instead of the higher spot market price associated with peaking power generation. Also, as the overall capacity requirement is reduced, generation assets can be better utilized, which helps to manage cost more effectively. Another benefit of operating fuel free CAES systems such as adiabatic CAES for providing peaking power, ancillary services, spinning and operating reserve is the lack of GHG emission. While the round trip efficiency of these systems will still be affected from a thermodynamic standpoint, this will only impact their total capacity, and it is not impacted by the cost of burning fuel and lower efficiencies and other environmental regulatory charges such as carbon tax or cap and trade.

## 2.7 Literature Review

In order to understand the CAES system, a study of all its different components is required. CAES is a complex system which operates based on the interconnection of the electrical, mechanical and geomechanical components, which all require their own optimization and understanding of their unique technical and economical challenges. The following section covers the literature related to CAES integration into the electrical grid, as well as thermodynamics, and geomechanical aspects of the CAES system.

## 2.7.1 Electrical Power Grid and EES

There have been multiple studies on CAES technology, and its role and operation in the electrical grid [20,25]. Lund et al. looked at the optimal operation strategies for CAES in the electricity spot markets with fluctuating prices [108,109]. They also analyzed and discussed how to design and use CAES in load leveling applications in the electricity supply market. CAES potential role in the integration of renewable energy sources, particularly wind, has also been the subject of multiple studies [19,110–114]. de Bosio and Verda [25] stated that the majority of CAES analyses in the literature were focused on the economic feasibility and optimal operation of these plants, due to the fact that the economic convenience was the main factor behind introducing CAES plants into existing energy systems.

Hirst et al. [75] provides a comprehensive overview of the electric power ancillary services and their role in the power system. They define ancillary services as those functions performed by the equipment and the people that generate, control, transmit, and distribute electricity to support the basic services of generating capacity, energy supply, and power delivery, which is similar to Federal Energy Regulatory Commission (FERC) description of ancillary services. A new set of revised ancillary services is proposed, which is also like the one suggested by FERC. The set includes scheduling and dispatch, load following, reliability, supplemental operating, energy imbalance, real power loss replacement, and voltage control. The main purpose of the report is to point out the importance of ancillary services, and how they relate to reliability requirements. The authors emphasize the importance of continuously updating and adjusting the reliability requirements, in order to reflect the changes in the electricity system. Issues like the trade-offs between cost and reliability, potential changes to rules based on future requirements, and a better understanding of the current reliability standards and their adequacy are also discussed. Additionally, the paper mentions the cost associated with ancillary services. The authors point out that these services account for about 6-20% of the total generation and transmission cost.

Kassakian, John G., et al. [45] studied the requirements and structure of the grid of the future. They identified enhancing efficiency and reliability, increasing capacity utilization, reducing contingencies through the ability for fast response and increased flexibility in controlling power flows on transmission lines, as the key opportunities for improving the functionality and reliability of the future grid.

### 2.7.2 Wind Integration and System Utilization

A primary focus of this research is the CAES design implications with regards to integration of wind energy and utilization of gas power plants as they have the most significant impact on the cost of energy generation in Ontario grid. The integration of wind energy into the electrical grid has been extensively studied, and many papers have been published on different aspects, issues, implications, challenges, and opportunities of using this type of renewable and intermittent generation source. One area of special interest has been the use of energy storage technologies, including CAES, in support of integration of wind energy into the electrical system.

Swider et al. [19] applied a stochastic electricity market model to estimate the economic value of investments in compressed air energy storage and also impact of significant wind power generation on the operation of the electrical system in which CAES is utilized. The main finding of this study was:

a) Higher flexibility is required in electrical power systems when wind energy generation is increased.

b) Investment in CAES can provide a way to increase flexibility.

c) Investment in CAES is not solely driven by increased integration of wind energy in our system.

The impact of wind on the operation of the power system is due to the poor predictability and controllability compared to the conventional generation sources. As a result, over time, the technical operation of the system and development can be impacted by the integration of wind power due to intermittency [19]. This paper also points out the ability of energy storage to improve the system flexibility by separating and decoupling of intermittent energy generation from the fairly predictable energy demand.

The efficiency and availability of thermal power plants are discussed in [108]. The paper provides an excellent review and background on how the efficiency of thermal power plants is measured, the impact of the operating environment on their performance, and the terminology used in the industry. The concept of heat-rate is introduced as the measure of efficiency, and the term "availability" is described as "the percentage of energy the unit is capable of producing over any given period of time, relative to its design capacity." The operational and maintenance factors affecting the overall performance of power plants are discussed. Their study shows that improving the availability and performance of thermal power plants could globally reduce CO2 emissions and annual cost by about one billion tones and \$80 billion respectively, each year. As such, efficiency is identified as the most critical performance metrics. Moreover, the need for increased flexibility and improved performance, in the context of the power system transition from a centralized and base-load generation to a base-load plus peaking power distributed generation model is mentioned. The paper concludes that reducing planned and unplanned outages increases the dispatch opportunities and energy availability factor and reduces energy losses and cost.

Halamay et al. [49] analyzed the interaction between the variability characteristics of the utility load, when wind, solar, and ocean wave power generations are integrated. It showed that growth in installed wind capacity would result in increased imbalance requirements of the system. The authors used a one-hour persistent method for simulating the wind forecasting method. While this approach helps in simplifying the model, the method's main shortcoming is the delayed forecasting of rapidly increasing or decreasing wind power, which essentially is the ramping requirement. Analyzing the impact of the intermittent renewable energy sources on the power system reserve requirements is the main focus of this paper [49].

### 2.7.3 Thermodynamics Analysis and Modeling of CAES

Thermodynamic analysis, modeling and simulation, and optimization of CAES system has also been well covered in the literature [115–119]. Some studies have specifically looked at the design, thermodynamic modeling, performance, optimization, and operation of Adiabatic CAES (A-CAES) [22,87,120–123].

As one of the very first publications on the thermodynamic modeling of CAES systems, Zaugg, P. [33] presented a volume calculation method for a CAES plant that uses a salt cavern as the air storage reservoir. This paper is very informative and valuable as a first step for studying a CAES system from a thermodynamics perspective. Three different types of reservoir configurations are discussed: Constant pressure, Constant volume, and Constant volume with constant output pressure. It was suggested that among the three different reservoir configurations, constant pressure reservoir would require the smallest size for the same amount of energy stored. However, keeping the pressure constant will result in a higher cost due to the added complexity. It is also argued that the temperature of the compressed air (outflow from compression unit) should be reduced to the existing cavern temperature before flowing in, in order to reduce heat loss to the cavern surroundings. The difficulty with this approach is that the cavern temperature varies based on the fluctuations in cavern's pressure.

Kushnir et al. [32] analyzed the behavior of temperature and pressure inside an adiabatic compressed air storage cavern. The simplified real gas model used in the study is similar to the ideal gas model. The only difference with an ideal gas model is the use of the compressibility factor Z. They concluded that a simplified real gas model could give accurate enough data as the variation between the simplified model and the real one is negligible. In contrast, the ideal gas results are similar or close to the real gas (with a high degree of accuracy), only when the ratio of mass-flow-rate to the mass inside the cavern is smaller than 0.3, and not for all the other conditions. The findings of the paper are good guidelines for designing CAES systems; however, the limitation of the study should be considered. Most significantly, the adiabatic cavern assumption, which unlike a real underground cavern, theoretically has no heat loss, results in higher rate of pressure increase in the cavern and will be a different rate, compared to an isothermal or polytropic cavern.

Kushnir et al. [26] presented a model for heat transfer in cavern for a conventional (non-adiabatic) system. The results were compared to the real data measured at the Huntorf plant, which showed a small difference between the measured temperature variation and the one from the simulation. This was contributed to the flaws in the real cavern (bulges and waves) compared to the perfectly cylindrical cavern considered in the simulation. Furthermore, the authors state that the Huntorf plant has an oversized cavern since a smaller heat transfer rate was predicted during the planning and design process.

Mandhapati et al. [27] developed a heat transfer model of a CAES system utilizing the operational data from the existing Huntorf plant in Germany. The convection coefficient was calculated using the pressure data combined with some assumptions by the authors. The result was then used to simulate the temperature variation inside the cavern. Only convective heat transfer calculation is considered in the model. This assumption is flawed, as there is going to be some conduction heat transfer through the rocks, which is ignored. To calculate the convection factor, an exponential equation with two unknowns and the exponent of the Dittus-Boelter convection equation was created. The two unknowns were solved by calibrating their possible values to match the available data from the Huntorf plant. This approach to solving the equations, limits the model almost exclusively for the Huntorf plant, as the estimation can vary depending on the plant and operation. When compared, there seems to be a close match between the measured pressure of Huntorf and the calculated value from the model. However, this is inconclusive, as the authors have only included graphs, and did not publish the values (numbers). The model is compared with both an adiabatic and an Isothermal CAES model. The reliability of the isothermal and adiabatic model is questionable, as the temperatures and pressures predicted by them have the same trend as the measured data, but their results are out of a confident range.

Hartmann et al. [28] compared the efficiency of four different fuel free CAES configurations, all of which include thermal energy storage (TES) that is set to a fixed temperature, and they all use a single turbine. The main difference between the configurations is the number of compression stages. It is assumed that in all four configurations, the temperature of the thermal storage unit will increases by 20 K after heat transfer is completed and that the storage cavern is adiabatic. The main finding of this study is that more compression stages result in higher efficiency of the system, due to the fact that it will be closer to an isothermal process. However, increased efficiency is minimal (less than 3% from 2 to 3 stages), and might not justify the additional cost of adding a third stage. Finally, no explanation is given for not using a thermal storage unit with higher operating temperature, which could have removed and stored the heat in the compression stages.

Guo et al. [124] presented a modification to an Adiabatic CAES (A-CAES) system by the addition of an ejector after the regulator valve, located before the turbine, and analyzed its effect on the system efficiency. The first model only has a regulator before the turbines, while the second model considers a smaller regulator with an ejector, which decreases the pressure of the compressed air to a lesser extent, compared to the base regulator. Due to its design, the ejector acts as a pressure reducer, but with better efficiency (reduced energy loss). The results showed that the addition of the ejector could improve the overall system efficiency by about 4%. However, the study lacks clarity on the source of some of the assumptions. For example, the polytropic indexes used in relation to both the compressors and the turbines were not cited. Furthermore, the operation of the thermal storage of the model is too idealistic. Since the turbine's performance strongly depends on the air temperature, ignoring how the thermal energy storage actually operates (assuming ideal system) affects the validity of the results. Overall this paper makes a good case for the use of an ejector a CAES system, but better and more detailed models are needed to test the actual benefit of this modification.

Grazzini et al. [30] conducted an exergy analysis of an A-CAES system, including testing different configurations of parallel and series compression and expansion trains, and documenting the effect of selected pressure ratio could have on the stored energy over air container density. The density is used to calculate the cavern/container's volume and therefore the cost. The result showed that compression ratios of 150 or greater provide better energy over volume ratios. Next, the maximum temperature of the cooling fluid and time required to fill and empty the container were calculated. It should be noted that the heat exchangers' efficiencies were assumed, which can impact the result of the exergy analysis. The study stated that an exergy efficiency of 67% was achieved, which is similar to battery systems. However, the authors did not consider any potential losses in the thermal storage unit, as well as pressure losses in the heat exchangers, which affect the exergy efficiency. In summary, this study is very useful in understanding A-CAES system from an exergy analysis viewpoint.

Xia et al. [31] created a simple and fast solution for calculating the pressure and temperature variations in the Huntorf salt cavern. The basis for their model is the Kushnir energy balance differential equation. The model is then modified by changing some transient calculations to assumed constant conditions. These include the values of average mass density, constant mass flow rates, and ideal gas. The comparison showed that the temperature results of the test data were in line with the Kushnir solution; however, this does not hold true for pressure results. The explanation given for this disparity is the fact that in the Kushnir model it is assumed that the injected air mass is equal to the extracted air mass, however, in reality, this ratio is different. It is stated that in the Huntorf test, where the only published test data exists, the amount of withdrawn air mass was much larger than the injected air mass. The authors specified that their model could only be used in caverns with perfectly conducting rocks, and when the ratio of injected to original air mass was small.

Gonzalez-Gonzalez and Kakodkar created a transient thermodynamic model of CAES, focusing on the turbomachinery [125,126]. The result of their simulation showed that an A-CAES plant with a TES could achieve a round trip efficiency of over 70%. Start-up and part load behavior of turbomachinery were accurately captured, in addition to the time-dependent storage losses. The flexibility of the model allows for simulation other turbomachines as long as their associated operation or performance map is provided.

### 2.7.4 Cavern and Geomechanics

While different underground caverns have been proposed [83,127], Porous Rock, Salt, and Hard Rock have been the main geological formation/type under consideration [52]. Among these three, salt caverns seem to be the most promising geological formations for CAES applications. Salt caverns storage hold the advantages related to higher deliverability, lower cushion (or base) gas requirements, less development cost, faster to initiate the gas flow, and quicker to refill [128]. Underground salt deposits are categorized into two types: bedded salts and salt domes. In both Canada and the United States, there are several areas with bedded salts formations. Both existing CAES facilities utilize salt domes for the storage medium. There are however some considerations that should be taken into account with regard to salt caverns. The salt layers in salt bedded formations often contain significant impurities which can impact the overall stability and geomechanical behavior. Also, the operating pressures of salt caverns are limited [83]. Tensile fractures can be caused by high pressure that can reduce the stability of the cavern. The rate of the depressurization of the cavern is also crucial as it can result in roof instability, cavern collapse, or excessive closures. In low cavern pressures, the creep response of salt could accelerate cavern closure if there is a lack of hydrostatic state of stress [128]. In designing caverns for CAES system, the impact of the conversion process against the geomechanical properties of the cavern such as salt inelastic deformation, creep properties, in/situ stresses, moister content, and fabric anisotropy should be an essential part of the design modeling and risk studies.  Temperature and stress are the primary drives of the rate of salt deformation. Han et al. [128] stated that the lower limit of the cavern pressure is the most critical parameter for gas subtraction. They also concluded that hydrostatic pressure results in the most stable conditions of the cavern and that lowering the cavern pressure can cause extensive damages to the cavern. However, the cavern appears stronger when their sizes became smaller. Therefore, it appears that from cavern stability perspective, a smaller cavern with a higher minimum operating pressure limit would be preferential.

# Chapter 3

# Thermodynamic System Model

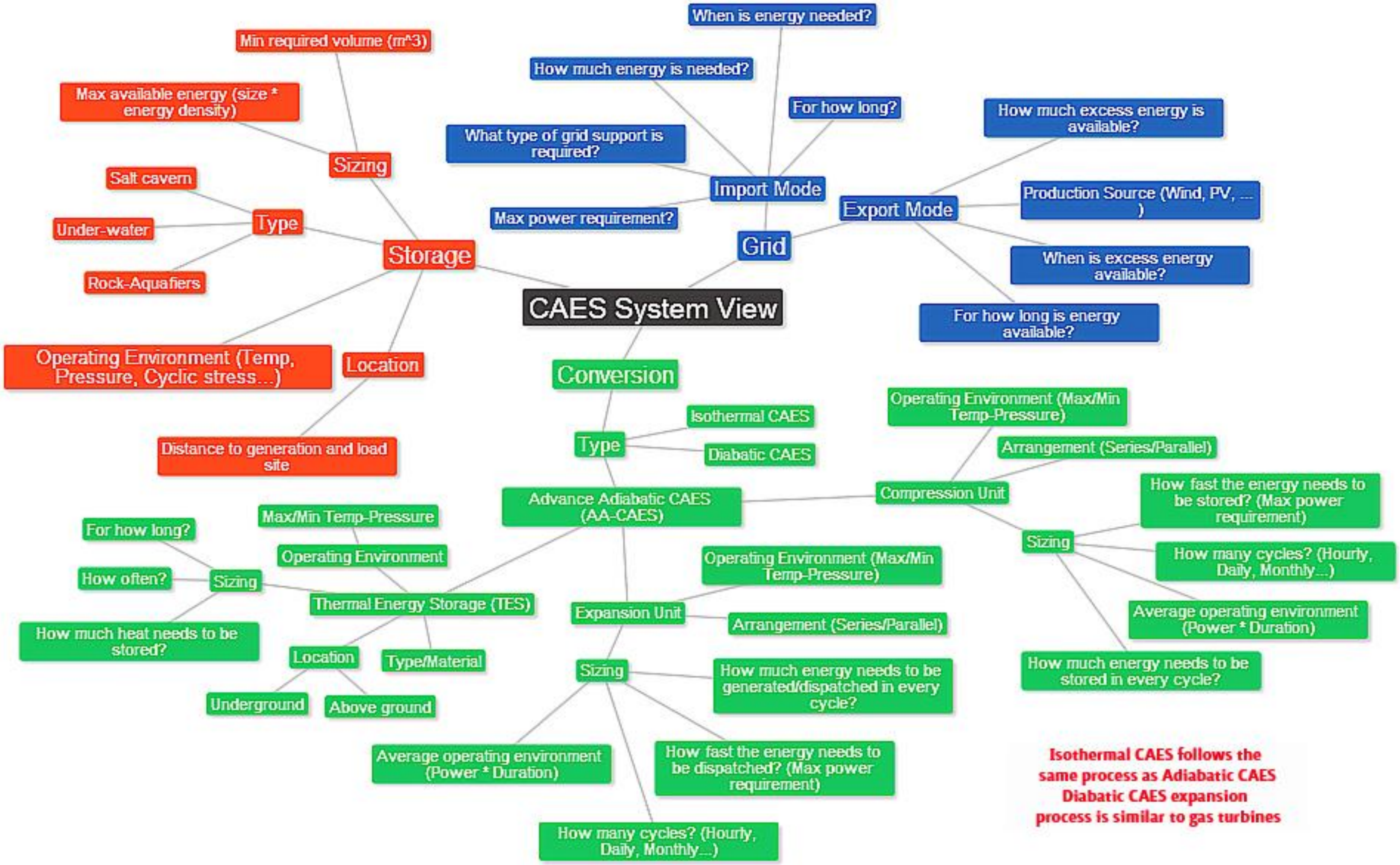
This chapter describes the development of conceptual, operational, and thermodynamics model for CAES system. Following that, the governing equations are shown for component, and the interactions are explained. Finally, the initial assumptions and boundaries applied to the system are defined.

## 3.1 CAES System Modeling

"System modeling is the process of developing abstract models of a system, with each model presenting a different view or perspective of that system" [129]. System modeling provides an overview of the overall system, its structure, components, interactions, and behavior. Therefore, in order to evaluate CAES system operation in the electrical grid and understand its functionality, system-level modeling of CAES is discussed in this chapter. First conceptual model of CAES system is introduced. Then, an operating model followed by a simple thermodynamic model of an A-CAES system are presented.

### 3.1.1 Conceptual Model

The conceptual model presented in this section provides a high-level view of CAES systems and the general elements/components that form the system. External and internal relationships and common relationships are identified. In addition, potential quantitative performance factors are recognized. Figure 7 illustrates the whole CAES system model. It was developed at the beginning of this work to understand how full CAES system evolves based on a summation of all the papers reviewed. It is a novel approach to provide a complete system view by incorporating storage, electrical grid, and conversion aspects of CAES into a single model. Figure 8 displays the conceptual/physical model of an A-CAES system, which is created based on the literature reviewed in chapter 2, and shows the major components and considerations of this type of system. This is done to breakdown the complexity of the system by providing different levels of abstraction.



Isothermal CAES follows the same process as Adiabatic CAES
Diabatic CAES expansion process is similar to gas turbines

**Figure 7 - CAES System overview**

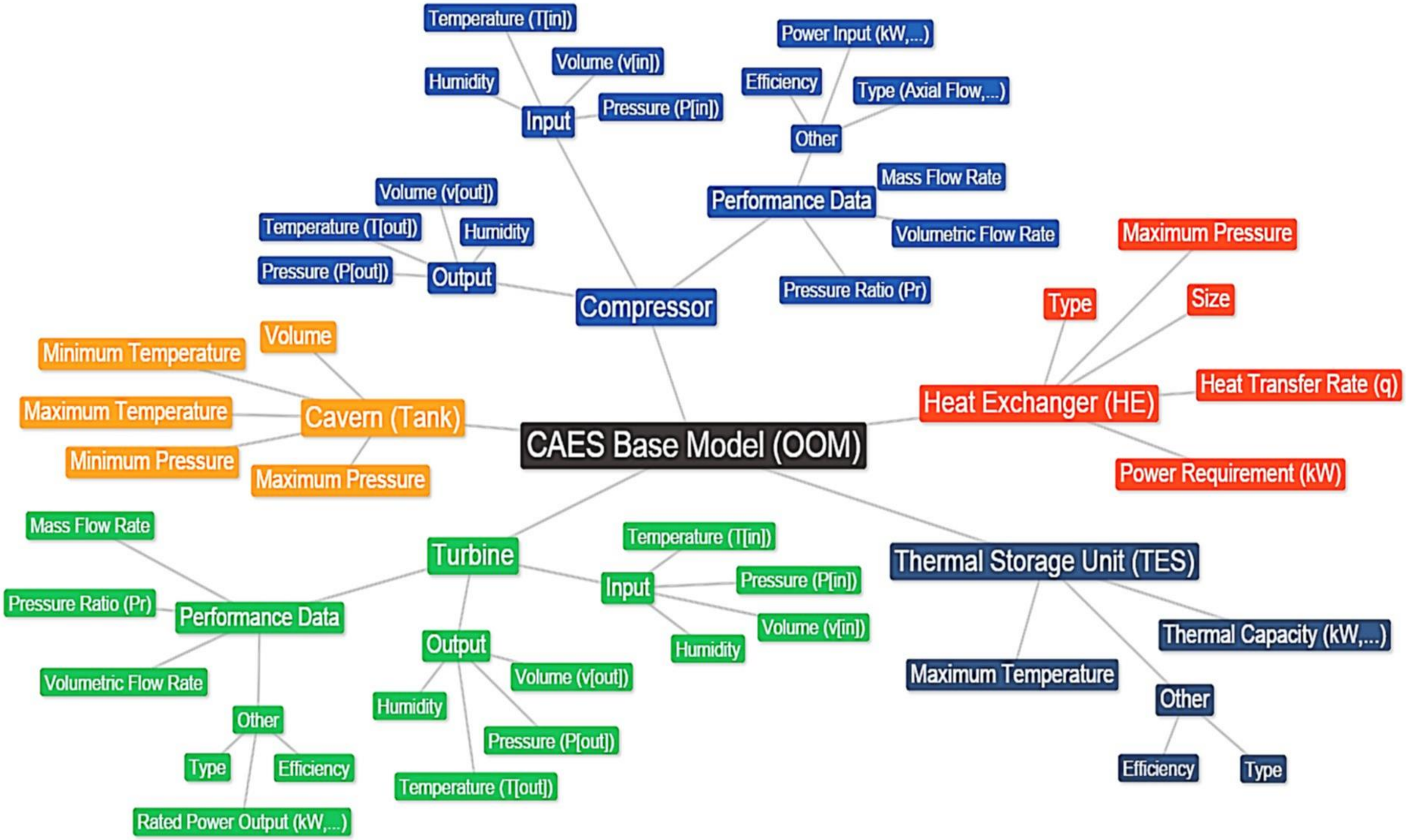


**Figure 8 - Object-based model of A-CAES system**

## 3.1.2 Operational Model

The A-CAES operating model is developed based on the conceptual model demonstrated in the previous section (Figure 8), to help understand system behavior, processes, and control mechanism. Figure 9 illustrates the flowchart of A-CAES operational model.

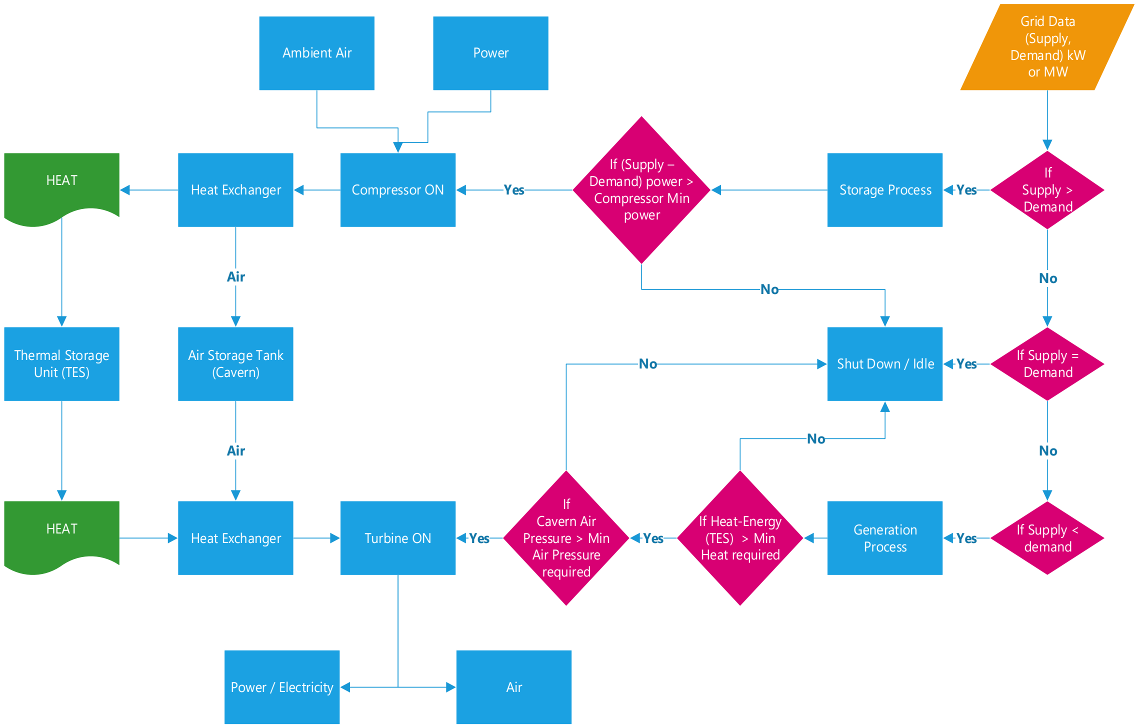


**Figure 9 - Flowchart of A-CAES system thermodynamics model**

## 3.1.3 Thermodynamic Model

In this section, a thermodynamic analysis of A-CAES operation is presented to demonstrate how system operating conditions affect the design parameters. For this purpose, commonly used mathematical models for each component in an A-CAES system is reviewed first. Afterward, several operation scenarios are assumed, and the impacts of each scenario in terms of system capacity and dynamic behavior are discussed. Figure 10 represents the thermodynamic model of an A-CAES system.

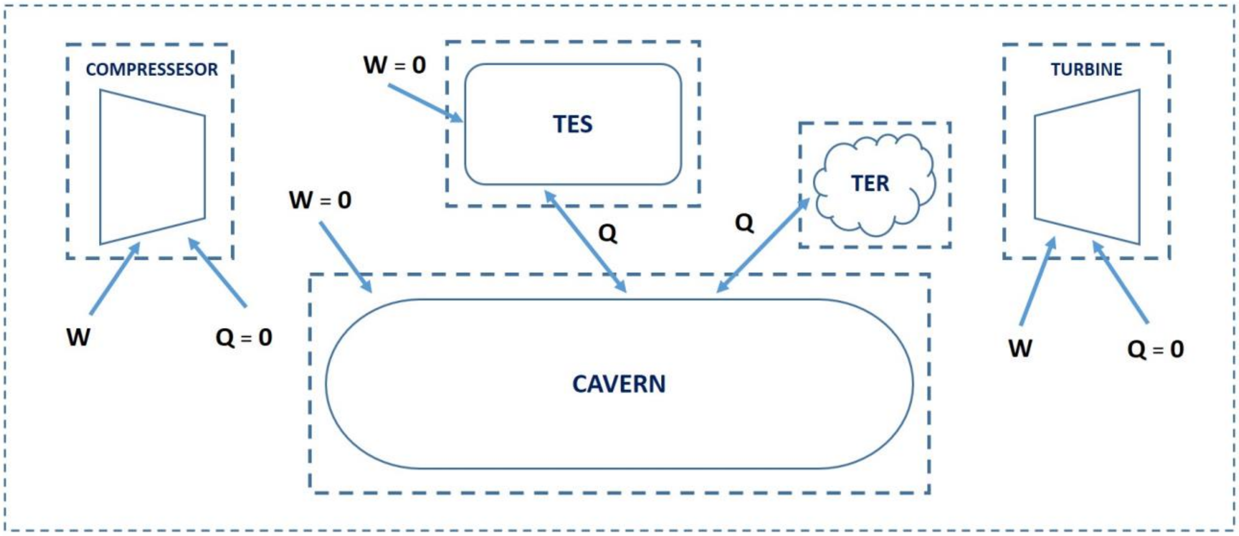


**Figure 10 - Adiabatic CAES thermodynamics system**

### 3.1.3.1 Compressor

The air is assumed to be compressed through an isentropic path in the compressor from the atmospheric pressure at the inlet. The rate of flow of the air mass into the reservoir in a single stage compressor is given by [130–132]:

$$\dot{m}_{air,in} = \frac{Power_{Comp}}{C_p T_{air,Comp,in}[\left(\frac{P_{Comp,out}}{P_{Comp,in}}\right)^{\frac{\gamma-1}{\gamma}} - 1]} \qquad \textbf{Eq. 3-1}$$

$P_{Comp,out}$ is the compressor outlet pressure and $P_{Comp,in}$ is the inlet pressure (ambient pressure), $\gamma$ is the heat capacity ratio ($\gamma = \frac{C_p}{C_v}$), and $T_{air,Comp,in}$ is the inlet air temperature (K). $\frac{P_{Comp,out}}{P_{Comp,in}}$ is the compressor pressure ratio, which is a design parameter in the sizing process. The outlet temperature is calculated using the isentropic process equation:

$$\frac{T_{air,Comp,out}}{T_{air,Comp,in}} = (\frac{P_{Comp,out}}{P_{Comp,in}})^{(1-\frac{1}{\gamma})}$$ **Eq. 3-2**

$T_{air,Comp,out}$ is the temperature of the air entering the cavern.

