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Feasibility of compressed air energy storage to store wind on monthly and daily basis

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Feasibility of compressed air energy storage to store wind energy on daily and monthly basis

by

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CHAPTER 1

INTRODUCTION

1.1 Background

The need for sustainable energy is the key in creating a better and clean environment of the world. This need is increasing our dependency on renewable energy resources. The world currently relies heavily on fossil fuels such as oil, coal and natural gas for energy production. Environmentalists view the use of non-renewable resources as a threat to the natural environmental balance of the world. These energy resources are non-renewable, i.e. if we keep on using them, we might not have any more of these resources one day. The non-renewable energy resources cause pollution by giving out harmful by-products such as carbon dioxide, sulfur dioxide, nitrogen oxides and mercury. The harmful effects caused by the mentioned by products include acid rain, respiratory illnesses, photochemical smog, global warming, developmental and neurological damage in humans, etc.

Besides the environmental issues of non-renewable sources, economic issues are also becoming a concern. Statistics show that the prices for non-renewable energy resources have increased abruptly during the last ten years. According to U.S. Energy Information System the oil price in January 2000 was 23.17$/barrel, which increased to 135.55$/barrel in July 2008. The natural gas electric power price in January 2002 was 3.10$/cubic feet, which increased to 6.97$/cubic feet in January 2010. United States heavily relies on coal for energy production. According to U.S. Energy Information System coal was sold to electric generation companies at 27.5$/metric ton in 2000, which increased to 47$/metric ton in 2008.

Renewable energy resources include wind, solar, biomass, geothermal, hydropower, etc. Among renewable energy resources, wind energy is one of the fastest growing technologies in United States. According to American Wind Energy Association, U.S. wind industry broke all previous records by installing nearly 10,000 MW of new generating capacity in 2009. Despite its growth, since wind energy is an intermittent source of energy, it is not completely reliable. Actions must be taken to increase the reliability of wind energy. Wind has dynamic behavior. At times wind is more than what is required and sometimes it is not. During high wind, the amount of excess energy produced through wind is not used and hence wasted. To address this issue a strategy needs to be employed to exploit the use of excess wind at times when there is not enough wind to meet the demand. One of the solutions is to install energy storage technologies at wind farms. These storage technologies would serve the purpose of storing the excess energy produced through wind. This energy could then be used to make up the mismatch between wind generation and the load during times when the wind is not able to serve the load completely.

Compressed Air Energy Storage (CAES) is one of the most reliable energy storage technologies for wind farms. Among other storage technologies CAES is known to have one of the highest power and energy rating. During off-peak hours, an air compressor driven by an electric motor is fed the excess amount of power produced through wind. The compressor compresses the air and stores it inside an air storage tank. The storage tank can be underground or above the ground. Today, underground caverns are being used to store the compressed air. Among underground caverns, salt domes, hard rock mines and aquifers are very ideal for underground storage in terms long term storage. According to the U.S.

geological survey, underground caverns are very abundant in United States. Therefore the geology of United States is very suitable for CAES. During peak hours, when wind energy is not enough the meet the needs of the load, a gas turbine is driven by the combustion of the stored compressed air and natural gas. The shaft of the gas turbine is coupled with electric generator. Hence the gas turbine drives the electric generator. The electric power produced by electric generator is used to meet the needs of load.

1.2 Motivation

The most expensive part of CAES is the storage volume. There are two main types of ways in which underground storage volume can be designed for CAES operation.

1. Mining to create storage
2. Use existing mines for storage

Mining costs are very high and it is not preferred to create an underground storage through mining. The storages presently used by CAES plants were existing mines and the option of mining to create storage has never been used. Hence investing in existing mines saves a lot of investment as compared to mining the storage.

Existing underground mines are not very abundant. Since these are not designed for the purpose of storing air, only some of these mines would be ideal for air storage. This is one of the reasons why there are only three operational CAES plants in the world. Therefore it is very important to optimize the use of storage since it is limited in terms of availability.

Wind profiles have a typical behavior throughout the year. These winds are typically low in seasons and high during others. Energy produced through high wind season must be captured and used during seasons of low wind.

1.3 Purpose

The overall purpose of this work is to develop a configuration of compressed air energy storage which would improve the energy rating of CAES. The decision variables that govern the amount of storage that can be stored in a given storage volume are pressure and the mass of air. These decision variables characterize both, the configuration and operation of CAES. Pressure and volume characterize the configuration of CAES. Pressure and mass characterize the operation of constant volume configuration. Volume and mass characterize the operation of constant pressure configuration.

This is significant because the storage volumes are often limited in terms of availability. Since volume is expensive, optimizing its use is very important to make a reasonable rate of return on the investment.

Methods would be developed to compare the hourly basis operations of constant pressure and constant volume CAES for a particular day. This is significant because we do not need large amounts of storage energy for operations on hourly basis. This method would help us determine the amount of energy required for hourly operations.

Methods would be developed to determine the operational and economic benefit of high energy rating CAES configuration to store energy on monthly basis and storing energy on daily basis. This is significant because high energy rating CAES configuration might surpass the operational requirements on hourly basis. In addition, wind does not only change on hourly basis but also on daily and monthly basis. This would make wind energy more economical and reliable on daily and monthly basis.

This thesis is divided into four main portions. The first part addresses the component level and system level modeling of CAES constant volume and constant pressure configurations. The second part compares these storage technologies based on operations on hourly basis. In the third part, methods have been developed for high energy rating configuration to store energy on the basis of daily and monthly basis. In the fourth part, methods have been developed to analyze the economic benefits of storing energy on daily and seasonal basis. The conclusion is provided on the basis of the analysis.

CHAPTER 2

LITERATURE REVIEW

To realize the need of energy storage systems for wind hybrid system, a thorough understanding of the operation of wind energy is required.

2.1 Wind Energy

2.1.1 History of Wind Energy

Wind energy records back to be in operation as early as 5000 B.C. In 200 B.C., windmills were used to pump water in China. Windmills were also used in Persia and the Middle East to mince the grain. As time passed by, new ways of using wind energy were explored. Windmills were widely used for producing food in the Middle East by 11th century. Windmill was later used to drain lakes and marshes in Netherlands. During the 19th century windmills were used to deliver water to farms. (US DOE)

A steady decline was seen in the use of windmills after industrial revolution. With the introduction of steam engine, windmills were replaced for the purpose of pumping water. The industrial revolution also caused in increased production and use of larger windmills called wind turbines. These wind turbines were mostly used to generate electricity. Wind turbines are believed to be introduced in 1890 in Denmark.

The motivation of using wind energy has always been dependent on the prices of fossil fuels. Wind energy became less popular after World War II, due to the decrease in price of fossil fuels. The wind energy got its fame back in the 1970’s, when the price of oil increased abruptly. After the embargoes on oil in 1970, new ideas were introduced to address efficient ways of converting wind energy into electrical power.

2.1.2 Operation of Wind Energy

When air comes in motion, it is called wind. The irregular heating of the Earth's surface by the sun causes wind. Earth's surface is composed of different kinds of land and water which makes it absorb the sun's heat at different rates. Daily wind cycle is an example of this irregular heating. In a daily wind cycle, the air over the land heats up more rapidly than the air over water during daytime. This warm air expands and rises. The cooler air, which is also heavier than warm air creates wind by replacing the warm air. At night, this process is reversed because the air cools more quickly over land than over water.