### 3.1.3.2 Cavern charge and discharge:

The charging process of the cavern is modeled by taking the cavern content as an open system and applying the first law of thermodynamics. It is assumed that the airflow is uniform, the process is adiabatic, changes in kinetic and potential energies are negligible, and no shaft work crosses the boundaries of the system [26,31]. Following these assumptions, the first law is simplified as:

$$m_{final}U_2 - m_{initial}U_1 = m_{in}H_{in}$$ **Eq. 3-3**

$U_2$ and $U_1$ are the final and initial internal energy of the cavern content. $H_{in}$ is enthalpy of the air flowing into the cavern. The integral form of the transient mass balance on the cavern is simply equal to the air mass entering the cavern:

$$\Delta m_{Cav} = m_{in}$$ **Eq. 3-4**

Therefore, we will be able to determine the internal energy of the air in the cavern in the final state from the 1st Law. Assuming air as an ideal gas, and an initial temperature for the cavern content, the final temperature of the air in the cavern over each time step can be calculated as:

$$T_{final} = T_{initial} + \frac{U_2 - U_1}{C_v}$$ **Eq. 3-5**

$U_1$ is readily read from thermodynamics tables based on the assumed initial temperature and pressure. In addition, it is important to take into account the required (and available) time for charging the cavern. Assuming a constant mass flow rate from the compressor to the cavern, the time required to displace $\Delta m = |m_{total} - m_{initial}|$ amount of air is simply equal to:

$$t_{chg} = \frac{\Delta m\ (added\ to\ the\ system)}{\dot{m}_{in}}$$ **Eq. 3-6**

The discharge process is modeled in a similar way, and the time required for discharging is found as:

$$t_{dischg} = \frac{\Delta m\ (removed\ from\ the\ system)}{\dot{m}_{out}}$$ **Eq. 3-7**

At a given cavern volume $(V, m^3)$ , temperature $(T, K)$ and pressure $(P, MPa)$, we can find the total available energy $(U, kJ)$ using the following equation:

$$U_{Cav} = m_{Cav}\, C_v T_{Cav}$$ **Eq. 3-8**

For an ideal gas, $C_v$ $(\frac{kJ}{kgK})$ is only a function of temperature. Cavern air mass $(m, kg)$ is found using the ideal gas relation:

$$m_{Cav} = \frac{P_{Cav} V_{Cav}}{R_{air} T_{Cav}}$$ **Eq. 3-9**

In electrical applications, energy is usually expressed in kilowatt-hour:

$$1\ kJ = 2.77778\ \times 10^{-4}\ kWh$$

### 3.1.3.3 Turbine flow and output power:

For this analysis, we use the Ontario grid data to demonstrate how to determine the amount of required electric power at each time step (in each discharge event). This amount of power must be generated by the CAES system. Assuming that a total amount of $Power_{dischg}$ is to be generated by the CAES, a proper turbine rating can be selected. The air mass flow rate through the turbine is calculated using the following equation [109,133,134]:

$$\dot{m}_{air,Turb,in} = \frac{Power_{Turb}}{C_{p1} T_{air,Turb,in}[\left(\frac{P_{Turb,out}}{P_{Turb,in}}\right)^{\frac{\gamma-1}{\gamma}} - 1]} \quad \textbf{Eq. 3-10}$$

### 3.1.3.4 Thermal storage (TES):

During the compression process, a high amount of heat is generated which results in increasing the air temperature. While some pressure vessels are capable of storing heat and pressure at the same time, underground salt caverns are very sensitive to temperature increase and decrease. The optimal operating temperature range of salt caverns is between 20-40° C [135,136]. As such, the heat of compression needs to be removed from the pressurized air before entering the cavern. Since the process is adiabatic, the heat needs to be stored in a thermal energy storage (TES) unit, and later used to reheat the air before entering the turbine for expansion. The TES unit generally consists of the following heat exchanging loops: 1- Hot loop, which removes heat from the hot air prior to entering cavern on the compression side, and adds it to the heat storage container, that is filled with a heat retaining material (such as a fluid, solid, or phase-change material). 2- Cold loop, which is used to reheat the air, exiting cavern on the expansion side [117,137,138]. Design factors in sizing TES include thermal characteristics of heat retaining material and the heat transfer fluid, the maximum required heat addition or removal rates, as well as the maximum total heat added or removed [139–142]. The energy balance in a TES unit can be described as follows:

$$mC_p \frac{dT_{TES}}{dt} = \dot{q}_{chg} - \dot{q}_{dischg} - \dot{q}_{loss} \quad \textbf{Eq. 3-11}$$

$\dot{q}_{chg}$ is the rate of heat removal from the hot air, resulting in charging the TES. $\dot{q}_{dischg}$ is the rate of heat addition to the air prior to expansion, which translates to discharging the TES unit.

$\dot{q}_{loss}$ refers to the rate of total heat loss from the TES unit to the environment. The speed by which the heat needs to be added and removed from the outlet and inlet airflow determines the required heat transfer rate of the thermal storage material. During the charge process, the rate of heat addition to the TES unit over two consecutive time steps $(i-1, i)$ is equal to change in the cavern enthalpy:

$$\dot{Q}_{chg} = m_{Cav,i+1}.h_{Cav,i+1} - m_{Cav,i}.h_{Cav,i} \qquad \textbf{Eq. 3-12}$$

Ideally, the TES unit should be designed to capture the heat at a rate equal to the maximum rate found in Eq.3-12. Also, the rate at which heat must be discharged from the TES and added to the air before entering the turbine is calculated based on the difference between the air flow temperature and the required temperature at the turbine inlet:

$$\dot{Q}_{dischg} = \dot{m}_{dischg}.C_p(T_{Turb,inlet} - T_{Cav,i}) \qquad \textbf{Eq. 3-13}$$

Finally, the overall heat capacity of the TES is equal to the maximum of total heat flow to/from the TES during charge/discharge process:

$$TES_{capacity} = \max(\int \dot{Q}_{dischg}\,, \int \dot{Q}_{chg}) \qquad \textbf{Eq. 3-14}$$

The operating parameters of the compressor and turbine needed to solve Eq.3-3 and Eq. 3-4 are summarized in Table 4.

**Table 4 - Assumed compressor and turbine operating parameters**

| | **Compressor** | **Turbine** |
|---|---|---|
| **Pressure Ratio** | 50 | 40 |
| **Inlet pressure** | $P_{amb}$ (~ 1 atm) | calculated assuming an isentropic expansion in the turbine |
| **Outlet pressure** | 50 atm | Ambient pressure |
| **Inlet temperature** | $T_{amb}$ $(\sim 25°C)$ | minimum ($T_{amb}$, 3°C) |
| **Outlet temperature** | calculated assuming an isentropic compression | calculated assuming an isentropic expansion in the turbine |

## 3.1.4 Limitations of the Model

The thermodynamic model presented in this thesis is solely developed based on the first law of thermodynamics, through which system characteristics such as the energy content and required heat and mass flow rates can be identified. Within the scope of this research, this is sufficient; however, it is important to point out that this model has certain limitations. The first law does not account for irreversibility and makes no reference to the best possible performance, therefore, it may not provide the most accurate measure of performance of the CAES system. For a thorough and complete understanding of CAES system operational efficiency, a second-law efficiency study should be conducted and the ratio of the actual thermal efficiency to the maximum possible (reversible) thermal efficiency under the same conditions be investigated. An exergy analysis would provide a more reliable metric in comparing operating scenarios, as it identifies the maximum amount of available work that can be extracted from the system. To identify the opportunities to improve the efficiency associated with each process, this type of analysis can also be conducted for all of the sub-processes of the CAES system (e.g. compression, heat exchange, etc).

Another important issue to point out is that for modeling and simulation, it was assumed that the operation was steady state. In reality, there are some delays in responding to ramp-up or ramp-down command signals due to the system inertia. The system coverage rate, efficiency, and potential value to grid is affected by these delays. Enhancing the model to account for the transient behavior of the CAES system components such as turbine and compressor will improve the fidelity of the current model.

## 3.2 Summary

A steady-state thermodynamic model is developed, and the governing equations are introduced. The initial conditions are set based on data extracted from existing literature.

# Chapter 4

# Methodology

This chapter contains an overview of the methods used in this study and the data collection and processing steps. User-Centered Design (UCD), Object-Oriented Analysis and Design (OOAD), and Data-Driven Analysis Methodology (DDAM) concepts are introduced and discussed. Next, the data collection process is explained. Descriptive statistical analysis of the collected data concludes this chapter.

## 4.1 Overview

As previously discussed in chapter one, the main objective of this thesis is to identify potential opportunities to utilize the CAES Electrical Energy Storage (EES) system to provide high-value grid services to the electrical grid. The feasibility of CAES projects can then be improved, due to increased (enhanced) usability and effectiveness. In order to accomplish this, a new holistic approach to designing CAES systems is proposed. The focus of this approach is to first understand the whole system by analyzing the external (with the environment) and internal interactions within the system and all the sub-systems and then creating a process to identify the optimal configuration of system components to achieve a specific objective and performance metric [143]. Reduced component sizing, enhanced performance, and increasing the number of provided services within the electrical power system, are examples of these objectives. This type of analytical and systematic procedure is closely aligned with the academic domain of system engineering [144,145], as such, a combination of system analysis and design methodologies and techniques are used in this study and form the basis for the new proposed approach which is introduced in later chapters.

The following methodologies and techniques are employed in this study:

- User-Centered Design (UCD)
- Object-Oriented Analysis and Design (OOAD)
- Data-Driven Analysis Methodology (DDAM)

## 4.2 User-Centered Design (UCD)

The core concept of UCD methodology is the focus on understanding user requirements and then designing the system functionalities around those requirements [37]. The benefit of UCD approach includes early detection of system boundaries, ability to create a uniform process for analysis and assessment, and improved design adaptability [38–42], which were discussed in more details in chapter1. UCD approach was therefore used for the overall design of the system. The approach allows the system designers to understand what kind of features/configurations are most needed and brings more benefit to the user, and therefore what kind of technical capabilities are required.

In the context of this study, CAES system is meant to be operated by and integrated within the grid; therefore, from a UCD perspective, the user is the electrical grid. Subsequently, understanding of electrical grid requirement is essential for application of UCD method to the design of CAES systems.

### 4.2.1 UCD Principals

The UCD methodology is based on the following principals:

a) Focus on end-user tasks early on

b) Gathering user requirements and data in a structured and systematic manner

c) Testing, Measurement, and validation of product usage through empirical data (This can be achieved through simulation)

d) Product designed, modified and tested repeatedly

The first three parts are covered in this thesis. The last step is concerned with early testing of conceptual models and design ideas, which helps speed up product development by allowing for the complete overhaul and rethinking of the design before progressing too far in the process [37,144]. However, a complete design of a CAES system is outside of the scope of this study, and thus, the last step is not included in this thesis.

### 4.2.2 UCD Project Phases:

The UCD principals mentioned above can be streamlined into four general phases in any design project [39,146,147]:

1) Understand and specify the context of use

2) Specify the user and organizational requirements

3) Produce design solutions

4) Evaluate designs

Adopting a UCD approach will allow the creation of a platform to collect, assess, and integrate inputs from different stakeholders during the design process with measurable impact factors

Example of these factors are:

a) Cost vs. Functionality

b) Performance vs. Coverage

c) Technical difficulty vs. Performance (Capability)

The design approach encompasses the whole system instead of individual parts. Trade-offs and improvements can be measured. Furthermore, any potential problem affecting feasibility can be detected earlier in the process. Additionally, usability of the system is improved.

### 4.2.3 Usability

The goal of employing UCD is increased usability of the designed product or system [148]. International Organization for Standardization (ISO) defines usability as the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use."[149]

The main objectives of usability are [149,150]:

- Effectiveness: measured by the level of accuracy and completeness with which the users achieve specified goals
- Efficiency: measured by how efficient resources were used to achieve a specific level of effectiveness

Improving efficiency and effectiveness of CAES system is essential for larger adaptation of the technology due to increased feasibility.

## 4.3 Object-Oriented Analysis and Design (OOAD)

The object-oriented (OO) approach, also called Object-orientation, is a structuring concept that is used to reduce the difficulty of describing complex large systems [151,152]. This is achieved by employing two primary methods, abstraction and encapsulation [151,153]. Abstraction reduces complexity by ignoring the irrelevant information and only showing the essentials details of each part of the system. The process of encapsulation allows the related properties (data) and behavior (functions) of each component to be combined into a single entity. Encapsulation is the foundation of OO system development strategy [154]. In an object-based model of a physical system, the system's components which interact with each other, are defined as objects.

OOAD is a system analysis and design method that is used in conjunction with object-based models [151,152,155].

The OOAD method is divided into two separate processes, OOA and OOD. Object-oriented Analysis (OOA) is a repetitive process that is concerned with modeling the functional requirements of the system throughout the analysis phase of the development. As discussed above, objects that form the system encapsulate both the properties and behavior of that component. As such, instead of a multi-stage analysis process, the task can be performed in a single stage. It is important to point out that any potential requirements for system implementations are not considered in the OOA process. The general steps in the OOA phase are as follows[152,155–157]:

1) Identify and define the objects
2) Organize the objects
3) Describe the interaction between objects
4) Define the external and internal behavior of the objects

The object-oriented design (OOD) process is the other half of OOAD. The focus of OOD is finding solutions to implement the required functions that were identified and modeled in the analysis stage [151,152,156]. Therefore, unlike OOA, any constraints to implementation are considered in the OOD process.

### 4.3.1 Benefits of Object-Oriented Analysis and Design Approach

The primary advantage of employing an OOAD approach is that the complexity of the system can be broken down into completely independent sub-systems that are linked through interactions. This is very beneficial, as different parts of the system can be developed separately and then integrated into desired configuration. Additionally, the risk of spreading potential design errors from any sub-system to the rest of the system is significantly reduced.

#### 4.3.1.1 Object-based Thermodynamics Model

The development of the thermodynamic model was done based on the principles of OOAD described in the above sections. The main components of the system are categorized as objects, and the common relationship between them are identified. The whole system model is then developed by connecting the sub-model related to each object/component. The advantage of this Object-oriented modeling (OOM) [152,155] approach, is that sub-models for each component can be developed independently, potentially with different levels of fidelity, and then integrated based on common elements that link them. Also, the impact of the design decisions made in the requirement gathering and planning stages can be identified before the actual detailed design, and implementation of the CAES system has started. By compartmentalizing different parts of the model, any design error can be corrected without affecting the rest of the model. The model's fidelity can also be improved in stages and separately as more data becomes available, and the design progresses. Figure 8 in chapter 3 is effectively an object-based model for an A-CAES system.

## 4.4 Data-Driven Analysis Method (DDAM)

A Data-driven Analysis Method (DDAM) is used to gain an in-depth understanding of the challenges and requirements of the grid and determine the factors and degree to which they affect the design of the CAES system. This type of approach is common in system design [158,159] and more recently in design and analysis of energy systems [160]. Furthermore, the use of quantitative requirement analysis is a well-established approach in design, sizing, and optimization of hybrid vehicles [161–163], which conceptually is very similar to CAES systems. Based on EES characteristics discussed previously, CAES operational design targets are set as cycling, capacity, and response time. Steps involved in this methodology are as follows:

1. Data collection and processing
2. Performance metric derivation
3. Statistical Analysis
4. Data visualization and pattern recognition
5. Thermodynamic Simulation and analysis

Steps 1 to 3 are covered in the rest of this chapter, whiles steps 4 and 5 are covered in chapter 6.

### 4.4.1 Data Collection and Processing

IESO, which is the independent electricity system and market operator in Ontario, is selected as the potential operating environment for a hypothetical A-CAES system. Ontario power grid data was collected and analyzed to identify significant operating points, and design parameters of the assumed A-CAES system.

Two sets of data were collected for this analysis. The first set (Data-1) consists of hourly grid operating data collected over a one-week period in October 2015, which was used to evaluate the design methodology introduced later in this thesis, and test the thermodynamic model. The processing and analysis steps applied to sample hourly data is explained in details in Chapter 5.

For the second set (Data-2), high resolution (5-min increments) Ontario grid operational data (demand, supply) was collected from the IESO over the period of one year (Jan 2015 – Dec 2015). The generation output and available capacity data of grid-tied nuclear, wind, gas, hydro, biomass power plants were also collected over the same period. Using Python/Excel, the raw data files were concatenated, organized, and cleaned to form a data matrix of 105120 operating points, each with initially 5 attributes: time stamp (minute/hour), supply (MW), actual demand (MW), projected demand (MW) and constraints (MW). In this context, constraints refer to the capacity output limitations set by the generator or the system operator. This could be due to the lack of available capacity on the transmission line or scheduled maintenance. The data was then divided into two subsets according to their functions as a charge or discharge event. These events are defined based on the difference between the actual and projected power demands, where a positive difference translates into a charge event, and a negative difference implies a discharge opportunity.

Furthermore, the meteorological information (temperature, pressure) for the city of Sarnia in southwestern Ontario was also gathered during the same period. Southwestern Ontario is selected because it is the most technically suitable area for a hypothetical underground A-CAES facility [164,165], as well as the fact that the area is suffering from limited system flexibility. The technical factors that were considered include:

- Existing salt caverns (Windsor, Sarnia, Goderich)
- Close proximity to the major transmission corridor of Windsor-Toronto
- Concentration of variable generation capacity in the surrounding area, including the 270 MW South Kent wind farm south [166]

Several performance metrics were then derived from the raw dataset in order to analyze the operational requirements of the grid. These metrics are explained in detail in the following section.

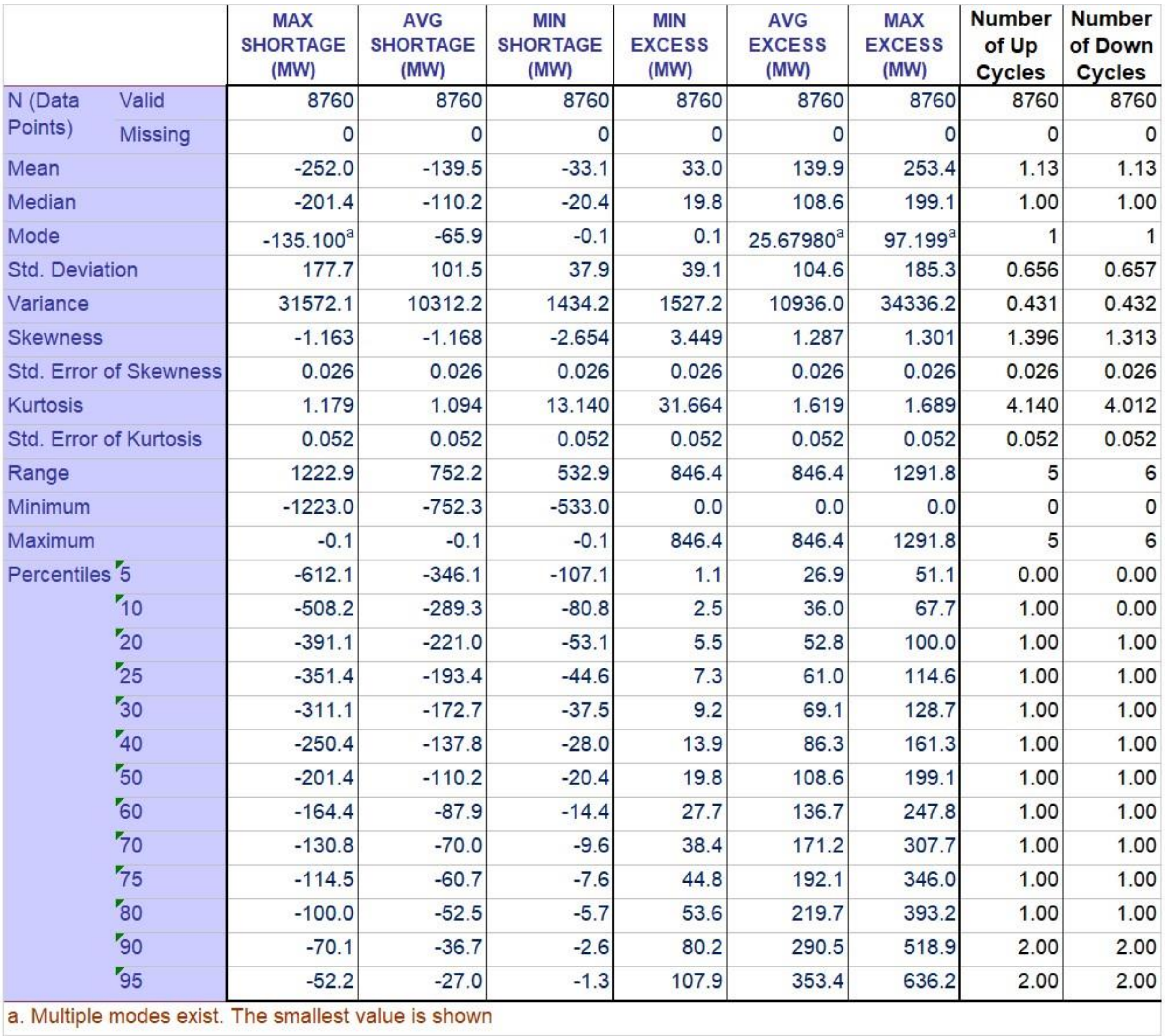
### 4.4.2 Performance Metrics Derivation

The collected data was used to compute the number of hourly, daily, and annual up and down cycles. Additionally, the duration (timescale) of each cycle was calculated. The duration of cycle is defined as the period in which the power system continuously required either ramp-up (reacting to a shortage) or ramp-down (reacting to an excess) services. The type and power capacity (MW) of needed service are determined from the difference between the projected demand (forecasted) and the actual demand at each time-interval (5 min). If the actual demand was higher than the forecasted demand, the grid experiences shortage, requiring ramp-up services in order to avoid blackouts. Conversely, if the actual demand was lower than projected demand, ramp-down services are needed to absorb the excess capacity that was scheduled to come online, so the safety and reliability of the system can be maintained. Collectively this data represents the drive cycle of the electrical grid. Appendices B includes a sample of data and the calculation process.

## 4.5 Statistical Analysis

In this section, descriptive statistical analysis is performed using IBM SPSS software to gain insight from the collected and calculated data. Particularly, exploratory data analysis (EDA) approach [167] is used to identify the likelihood, probability, potential trends and patterns, and overall importance of each of the factors that were previously discussed. Exploratory data analysis (EDA) is best described by J. T. Behrens, which defines it as “a well-established statistical tradition that provides conceptual and computational tools for discovering patterns to foster hypothesis development and refinement”[168]. The results are shown in Table 5 through Table 8:

**Table 5 - Forecasted capacity error and cycle up/down statistics (From Data-2)**



| | | MAX SHORTAGE (MW) | AVG SHORTAGE (MW) | MIN SHORTAGE (MW) | MIN EXCESS (MW) | AVG EXCESS (MW) | MAX EXCESS (MW) | Number of Up Cycles | Number of Down Cycles |
|---|---|---|---|---|---|---|---|---|---|
| N (Data Points) | Valid | 8760 | 8760 | 8760 | 8760 | 8760 | 8760 | 8760 | 8760 |
| | Missing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mean | | -252.0 | -139.5 | -33.1 | 33.0 | 139.9 | 253.4 | 1.13 | 1.13 |
| Median | | -201.4 | -110.2 | -20.4 | 19.8 | 108.6 | 199.1 | 1.00 | 1.00 |
| Mode | | -135.100[a] | -65.9 | -0.1 | 0.1 | 25.67980[a] | 97.199[a] | 1 | 1 |
| Std. Deviation | | 177.7 | 101.5 | 37.9 | 39.1 | 104.6 | 185.3 | 0.656 | 0.657 |
| Variance | | 31572.1 | 10312.2 | 1434.2 | 1527.2 | 10936.0 | 34336.2 | 0.431 | 0.432 |
| Skewness | | -1.163 | -1.168 | -2.654 | 3.449 | 1.287 | 1.301 | 1.396 | 1.313 |
| Std. Error of Skewness | | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 |
| Kurtosis | | 1.179 | 1.094 | 13.140 | 31.664 | 1.619 | 1.689 | 4.140 | 4.012 |
| Std. Error of Kurtosis | | 0.052 | 0.052 | 0.052 | 0.052 | 0.052 | 0.052 | 0.052 | 0.052 |
| Range | | 1222.9 | 752.2 | 532.9 | 846.4 | 846.4 | 1291.8 | 5 | 6 |
| Minimum | | -1223.0 | -752.3 | -533.0 | 0.0 | 0.0 | 0.0 | 0 | 0 |
| Maximum | | -0.1 | -0.1 | -0.1 | 846.4 | 846.4 | 1291.8 | 5 | 6 |
| Percentiles | 5 | -612.1 | -346.1 | -107.1 | 1.1 | 26.9 | 51.1 | 0.00 | 0.00 |
| | 10 | -508.2 | -289.3 | -80.8 | 2.5 | 36.0 | 67.7 | 1.00 | 0.00 |
| | 20 | -391.1 | -221.0 | -53.1 | 5.5 | 52.8 | 100.0 | 1.00 | 1.00 |
| | 25 | -351.4 | -193.4 | -44.6 | 7.3 | 61.0 | 114.6 | 1.00 | 1.00 |
| | 30 | -311.1 | -172.7 | -37.5 | 9.2 | 69.1 | 128.7 | 1.00 | 1.00 |
| | 40 | -250.4 | -137.8 | -28.0 | 13.9 | 86.3 | 161.3 | 1.00 | 1.00 |
| | 50 | -201.4 | -110.2 | -20.4 | 19.8 | 108.6 | 199.1 | 1.00 | 1.00 |
| | 60 | -164.4 | -87.9 | -14.4 | 27.7 | 136.7 | 247.8 | 1.00 | 1.00 |
| | 70 | -130.8 | -70.0 | -9.6 | 38.4 | 171.2 | 307.7 | 1.00 | 1.00 |
| | 75 | -114.5 | -60.7 | -7.6 | 44.8 | 192.1 | 346.0 | 1.00 | 1.00 |
| | 80 | -100.0 | -52.5 | -5.7 | 53.6 | 219.7 | 393.2 | 1.00 | 1.00 |
| | 90 | -70.1 | -36.7 | -2.6 | 80.2 | 290.5 | 518.9 | 2.00 | 2.00 |
| | 95 | -52.2 | -27.0 | -1.3 | 107.9 | 353.4 | 636.2 | 2.00 | 2.00 |

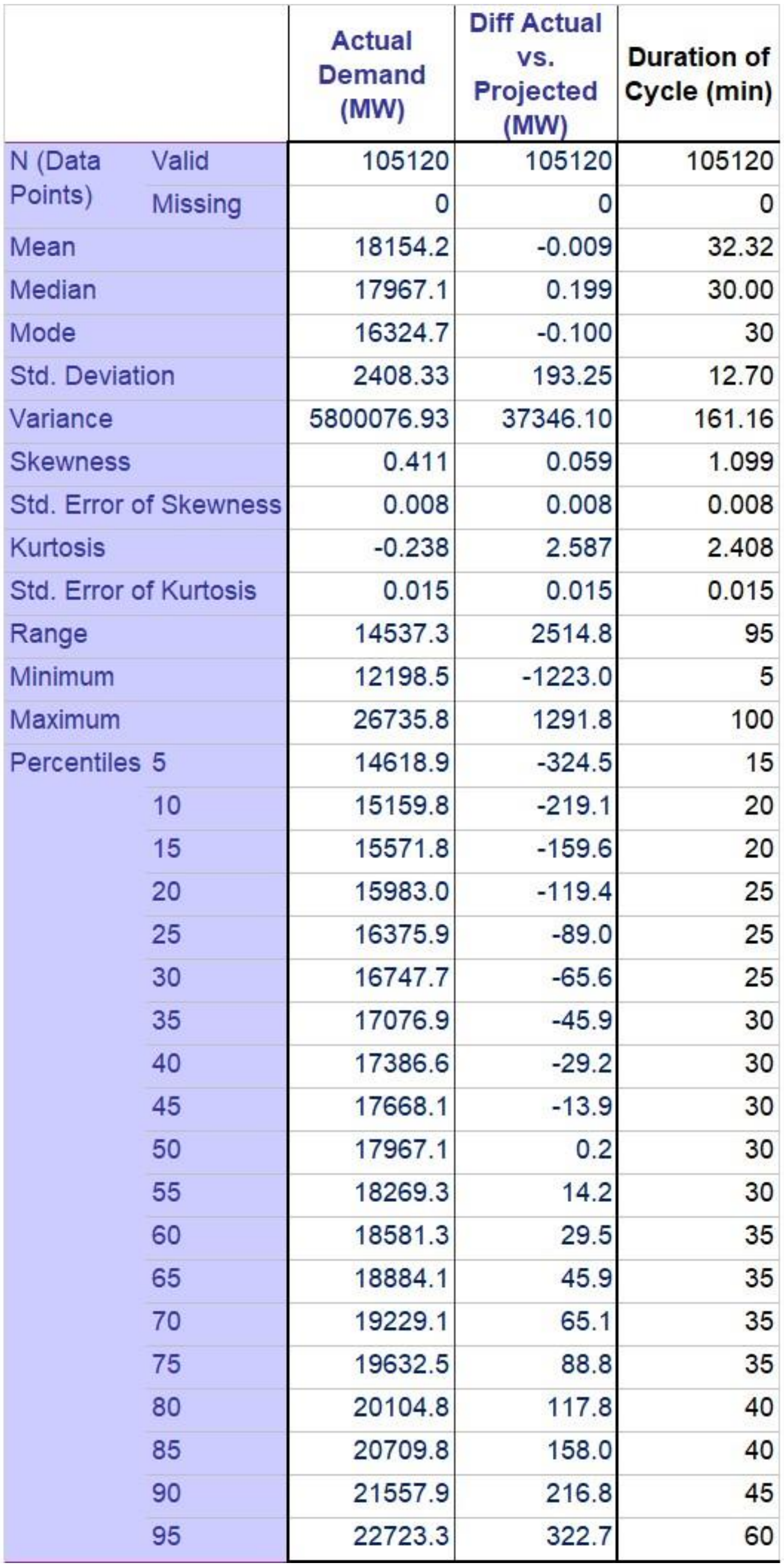
a. Multiple modes exist. The smallest value is shown

Table 5 shows the summary of annual hourly forecasting errors and number of cycle's statistical data analysis. The forecasting error which is defined as the difference between the projected demand and the actual demand, was analyzed under three scenarios (maximum, minimum, average) for both positive (Excess Capacity) and negative (Capacity Shortage) values.

Under maximum scenario, the values of excess capacity and capacity shortage for each hour is assumed to equal the largest positive and negative data points in the dataset (12 data point for each hour – based on 5 min intervals) respectively. This assumption represents the worst-case scenario. In the minimum scenario, values of excess capacity and capacity shortage for each hour is assumed to equal the smallest positive and negative data points in the dataset, respectively. This assumption represents the best-case scenario. Finally, in the average scenario the values of excess capacity and capacity shortage for each hour are set to equal the calculated average value of all positive and negative data points in the dataset, respectively.

The table also summarizes the overall tendencies of the number of up and down cycles for each hour. It can be observed from the table that the spread of data is close to a normal distribution for all three scenarios. Another important observation is across all scenarios; the range is much larger than the mean value. This indicates that the distribution is centered heavy but with long tails.

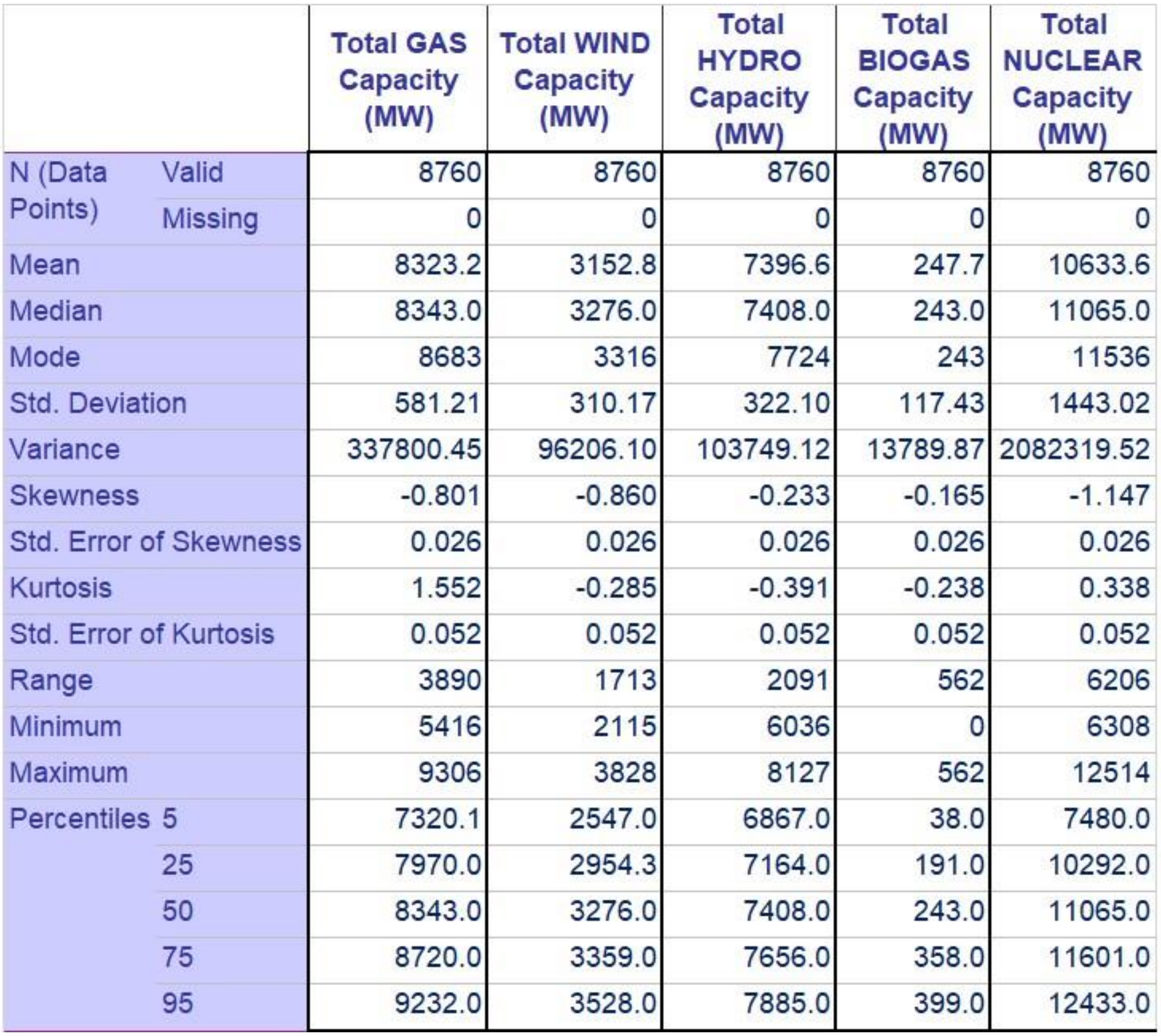
**Table 6 - Actual/Projected demand and duration of cycle statistics (From Data-2)**



| | | Actual Demand (MW) | Diff Actual vs. Projected (MW) | Duration of Cycle (min) |
|---|---|---|---|---|
| N (Data Points) | Valid | 105120 | 105120 | 105120 |
| | Missing | 0 | 0 | 0 |
| Mean | | 18154.2 | -0.009 | 32.32 |
| Median | | 17967.1 | 0.199 | 30.00 |
| Mode | | 16324.7 | -0.100 | 30 |
| Std. Deviation | | 2408.33 | 193.25 | 12.70 |
| Variance | | 5800076.93 | 37346.10 | 161.16 |
| Skewness | | 0.411 | 0.059 | 1.099 |
| Std. Error of Skewness | | 0.008 | 0.008 | 0.008 |
| Kurtosis | | -0.238 | 2.587 | 2.408 |
| Std. Error of Kurtosis | | 0.015 | 0.015 | 0.015 |
| Range | | 14537.3 | 2514.8 | 95 |
| Minimum | | 12198.5 | -1223.0 | 5 |
| Maximum | | 26735.8 | 1291.8 | 100 |
| Percentiles | 5 | 14618.9 | -324.5 | 15 |
| | 10 | 15159.8 | -219.1 | 20 |
| | 15 | 15571.8 | -159.6 | 20 |
| | 20 | 15983.0 | -119.4 | 25 |
| | 25 | 16375.9 | -89.0 | 25 |
| | 30 | 16747.7 | -65.6 | 25 |
| | 35 | 17076.9 | -45.9 | 30 |
| | 40 | 17386.6 | -29.2 | 30 |
| | 45 | 17668.1 | -13.9 | 30 |
| | 50 | 17967.1 | 0.2 | 30 |
| | 55 | 18269.3 | 14.2 | 30 |
| | 60 | 18581.3 | 29.5 | 35 |
| | 65 | 18884.1 | 45.9 | 35 |
| | 70 | 19229.1 | 65.1 | 35 |
| | 75 | 19632.5 | 88.8 | 35 |
| | 80 | 20104.8 | 117.8 | 40 |
| | 85 | 20709.8 | 158.0 | 40 |
| | 90 | 21557.9 | 216.8 | 45 |
| | 95 | 22723.3 | 322.7 | 60 |

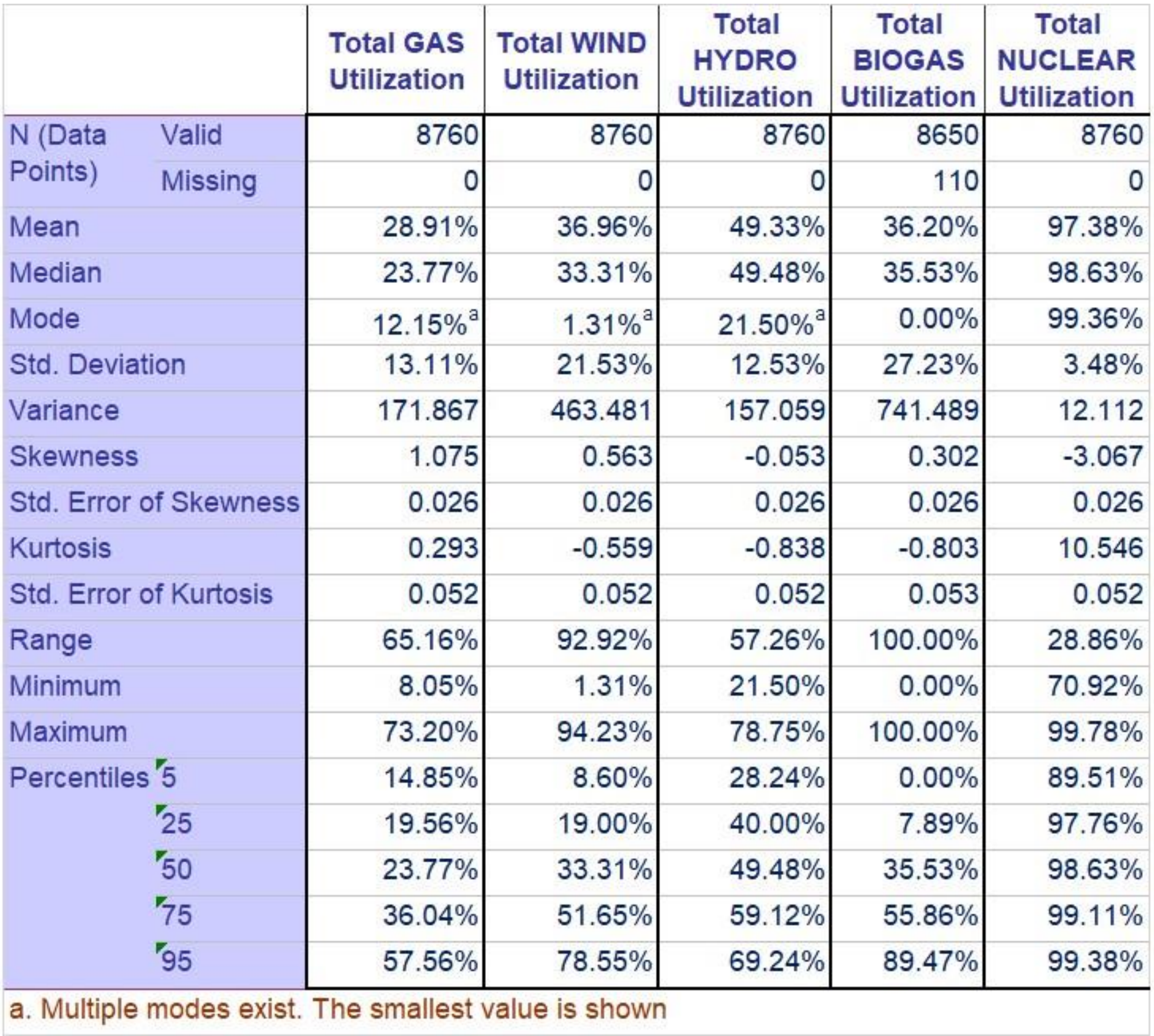
Table 6 summarizes the actual system demand vs. the forecasted error. It also includes the derived cycle duration data. The analysis shows that on average, the forecasted error is less than 3% of the total system demand. Also, the duration of 95% of all cycles are 60 minutes or less.

**Table 7 - Generation capacity (by fuel type) statistics (From Data-2)**



| | | Total GAS Capacity (MW) | Total WIND Capacity (MW) | Total HYDRO Capacity (MW) | Total BIOGAS Capacity (MW) | Total NUCLEAR Capacity (MW) |
|---|---|---|---|---|---|---|
| N (Data Points) | Valid | 8760 | 8760 | 8760 | 8760 | 8760 |
| | Missing | 0 | 0 | 0 | 0 | 0 |
| Mean | | 8323.2 | 3152.8 | 7396.6 | 247.7 | 10633.6 |
| Median | | 8343.0 | 3276.0 | 7408.0 | 243.0 | 11065.0 |
| Mode | | 8683 | 3316 | 7724 | 243 | 11536 |
| Std. Deviation | | 581.21 | 310.17 | 322.10 | 117.43 | 1443.02 |
| Variance | | 337800.45 | 96206.10 | 103749.12 | 13789.87 | 2082319.52 |
| Skewness | | -0.801 | -0.860 | -0.233 | -0.165 | -1.147 |
| Std. Error of Skewness | | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 |
| Kurtosis | | 1.552 | -0.285 | -0.391 | -0.238 | 0.338 |
| Std. Error of Kurtosis | | 0.052 | 0.052 | 0.052 | 0.052 | 0.052 |
| Range | | 3890 | 1713 | 2091 | 562 | 6206 |
| Minimum | | 5416 | 2115 | 6036 | 0 | 6308 |
| Maximum | | 9306 | 3828 | 8127 | 562 | 12514 |
| Percentiles | 5 | 7320.1 | 2547.0 | 6867.0 | 38.0 | 7480.0 |
| | 25 | 7970.0 | 2954.3 | 7164.0 | 191.0 | 10292.0 |
| | 50 | 8343.0 | 3276.0 | 7408.0 | 243.0 | 11065.0 |
| | 75 | 8720.0 | 3359.0 | 7656.0 | 358.0 | 11601.0 |
| | 95 | 9232.0 | 3528.0 | 7885.0 | 399.0 | 12433.0 |

**Table 8 - Capacity utilization (by fuel type) statistics (From Data-2)**



| | | Total GAS Utilization | Total WIND Utilization | Total HYDRO Utilization | Total BIOGAS Utilization | Total NUCLEAR Utilization |
|---|---|---|---|---|---|---|
| N (Data Points) | Valid | 8760 | 8760 | 8760 | 8650 | 8760 |
| | Missing | 0 | 0 | 0 | 110 | 0 |
| Mean | | 28.91% | 36.96% | 49.33% | 36.20% | 97.38% |
| Median | | 23.77% | 33.31% | 49.48% | 35.53% | 98.63% |
| Mode | | 12.15%[a] | 1.31%[a] | 21.50%[a] | 0.00% | 99.36% |
| Std. Deviation | | 13.11% | 21.53% | 12.53% | 27.23% | 3.48% |
| Variance | | 171.867 | 463.481 | 157.059 | 741.489 | 12.112 |
| Skewness | | 1.075 | 0.563 | -0.053 | 0.302 | -3.067 |
| Std. Error of Skewness | | 0.026 | 0.026 | 0.026 | 0.026 | 0.026 |
| Kurtosis | | 0.293 | -0.559 | -0.838 | -0.803 | 10.546 |
| Std. Error of Kurtosis | | 0.052 | 0.052 | 0.052 | 0.053 | 0.052 |
| Range | | 65.16% | 92.92% | 57.26% | 100.00% | 28.86% |
| Minimum | | 8.05% | 1.31% | 21.50% | 0.00% | 70.92% |
| Maximum | | 73.20% | 94.23% | 78.75% | 100.00% | 99.78% |
| Percentiles | 5 | 14.85% | 8.60% | 28.24% | 0.00% | 89.51% |
| | 25 | 19.56% | 19.00% | 40.00% | 7.89% | 97.76% |
| | 50 | 23.77% | 33.31% | 49.48% | 35.53% | 98.63% |
| | 75 | 36.04% | 51.65% | 59.12% | 55.86% | 99.11% |
| | 95 | 57.56% | 78.55% | 69.24% | 89.47% | 99.38% |

a. Multiple modes exist. The smallest value is shown

The system total generation capacity and utilization of generation capacity are summarized in Table 7 and Table 8, respectively. It can be observed that among all major grid generation sources, gas power plants have the lowest utilization on average. Given that they have the second highest maximum output (nuclear is 1st), this reiterates the importance and confirms the validity of the problems stated in sections 2.5 and 2.5.3.1. Wind generation has a slightly better overall utilization; however, the range was much wider (~93%). This indicates that there are instances that the available capacity from wind generation is not utilized or is curtailed, which further validates the challenges identified in section 2.5.

## 4.6 Summary

In this chapter, UCD, OODM, and DDAM concepts and methodologies were introduced and discussed. The grid data collection process and steps were also described. Finally, the results of descriptive statistical analysis for Data-2 are summarized and discussed. This data will be further analyzed in chapter 6.

# Chapter 5

# CAES-by-Design

This chapter introduces a new approach called "CAES-by-Design" to designing CAES systems for operation in the electrical grid. The advantages and applications of this approach are shown. Then an application of this method, based on analysis of a sample hourly data of Ontario's electrical grid, is displayed. Multiple scenarios are considered, and simulation is conducted. Finally, the results are compared, their design implications are discussed, and major conclusions are highlighted.

## 5.1 CAES-by-Design

In this chapter, a methodology, for redesigning the CAES system for high-value applications, is developed to enable participation of CAES in grid ancillary market. The author calls this approach CAES-by-Design. The method is developed based on the UCD approach, and DDAM introduced in chapter 4. As such, the process closely resembles the requirement gathering and analysis steps of those methodologies. As illustrated in Figure 11, through this approach, not only the benefits of conventional and adiabatic systems are retained, but also additional advantages would become available. Conventional diabetic CAES systems (D-CAES) are mainly designed and used for black start and peak shaving applications [77]. Adiabatic systems offer the benefit of being fuel free with no greenhouse gas (GHG) emissions. On the other hand, through a CAES-by-Design approach, it is possible to design a CAES system for higher value grid ancillary services and at the same lower the total cost of ownership (TCO); therefore, increased revenue and operational flexibility would be achieved.

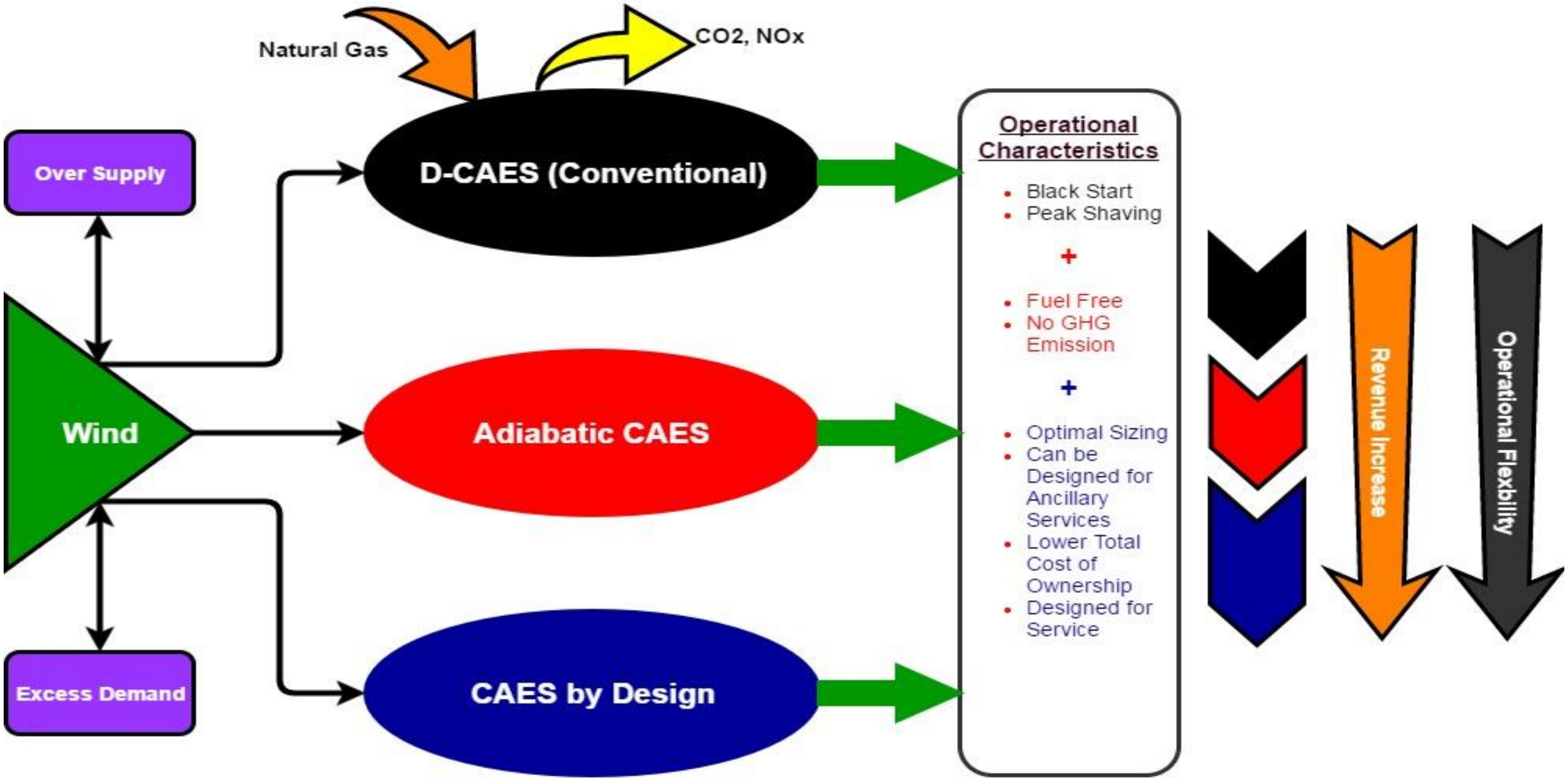


Figure 11 - Improvements achieved in CAES utilization value through the CAES-by-Design methodology

## 5.2 General Considerations

The current analysis is based on the hourly energy generation data of the Ontario grid. This energy is being delivered to the electric grid from different power plants, and it is assumed that the total energy generation value at each hour is equal to the total energy demand of the grid during that same period. In designing a CAES system for ancillary services, we propose to maintain the gas power plant operation as close to steady state as possible, and at the lowest total/overall capacity as well; i.e., the total capacity is to be minimized for both operating cost and emission reduction considerations. At the same time, we want the CAES system to compensate for deviations (shortcoming) in the wind power generation output from the actual demand. Based on these requirements, different scenarios could occur and should be considered. Usually, gas power plants have the highest response dynamics to the power demand variations. In this regard, the power generation plot would reveal some facts. It displays that by extracting the changes in the demand profile, which is equivalent to the total generation, over 1-hour time steps, and the corresponding changes in other generation sources (gas, nuclear, wind, etc.) response plots, it could be determined what percentage of the changes in demand is covered by each of the power generating sources.

## 5.3 Analysis of Ontario Grid Profiles

The purpose of this analysis is to determine the sizing requirements of a hypothetical CAES that can be integrated into the Ontario electrical grid, fulfilling some of the primary grid services. Ability to provide these types of high-value service translates to a shift of the current positioning of the CAES systems from a designated bulk energy storage system to a more robust and flexible storage technology, similar to flow and Li-ion batteries. For this purpose, an analysis is presented on a seven-day sample of generation and demand hourly data (144 data points) which is collected from the IESO. Based on the collected data, availability and utilization of system capacity are identified by calculating the variations in the power output for each of the generation types and also for the total system generation. Next, to identify the actual reaction time of each generation type, changes in power generation value are calculated by taking the difference of each data point with respect to its previous value, as shown in Figure 12.

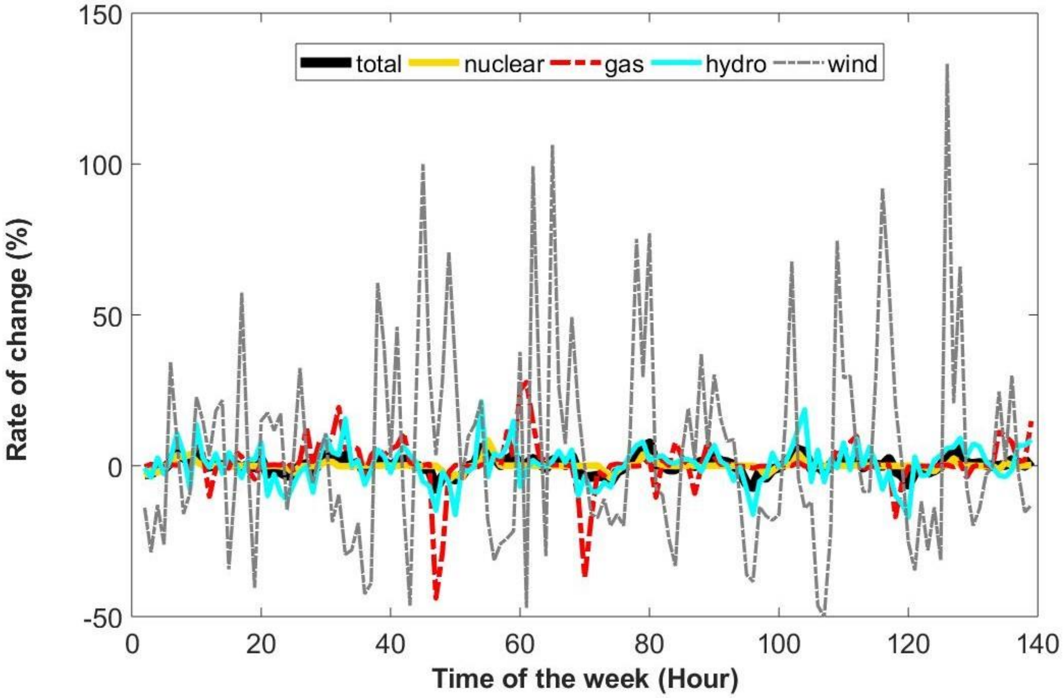


**Figure 12 - Rate of change for each generation type, over measured period (1-week)**

### 5.3.1 Constraints Applied to the Analysis

In this analysis, gas, and wind power generators are selected as the main components of interest, as they have the most significant impact in terms of efficiency, cost saving, and emission reduction. This is due to inefficiencies associated with part-load operation of thermal power plants, and intermittency of wind power generation [81,169–174]. As such, the overall objective of the current study is to propose an optimal design approach for CAES that provides the opportunity to capture the maximum available wind power and compensate for the transience in the gas plant operation. Since the capacity of other intermittent renewable energy sources such as solar energy is still very limited to have a significant impact, they are not considered in this analysis.