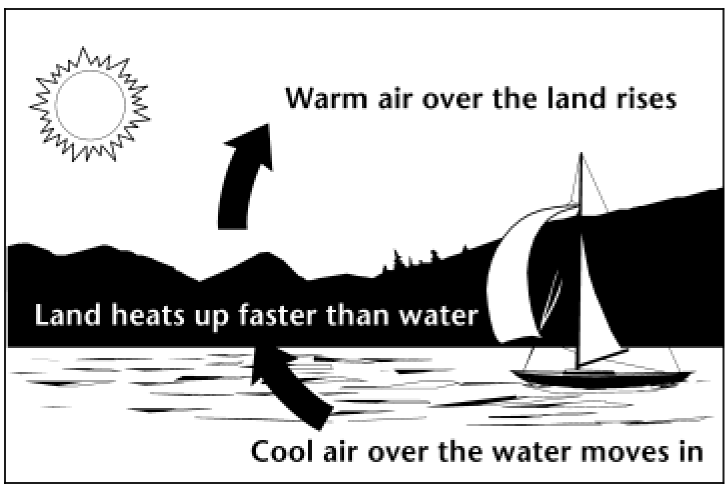


Figure 2.1 Uneven heating of water and land causing wind

Source: (National Energy Education Development Project)

The atmospheric winds are also created in the same way. These earth circling winds are created because the regions that fall on Earth's equator are heated more by the sun than the regions near the North and South Poles. The terms wind energy or wind power is used to describe the procedure through which the wind is used to generate mechanical or electrical power. As the wind turbines rotate through wind, they convert kinetic energy from the wind to mechanical power. This mechanical power is used to run an electrical generator which converts the mechanical power into electrical power. The electricity produced is distributed among homes, businesses, schools, etc. through transmission and distribution lines.

There are two basic types of wind turbines present today. These are known as follows:

1. Horizontal axis wind turbines (HAWT)
2. Vertical axis wind turbines (VAWT)

The axis of rotation of the HAWT is almost parallel to the wind stream and horizontal to the ground. The axis of rotation of VAWT is almost perpendicular to the wind direction and vertical to the ground.

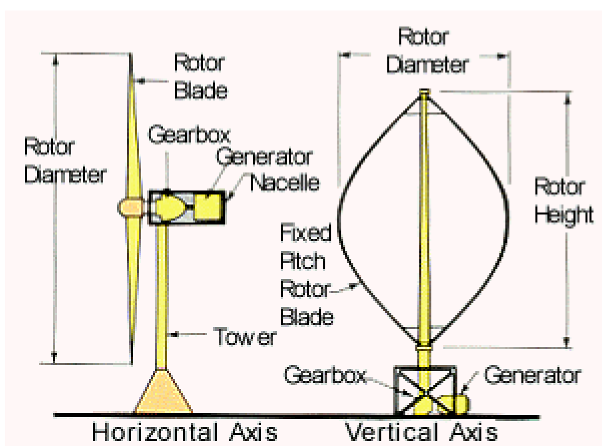


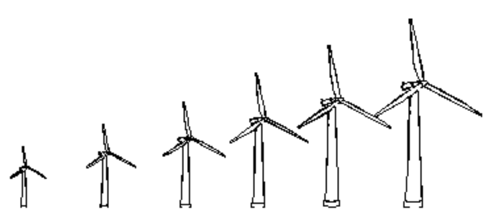
Figure 2.2 Wind Turbine Configurations

Source: (American Wind Energy Association)

VAWT is capable of receiving wind from any direction. No pitch control is required for VAWT system. VAWT is not capable of self-starting. Starting mechanisms are required to run VAWT systems. VAWT system is known to be less efficient due to the fact that it passes through aerodynamically dead zones when the rotor completes its rotation.

Wind turbines come in various different types of sizes depending upon the power rating and efficiency. For land based wind farms, utility-scale wind turbines have rotor diameters ranging from about 50 meters to about 90 meters. Offshore turbine designs have larger rotors due to the fact that it is more convenient to transport the large rotor blades through ships. These wind turbines being designed today are capable of producing from 250W to 5 MW of power.

The wind turbines can be divided into two categories with respect to size as large and small wind turbines. Small wind turbines have rotor diameters ranging up to 8 meters. These turbines are mounted on towers up to 40 meters high. Small wind turbines range below 100 KW. Small wind turbines are designed for residential and small business use. Large wind turbines range above 100 KW up to several MW. The largest wind turbine installed is Enercon's E 126. Its rated power is 6 MW. The rotor diameter of this turbine is 127 meters.



	1981	1985	1990	1996	1999	2000
Rotor (meters)	10	17	27	40	50	71
Rating (KW)	25	100	225	550	750	1,650
Annual MWh	45	220	550	1,480	2,200	5,600

Figure 2.3 Turbine sizes and power rating

Source: (American Wind Energy Association)

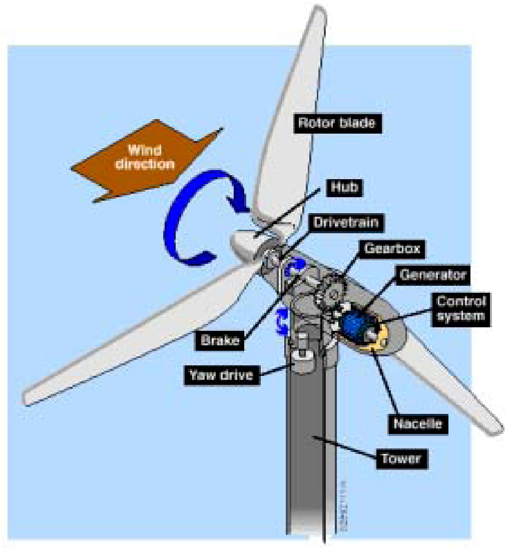


Figure 2.4 Components of Wind Turbine

Source: (Princeton Energy Resources Internationalonal, LLC)

Figure 2.4 shows the major components of the wind turbine. Most wind turbines are composed of two or three blades. The blades are lifted and hence rotated as the wind blows over them. Blades are also pitched, out of the wind to control the rotor speed. Blade pitching is also done to avoid the rotor from whirling in high or low winds. The disc brake is used to stop the rotor during emergency situations. The brakes can be applied mechanically, electrically, or hydraulically. The control system starts the machine at wind speeds of about 8 to 16 miles per hour (mph) and shuts off the machine at about 55 mph. Turbines are not designed to tolerate wind speeds above 55 mph and might get damaged by the high winds. Since the rotor blade does not spin at the generator's rated speed, gears are introduced ro increase the rotational speed of high speed shaft from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm. The gears connect the low-speed shaft to the high-speed shaft. The gear box is an expensive and heavy part of the wind turbine. Direct-drive generators are being explored run at lower rotational speeds to eliminate the need of gear boxes. The commonly used generator is the induction generator which is capable of producing 60 Hz AC electricity. The nacelle comprises of the gear box, generator, low and high speed shafts, control system, and brake. Towers are either made of concrete, tubular steel or steel lattice. Winds are high at more heights. The taller the tower, more wind can be extracted and hence more power can be produced. The yaw drive is used to control the rotor direction with the wind direction such that it faces into the wind at all times. The yaw drive is not required in downwind turbines.

2.1.3 Advantages of Wind Energy

Wind is clean source of energy which does not pollute the air. Power plants which make use of combustion of fossil fuels, such as coal or natural gas produce by-products which pollute the environment. Wind turbines do not produce such atmospheric emissions. Wind energy is a renewable form of energy, which cannot be expended. It is one of the cheapest renewable energy technologies available today. It costs in the range of 4 to 6 cents per KWh. The cost of wind energy depends upon various factors, such as wind resource and project costs. Wind turbines can be built in a variety of places such as farms, ranches. It does not occupy much space and is also a source of benefit to the economy of rural areas, which is the ideal space to build wind farms. Rent payments are made to the farmer or rancher by the wind farm owner for the use of land. The development of wind energy resources is a one-time investment. Since wind blows free of cost, the operational costs for such power producing plant is decreased since no fuel is required to run the plant. Operational costs mainly include rent for the land and maintenance of equipment.