### 5.3.2 Analytical Procedure

To demonstrate the real-life power generation trends and associated opportunities for integration of a CAES into the grid, the hourly rate of change in the wind and gas power generation are derived based on the collected data. A positive trend in the wind generation implies the presence of excessive wind power (higher than the expected average/baseline) and an opportunity for charging CAES. On the other hand, a positive trend in gas indicates an extra demand signal from the grid, and as such, CAES should operate in discharge mode to compensate for additional gas capacity required. This shows that the wind and gas profiles will affect CAES operation inversely; therefore, the absolute value of the difference between gas and wind generation values represents the opportunity for charge or discharge. For example, wind generation of 25 MW above and gas generation of 10 MW below their respective baselines result in a 35 MW of charging power opportunity. This will ensure that the gas turbines are operating at their full load (although the demand is lower than average), while the extra generated wind power is stored, avoiding curtailment. Figure 13 shows the combined wind-gas data divided into positive (charge) and negative (discharge) trends.

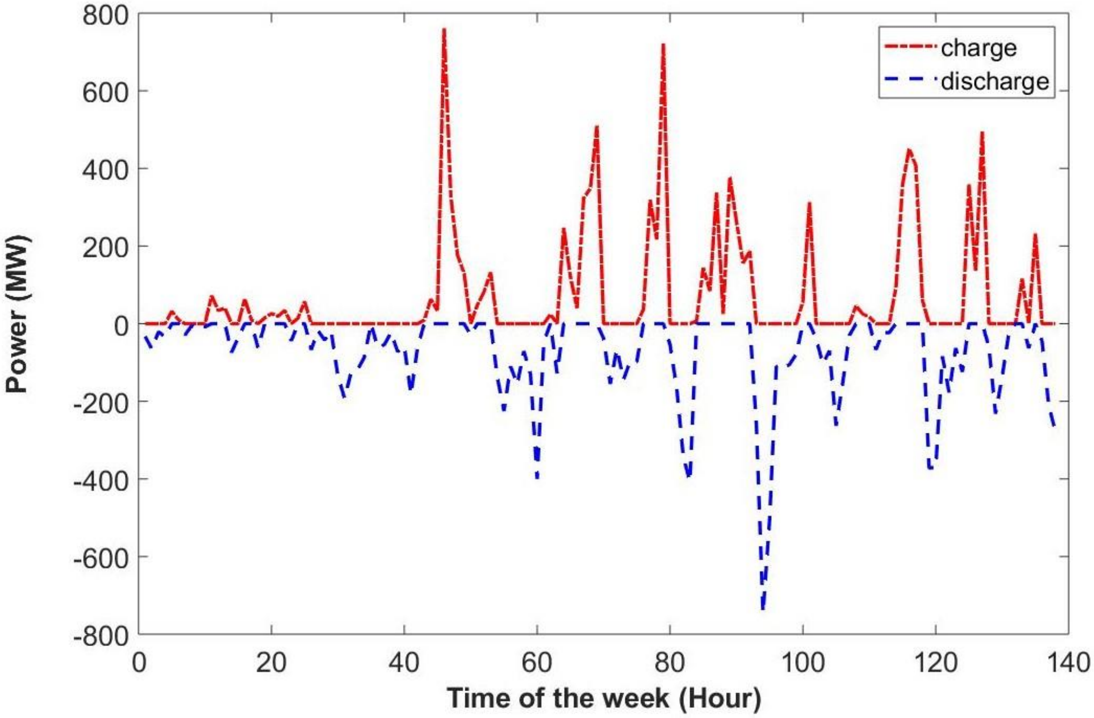


**Figure 13 - Power distribution for charge-discharge operating cycles (derived from grid data)**

The histogram in Figure 14 shows the distribution of the charge and discharge opportunities and their corresponding energy content value. Based on the desired coverage percentage and using this histogram, required capacity for charging (compressor sizing) and discharging (turbine sizing), as well as the cumulative capacity (for cavern sizing), can be estimated. This provides a tool for rapid sizing of CAES systems. It is important to note that the current analysis is based on data with 1-hour resolution. The effectiveness and accuracy of this type of histograms as a sizing tool essentially depends on the time span of the historical data, as well as the resolution. Therefore, a more realistic sizing estimation can be achieved once a higher resolution data (for example, 5-minute data) is considered.

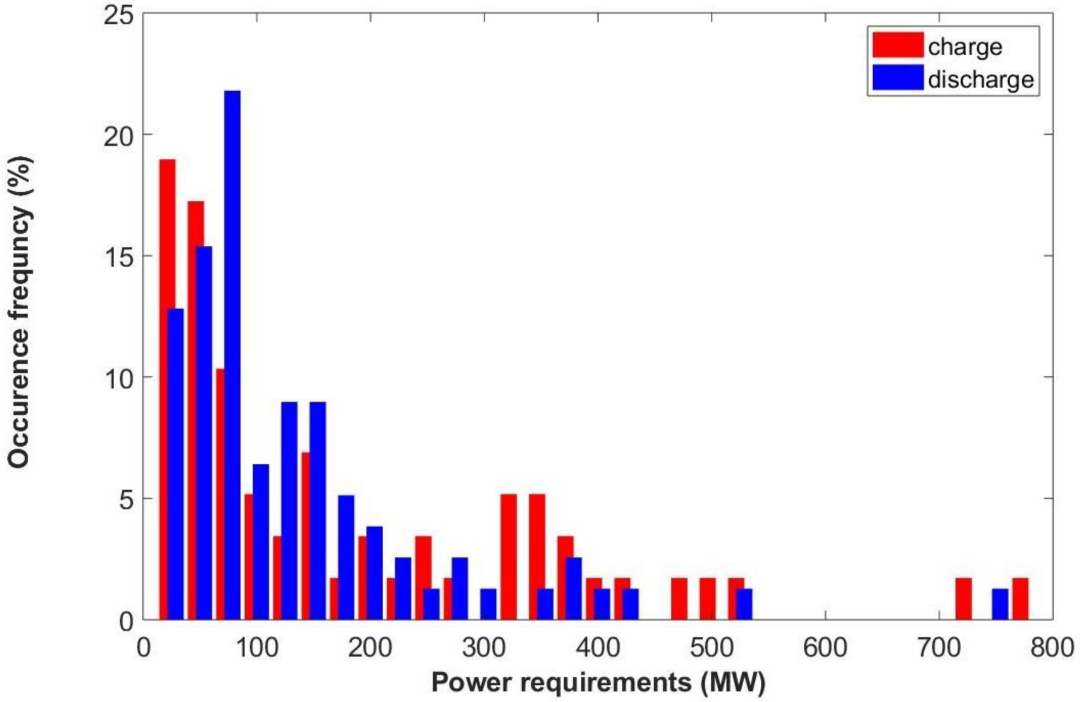


**Figure 14 - Frequency and level of power requirement (combined charge and discharge)**

### 5.3.2.1 Turbine and Compressor Size Estimation Method

The main criteria for designing an energy storage system is the capacity and performance requirements. In this context, capacity refers to turbine/compressor power rating and cavern sizing, while performance refers to the compressor/turbine response time (ramp time), which is the time required for the device to reach its rated power capacity. From a decision making perspective, the focus can be either maximizing the energy content, minimizing the cost (capital, maintenance), maximizing the overall energy efficiency, and maximizing the ramping capability or a combination of any of these, leading to a multi-objective optimization problem. The importance of this problem can be illustrated if we consider that the power requirement to cover 100% of data points is 775 and 750 MW for charging and discharging, respectively. However, it is observed from the collected data set that the frequency of high power events was much lower than those of the average and lower power levels, as shown in Figure 14. Therefore, designing the system based on 100% capacity will be inefficient as it would be operating at part load condition most of the time.

On the other hand, if 50% of the events are to be covered, a compressor capacity of 100 MW and a turbine capacity of 75 MW would be sufficient. A reduced system capacity not only ensures that the system is operated at full load more often, therefore achieving higher system efficiency, but also translates into significant cost savings.

#### 5.3.2.2 Cavern Sizing

Similar to the compressor and turbine, cavern sizing is primarily influenced by cost, operational efficiency, and the type of application it is used for. For example, in arbitrage applications, the focus is on maximizing the amount of stored energy for an extended period. Therefore, the cavern is designed at its largest possible size. On the other hand, providing most ancillary services and improving the flexibility of the power system, does not necessarily require the maximum energy storage capacity, as the charge and discharge duration can be much shorter. In order to estimate the cavern sizing, data was sorted into charge and discharge events. The sum of energy that needs to be stored/delivered at each continuous duration of either charge or discharge is categorized into bins of increasing 25MWh intervals, resulting in a set of energy values and their corresponding frequency, which is demonstrated as the bar charts (for both charge and discharge) in Figure 15.

Additionally, to account for the desired event-coverage rate, the cumulative number of events which fall under a certain level of cavern energy capacity is determined and plotted for both charge and discharge modes. For example, it is observed that if 50% of the total number of charge events (equal to 43 data points) is to be covered, a cavern capacity of 575 MWh is required. The same capacity corresponds to 53.4% of discharge events (equal to 55 data points). One interesting finding is that the chosen cavern capacity may result in either oversizing of charge or discharge events. The choice would depend on the preference defined by the application.

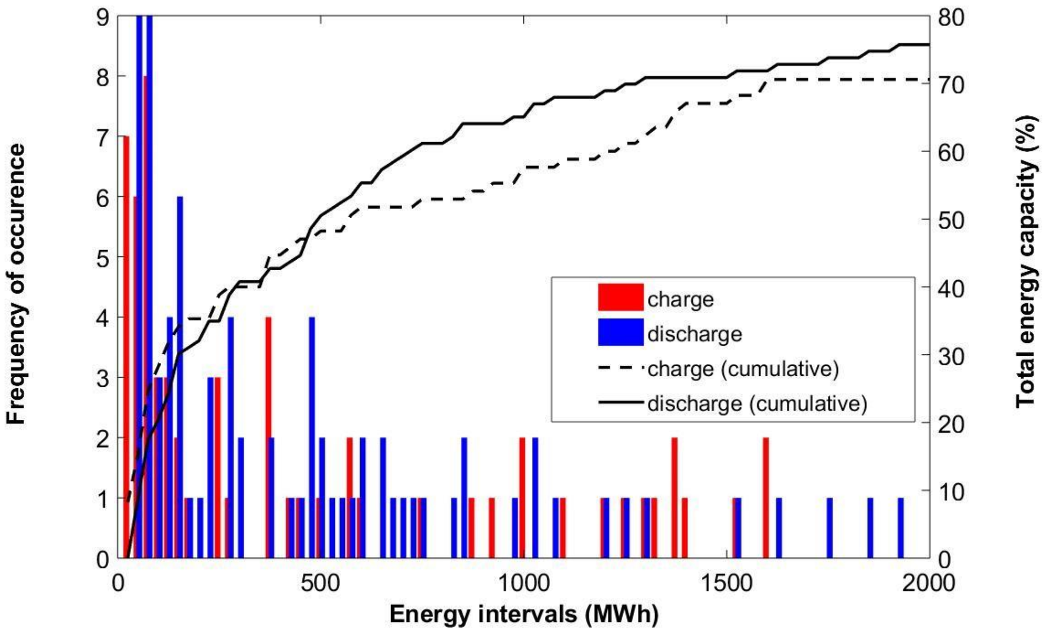


Figure 15 - Input and output capacity requirements (MWh)

Once a cavern capacity is derived, the cavern state of charge (SOC) with respect to time is calculated as the ratio of instantaneous cavern air charge to the maxim cavern capacity. Figure 16 shows a sample SOC profile based on a 50% corresponding capacity.

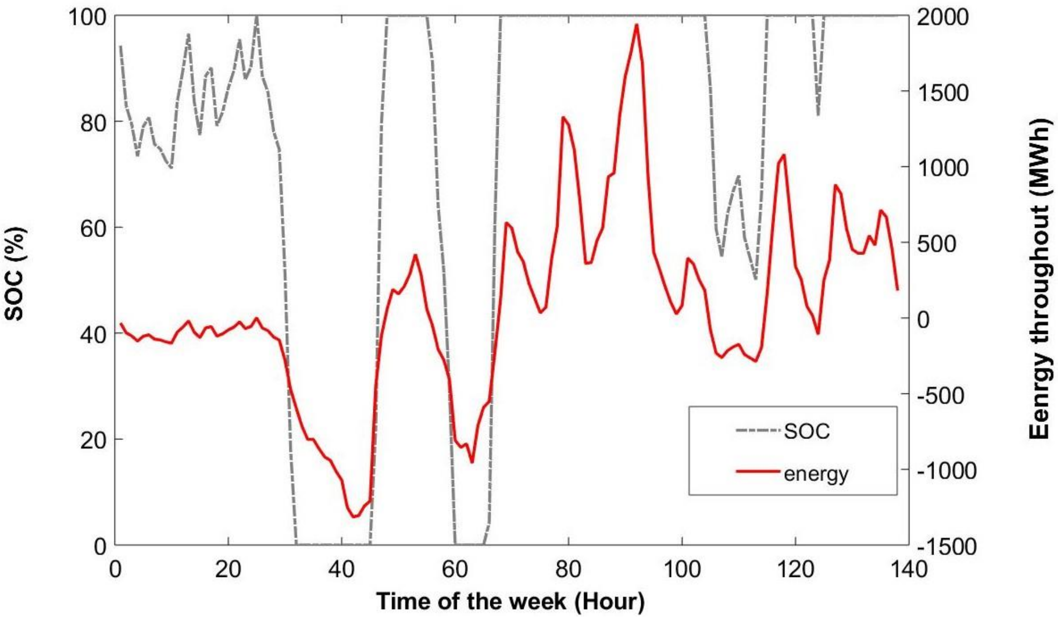


Figure 16 - State of Charge (SOC) of cavern during measured period

## 5.4 Cavern Daily Cycling

Based on the one-week data of the Ontario grid, key CAES cycling metrics, including number, and duration of ramp-up and ramp-down periods, are calculated. Table 9 presents these results. It is observed that unlike the general assumption of one cycle per day [94], the cavern would have to undergo several partial charge and discharge cycles to follow the power demand/supply profile. For example, a total of 33 partial cycles and an average of 5.6 cycles per day are calculated for the current analysis. This has significant implications on the CAES design requirements and has to be accounted for from the mechanical and geo-mechanical point of views.

**Table 9 - CAES cycling metrics calculated from a sample of Ontario grid data (1 week)**

| | |
|---|---|
| Number of times Ramp-down was needed | 17 |
| Number of times Ramp-up was needed | 16 |
| Average number of ramp-up or down per 24hr | 5.7 |
| Longest duration of charging (Ramp-Down) | 12 hr |
| Longest duration of discharging (Ramp-Up) | 10 hr |
| Average duration of charging (Ramp-Down) | 5.5 |
| Longest duration of discharging (Ramp-Up) | 3 |
| Shortest duration of charging (Ramp-Down) | 1 hr |
| Shortest duration of discharging (Ramp-Up) | 1 hr |

### 5.4.1 Simulation of CAES operation

To demonstrate how the operating parameters of a CAES system affect the design requirements, a simplified adiabatic CAES system is assumed with the following considerations:

- The system is comprised of a single-stage compressor, a generic pressure vessel, and a single-stage turbine.
- No TES exists, and all the thermal energy is stored in the pressure vessel. This assumption helps to identify the maximum amount of heat and temperature rise in the system with no temperature limit. Afterward, applying an upper limit for the temperature in the vessel (cavern), and assuming the percentage of the available heat that is to be retained in the

TES, a rough estimate of the required TES capacity can be achieved.

- The conversion system is adiabatic, therefore no heat loss to the ambient upon charging and discharging.
- The rock salt around the cavern act as a thermal energy reservoir (TER). Therefore, while the system is in idle mode, some heat loss occurs and the energy content of the compressed air decreases. This heat loss is modeled by considering the heat convection between the air in the cavern and the cavern wall, which is assumed to be at a constant temperature of ~300 °K.

The initial operating parameters of the compressor and turbine for the thermodynamic model remains the same as it was listed in Table 4 under Chapter 3. It should be noted that no specific pressure limits were taken into consideration, as the cavern upper and lower pressure values vary significantly based on the depth and design of the cavern [175–178]. It should also be clarified that in sizing the turbine and compressor, the actual power capability that is required as input for compressor and output for turbine is calculated. Therefore, this analysis is not limited to a specific efficiency. Once a specific turbine/compressor model is selected, the associated efficiency can be incorporated in developing the system layout (e.g., number of required units in series). For example, if the power output requirement is calculated as 100 MW, and the selected turbine has an efficiency of 90%, the actual power rating of the turbine is calculated as $\frac{100}{90} = 111\ MW$. While these assumptions are idealistic, this approach to the analysis will help determine the system thermal boundaries. The sizing parameters of the system are selected based on values calculated in the analysis of charge-discharge power and cavern sizing (Figure 14 and Figure 15). The baseline sizing of the compressor and turbine are set to the power rating value that is sufficient to cover at least 10% of both charge and discharge events. Assuming a minimum increment of 25 MW, a 25 MW compressor and turbine cover ~19% and ~ 13% of the events respectively. Similarly, the sizing of cavern is selected based on the required energy capacity, sufficient to provide at least 10% of charging and discharging events. The increment for energy is assumed 100 MWh; therefore, a cavern with 100 MWh capacity is selected. This capacity accounts for ~28% charging and ~20% discharging events. To establish the basis for comparison, an extreme sizing level of 100 MW was assumed for the compressor and turbine, which translates to ~52% and ~56% event coverage. Based on the results obtained from the system cycling analysis (Table 9), twelve scenarios for charging, discharging, and idling for the assumed CAES system are considered and summarized in Table 10. The initial cycle durations are selected based on the previously identified minimum, maximum, and average charging and discharging cycles. The change in compressor and turbine power ratings are reflected in the charging and discharging cycle duration for each scenario (i.e., accounting for changes in mass flow rate).

**Table 10 - Assumed scenarios for simulation of typical CAES operation**

| | Cyclic Condition | Charging duration (h) | Idling duration (h) | Discharging duration (h) | Compressor Power (MW) | Turbine Power (MW) |
|---|---|---|---|---|---|---|
| **Scenario 1** | **(Max)** | 12 | 0 | 10 | 25 | 25 |
| | **(Average)** | 5.5 | 14.5 | 3 | | |
| | **(Min)** | 1 | 20 | 1 | | |
| **Scenario 2** | **(Max)** | 3 | 9 | 10 | 100 | 25 |
| | **(Average)** | 1.375 | 17.625 | 3 | | |
| | **(Min)** | 0.25 | 20.75 | 1 | | |
| **Scenario 3** | **(Max)** | 12 | 7.5 | 2.5 | 25 | 100 |
| | **(Average)** | 5.5 | 15.75 | 0.75 | | |
| | **(Min)** | 1 | 20.75 | 0.25 | | |
| **Scenario 4** | **(Max)** | 3 | 16.5 | 2.5 | 100 | 100 |
| | **(Average)** | 1.375 | 19.875 | 0.75 | | |
| | **(Min)** | 0.25 | 21.5 | 0.25 | | |

The temperature, pressure, heat rates, and cumulative heat variations of air in the pressure vessel for each scenario are calculated using Eq. 3-3 and the results are displayed in Figure 17 to Figure 20. Higher resolution copies of the above figures are included in Appendices C.

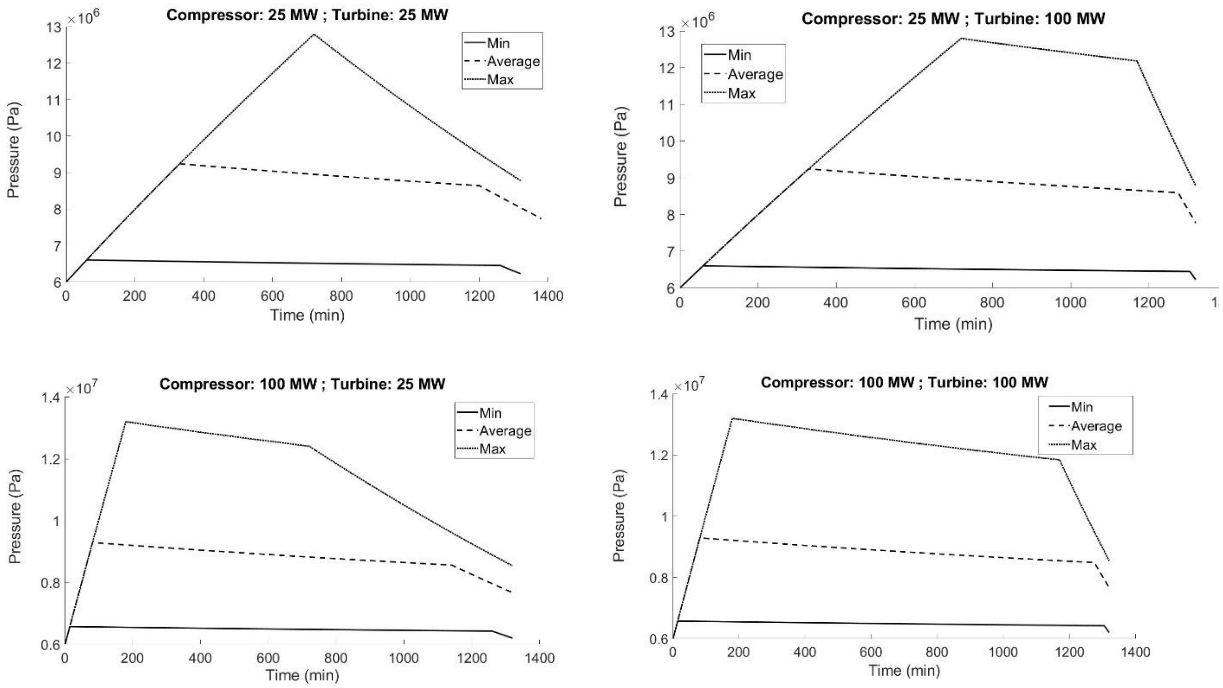


Figure 17 - Cavern pressure profiles under assumed operation scenarios (minimum, average and maximum loading cycles) and various generation/compression capacities (simulation)

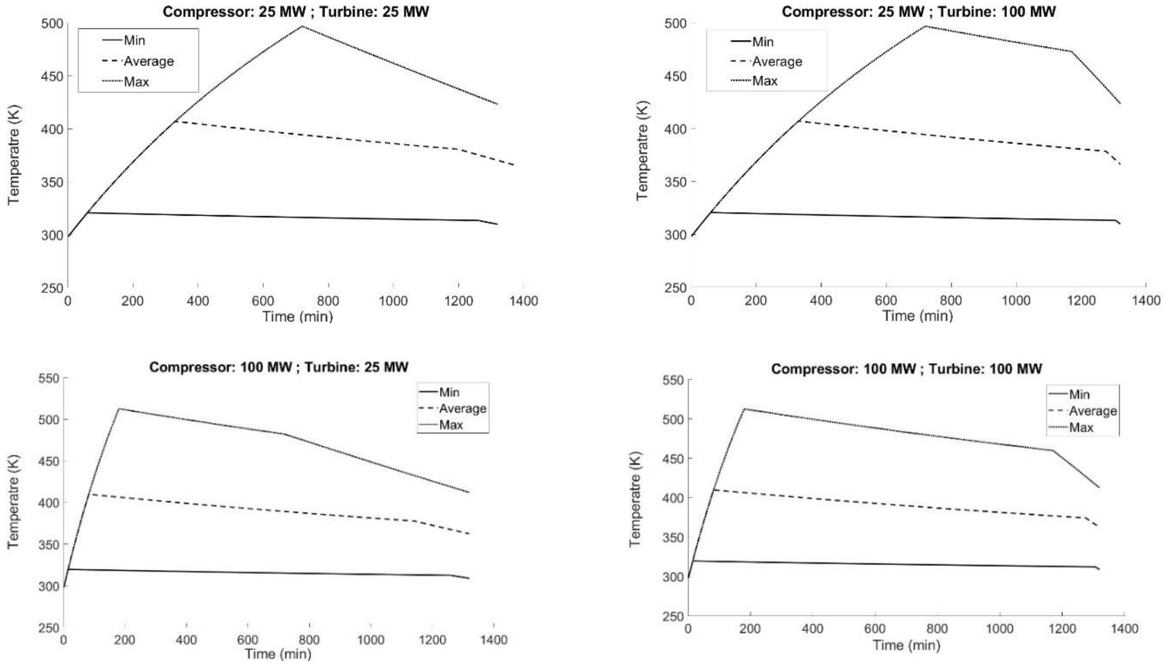


Figure 18 - Temperature profiles under assumed operation scenarios (minimum, average and maximum loading cycles) and various generation/compression capacities (simulation)

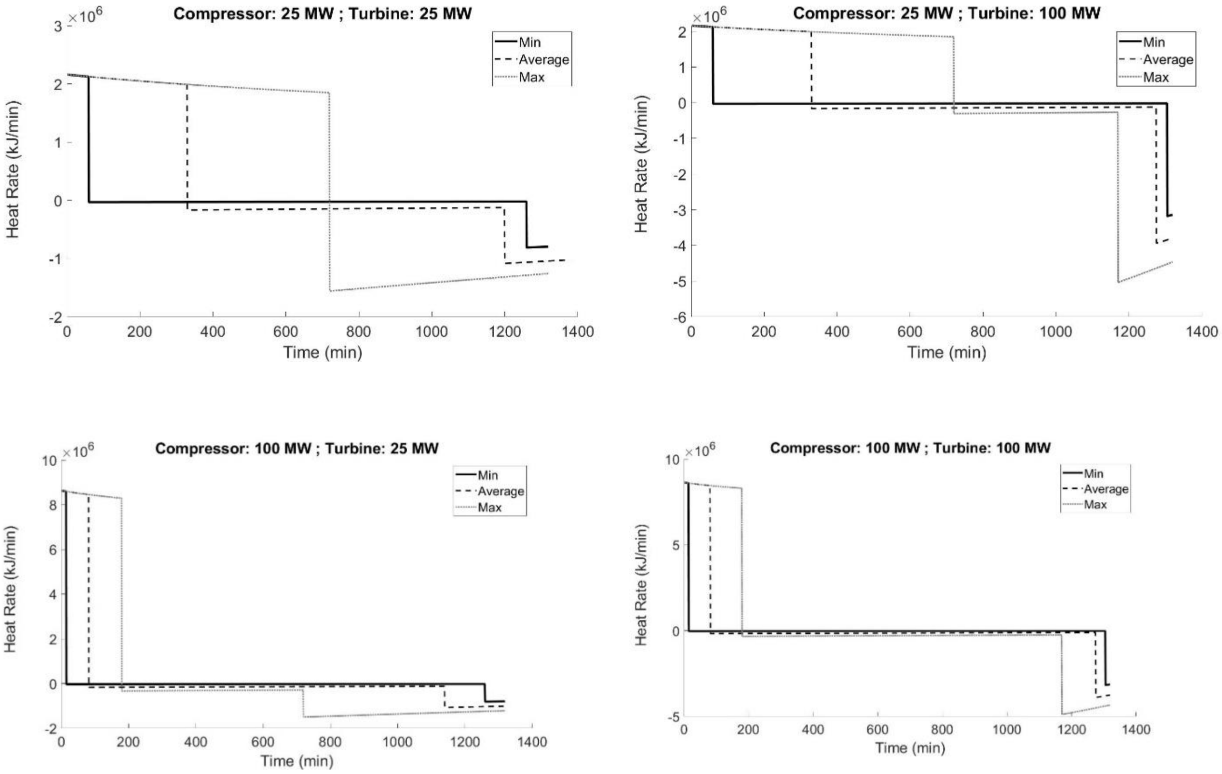


**Figure 19 - Heat rate profiles under assumed operation scenarios (minimum, average and maximum loading cycles) and various generation/compression capacities (simulation)**

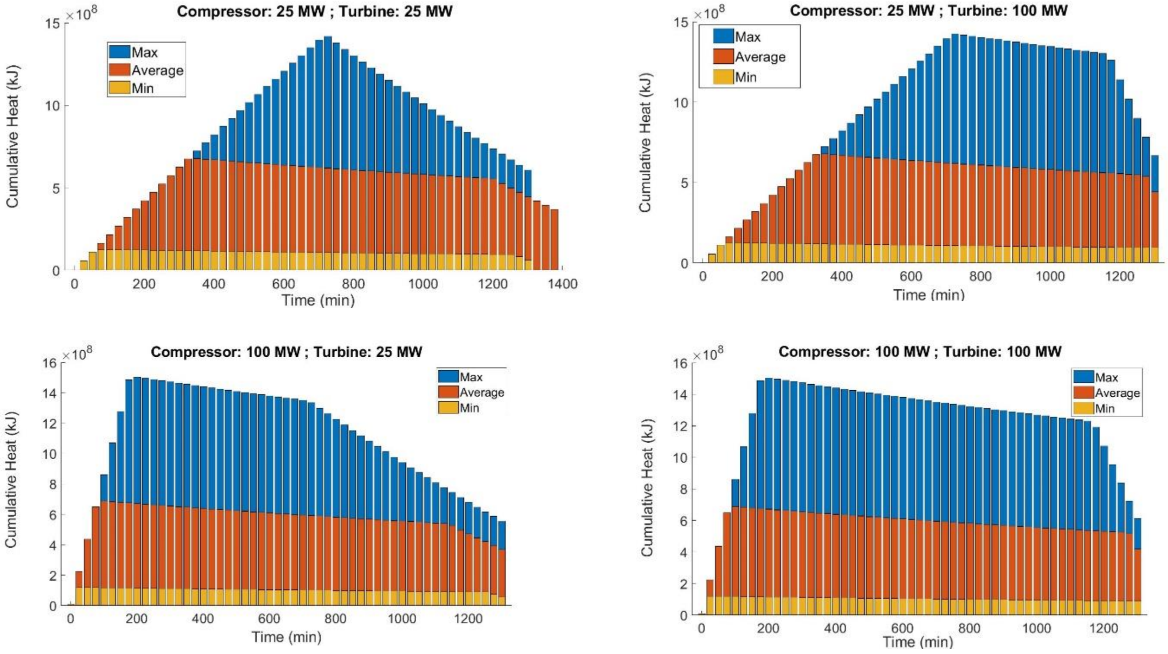


**Figure 20 - Cumulative heat profiles under assumed operation scenarios (minimum, average and maximum loading cycles) and various generation/compression capacities (simulation)**

As can be observed from the above figures, the difference between the minimum and average cycling profile is not significant. Therefore, the focus of this analysis is on comparing CAES thermodynamics behavior under maximum versus average cycles. Results of the comparison are summarized in Table 11 and discussed in the following section.

**Table 11 - Impact of baseline system capacity compared to increased system capacity on CAES operating behavior**

| | | **Baseline Capacity Scenario** | | **Increased Capacity Scenario** | |
|---|---|---|---|---|---|
| | | Average Cycling | Maximum Cycling | Average Cycling | Maximum Cycling |
| **Pressure** | Maximum | 9.24 MPa | 12.8 MPa | 9.29 MPa | 13.2 MPa |
| | Depressurization rate | 9-7.7 MPa (15%) over 200 min | 13-9 MPa (30%) over 700 min | 9.5-6 MPa (37%) over 150 min | 12-6 MPa (50%) over 200 min |
| **Temperature** | Max | 410 K | 500 K | 410 K | 520 K |
| | Changes | 300-410 K (37%) over 300 min | 300-500 K (66%) over 700 min | 300-410 (37%) over 90 min | 300-520 (73%) over180 min |
| **Average heat rate** | Charge | $2.12 \times 10^8$ kJ over 340 min | $2.1 \times 10^8$ kJ over 700 min | $8.5 \times 10^8$ kJ over 700 min | $8.2 \times 10^8$ kJ over 90 min |
| | Discharge | $0.9 \times 10^8$ kJ over 200 min | $1.3 \times 10^8$ kJ over 600 min | $3.8 \times 10^8$ kJ over 40 min | $4.2 \times 10^8$ kJ over 120 min |
| **Cumulative heat** | Total capacity | $6.8 \times 10^8$ kJ over 330 min | $14.1 \times 10^8$ kJ over 720 min | $6.9 \times 10^8$ kJ over 90 min | $15 \times 10^8$ kJ over175 min |

### 5.4.1.1 Discussion of results

The pressure profiles are shown in Figure 17. The behavior of concern here is the maximum pressure and rate of depressurization, which affects cavern stability. It is observed that under average cycling conditions, the cavern experiences significantly lower pressure variations. This implies that from the geo-mechanics point of view, it would be more favorable to operate the CAES under a duty cycle with lower dynamics. Temperature variations impact the CAES design in several ways. In order to remove and return the heat at full capacity, the temperature of the TES unit needs to reach the maximum temperature of the compressed air, which in turn determines the TES material properties. Figure 18 shows that the required max temperature of the TES, under the average versus the maximum cycling conditions, is 18% lower at 25 MW and 21% at 100 MW respectively. The exergy losses in the system also depend on the temperature difference between the TER and compressed air, and the temperature drop during the idle state. Therefore, to maintain the system efficiency, both the idling time and the maximum air temperature should be minimized. Stability of the cavern (or any pressure vessel for that matter) is another factor affected by the maximum temperature. The heat rate determines the required reaction time of the TES unit. As shown in Figure 19, at average cycling conditions, the TES system requires to operate for about 1/3 of the duration that is required under the maximum conditions, and a lower heat rate removal capability during discharge. Finally, the cumulative heat that needs to be removed from or added to the air during the charge/discharge process determines the overall sizing of the TES unit. Under the average cycling conditions, the TES system requires 52% (scenario 1, 3) and 54% (scenario 2, 4) lower capacity compared to the maximum cycling conditions. This can be seen in Figure 20.

## 5.5 Summary

In this chapter, a new approach to designing CAES systems called “CAES-by-Design” is introduced. The approach is tested under multiple scenarios and design considerations. It is shown that the relationship between component sizing, performance characteristics, and overall coverage of electrical system requirements is not 1-to-1. Therefore, the technical and economic feasibility of design and operation of a CAES is highly sensitive to the specific application and the amount of coverage that the system is rated to provide in a particular grid system. The approach is shown to provide a feasibility assessment tool based on a limited sample of a grid’s operating data.

# Chapter 6

# Long-Term Analysis

Based on the CAES-by-Design approach introduced in the previous chapter, this chapter starts with a detailed study of IESO system operating requirements. Employing data-driven analytical method (DDAM) and exploratory data analysis (EDA) techniques, high fidelity long-term historical operating data are analyzed, and significant operating points and patterns are identified. These results are visualized and discussed. Then, based on CAES's potential application and intended type of service provided, multiple design criteria are defined. Following that, the results from several thermodynamic simulations for different applications are compared and discussed. In the conclusion section, the implications and recommendations are highlighted.

## 6.1 Operational Data Analysis

In the following sections, steps 4 and 5 of the data-driven analytical method (DDAM), introduced in 4.4, are covered. The long-term data is explored to gain insight into the performance requirements of Ontario's power system.

### 6.1.1 Data Visualization and Pattern Recognition

The first step in data analysis is to identify the trends. For this purpose, multiple charts were created, visualizing the results of time-series and cross-sectional data analysis. These analyses show, when, how much, how often, and for how long power adjustments are required by the grid to ensure stable operation.

### 6.1.2 Forecasting error

The overall trend in forecasting error of the IESO system is shown in Figure 21. Errors in forecasting are signified by how often and by how much the projected required capacity was inaccurate.

It can be observed from the chart that while there were many hours throughout the year that the forecast was not accurate, in a majority of those events, the actual capacity required to mitigate the error was about 400 MW for both excess and shortage in the system. The same data is transformed and categorized into monthly (instead of hourly) format, to provide a high-level view of the forecasted capacity error. The results are shown in Figure 22

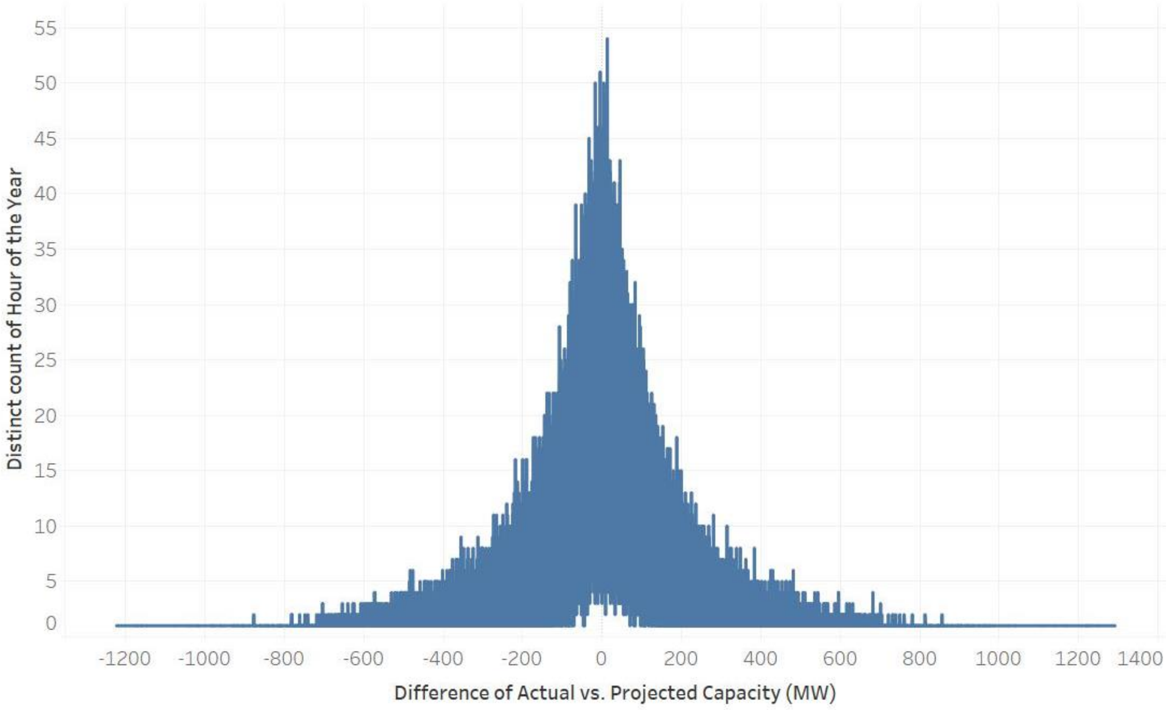


**Figure 21 - The difference of actual vs. forecasted capacity and the number of hours in the year each error occurred**

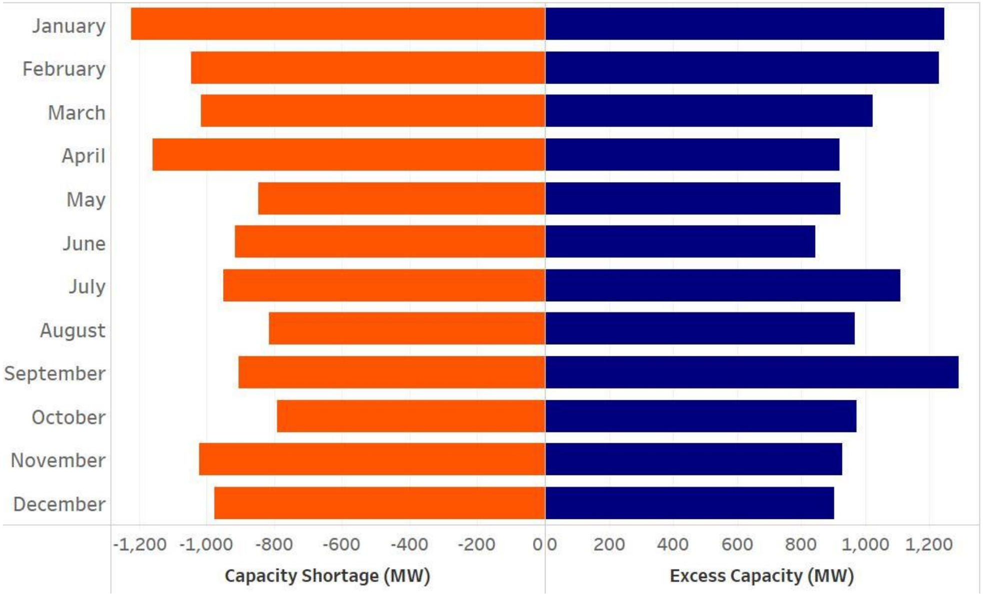


**Figure 22 - Variation of shortage and excess forecasted capacity error (MW) for each month**

It can be seen that the, in general, the error in the actual required capacity (MW) is higher during winter months compared to the rest of the year.

### 6.1.3 Cycling Analysis

The frequency of daily and hourly cycles are an essential part of grid operational characteristics. In order to operate in the electrical grid system, any EES system, including CAES, has to be designed to tolerate the long term cycling requirements of that grid. Therefore, understanding cycling requirements is necessary for designing CAES systems. Figure 23 illustrates the daily cycling distribution (Up and Down Cycles) and the corresponding capacity forecast error over the period of one year. It is noted that due to the large number of data points, some details might be hard to distinguish in this chart. As such, Figure 24 and Figure 25 which show the same analysis for the period of one month and one week respectively, are included to provide better clarity.

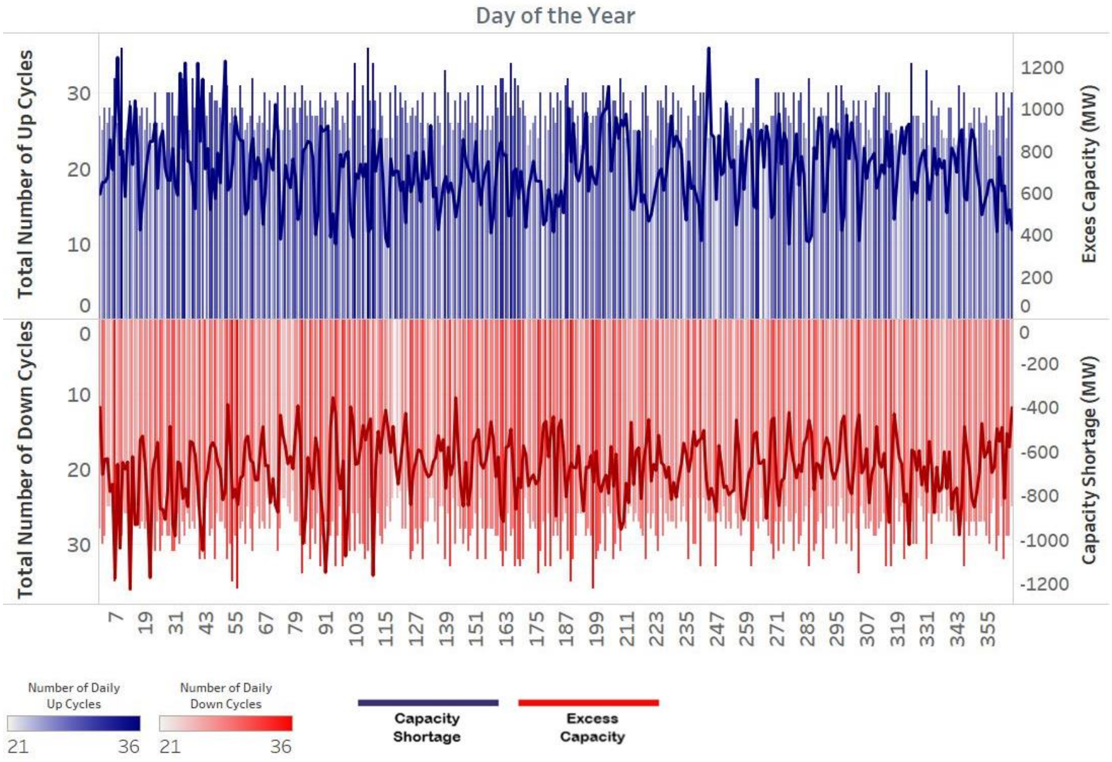


**Figure 23 - Number of daily up and down cycles and maximum positive and negative forecasted capacity error (2015)**

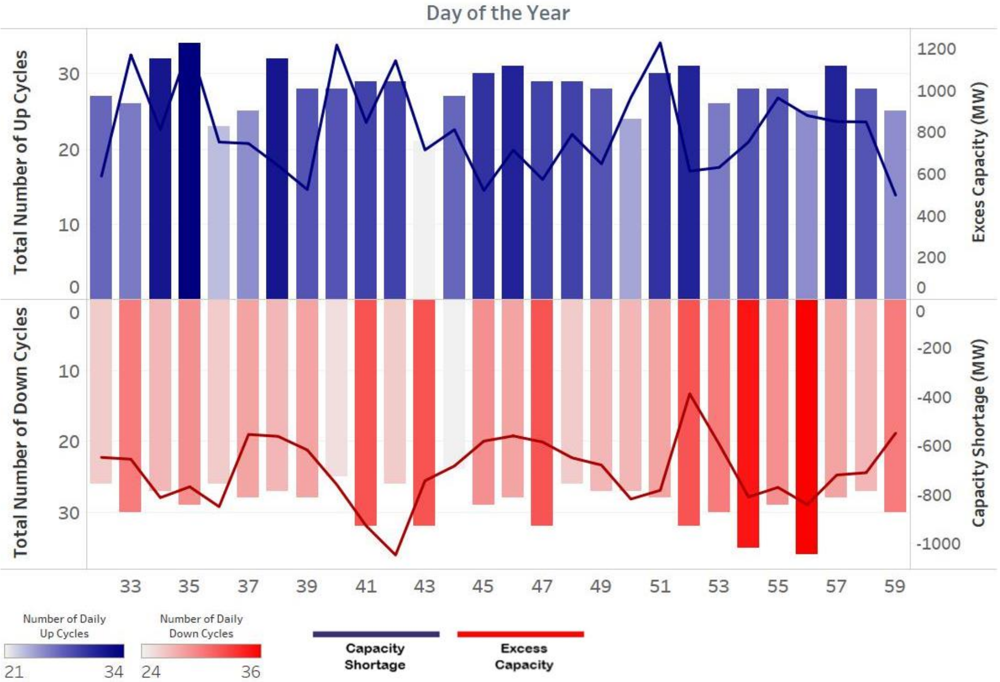


Figure 24 - Number of daily up and down cycles and maximum positive and negative forecasted capacity error (Feb 2015)

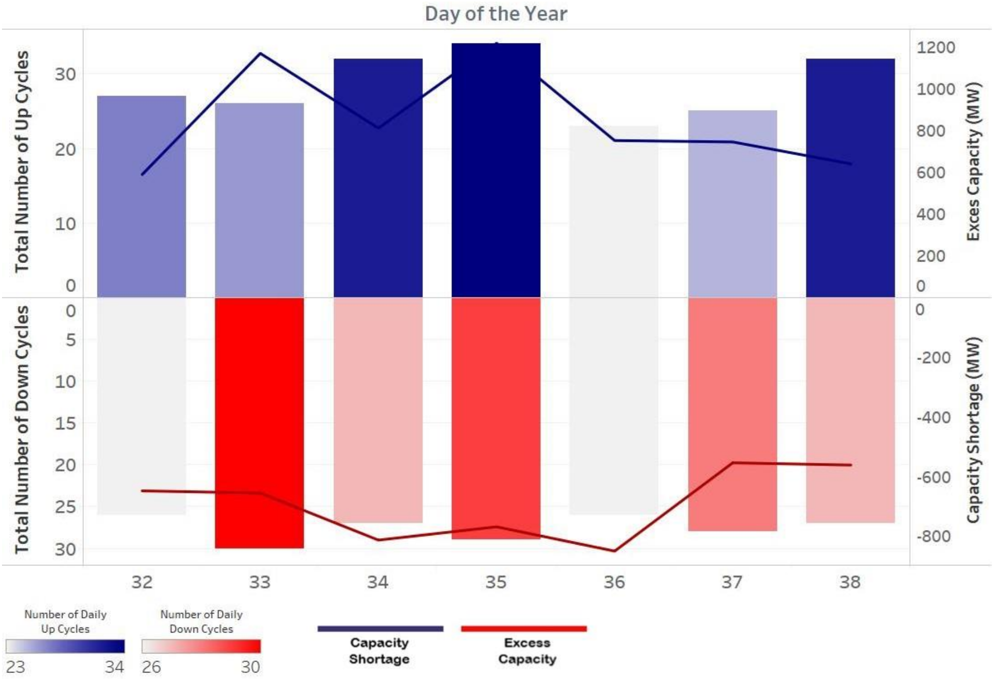


Figure 25 - Number of daily up and down cycles and maximum positive and negative forecasted capacity error (1st week of Feb 2015)

The charts show that the average number of daily up and down cycles is between 21 to 36. This translates to about 30 full cycle per day or more than 10,000 cycles per year. The ramping requirements are another design factor that needs to be taken into account. A system needs ramp-up when there is a capacity shortage in the system, and a ramp-down when there is excess capacity. The actual energy storage capacity required is the product of the ramp up/down capacity requirement, and the duration of the ramping event (cycle duration). The distribution of the number of ramp-up and ramp-down cycles (per year) for each cycle duration is shown in Figure 26.

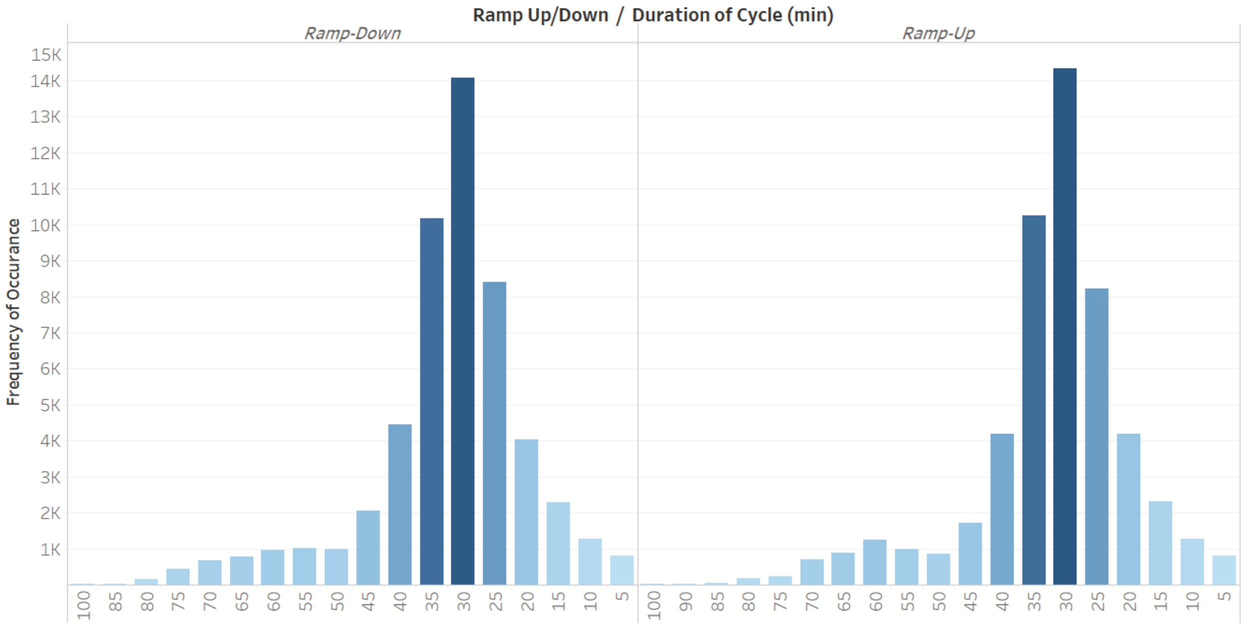


**Figure 26 - Annual frequency distribution of ramp up and ramp down event**

The graph indicates that the majority of both charge and discharge cycles last between 20 to 40 minutes.

### 6.1.4 Operation planning and scheduling

The product of power (charge or discharge) and cycle duration gives the energy capacity needed by the system at any time period. Figure 27 shows the annual aggregated distribution of capacity (excess/shortage) and cycle durations. This chart can be used in the design process in order to rapidly recognize the crucial capacity values, which provide coverage for the largest share of operating points.

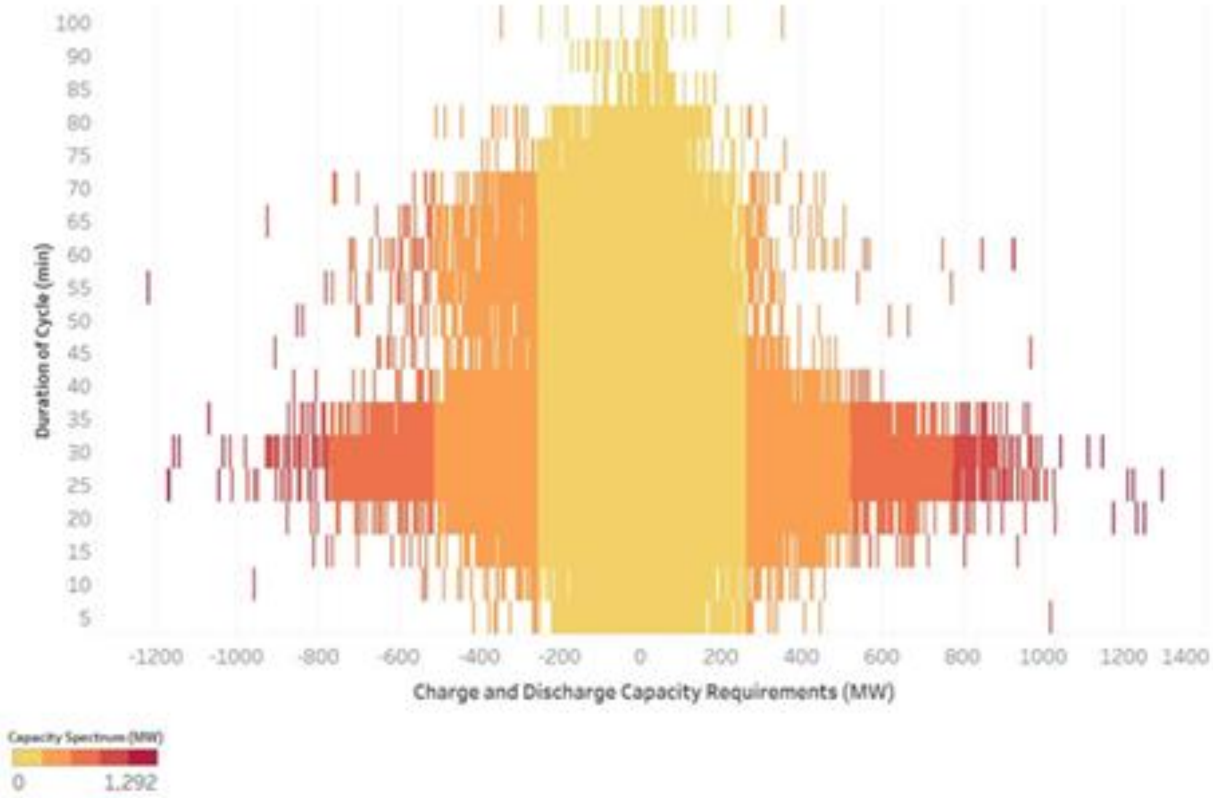


**Figure 27 - Cycle's charge and discharge storage capacity requirements vs. the duration of cycles (annual distribution)**

The pattern shows that the majority of charge and discharge events require a power capacity of 400 MW or less and also lasted between 15 to 45 minutes.

Another critical factor is the daily pattern (24hr cycle) of capacity requirements, reflecting how much charge and discharge capacity will be typically needed at each hour of the day, throughout the year. Figure 28 through Figure 31 show these patterns. The darker colors represent hours with higher charge/discharge capacity needs. The system and plant operators can plan their available capacity and market participation strategy based on the patterns that emerge in the chart. The chart shows the combined pattern of average cycle duration and the power capacity required at each hour of the year. This helps identify energy and by extension cavern capacity requirements, used for operational planning.