2.1.4 Disadvantages of Wind Energy

The main disadvantage of wind energy is that it is an intermittent source of energy. The energy provided through wind farms depends upon the amount of wind blowing. Since wind has a dynamic behavior, wind farms do not guarantee the delivery of specific amount of power at all times. Most of the times wind is not available when there is much power demand. Wind energy can be stored using storage technologies such as Compressed Air Energy Storage (CAES), batteries, etc.

Wind power must also be economically feasible and be able to compete with conventional generation systems. Large wind farms producing large amounts of power do not guarantee that it is cost effective. A large amount of investment, more than that of conventional fossil fuel generators is required to build wind farms.

Power demand is known to be higher in dense cities rather than the country side. Wind farms cannot be built in cities. Hence, transmission lines are required to deliver the electricity from the wind farm to the city.

Since open fields are required to build a wind farm. It is very difficult to decide whether the land to be used for generating electricity would be more suitable for wind generation or other numerous options. Even though wind farms are much more environment friendly compared to other conventional generating systems, there are some issues like the noise produced by the rotor blades, visual impacts, and killing incidents of birds by flying through rotor. These problems can be avoided by choosing appropriate location for wind farms where there are less chances of having the above mentioned problems.

2.1.5 Wind Energy Resource Potential

For wind farms to be economically feasible, strong recurrent winds are required at places where wind farms are installed. Therefore it is very important to know the wind potential of the land where wind farms are to be installed. The United States wind resource map provided by National Renewable Energy Laboratory (NREL) is shown in figure 5.

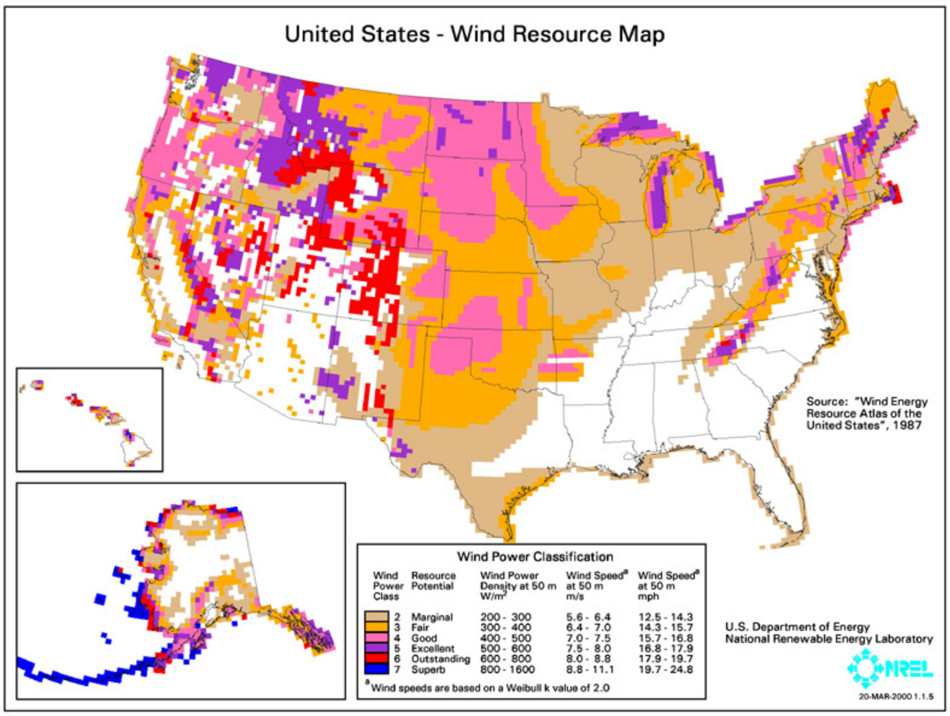


Figure 2.5 Wind resource map of United States

Source: National Renewable Energy Laboratory (NREL)

The map in figure 2.5 shows the annual average wind power density in terms of watts per square meter and speed in terms of meters per second and miles per hour at a height of 50 meters above ground. The wind power density was used to obtain the wind power class ranging from one to seven, seven being a superb wind resource. Wind energy is capable of supplying about 20% of the nation's electricity, according to Battelle Pacific Northwest Laboratory. Almost every state is capable of producing electricity from wind. North Dakota in theory is capable (assuming adequate transmission capacity) of producing enough wind power to fulfill more than fourth of electricity demand in the U.S.

According to the wind energy growth data of figure 6, the wind power capacity expanded from 1416 MW in 1995 to 35,086 MW in 2009 with the annual capacity addition of 10,010 MW in 2009.

Table 2.1 Annual and cumulative wind power capacity growth in U.S.

Source: (American Wind Energy Association)

Year	Annual Capacity Additions (MW)	Cumulative Capacity (MW)
Through end 1995		1416
1996	1	1417
1997	17	1434
1998	140	1574
1999	819	2394
2000	67	2460
2001	1691	4151
2002	412	4563
2003	1670	6233
2004	397	6629
2005	2385	9014
2006	2462	11476
2007	5258	16725
2008	8366	25076
2009	10010	35086

The facts and figures in table 2.1 clearly show that wind energy is growing at such a high rate that has never been achieved before. With this increase capacity it is important to focus on issues related to wind power. With the growth of wind energy resources our dependency on it is also increasing. Wind energy has the potential of becoming one of the largest energy sources in the coming years. Hence it is becoming more important day by day to address the reliability issues of wind energy.

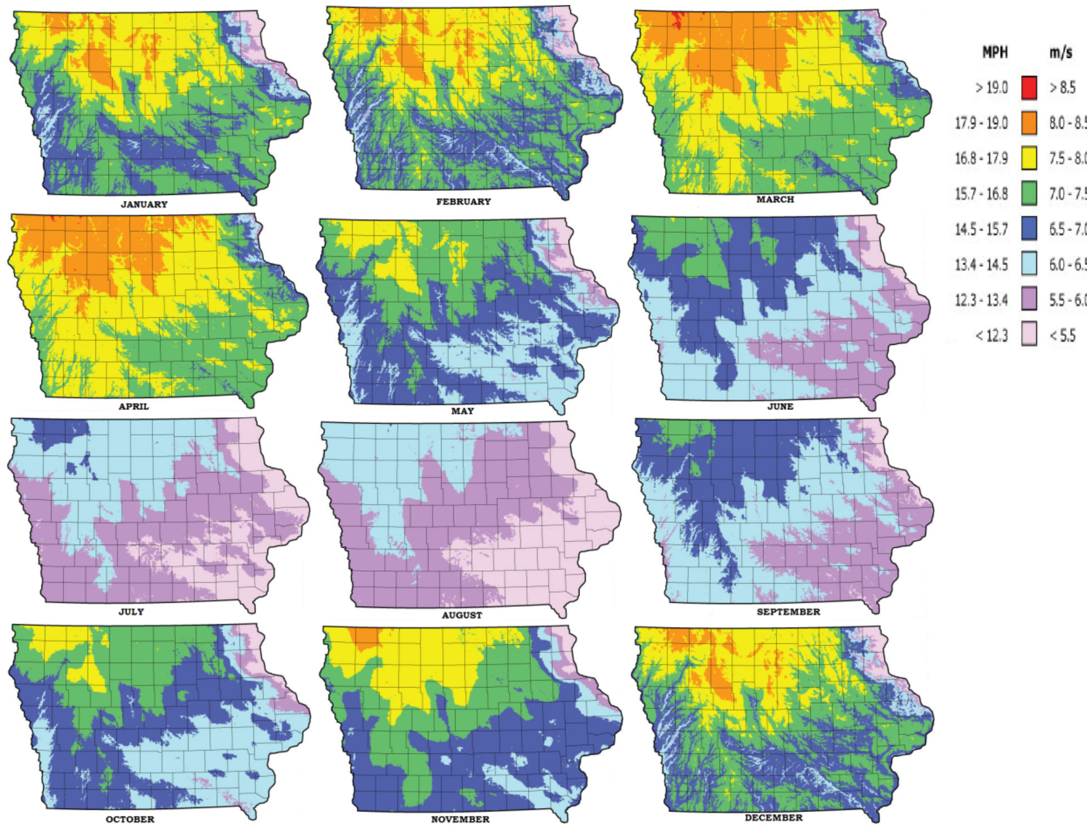


Figure 2.6 Estimated average monthly wind speeds

Source: (Iowa Energy Center)