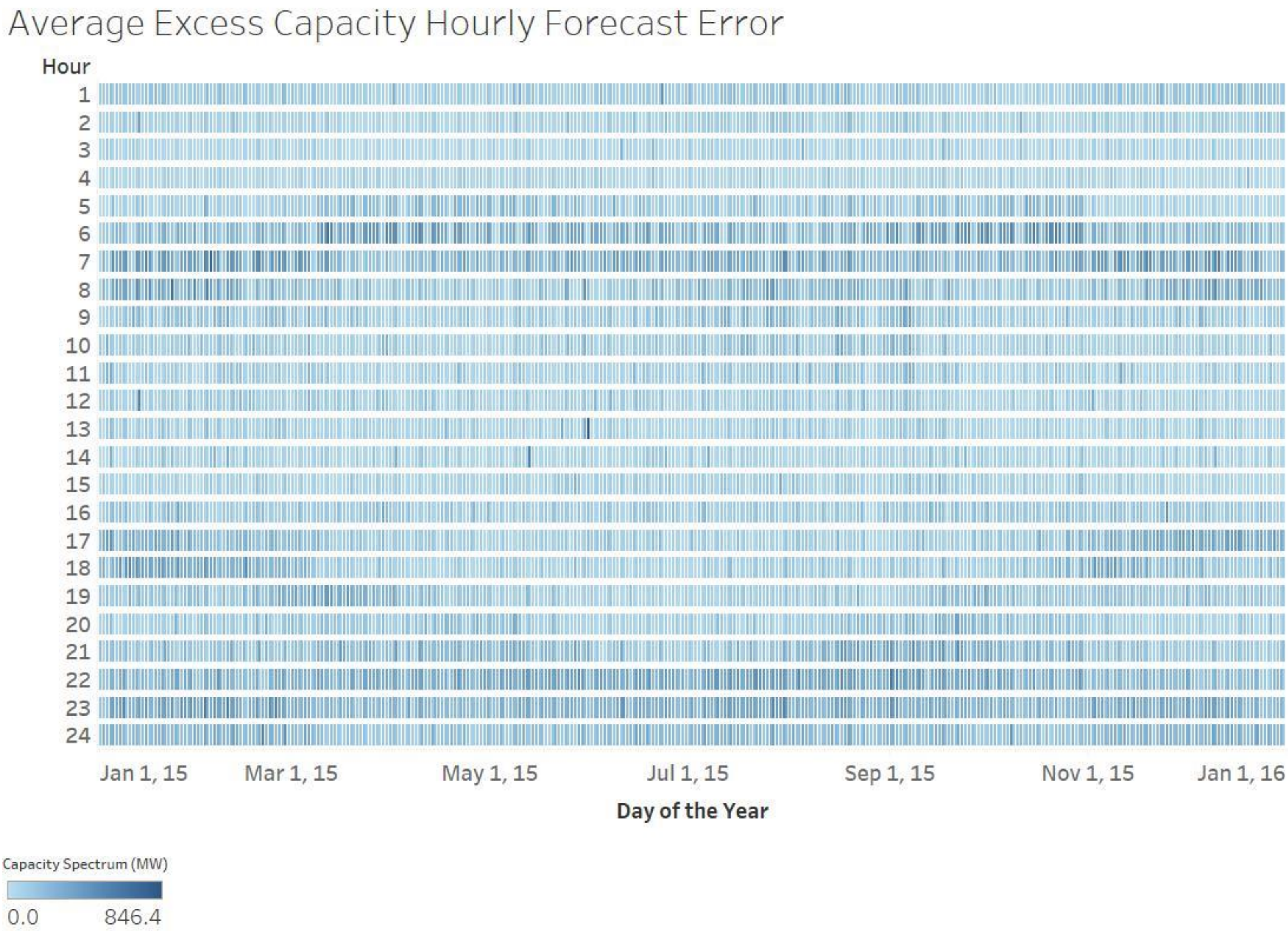


Figure 28 - Average hourly excess capacity due to forecast error

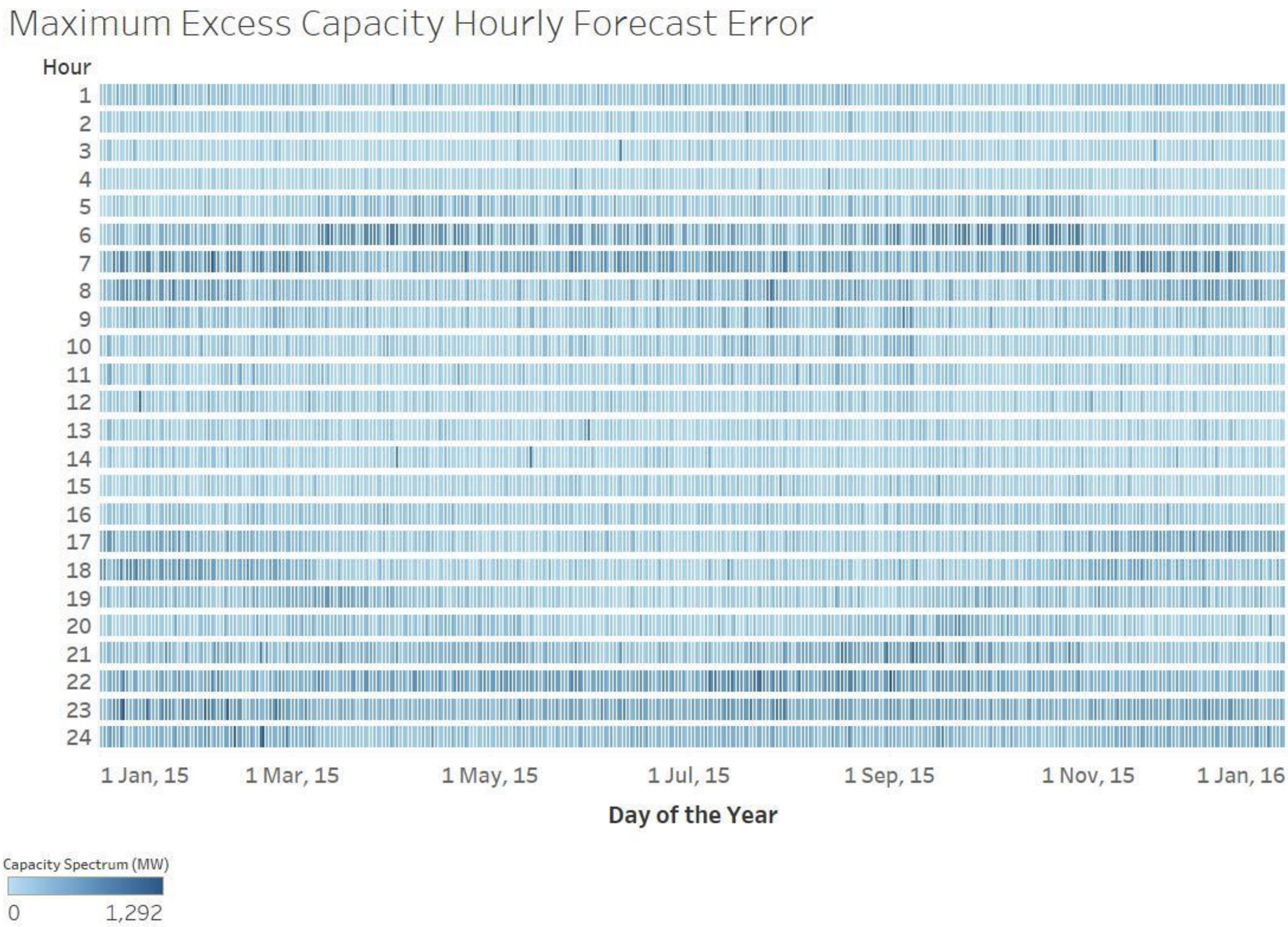


Figure 29 - Maximum hourly excess capacity due to forecast error

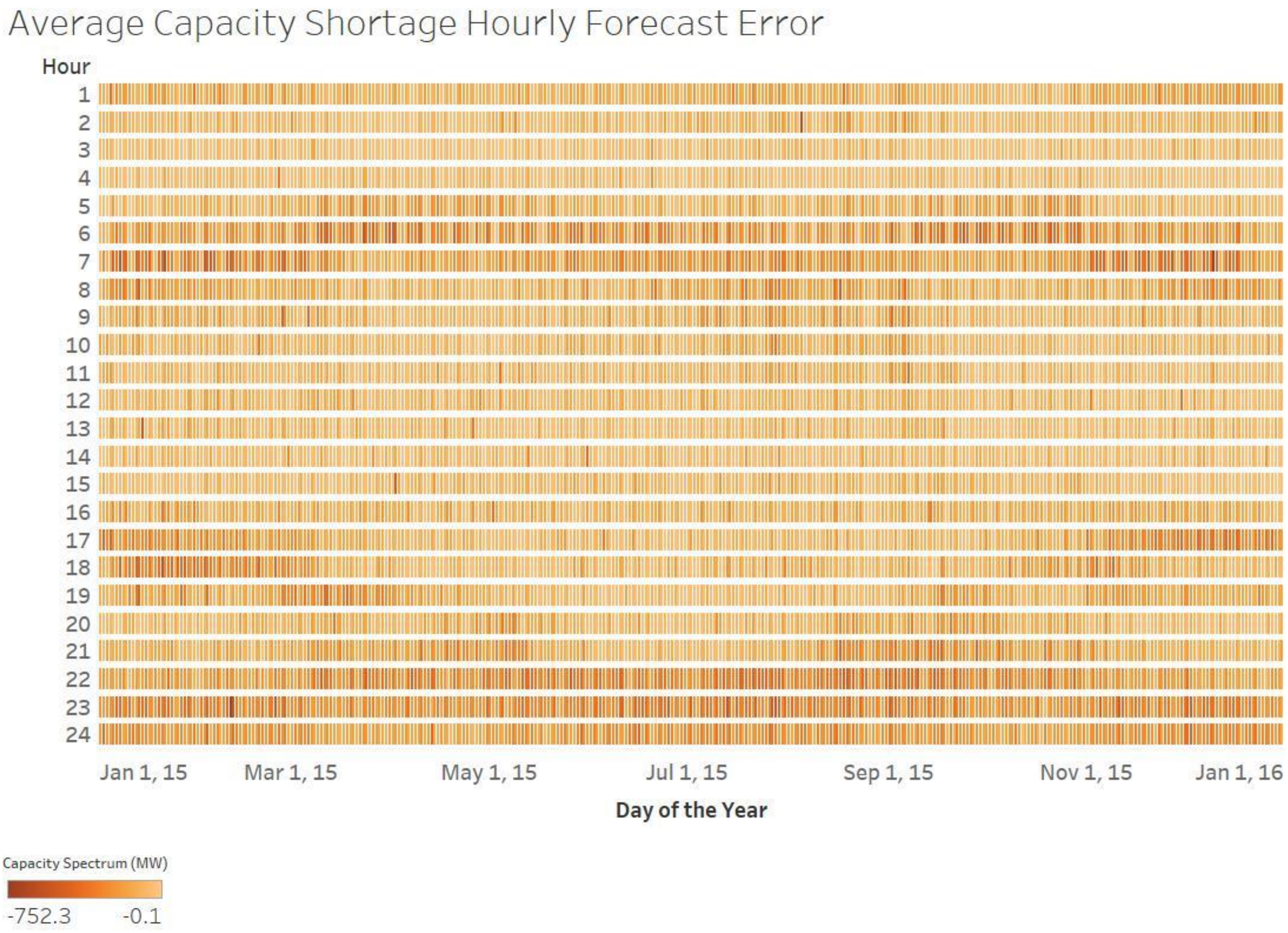


**Figure 30 - Average hourly capacity shortage due to forecast error**

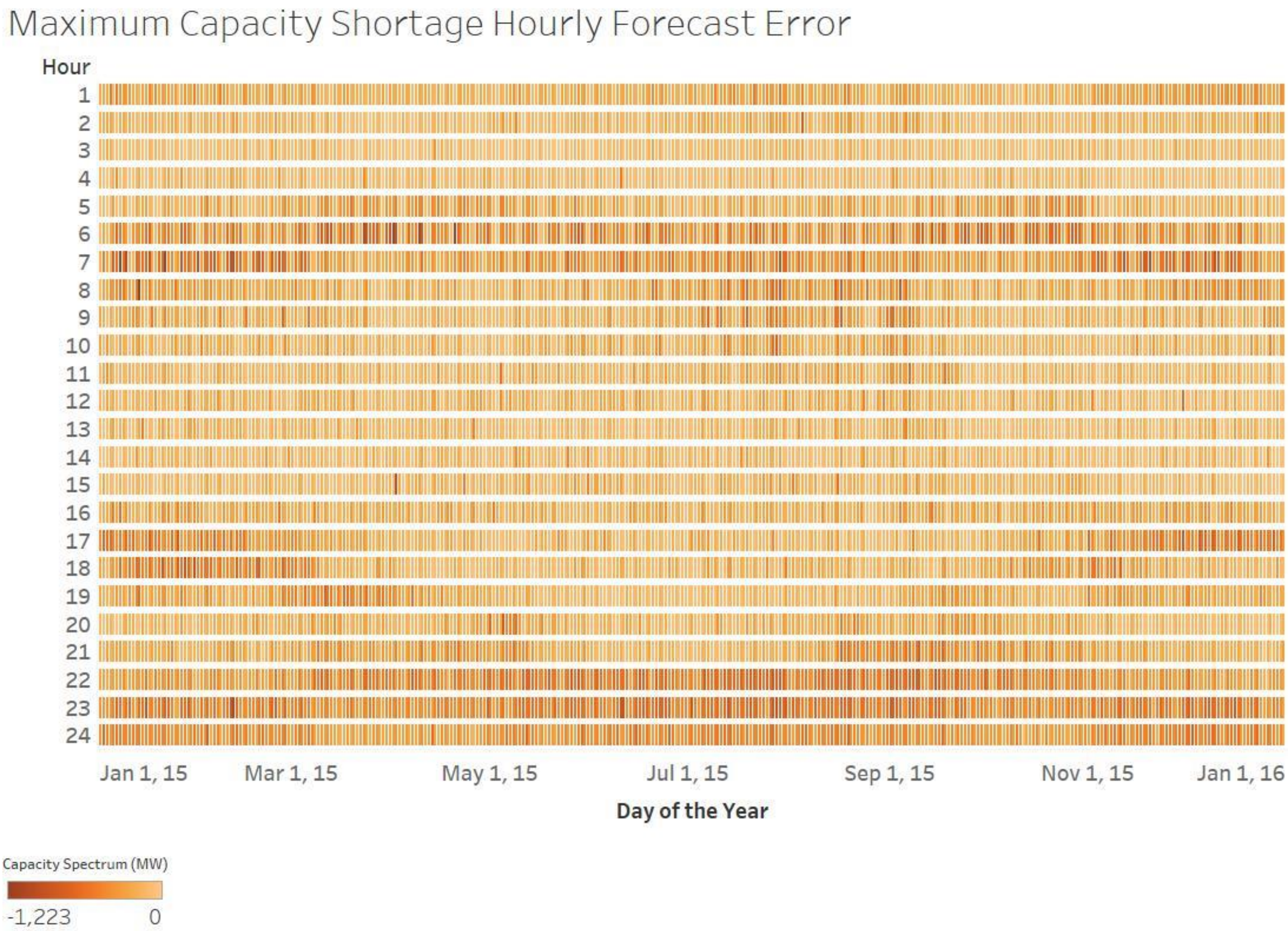


**Figure 31 - Maximum hourly capacity shortage due to forecast error**

The data shows that the majority of cycles are about 30 minutes long throughout the year. From the CAES operation perspective, this indicates the hours for higher availability (readiness). Given the average cycle time, having a minimum of 30 min capacity for both charge and discharge (SOC) would ensure that the system could participate and provide required service during those high demand periods.

The value of understanding this heat map pattern is that we can see there are certain hours of the day across the whole year where there are high capacity requirements (due to forecasting error). This can be used by the CAES operator to plan their charge and discharge schedule and how and when to participate in the market, to maximize their impact or financial gains.

### 6.1.5 Utilization

Figure 32 shows the utilization of all major grid-tied generation systems categorized by technology.

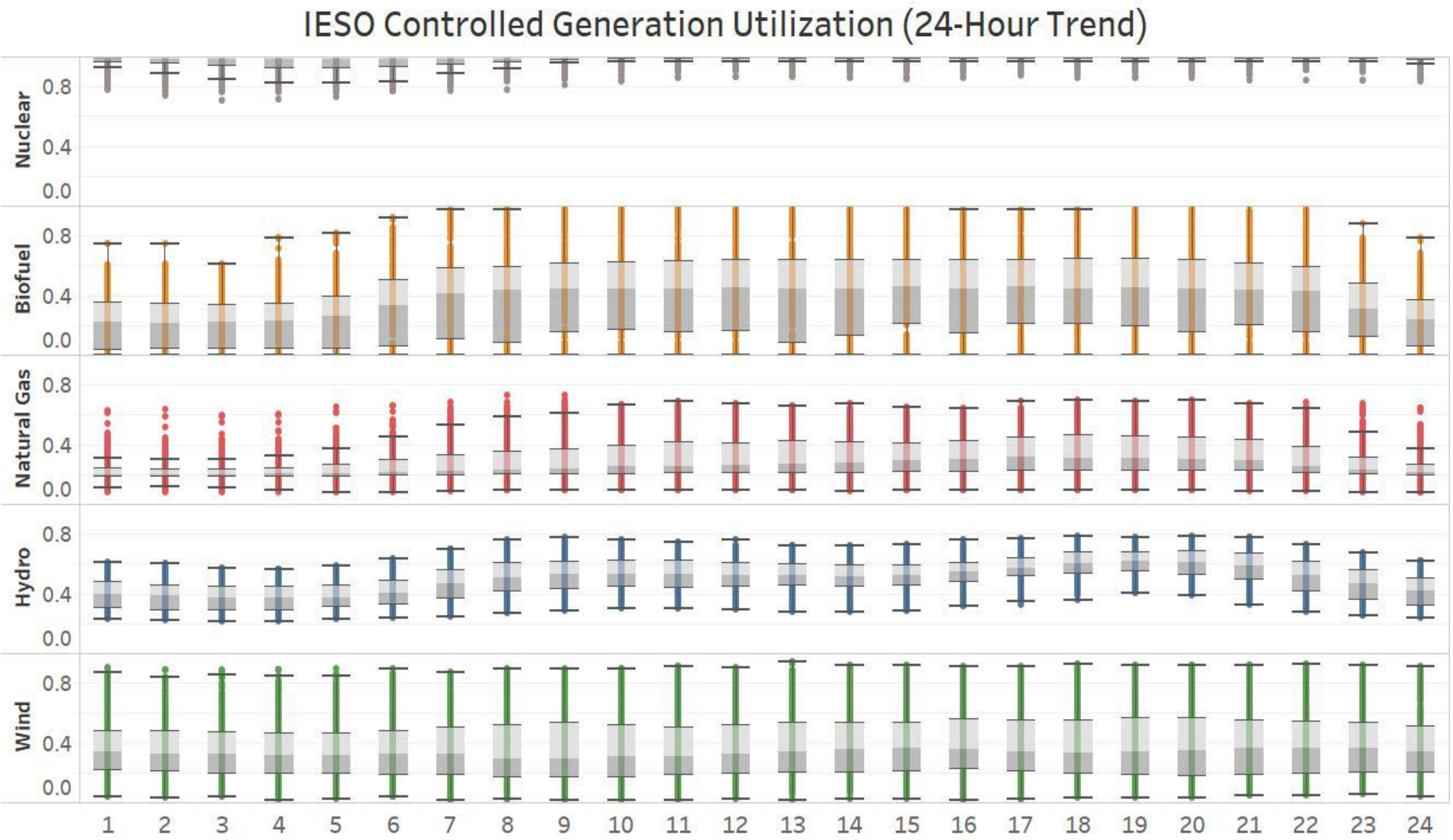


**Figure 32 - Annual utilization of IESO controlled generation 24hr trend**

The data shows that except for Nuclear, all other types are severely underutilized. The largest inefficiency (based on their share of total system capacity) is by gas power generators. The average utilization of these plants is just about 29%, meaning that most of the time, they are either operating at part-load conditions or not operating at all. In total, this amounts to 5910 MW of untapped capacity. Only during five out 8760 hours in the year the total capacity utilization of these plants reached above 70%, therefore improving this should be considered as a critical factor in designing CAES systems. Wind plants had a better overall average utilization at 37%; however, the width of the spread meant that there were many hours that wind was available but was not used (potentially due to curtailment).

## 6.2 CAES Design Criteria

The design criteria of A-CAES system needs to be altered based on the designated purpose and intended applications. As a result of this study, the following high-value potential applications are identified:

- Very Fast response (5 min) - Thermodynamic implication and system sizing (responsive to all ramp-up and ramp-down requests)
- Fast response (10 min or greater) - Spinning reserve participate and provide Spinning and non-Spinning reserve services and extra capacity
- Improved utilization rates (Gas-Wind)
- Design and operate to capture untapped capacity in the grid and improve the overall underutilization, reduce part-load operation, and reduce curtailment

In this study, the first two applications are considered and analyzed from the thermodynamic perspective. Assessment and analysis of other identified applications on the performance and design implications for A-CAES systems are suggested as valuable future research. The patterns that emerged in the above charts are then used to set up the simulation scenarios.

### 6.2.1 Thermodynamic implications for design of A-CAES system

A thermodynamic model developed based on commonly used mathematical sub-models for each component in the A-CAES system, is used to evaluate the system thermodynamic behavior and identify its boundaries (e.g., sizing of TES unit). The model is described in details in Chapter 3 of this thesis. From the statistical analysis of the grid 1-year performance, several scenarios for the CAES configuration, including the energy storage capacity and power capability, are considered for simulations, as presented in Table 12. Each scenario corresponds to a certain ramp rate (response time) for charging/discharging events. Accordingly, several annual drive cycles are defined based on the grid instantaneous (5-minute resolution) power shortage/excess rates. The amount of power shortage/excess is determined as the difference between the actual power supply and the projected value at each operating point. Power shortage translates into CAES discharge, and power excess means the CAES can be charged. The model is then utilized to simulate the CAES system performance and requirement.

**Table 12 - Scenarios considered for CAES thermodynamic simulation**

| **Cavern Capacity (MWh)** | **Compressor/Turbine Power Capacity (MW)** | **Idling Criterion (Response time)** |
|---|---|---|
| 200, 100 | 200, 110 | 5 min (very fast)<br>10, 15 min (fast) |

For the very fast response application, all operating points are considered in the simulation; i.e., the CAES system is covering 100% of the events. In the fast response applications, the events with a duration of less than 10 minutes are ignored and considered as idling.

Table 13 summarize the assumptions, governing equations, and constraints applied in the thermodynamic model. Depending on the power mode, the model calculates the cavern temperature, pressure, SOC, and the compressor/turbine mass flow rate. At each time step, the condition of the cavern is checked against the maximum/minimum allowed temperature and pressure. Accordingly, the amount of heat that can be extracted from the air (prior to storage) and stored in a TES, as well as the amount of heat required to reheat the air prior to expansion is calculated.

### Table 13 - Thermodynamics model assumptions, constraints, and equations

| Process | Assumptions/Constraints | Modeling approach | Equations |
|---|---|---|---|
| Compression | Steady state operation<br>Equivalent pressure ratio=100<br>Inlet pressure, temperature: retrieve from weather data | Isentropic process | $\dot{m}_{air,in} = \frac{Power_{Comp}}{C_{p1}T_{in}[\left(\frac{P_{Comp,out}}{P_{Comp,in}}\right)^{\frac{\gamma-1}{\gamma}} - 1]}$<br>$PV^{\gamma} = constant$ |
| Expansion | Steady state operation<br>Equivalent pressure ratio=100<br>Inlet temperature ≥ 3℃ | Isentropic process | $\dot{m}_{air,Turb,in} = \frac{Power_{Turb}}{C_{p,air}T_{Turb,in}[\left(\frac{P_{Turb,in}}{P_{Turb,out}}\right)^{\frac{\gamma-1}{\gamma}} - 1]}$<br>$PV^{\gamma} = constant$ |
| Cavern Charging & Discharging | $4\ MPa \le P_{cavern} \le 15\ MPa$<br>$288\ K \le T_{cavern} \le 323\ K$ | At each time step, apply the first law of thermodynamics to determine instantaneous cavern states | $m_{final}U_{final} - m_{initial}U_{initial} = m_{air,in}H_{air,in} - Q_{wall}$<br>$T_{final} = T_{initial} + \frac{U_{final} - U_{initial}}{C_v}$ |
| Thermal Energy Storage | Total heat capacity is equal to the total heat transferred from/to the system | At each time step, apply the first law of thermodynamics to determine instantaneous cavern states | $mC_p\frac{dT}{dt} = \dot{Q}_{chg} - \dot{Q}_{dischg} - \dot{Q}_{loss}$<br>$\dot{Q}_{chg} = m_{Cav,final}.h_{Cav,final} - m_{Cav,initial}.h_{Cav,initial}$<br>$\dot{Q}_{dischg} = \dot{m}_{dischg}.C_p(T_{Turb,in} - T_{Cav})$ |
| Thermal Energy Reservoir | Convection heat transfer between the air and cavern wall at constant temperature of 313 K | At each time step, apply the first law of thermodynamics to determine instantaneous cavern states | $\dot{Q}_{TER} = \dot{h}_{cav}.A_{cav}(T_{TER} - T_{Cav})$ |

## 6.3 Results and Discussion

An important implication of these findings is that the relationship between the sizing of different components of an A-CAES system and the overall coverage it provides is not 1 to 1. The results clearly indicate that under regular operating conditions, the majority of both power and energy needs can be covered by a much smaller CAES system than one designed to cover all events. These results confirm the importance of incorporating the end-user expectations in the design process of the CAES system.

The data analysis of Data-2 (from chapter 4) reveals the following insights about the A-CAES sizing and operation:

- **Cycle duration-** Short ramp up/down cycles represent a small portion of the total events. More than ~85% of cycles are at least 10 min or longer, with most of cycles being around 30 min long.
- **Number of cycles-** It was observed that considering all forecasting errors a hypothetical EES facility will go through approximately 50 cycles per day. The cycles are distributed almost equally for both charge and discharge events. These numbers are much higher than the cycling values used in the majority of studies related to EES in general and CAES in particular. Also, more than 80% of the time the number of the hourly up and down cycle was limited to 1 or less.

### 6.3.1 Power and Energy Capacity requirements:

The data shows that under extreme situations 200 MW compression and generation capacity is sufficient for covering 50% of all ramping events. Furthermore, under average conditions, the required capacity is reduced to 108 and 110 MW respectively to provide the same coverage. The storage capacity (MWh) is a product of the power capacity times the duration for which the system needs to operate. Since 90% of all charging and discharging events last 60 min or less, we can estimate that an energy capacity of 200 MWh, should be sufficient enough for about 50% of all ramping cycles under extreme conditions.

### 6.3.2 Thermodynamics simulation results and impact factors

Figure 33 through Figure 35 illustrate the pressure, temperature, and SOC profiles of the A-CAES system under twelve operating scenarios. Each scenario results in a different set of thermodynamics states and cycling profiles, as well as required TES capacity and response rate. Higher resolution copies of the above figures are included in Appendices D.

### 6.3.3 TES rates observations

**Charge:** The heat rates are universally higher in all scenarios compared to discharge mode, reaching $2.9463 \times 10^7 \frac{kJ}{min}$. The maximum heat rate is reached when the sizing of the system is at its highest (200 MW compressor & turbine, and 200 MWh cavern). It is observed that the maximum and range of heat rate is a function of the size of the cavern. For the same compressor sizing, the maximum heat rates for the smaller cavern (100 MWh) is lower than the maximum heat rate for the larger cavern. The difference in the frequency of charge events (heat addition to TES) is not significantly different across fast (10 min) and very fast scenarios (5 min). The size of cavern has an impact on the shape of frequency distribution. It is observed that as the cavern size is reduced, the distribution curve becomes skewed towards lower rates. This observation is valid for both fast and very fast scenarios.