Wind does not only change on hourly basis, but also on monthly basis. Figure 2.6 shows the average wind speed for each month in United States. Wind speeds are typically the highest during the months of March and April, and the lowest during the months of July and August. Energy from wind can only be stored at times when wind generation is more than demand. Electricity demand is typically lower during months of high wind speed as compared to months of low wind speed and vice versa. Since electricity demand and wind generation has inverse relationship, there must be a way to store wind energy on monthly basis. The marginal prices during months of high electricity demands are also typically higher as compared to months of low electricity demand. The storage must be exploited in such a way so that financial returns can be made by delivering energy in the months of high marginal prices. Figure 2.7 shows the monthly average marginal prices for the year of 2008.

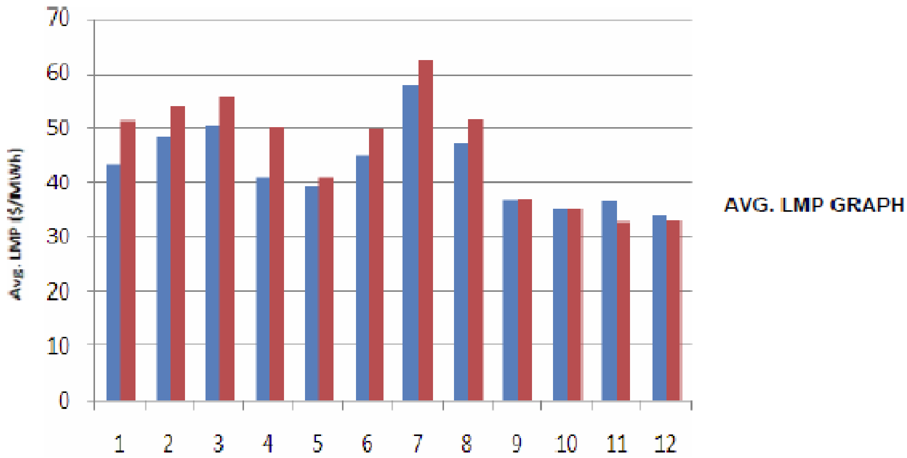


Figure 2.7 Marginal prices for electricity for 2008

Source: (MISO)

2.2 Storage technologies for Wind Energy

The intermittent nature of wind makes it obvious that it needs energy storage. Either the power is being produced by wind turbine or wind farm, the intrinsic problems of power supply and connectivity to electrical grid remain the same. Energy storage provides an opportunity to grasp and balance the wind energy as it is produced. It may be stored and used later when the demand is expected to increase the capacity of wind energy production.

Installing energy storage technologies into the grid has numerous benefits. Energy storage has following advantages according to The Electricity Advisory Committee to NREL:

1. Improves grid optimization for bulk power production
2. Facilitates in balancing power system which has renewable energy sources

3. Facilitates the power demands of plug-in hybrid electric vehicle (PHEV) with the grid
4. Defers investments in transmission and distribution (T&D) infrastructure to meet peak loads during outage
5. Provides supplementary services to grid or market operators

Energy storage devices facilitate the grid with power quality applications and frequency regulation for utilities. These devices can also be sued for load balancing to reduce emissions from conventional fossil fuel generators.

Energy storage has the potential of storing electricity from wind energy during times of inadequate transmission capacity. In Texas, wind curtailment is increasing due to inadequate transmission capacity. It is not possible to deliver the power produced in western Texas to other parts of the state which are densely populated.

2.2.1 Generation Applications

Governor response is the autonomous dynamic response of the generator to frequency. Most commonly, renewable sources do not have governor response, which is necessary for stability of the system. Increasing conventional unit governor response for renewable sources will result in costing the markets. Storage technologies compensate for lack of governor response for renewable resources.

Regulation is the adjustment of power production to balance the load, schedules at each second. It also regulates system frequency. Economically speaking, regulation is a service with annual costs to markets in terms of millions of dollars. Storage can be replaced by conventional fossil generation. This would cause the generation capacity for energy production to open up. Renewable generation typically lacks regulation capability. Storage technologies can be used for this purpose which can cause a change of 0.2–0.5% in system wholesale energy costs.

The real-time dispatch or energy balancing of the system is the economic adjustment of production based on a minute-by-minute basis to match demand. Hourly schedule changes can cause spikes in balancing the demand and prices. Since the nature of renewable energy might not fulfill the need of energy balancing, this might increase prices and decrease the capacity available for scheduled energy production. Introduction of storage would eliminate this problem.

The reserve augmentation is the conventional generation which supplies spinning and operating reserve as a back-up against the malfunction of resources. The additional capacity of the operating units can be saved by using storage application which provides short-term reserves. Opportunity cost is charged when reserves are used. This cost can be avoided by using storage.

2.2.2 Transmission Applications

Transmission capacity factor for renewable sources is one of the most important aspects. At times transmission is not available to deliver the peak power production. Storage technologies can be used to capture the power produced that cannot be transmitted and used later when required.

Storage also plays a vital role in terms of voltage stability. Voltage stability is affected when there is a sudden increase in demand or decrease in generation. Storage is capable of providing real power at high power factor which helps in stabilizing the voltage.

Storage enhances the reliability of the transmission system by providing power during outages. Hence outage costs can also be avoided by using storage. Storage also helps in maintaining the grid frequency. Short duration power to maintain the grid frequency can be obtained from storage technologies having fast response.

The need to upgrade or expand the system can be avoided by using the stored energy during low demand period to fulfill the demands of loads near the storage. This reduces the dependency on remotely generated power which makes use of transmission and distribution assets. This power is only imported during periods of peak load.

2.2.3 Comparison of Storage Technologies

There are four types of energy storage technologies that are proven to be most suitable for wind power. These are:

1. Pumped hydro storage
2. Compressed air energy storage
3. Flywheel storage
4. Battery storage

These technologies are being currently used in the industry. Keeping in view the implementation of these technologies on a large-scale, most of these technologies are in their initial stages. Storage technology like Flywheel provides short term storage capacity at high power levels. Whereas pumped hydro storage and compressed air energy storage provide long term storage capacity at high power levels. Pumped hydro storage is highly dependent upon the geographic location. It needs high elevations for storage purposes and suitable wind for wind farms. Same is the case with compressed air energy storage. Underground salt domes and rock aquifers must be available where compressed air energy storage plant is intended to be installed.

Figure 6 shows the comparison between different types of storage technologies that have already been developed. It shows the energy capacity and power ranges for which these technologies are designed and currently operational. It is obvious from the figure that pumped hydro storage and compressed air energy storage are high energy storage and power applications. These storage technologies can be used for the purpose of transmission curtailment, load shifting and forecast hedging. This figure was developed based on the data provided in the EPRI DOE Handbook of Energy Storage for Transmission and Distribution Applications.

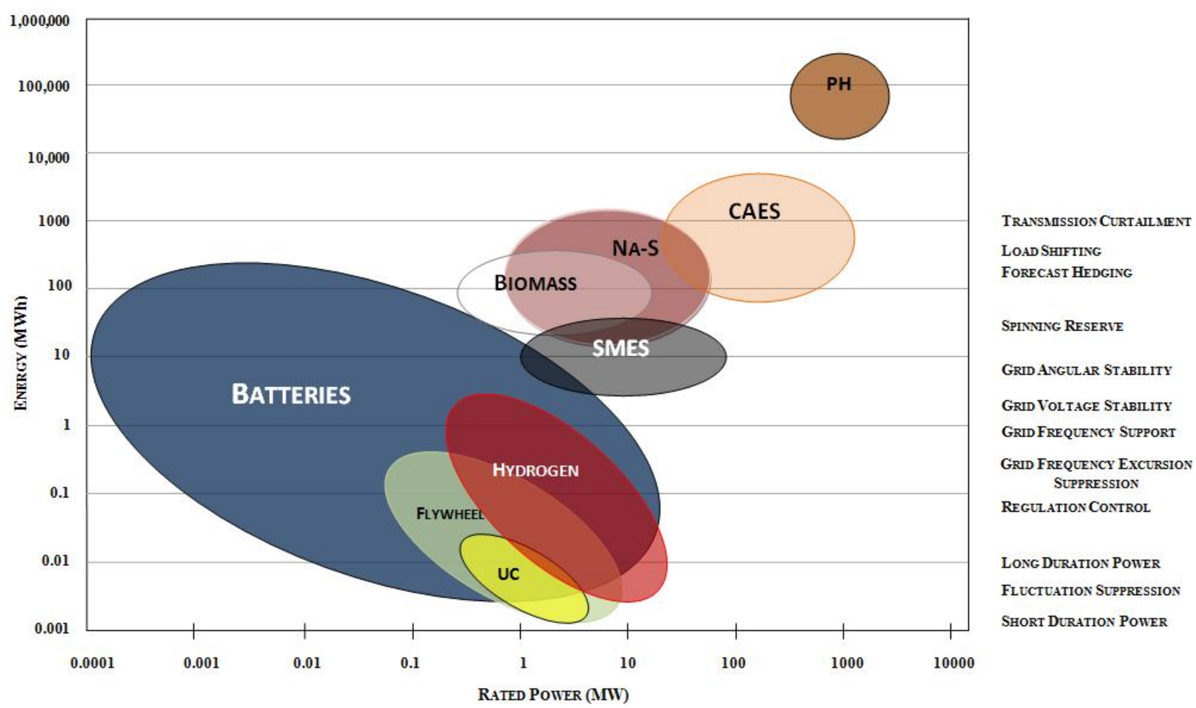


Figure 2.8 Comparisons of Storage Technologies

Source: (EPRI DOE Handbook of Energy Storage for Transmission and Distribution Applications)

The comparison of installation and operating costs for several storage technologies is given in figure 2.8. CAES has the lowest operating cost among all the storage technologies present today falling in the range of $25/kWh to $90/kWh. CAES is also competitive among other storage technologies in terms of installation costs which are about $500/kW to $950/kW. Based on the give facts and figures CAES can be proven as the most suitable storage technology in terms of the contrast of cost and performance. Although CAES is not a fast time responding storage technology likes batteries and SMES. It must be noted that CAES cannot be replaced with storage technologies having high power rating with low discharge time.

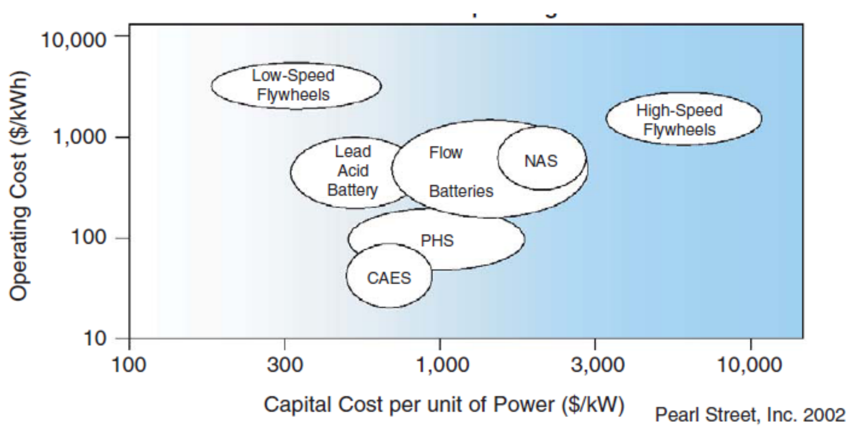


Figure 2.9 Installation vs. operating costs

Source: (Pearl Street Inc., 2002)

2.3 Compressed Air Energy Storage

2.3.1 Operation

Compressed air energy storage comprises of three main sections:

1. Compressor/Electric motor
2. Air storage

3. Turbine/Electric generator

The operation of CAES is explained in figure 2.10. During peak wind generation hours, power is drawn from the grid and used to run air compressor, which compresses air and pushes it in a storage which can be either an underground cavern, aquifer or on ground tank.

This compressed air is utilized at the time of peak load especially when wind generation is not enough to fulfill the load requirements. This compressed air is used to combust with fuel which in turn runs the gas turbine. The gas turbine is coupled with electric generator which is connected to the grid. This increases the efficiency of the gas turbine because the compression cycle of air has been eliminated by compressing the air through extra generation. Hence power spillage is also avoided.

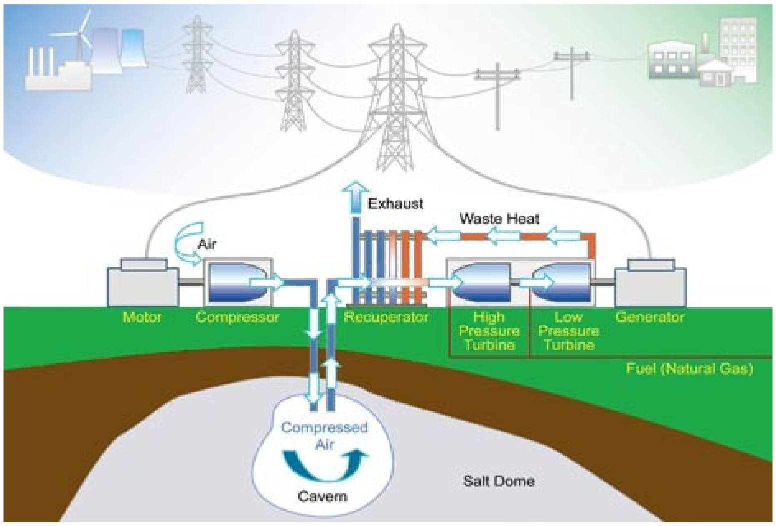


Figure 2.10 CAES Operation

Source: (Ridge Energy Storage and Grid Services)

2.3.1.1 Compressor/Electric Motor

Compressors come in a large variety based on the design and operation. In general there are two types of compressors as listed below.

1. Positive displacement compressors
2. Centrifugal compressors

In positive displacement compressors the gas to be compressed is contained in a certain amount of volume. This volume is reduced, hence reducing the volume of the gas which results in compression. This compressed gas is then discharged after being compressed. There are two major types of positive displacement compressors. They are known as rotary screw compressor and reciprocating compressor.

The rotary screw compressor comprises of helical-lobe rotors which are closely place against each other. These rotors make up a synchronous mesh. As the compressor turns these rotors the gas is pushed into the space between the lobes. As the gas passes through this space reduces hence compressing the air. Since the process of compression causes heating, multi-staging helps in keeping gas temperatures under a certain limit. The figure below shows how a rotary screw compressor works.