**Discharge:** While the heat rate values are lower in discharge mode (only reaching $9.4760 \times 10^6 \frac{kJ}{min}$), the frequency of heat rates at discharge is monotone and higher. Such a distribution means that the turbine sizing is the determining factor on the heat rates rather than the cavern sizing. This is reasonable, since for short cycle durations assuming steady-state operation, the heat rate provided to the turbine will be constant and a direct function of the turbine sizing and mass flow rate. Assumption of short cycle durations is in agreement with the result of data analysis presented in section 3. Essentially, this means that decreasing the turbine size results in lower TES discharge heat rates.

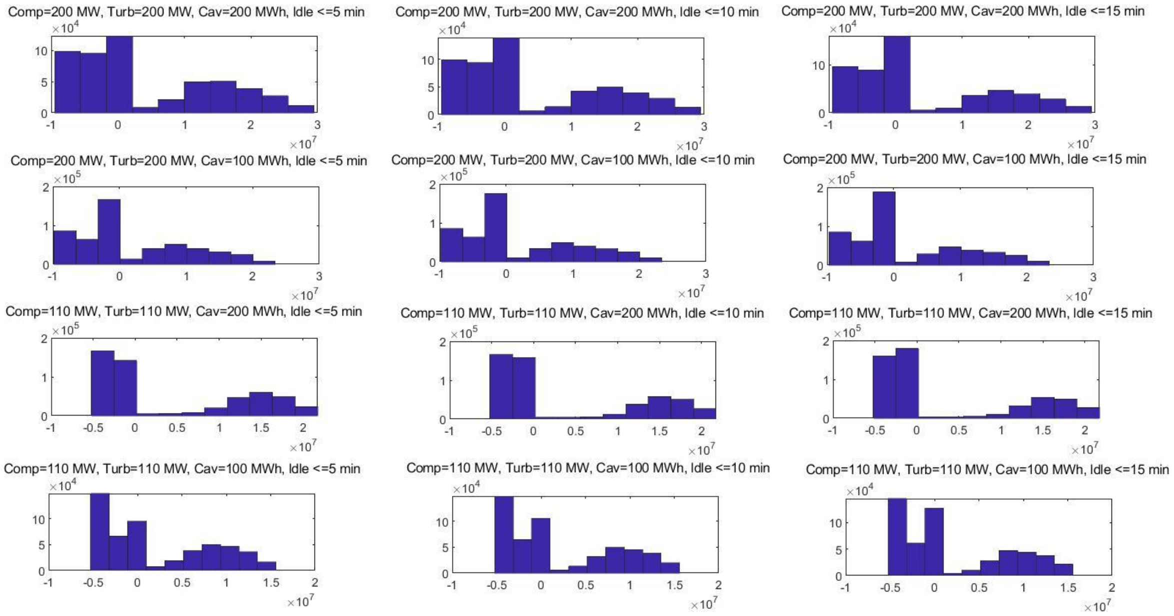


**Figure 33 - Thermal Energy Storage (TES) heat inflow and outflow rate**

### 6.3.4 Cavern pressure observations

Across all scenarios, the maximum pressure reached is ~ 11 MPa. When the system is operating under slower applications, the cavern experiences less pressure variations and a more uniform pressure distribution. This is an important point to consider in the geomechanical design of the cavern.

The sizing of cavern has a direct impact on pressure frequency distribution. A larger cavern means that the majority of the time the cavern is operating in the 10 MP range. While, if the size of the cavern is cut in half, the cavern pressure hits the lower limit of 4MP very often. This correlates with the fact that during the discharge process, a smaller cavern will discharge faster. This results in a bimodal pressure distribution shape, which is both top and bottom heavy, showing that the cavern operates under high-stress values the majority of times. However, it is observed that reducing the system response rate (5 min to 10 min to 15 min) will shift the distribution towards a unimodal shape and moves the peak frequency from the absolute extreme pressure levels to mid-level pressures.

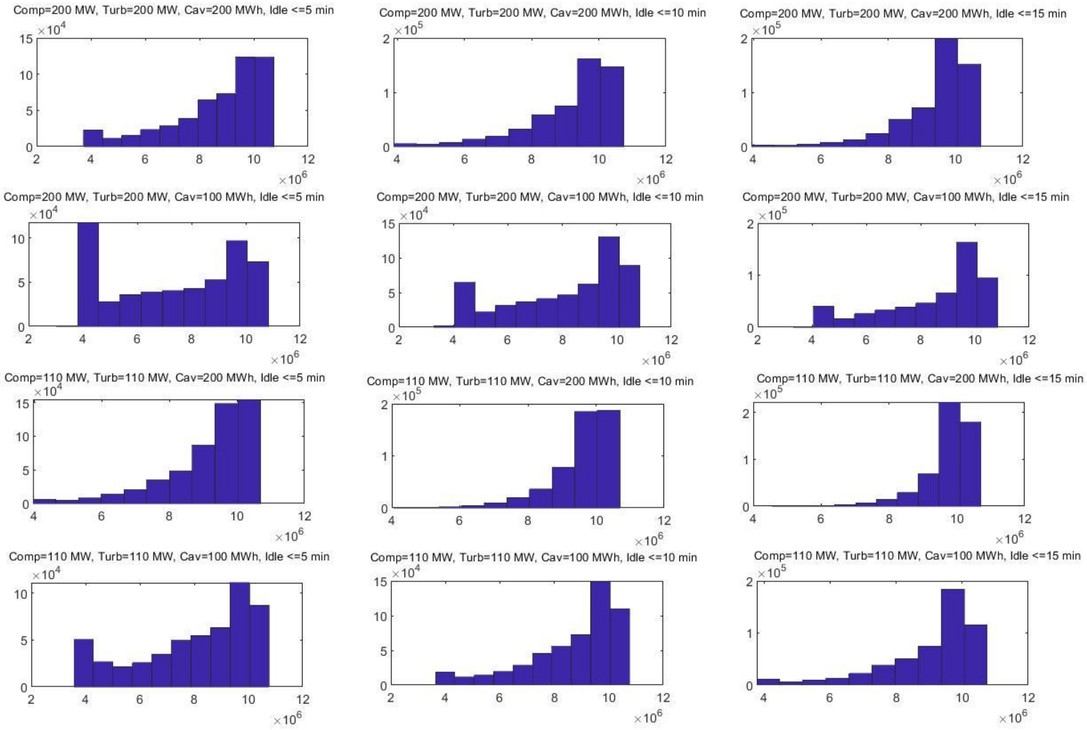


**Figure 34 - Cavern pressure change observation**

### 6.3.5 Cavern SOC observations

SOC distribution follows a similar pattern compared to pressure distribution. In a fast response system, the SOC is fluctuating with a higher frequency between the fully charged and discharged level. As more idle points are added to the system drive cycle, the cavern tends to operate mostly at full-charge status. From the geo-mechanics point of view, it would be best to maintain the SOC at mid-levels to avoid creeping, due to extreme high or low pressures. In this sense, applications with lower response rates are preferred. Another observation, as shown in Table 14, is that the variations in the number of operating points covered under 5, 10, and 15 minutes regiments are less than 10%. This trend changes significantly if the response time is further slowed down to 30 minutes, i.e., from about 55% to 22%. Therefore, the total system utilization is not affected by adopting a fast (15 min) versus a very fast system (5 min). This shows that the performance requirement of the system and stress levels on the system can be lowered without a significant loss of the total coverage. Therefore, designing the adiabatic CAES system for fast applications would be more feasible from both technical and economic perspectives. Such a design would significantly improve the applicability of A-CAES systems compared to the existing designs, without adding much more complexity to the system.

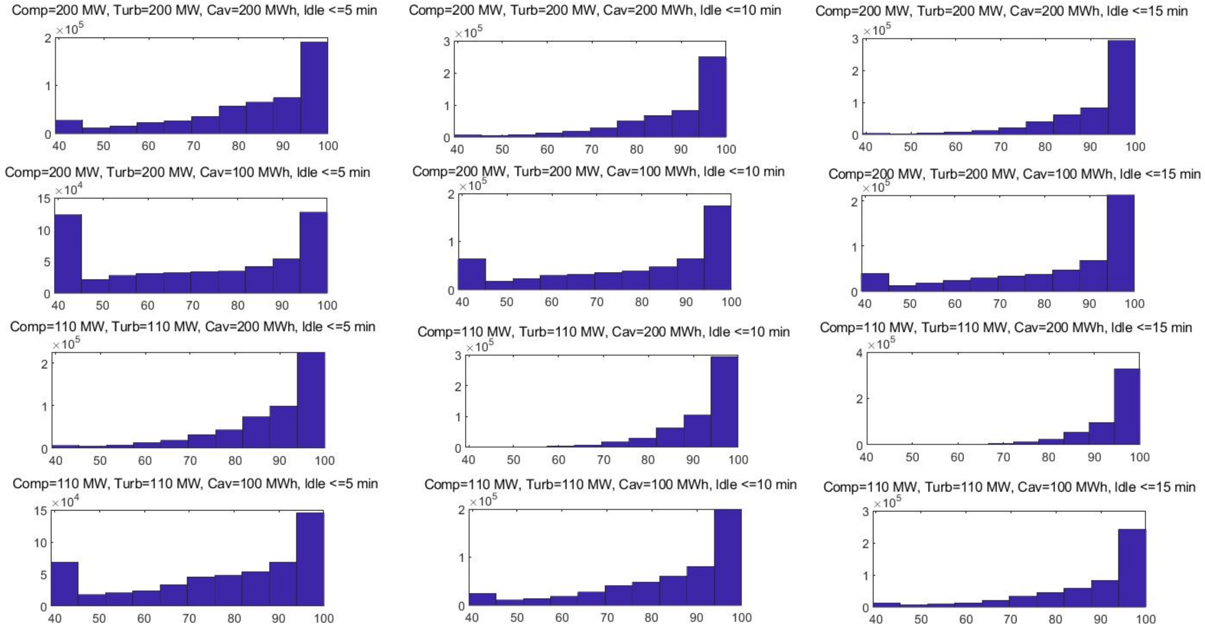


**Figure 35 - State of Charge (SOC) change observation**

**Table 14 - Coverage rate versus type of application**

| **Cavern Size (MWh)**<br>**Compressor/Turbine Rating (MW)** | **Very Fast (5 min)** | **Fast (10 min)** | **Slower response time**<br>**(15, 30 min)** | |
|---|---|---|---|---|
| 200- 200/200 | 57% | 56% | 53% | 21.55% |
| 200- 110/110 | 51% | 53% | 51% | 21.58% |
| 100- 200/200 | 57% | 55% | 52% | 21.52% |
| 100- 110/110 | 53% | 54% | 52% | 21.50% |

## 6.4 Summary

The results of the long term grid data analysis are shown and described. Using visualization, the major patterns and significant factors are identified and discussed. A thermodynamic analysis is performed based on the findings from the data analysis section, and results and implications for design of CAES systems are discussed. It was observed that across multiple CAES system configurations, there is no significant difference in coverage between very fast (5 min) and fast (10 min) applications.

# Chapter 7

# Conclusions and Future Works

This chapter summarizes the conclusions and main findings of the thesis and presents possible directions for future studies.

## 7.1 Conclusions

This thesis introduced a novel user-centered design approach for designing CAES systems called CAES-by-Design. Additionally, data-driven methods were employed to understand requirements for the design and integration of A-CAES systems into the electrical grid. Ontario power grid data was utilized as a test case. A comprehensive analysis of the high-fidelity annual data of the Ontario grid, including data of supply and demand, was conducted. Trends of power generation and demand were studied to identify the performance requirements of a CAES system to provide high-value services, with consideration for minimizing the cost, emissions, and improving system efficiency. Thermodynamic behavior of an A-CAES was modeled and analyzed under multiple operating scenarios, providing an insight into the impact of component sizing on the performance requirements. It was shown that analysis of grid requirements is critical to identifying A-CAES system design and performance parameters. One major advantage revealed as part of this work is CAES ability to be categorized differently than before. Following observations were also made:

1. There is no unique best design for a CAES system; but rather, it entirely depends on the targets set by the user, in terms of the energy capacity and efficiency levels to be fulfilled. Therefore, a user-centered approach best fits when designing a CAES system.
2. Depending on the type of grid services and the amount of coverage of the total power and energy requirement that a CAES system is going to provide, component sizing and operating parameters are greatly impacted. For example, depending on the cavern size and the number of charge and discharge cycles, the cavern wall design requirements, in terms of lifecycle and fatigue stress vary significantly.
3. The size versus service and energy coverage ratio is not a one to one relationship. This means that a properly sized CAES system is able to provide (capture) a significant portion of the required (available) power and energy. For the same reason, a large number of high-value grid services could be provided at a fraction of the maximum required operating parameters of a traditionally designed CAES system.
4. The charge, discharge, and idle cycle times have a significant impact on the sizing of the TES system and performance criteria. In addition to that, the rate by which the heat needs to be removed from and added to the cavern air determines the required operating

characteristics of the TES.

5. It can be determined from the above analysis that maximum sizing of the cavern and compressor/turbine is not necessarily the best strategy in designing a CAES system. As such, taking the lower end of the energy and power capacity requirement should be the basis for consideration in the overall sizing, number of plants, and location. Failing to take this into account, can result in overestimating the system requirement, which in turn can impact the feasibility of CAES projects.
6. If CAES is used to directly respond to the Ontario grid requirements, the duration in which the cavern has to be charged or discharged is less than two hours. This implies that compared to a typical cavern size of 300,000 cubic meters (e.g., Huntorf), systems with one-tenth of the cavern size could be capable of covering the majority of charge and discharge events.
7. Data analysis shows that the sizing of the compressor and turbine should not be based on maximum forecasting error points, as it results in a highly underutilized and oversized system. For example, 90% of all charge and discharge events can be covered by a system at a quarter of the size of a system designed for the maximum point.

## 7.2 Future Works

Based on the findings of this thesis, the following future works are suggested:

1. Exergy analysis can be performed for each scenario, and the results be compared to gain a better understanding of how system utilization differs under each of these scenarios.
2. A steady-state thermodynamic model was developed for this study. It is suggested that the model can be expanded to include transient operations.
3. Employ techno-economical and energy optimization algorithms to enhance the performance feasibility of CAES systems designed based on the new approach introduced in this thesis.
4. Collect and compare long-term grid data from multiple years and perform statistical analysis to identify multi-year patterns.
5. The current study is based on historical data. Sensitivity analysis can be conducted to understand and account for any major changes to the grid in the future and design for uncertainty.

## 7.3 Contributions

The main contributions and outcomes of this thesis and study are:

- Developed a new user-centered approach for designing A-CAES systems
- Analyzed the grid performance and behavior using one full year worth of high-resolution data
- Identified the system behavior and design requirements under realistic operational conditions

### Journal and Conference Papers

1) CAES by Design: A User-Centered Approach to Designing Compressed Air Energy Storage (CAES) Systems for Future Electrical Grid - A Case Study for Ontario (*Published*)
2) A Comprehensive Data-Driven Study of Electrical Power Grid and Its Implications for the Design, Performance, and Operational Requirements of Adiabatic Compressed Air Energy Storage (A-CAES) Systems (*Under Review*)
3) Study of Ontario Electrical Grid Challenges and Feasibility of Compressed Air Energy Storage (CAES) – A Lifecycle Cost Approach (*Ready for Submission*)

### Poster and Presentation

- Sarnia-Lambton Energy Symposium (2017)

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## Appendices (A)

The following is a list an description of the most common ancillary services:

**Energy arbitrage including load following:** This service is designed to take advantage of the price difference between peak demand prices and the average or low peak energy prices to store large amount of energy during the low demand period where there is surplus generation and then sell back that energy to the grid as a dispatchable source during peak hours when price of electricity is high. Load following is embedded into the arbitrage system, which allows for a merit-order approach to dispatching in the electricity grid. The actual service could include ramp up, ramp down, or similar flexible ramping products. It is used to manage the difference between day ahead scheduled generator output, actual generator output, and actual demand [32]. The time scale requirement for dispatching these services is about 15 minutes or less, which makes it a suitable application for most energy storage technologies, including CAES.

**Frequency regulation:** This is an ancillary service required to control power system frequency and also maintain the balance of supply and demand on a second by second timescale [47]. Due to the nature of this service and fast response time requirement, CAES is not best suited for providing this service.

**Spinning and non-spinning reserve:** This service refers to extra capacity available on demand at any point to provide uninterruptable supply in case of sudden supply shortage such as an unplanned outage. Spinning reserve is a generating capacity that is active and ramped up and therefore can be dispatched immediately. Non-spinning reserves are similar to spinning reserves with the main difference being that they are on standby but once called upon they can ramp up very quickly to their full load capacity and be dispatched. Every ISO is mandated to maintain a minimum level of spinning and non-spinning reserve (operating reserve) to comply with the North America electric reliability cooperation (NERC) compliance registry. The total capacity of the operating reserve is generally equal to or higher than the system’s largest generator with minimal power and frequency variation [32]. Spinning and operating reserves are especially well suited for CAES due to its seizing and scalability advantages.

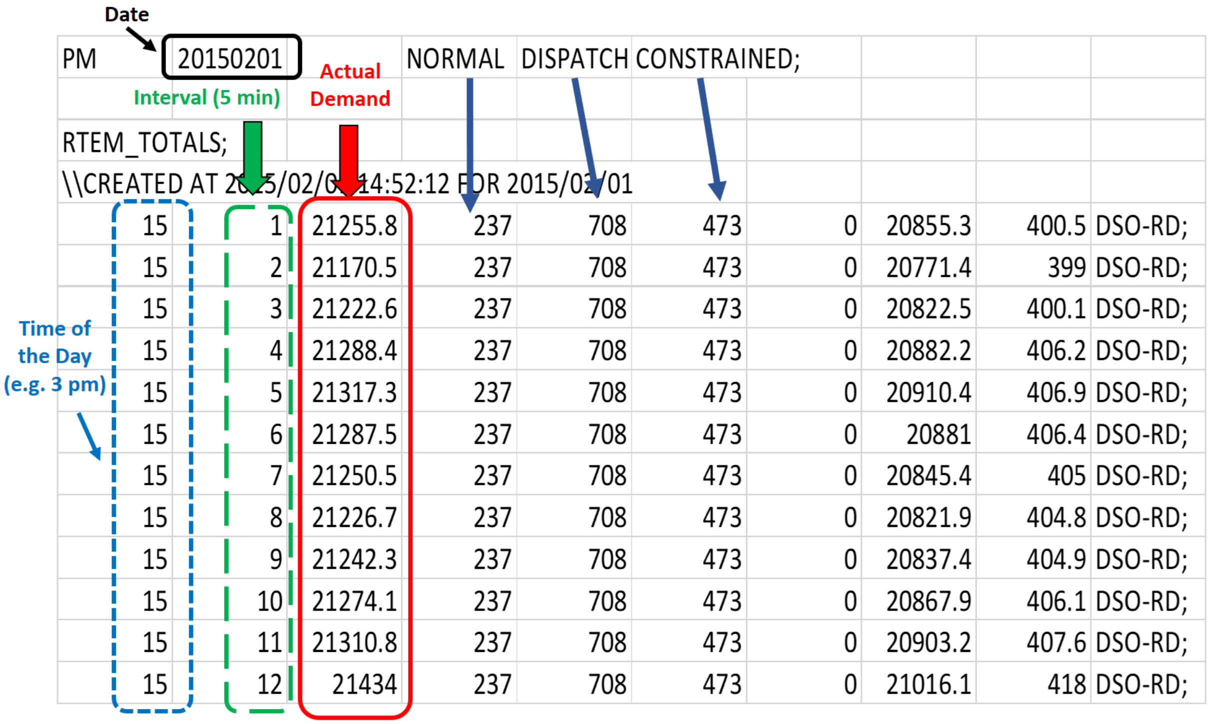
**Voltage support:** During the transmission and distribution of electric flow, the voltage can drop due to many reasons, including the changes in the load, which is mainly inductive. Therefore, voltage support is required to match both real and reactive power supply and demand in order to ensure reliable and smooth operation of the grid.

| |
|---|
| **Black start:** This service refers to the capability of starting generators from full blackout, or when there is not enough electricity in the grid to feed the start-up of the generators. Typically, Diesel generators are used in these applications; however, CAES systems can easily provide this type of service. In fact, black start capability was one of the main design criteria's and applications in construction of the Huntorf CAES plant in Germany. |
| **Resource adequacy:** This could include applications such as peak shaving and asset utilization. Peak shaving allows the grid operator to dispatch energy from storage units during high peak demands without increasing the total number of generating power to meet the peak requirements for a short duration of time. By the same token asset utilization means that many of the existing generators within the grid will be able to operate for longer hour and utilize the overall capacity as their surplus power can then be stored and used later during the peak period. Large scale energy storage technologies such as CAES are optimal choice for use in this type of applications. |
| **Transmission congestion relief:** Lack of sufficient transmission capacity can result in congestion. This happens when many generators need to access the same transmission line to respond to IESO's request for dispatch. When there is an increase in demand downstream, transmission congestion relief carries a cost for all generators, which increases the overall cost of electricity. If congestion is not managed, it can result in the failure of the power system, resulting in an interruption such as blackout. Storage systems can be used to reduce the stress on the transmission line by temporary storing the energy closer to the load or generation area. |

# Appendices (B)

Following are samples of "Supply" (**Figure 36**) and "Demand" (**Figure 37**) data table as provided by IESO:

***[Data is for the 15$^{th}$ hour of the 1$^{st}$ day of Februrary 2015 - (2015-02-01 @ 3 pm)]***



| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| PM | 20150201 | | | NORMAL | DISPATCH | CONSTRAINED; | | | | |
| | | | | | | | | | | |
| RTEM_TOTALS; | | | | | | | | | | |
| \\CREATED AT 2[illegible]5/02/0[illegible] 14:52:12 F[illegible]R 2015/02[illegible]01 | | | | | | | | | | |
| | 15 | 1 | 21255.8 | 237 | 708 | 473 | 0 | 20855.3 | 400.5 | DSO-RD; |
| | 15 | 2 | 21170.5 | 237 | 708 | 473 | 0 | 20771.4 | 399 | DSO-RD; |
| | 15 | 3 | 21222.6 | 237 | 708 | 473 | 0 | 20822.5 | 400.1 | DSO-RD; |
| | 15 | 4 | 21288.4 | 237 | 708 | 473 | 0 | 20882.2 | 406.2 | DSO-RD; |
| | 15 | 5 | 21317.3 | 237 | 708 | 473 | 0 | 20910.4 | 406.9 | DSO-RD; |
| | 15 | 6 | 21287.5 | 237 | 708 | 473 | 0 | 20881 | 406.4 | DSO-RD; |
| | 15 | 7 | 21250.5 | 237 | 708 | 473 | 0 | 20845.4 | 405 | DSO-RD; |
| | 15 | 8 | 21226.7 | 237 | 708 | 473 | 0 | 20821.9 | 404.8 | DSO-RD; |
| | 15 | 9 | 21242.3 | 237 | 708 | 473 | 0 | 20837.4 | 404.9 | DSO-RD; |
| | 15 | 10 | 21274.1 | 237 | 708 | 473 | 0 | 20867.9 | 406.1 | DSO-RD; |
| | 15 | 11 | 21310.8 | 237 | 708 | 473 | 0 | 20903.2 | 407.6 | DSO-RD; |
| | 15 | 12 | 21434 | 237 | 708 | 473 | 0 | 21016.1 | 418 | DSO-RD; |

**Figure 36 - Supply data from IESO (5 min)**

| Date | Hour | Total Market Demand | Ontario Demand |
|---|---|---|---|
| 1-Feb-15 | 15 | 21273 | 17901 |

**Figure 37 - Demand data from IESO (Hourly)**

The calculation process for each of the main derived data points for demand and cycle analysis is listed below:

### Difference between Actual vs. Projected demand (MW):

The value of Actual Demand in **Figure 36** is deducted from the value of the projected Total Market Demand in **Figure 37** for each time interval (5 min equivalent to 12 intervals per hour) of each hour (24) of each day (356). If the results are negative (Actual > Projected), it means that there was a ***Capacity Shortage*** in the grid. On the other hand, if the results are positive (Actual < Projected), it shows that there was ***Excess Capacity*** in the system. This is also called ***Forecasted Capacity Error***.

### Cycle Up/Down (Ramp Up/Down):

In each time interval, if the (Projected - Actual) is negative, this translates to a Cycle Up (Ramp Up) signal. Conversely, if (Projected - Actual) is positive, it is considered a Cycle Down (Ramp Down) signal. All consecutive cycle up/down signals count as a single cycle up/down event.

### Cycle duration:

The sum of all consecutive cycle up or cycle down intervals equals the duration of that particular cycle. For example, if there are four consecutive cycle up intervals, followed by three consecutive cycle down intervals, and then another six consecutive cycle up intervals, the result is:

$$1\ \text{Cycle Up}\ (4 \times 5\ \text{min} =\ 20\ \text{min}),\ 1\ \text{Cycle Down}\ (3 \times 5\ \text{min} =\ 15\ \text{min}),$$

$$1\ \text{Cycle Up}\ (6 \times 5\ \text{min} =\ 30\ \text{min})$$

The total result is 2 Up Cycles and 1 Down Cycle. demonstrates the calculated fields for the sample data.

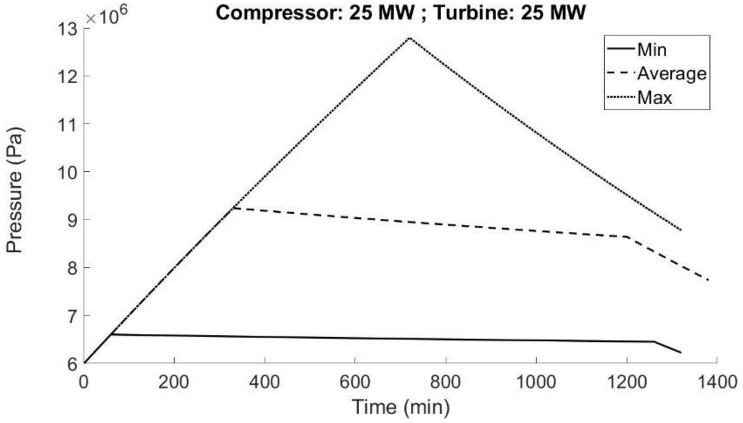
## Table 15 - Sample calculations

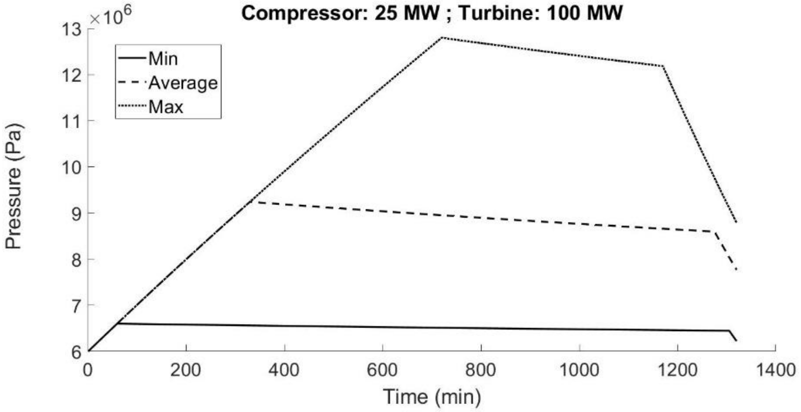
| Date | Hour | Interval | Total Market Demand (Projected) (MW) | Actual Demand (MW) | Difference between Projected and Actual Demand (MW) | Excess OR Shortage | Total Number of Up Cycle | Total Number of Down Cycle | Duration of Cycle (min) |
|---|---|---|---|---|---|---|---|---|---|
| 1-Feb-15 | 15 | 1 | 21273 | 21255.8 | 17.2 | Excess | 0 | 1 | 15 min |
| 1-Feb-15 | 15 | 2 | 21273 | 21170.5 | 102.5 | Excess | 0 | 1 | |
| 1-Feb-15 | 15 | 3 | 21273 | 21222.6 | 50.4 | Excess | 0 | 1 | |
| 1-Feb-15 | 15 | 4 | 21273 | 21288.4 | -15.4 | Shortage | 1 | 1 | 15 min |
| 1-Feb-15 | 15 | 5 | 21273 | 21317.3 | -44.3 | Shortage | 1 | 1 | |
| 1-Feb-15 | 15 | 6 | 21273 | 21287.5 | -14.5 | Shortage | 1 | 1 | |
| 1-Feb-15 | 15 | 7 | 21273 | 21250.5 | 22.5 | Excess | 1 | 2 | 15 min |
| 1-Feb-15 | 15 | 8 | 21273 | 21226.7 | 46.3 | Excess | 1 | 2 | |
| 1-Feb-15 | 15 | 9 | 21273 | 21242.3 | 30.7 | Excess | 1 | 2 | |
| 1-Feb-15 | 15 | 10 | 21273 | 21274.1 | -1.1 | Shortage | 2 | 2 | 15 min |
| 1-Feb-15 | 15 | 11 | 21273 | 21310.8 | -37.8 | Shortage | 2 | 2 | |
| 1-Feb-15 | 15 | 12 | 21273 | 21434 | -161.0 | Shortage | 2 | 2 | |

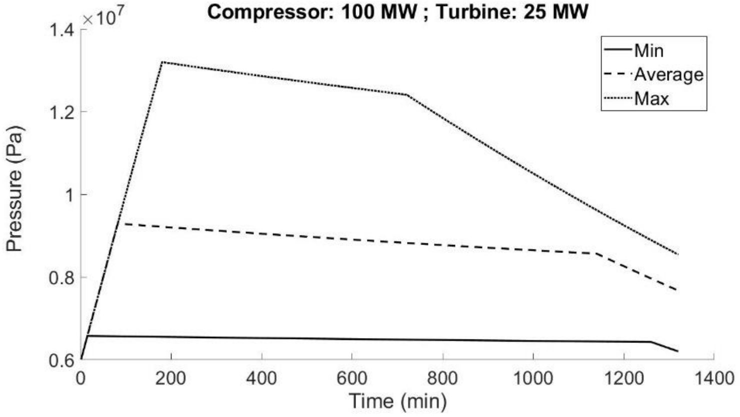
| | |
|---|---|
| **Maximum Capacity Forecasted Error (Excess)** | **102.5** |
| **Maximum Capacity Forecasted Error (Shortage)** | **-161.0** |

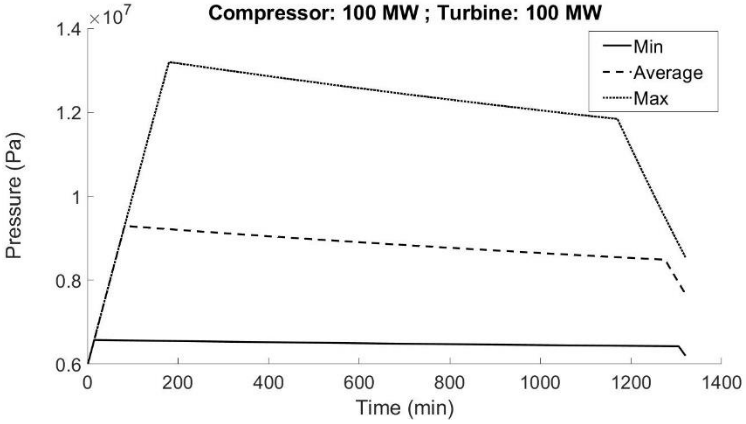
# Appendices (C)

## Pressure (Pa)

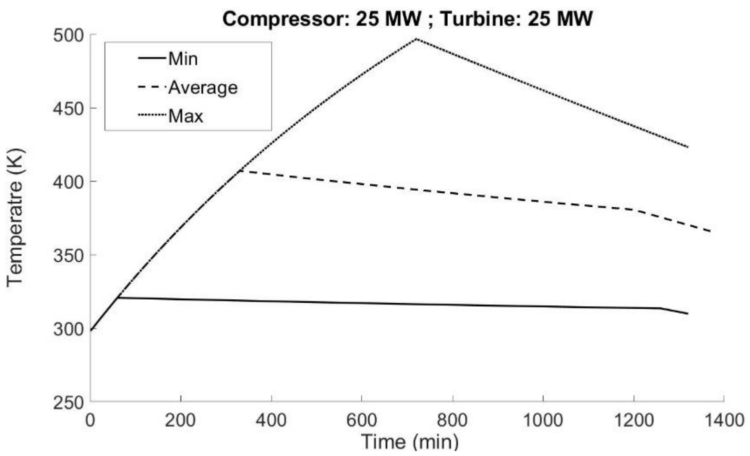


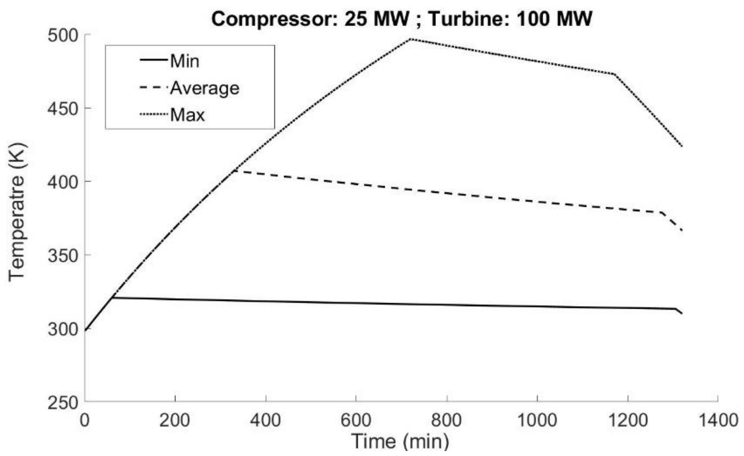


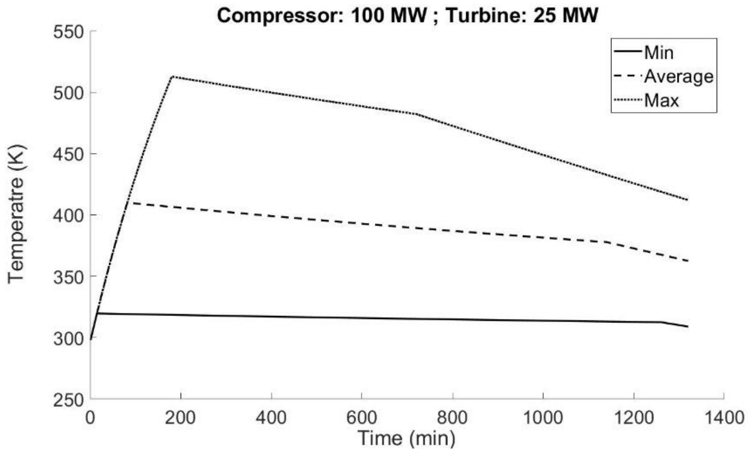


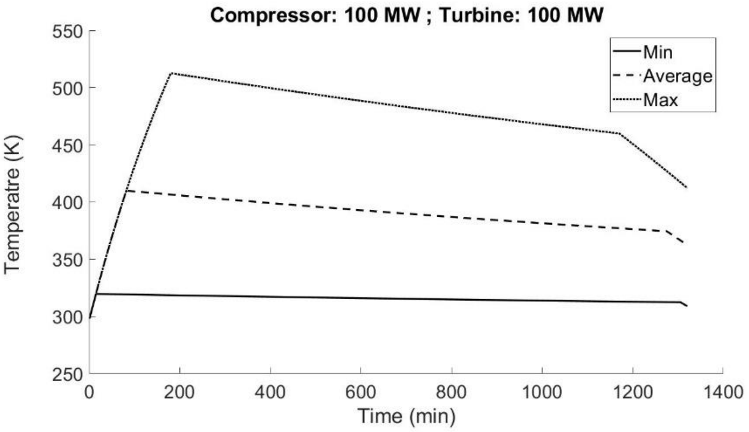


## Temperature (K)

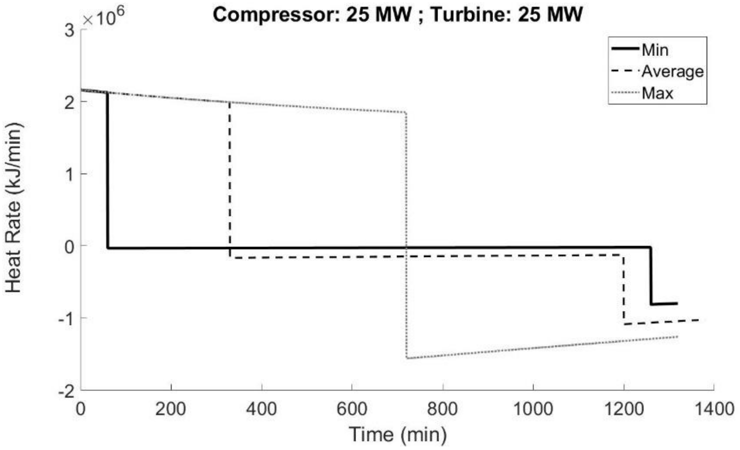


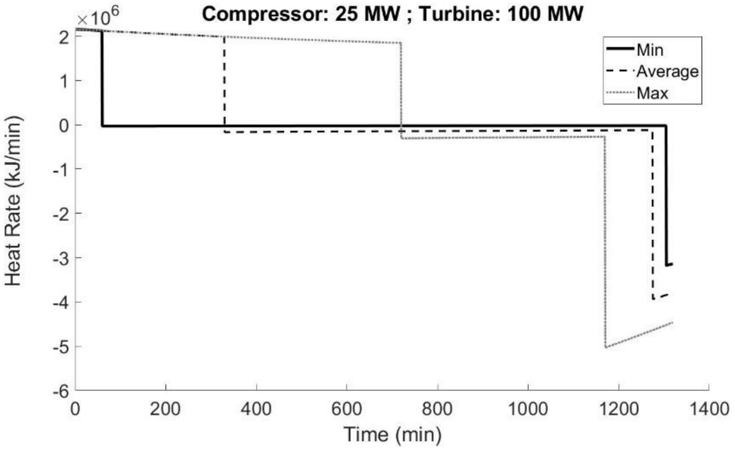


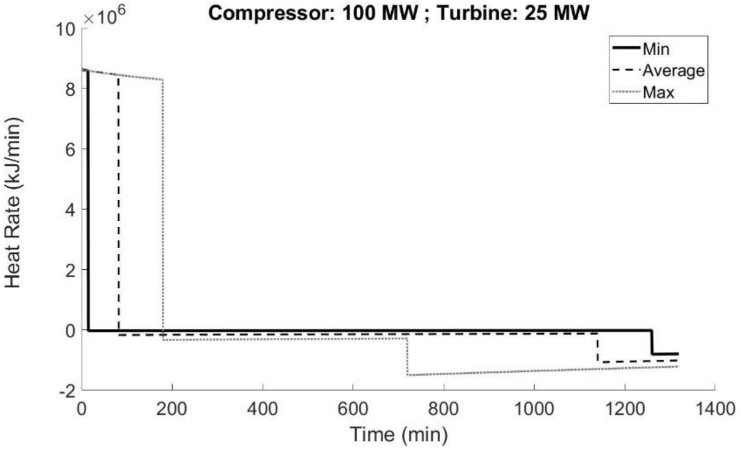


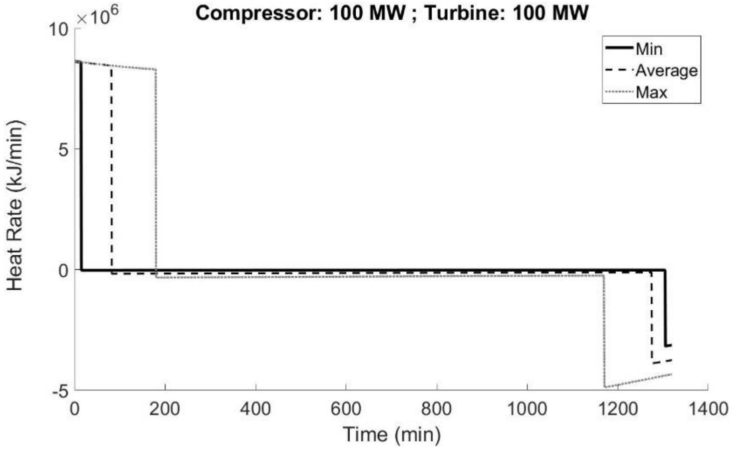


## Heat Rate (kJ/min)

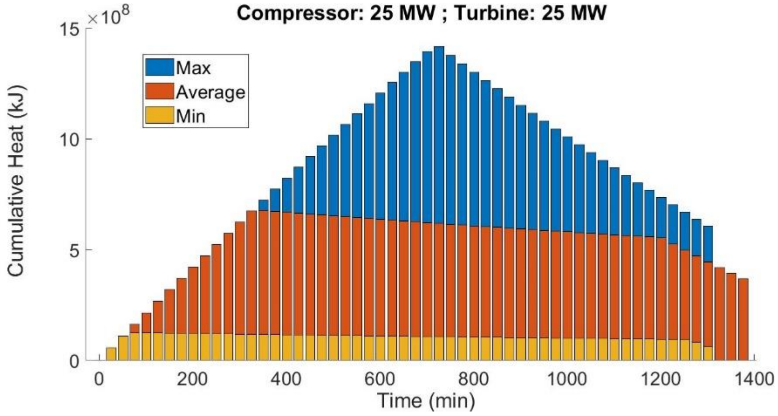


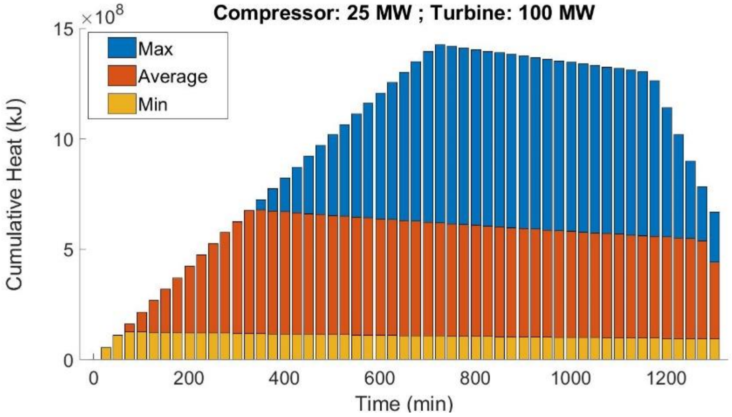


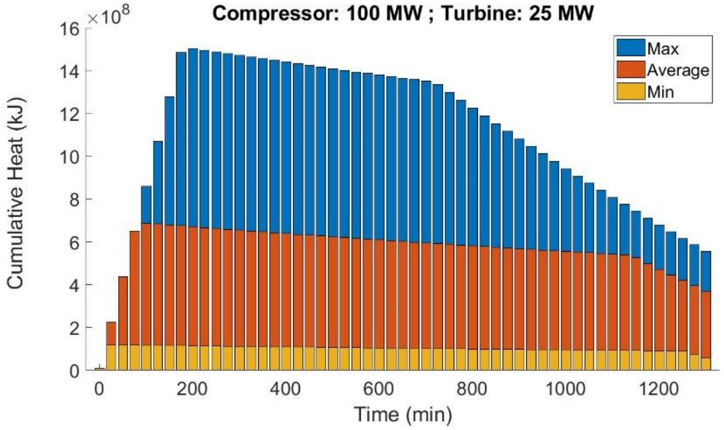


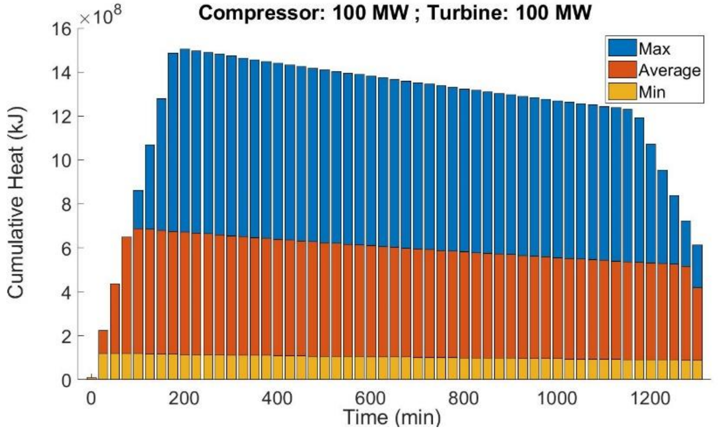


## Cumulative Heat (kJ)



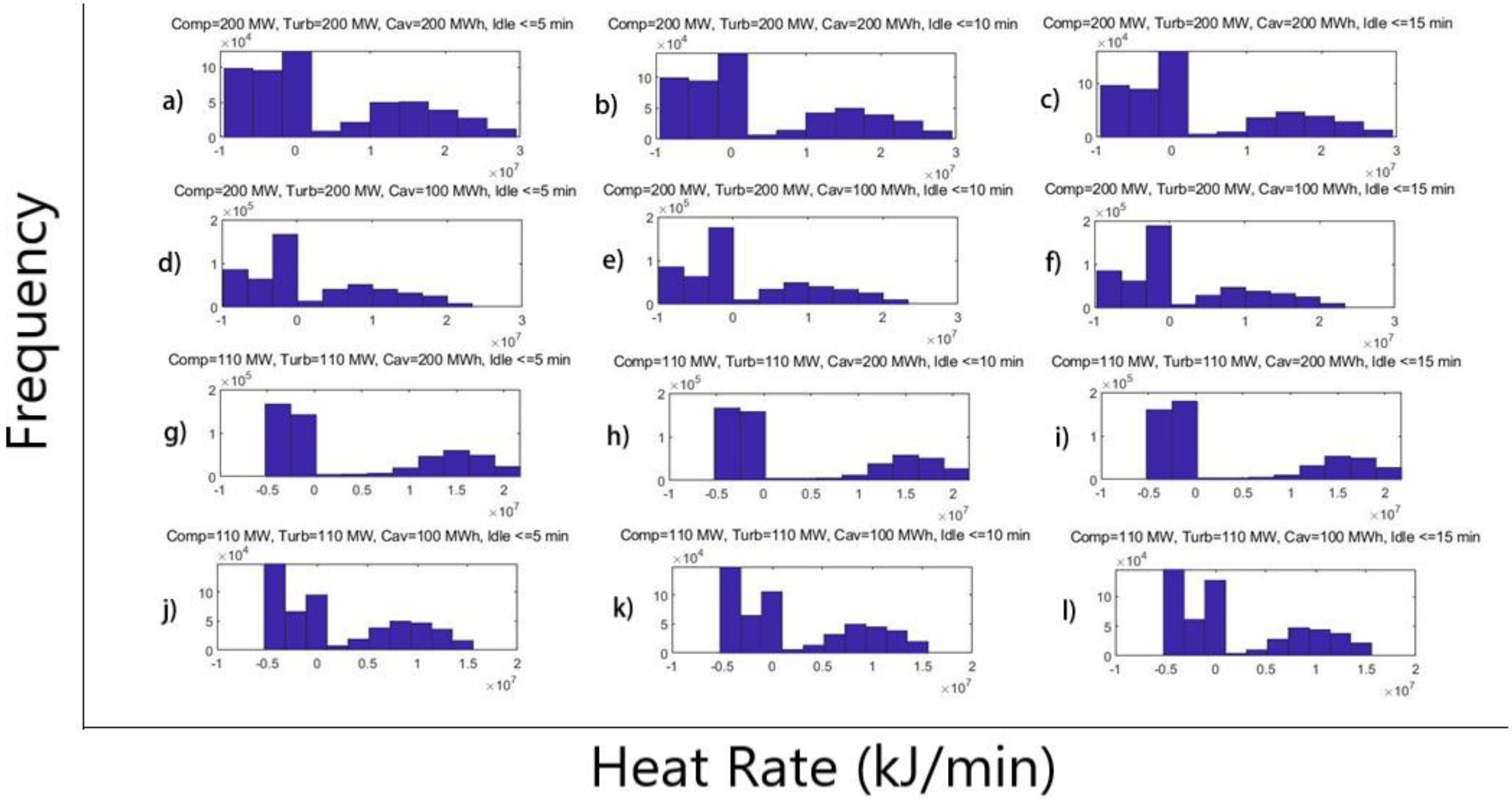




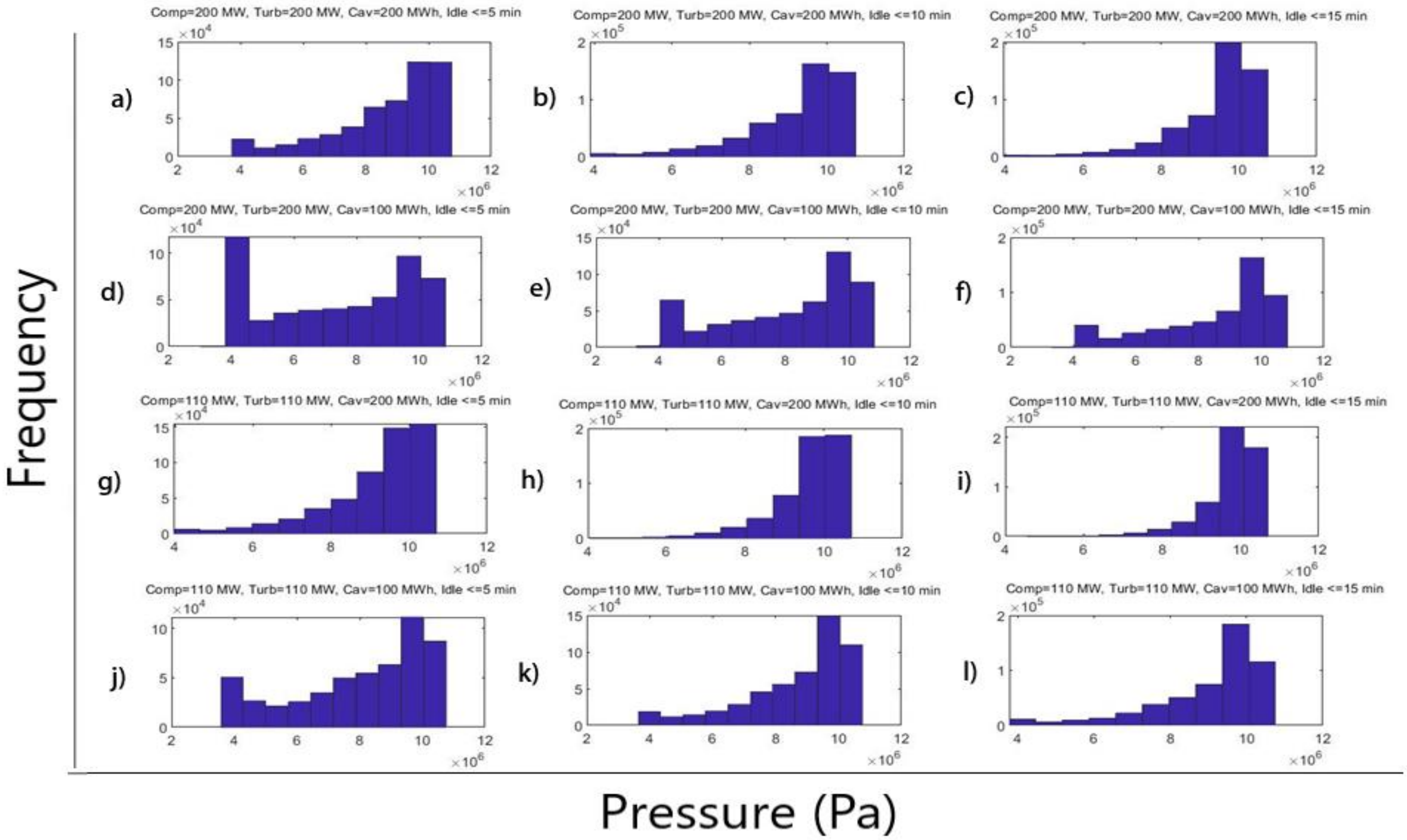


## Appendices (D)

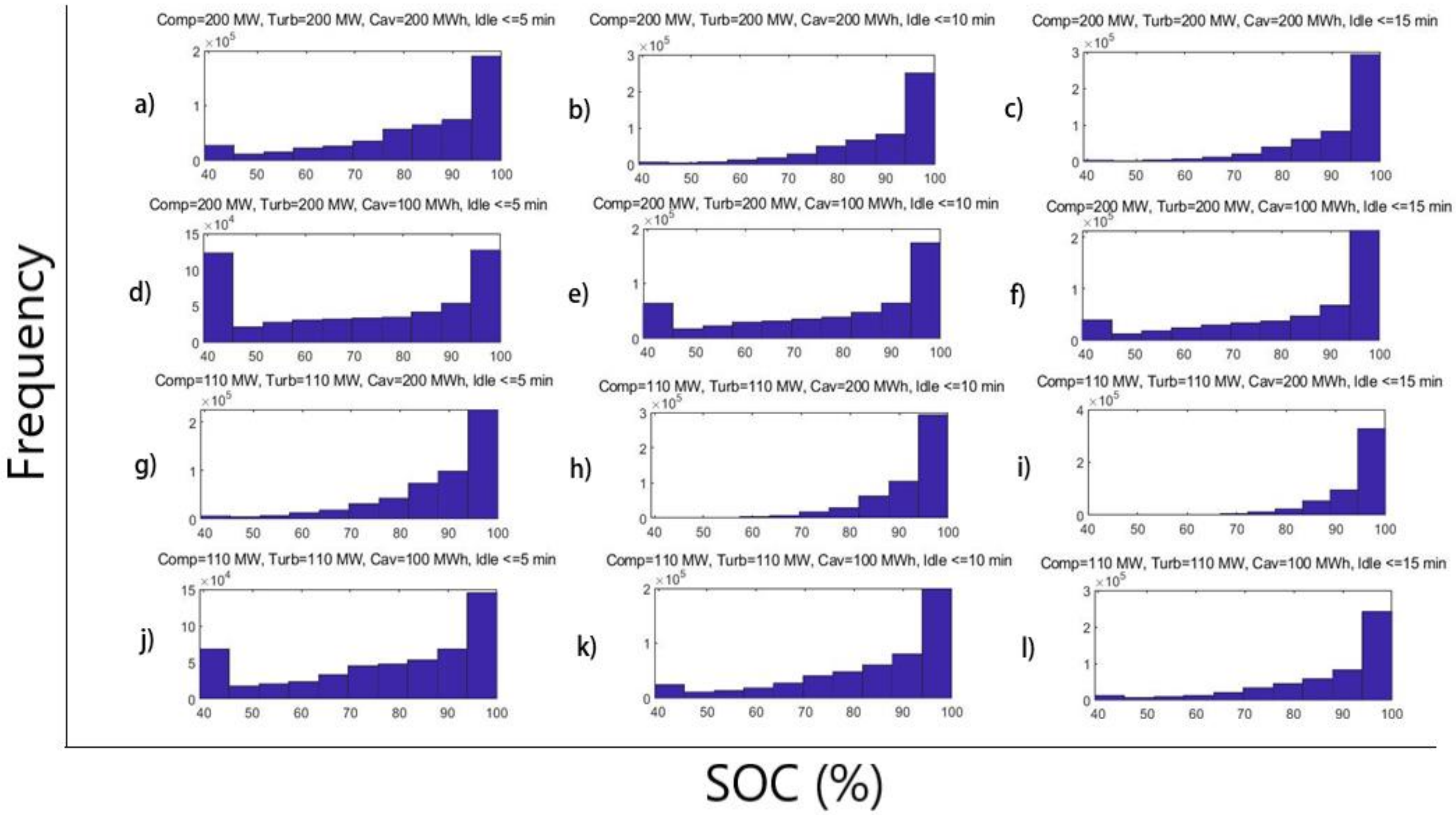
### TES Heat Rate



## Cavern Pressure



## Cavern SOC



a) Comp=200 MW, Turb=200 MW, Cav=200 MWh, Idle <=5 min

b) Comp=200 MW, Turb=200 MW, Cav=200 MWh, Idle <=10 min

c) Comp=200 MW, Turb=200 MW, Cav=200 MWh, Idle <=15 min

d) Comp=200 MW, Turb=200 MW, Cav=100 MWh, Idle <=5 min

e) Comp=200 MW, Turb=200 MW, Cav=100 MWh, Idle <=10 min

f) Comp=200 MW, Turb=200 MW, Cav=100 MWh, Idle <=15 min

g) Comp=110 MW, Turb=110 MW, Cav=200 MWh, Idle <=5 min

h) Comp=110 MW, Turb=110 MW, Cav=200 MWh, Idle <=10 min

i) Comp=110 MW, Turb=110 MW, Cav=200 MWh, Idle <=15 min

j) Comp=110 MW, Turb=110 MW, Cav=100 MWh, Idle <=5 min

k) Comp=110 MW, Turb=110 MW, Cav=100 MWh, Idle <=10 min

l) Comp=110 MW, Turb=110 MW, Cav=100 MWh, Idle <=15 min