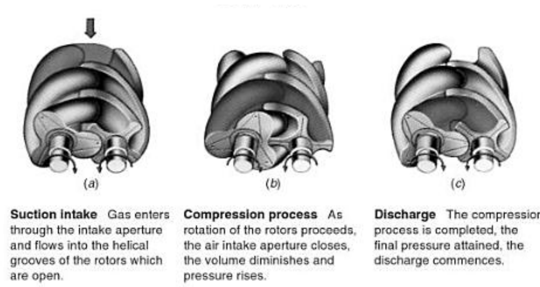


Figure 2.11 Working of rotary screw compressor

Source: (A Practical Guide to Compressor Technology, Bloch)

The reciprocating compressor comprises of a piston and cylinder. Gas is entered into the cylinder and piston is moved such that the volume available to air inside the cylinder is decreased. Lubrication through oil and cooling through air for small scale compressors and water for large scale compressors is required to keep the compressor from wearing.

The centrifugal compressor accelerates the flow of the gas at the inlet in an outward direction by the help of a rotating impeller. This accelerated air is then entered into a stationary element of the compressor known as diffuser. The pressure of the gas is partly increased during the rotary action and during the diffuser action. It is suitable to have more than one stage in centrifugal compressor to introduce intercooling process. Intercooling process cools the gas heated to high temperatures during compression process. This cooled compressed gas is again fed to another stage of compression. Centrifugal compressors are radial flow compressors. Axial flow and radial flow compressors, both are suitable to be used for CAES plants according to Dr. Chris Bullough of Alstom. A combination of low pressure axial and high pressure centrifugal compressors is used in Huntorf CAES plant.

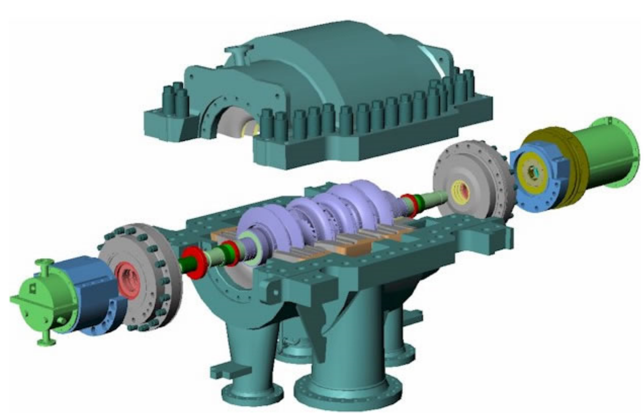


Figure 2.12 Centrifugal Compressor

Source: (Hitachi)

Axial and radial terms correspond to the type of flow of fluid inside the compressor. In axial flow compressors, the fluid flows parallel to the axis of rotation of the rotor. In radial flow compressors, fluid flows towards the center of the rotor. Centrifugal compressors and axial compressors fall into the category of dynamic compressors. Dynamic compressors provide high mass flow rates. Dynamic compressors have comparatively low pressure at the outlet.

The compressors are coupled with an electric motor. The electric motor is connected to the grid, and is fed the additional power available on the grid. This electric motor drives the shaft of the compressor.

2.3.1.2 Air Storage

Compressed air energy storage has a lot of potential in the United States because the geology of U.S. is very suitable for underground storage. The types of geologies suitable for compressed air energy storage can be classified into the following three types:

1. Salt
2. Hard rock
3. Porous rock

Over 75% of U.S. has the potential of having the mentioned geologies that are suitable for underground air storage according to “CAES: the underground portion” by K. Allen.

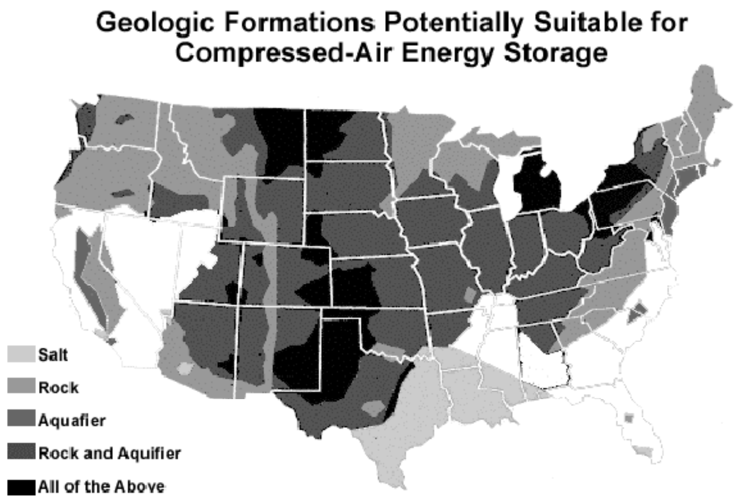


Figure 2.13 Geologic opportunities for CAES storage

Figure 2.13 shows the major salt deposits in the U.S. Solution mined storage can be developed in most of these areas by boring well into salt formation. Water is poured in to dissolve the salt. The brine solution is extracted to the surface resulting into a cavern. This cavern is sealed by an impenetrable salt which acts as a good seal and hence is practically leak proof. This cavern is very suitable for underground air storage.

Basically there are two types of salt deposits. These are bedded and domal formations. Although both formations can be used for underground air storage, salt dome formations are more suitable in terms of the structure of storage. Bedded formations often contain impurities and are relatively thinner than domal formations, which pose risk to structural stability. Operational caverns mined from salt domes for CAES are in Huntorf, Germany and McIntosh, Alabama.

Hard rock mined caverns are developed by boring and digging out the rocks by using blasting procedures. The cost of mining hard rock is relatively high. This cost can be reduced by using existing mines. The existing limestone mine, which is a hard rock, has been proposed to be used in the construction of Norton, Ohio CAES plant. Hard rock mines are known to be one of the best options for storage in terms of having the ability of storing pressurized air for long durations.

Porous rock storage costs the least in terms of construction of large scale storage. Due to the low developmental cost and the location of porous rock, this is one of the most suitable options for designing the storage for CAES. Porous rocks have extensively used to store the natural gas. Since air has very different physical and chemical properties as compared to the natural gas, there is still a need to find practical results for feasibility of porous rock for the storage of air. This is being tested by the Iowa Stored Energy Park group, Dallas Center, Iowa where porous rock is the proposed storage for this CAES plant.

There are mainly two kinds of air storage.

1. Constant volume storage
2. Constant pressure storage

The CAES plants that exist today are constant volume storage. There is a fixed range of pressures for which the storage plants operate. If the pressure falls too low, it wouldn't be efficient to run the turbine. Therefore some amount of mass of air is kept inside the storage at all times to maintain the minimum level of pressure required inside the storage.

Since the storage volume is very large therefore lot of mass of air is required to maintain the pressure inside the storage. Another technique of storing air is the constant pressure configuration. In this configuration the pressure of air inside the storage is kept constant by changing its volume through pumping the water inside the storage from beneath.

As the mass of air during discharge cycle falls inside the storage, the water fills in the space to keep the pressure constant. Similarly, water is pumped out during charging cycle. This can be done by keeping a constant level of water in the dam from which the water is fed to the storage. Constant pressure storage can only be implemented in hard rock formations because water starts to deteriorate the walls of salt dome storage through dissolving.

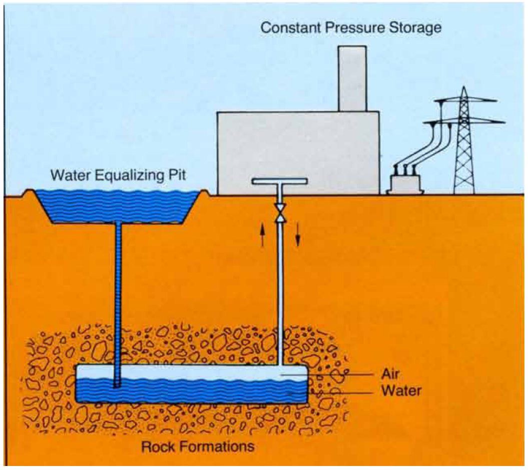


Figure 2.14 Constant pressure storage

Source: (BBC)

2.3.1.3 Turbine/Electric Generator

The stored compressed air is fed to the expanders in the turbine. This compressed air is either combusted with natural gas before entering the expanders or heated through thermal energy storage to run the turbine. Today, CAES is commonly based on gas turbines.

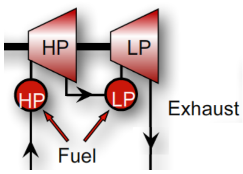


Figure 2.15 Gas Turbine

Source: (Energy Storage & Power LLC)

2.3.2 Existing and Proposed CAES plants

Following are the existing and proposed compressed air energy storage plants

2.3.2.1 Huntorf

Huntorf compressed air energy storage plant is located in North Germany near the city of Breman. Huntorf is the world's first CAES plant and was brought to operation in 1978. It was built by ABB, which was formerly known as BBC. Huntorf was used to start the nuclear power units near North Sea. It was also used for peak shaving unit. The availability for Huntorf is reported to be 90% and reliability 99%. Huntorf CAES is still in operation. The aerial picture of the plant is given as follows.

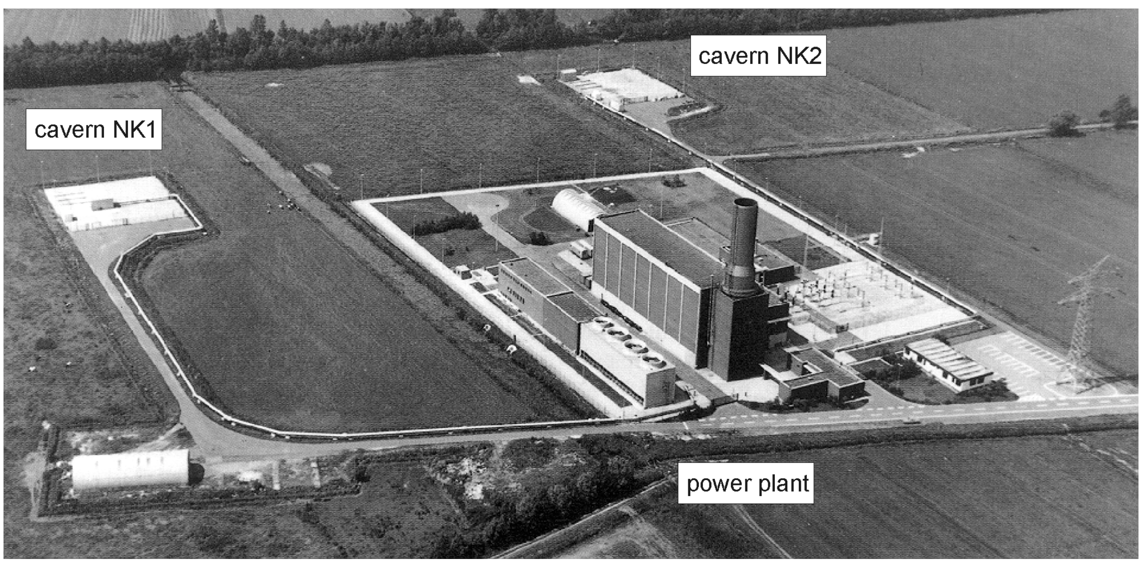


Figure 2.16 Aerial view of Huntorf plant

Source: (S. Succar)

The plant has two caverns, each having a volume of about 150,000 m^3. Both caverns are used during the operation of the plant. Air is stored between the range of 46 to 66 bars of pressure during operational pressure ranges. Well heads and related valves are the components of the plant which need maintenance most of the time. Huntorf plant is currently used to balance out the energy from the wind farms located in North Germany. The operational parameters of Huntorf plant are given in table 2.2.

Table 2.2 Specifications of Huntorf plant

Source: (BBC)

	Metric Units
Output	
turbine operation	290 MW
compressor operation	60 MW
Air mass flow rates	
turbine operation	425 kg/s
compressor operation	108 kg/s
air mass flow ratio in/out	1/4
Air cavern	2
total cavern volume	300,000 m^3
location of caverns - top	650 m
- bottom	800 m
maximum diameter	60 m
well spacing	220 m
Cavern pressures	
minimum permissible	1 bar
minimum operational (exceptional)	20 bar
minimum operational (regular)	46 bar
maximum permissible & operational	66 bar
maximum pressure reduction rate	15 bar/h

The parameters given above such as operating pressure range of 46 bars to 66 bars corresponds to the total volume of both caverns which is about 300,000 m^3. The storage caverns is an underground salt cavern. The compressor charges the air into the storage by taking 60 MW at the mass flow rate of air at 108 kg/s. The compressor operates at a maximum of twelve hours. The gas turbine discharges the storage by providing 290 MW for a maximum of three hours at the mass flow rate of air at 425 kg/s. The maximum ramp rate for the discharge cycle in terms of storage pressure is 15 bar/h.

The discharge curves for pressure, and air flow rate for the plant are shown in figure 2.17. It can be seen in the figure that as the pressure decreases from 46 bars, which is the minimum operational range for pressure, the storage ceases to output the air at 417 kg/s, which is required to drive turbine at 100% load conditions.

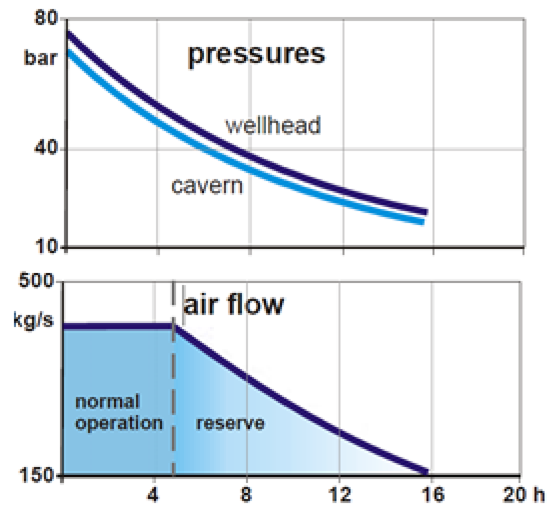


Figure 2.17 Pressures, and air flow during discharge

Source: (Crotogino 2001)

The pressure and temperature in the cavern and at the wellhead follow a similar behavior. The finite difference between the two is because of the thermodynamic losses. Caverns are completely emptied for maintenance work to be carried out on well head. The plant compressor needs to have at least 13 bars of pressure of air inside single cavern. When maintenance work is complete, the empty cavern is initially filled from the compressed air inside other cavern to a minimum pressure at which the plant compressor can operate. The cavern is filled by the plant compressor afterwards and it becomes operational. This is one of the reasons why two caverns are being used instead of one.

The data related to temperature and pressure at different stages of Huntorf plant is given in figure 2.18. It is shown that this plant uses a two-stage compressor. The inlet temperature and pressure to the compressor is 15^{o} C and 1 bar respectively. The output pressure of the first stage is 55 bars. The final output pressure, which is the final output pressure of the compressor, is 68 bars at a temperature of 37^{o} C. The aftercooler and the intercooler extract most of the heat produced during compression process.

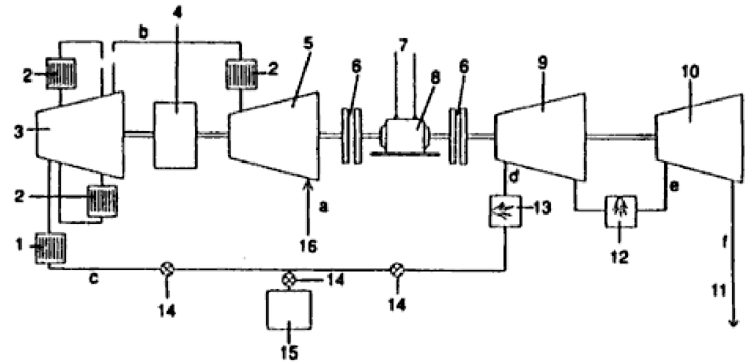


Fig. 7.9 *Huntorf CAES*

1 aftercooler
2 intercooler
3 compressor (high pressure stage)
4 gear box
5 compressor (low pressure stage)
6 clutch
7 transmission line
8 motor/generator
9 high pressure turbine
10 low pressure turbine
11 exhaust
12 low pressure combustor chamber
13 high pressure combustor chamber
14 valve
15 air cavity
16 intake

Power conditions
a - 15°C, 1 bar
b - 55 bar
c - 37°C, 68 bar
d - 550°C, 43 bar
e - 825°C, 11 bar
f - 390°C, 11 bar

Figure 2.18 Stages of Huntorf plant

Source: (Energy Storage for Power Systems, Ter-Gazarian)

The gas turbine used is based on two stages. After combusting air and fuel, air is fed to second stage at 43 bars of pressure and 550^{o} C of temperature. The temperature of the air rises due to combustion. Air is combusted again before entering the second stage. The second stage intakes air at 11 bars of pressure and 825^{o}C of temperature. The low pressure turbine expands the air from 11 bars to 1 bar.

The following figure provides the operational behavior of the gas turbine of Huntorf CAES. It shows the relationship between the mass flow rate of air through the gas turbine and the amount of load. Since the turbine operates at full load of 290 MW, this corresponds to the full load which is 100%. The mass flow rate at full load is 417 kg/s.

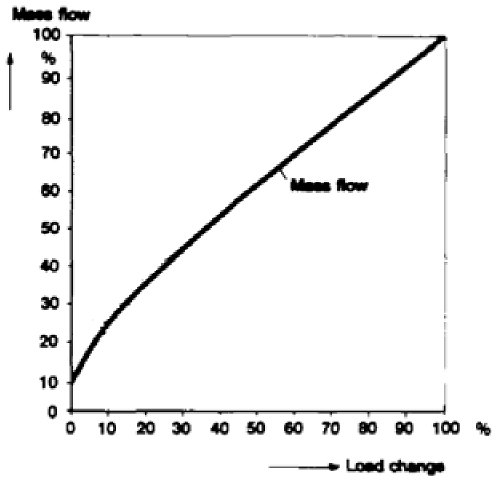


Figure 2.19 Partial load operation of Huntorf CAES
Source: (STYS)

2.3.2.2 McIntosh

McIntosh compressed air energy storage plant is located in southwestern Alabama. McIntosh is the world's second CAES plant and was brought to operation in 1991. The plant is designed to output 110 MW of power. It was built by Dresser-Rand. The plant has one cavern having a volume of 560,000m^3. Air is stored between 45 and 74 bars of pressure. The plant provides 26 hours of generation at full power. The McIntosh has almost similar operational features in terms of pressure and temperatures as compared to Huntorf plant. The main difference is that recuperators were installed which use the waste heat to preheat the air before combustion, which reduces the fuel consumption by approximately 22% at full output power. This plant was developed to meet the intermediate load following needs.

Figure 2.20 Aerial view of McIntosh CAES plant

Source: (Power South Energy Cooperative)

2.3.2.3 Norton

Norton CAES plant is a proposed project that is underway in Norton, Ohio. A limestone mine which is not in use is planned to be used to store the compressed air. This storage is 9.6 million cubic meters of storage. The operational pressure ranges are planned between 55 and 110 bars. Initially it is planned to provide a minimum power of 268 MW. It is planned to be expanded up to 2700 MW of power. It is planned for a daily operation of sixteen hours in five days a week.

2.3.2.4 Iowa Stored Energy Park

The Iowa Stored Energy Park is a proposed CAES project underway near Ankeny, Iowa. This is the first time that a CAES plant is being coupled with wind farm and porous rock storage reservoir is being considered for the storage of compressed air. It is planned to provide 268 MW of power. This project is being developed by the Iowa Association of Municipal Utilities (IAMU). Approximately twenty sites in Iowa have been tested for compressed air and good storage aquifer site has been reported to be found. The plant is planned to operate in 2011. The conceptual diagram for ISEP is given in figure 2.20.

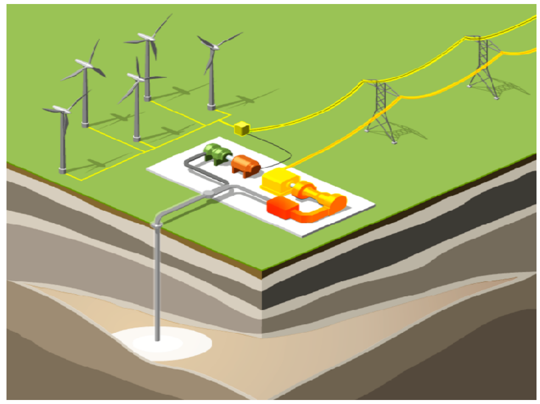


Figure 2.21 Iowa Stored Energy Park

Source: (Iowa Stored Energy Park)

2.3.3 Cost of CAES

The cost of CAES depends upon its size, configuration and the nature of storage being used. The figure below shows the comparison of developmental costs for air storage for different kinds of geology. Rock caverns cost the most in terms of volume and energy storage. Limestone or coal cost less than rock caverns. Solution mined salt and porous rock formations are least expensive among the storage geologies.

Source of Estimate	Power Related Cost (PCS) ($/kW)	Energy Capacity Related Cost (Storage System) ($/kWh)	BoP ($/kWh)	Fixed O&M ($/kW-yr)
Schoenung and Hassenzahl (2003) (bulk storage)	425	3	50	2.5
Schoenung and Hassenzahl (2003) (distributed generation/surface)	550	120	50	10
Schoenung and Eyer (2008) (distributed generation/surface)	550	120	50	*
EPRI-DOE (2003) (range 2002$)[1]	400–450	*	*	*
EPRI-DOE (2003) (salt mine 300 MWac)	270	1[2]	$170/kW	13
EPRI-DOE (2003) (surface 10 MWac)	270	40	$160/kW	19–24.6
Van der Linden (2006)	500–600[3]	*	*	*
EPRI (2003) (salt/ porous/hard rock/surface)	350 (all)	1/0.10/30/30	*	6
EPRI-DOE (2004) (salt/surface)[4]	300	1.75[5]/40	$ 210/ $200/kW	(23.6–24.6)/ (27–32.6)
Nakhamkin (2007) (72 MW adiabatic CAES)	1,700	*	*	6[6]

* Not available/not applicable
[1]Plants: 290 MW/10 hr, 110 MW/26 hr, 2,700 MW/30 hr (never completed), 540 MW/NA (canceled).
[2]"The reference energy storage capacity for large CAES technologies is 10 hours. A representative price for CAES systems over the range of 8 to 20 hours of storage can be obtained by applying increments/decrements at the rate of $1/kWh."
[3]100–300 MW.
[4]This is an update to the EPRI-DOE (2003) handbook.
[5]"The reference energy storage capacity for large CAES technologies is 10 hours. A representative price for CAES systems over the range of 8 to 40 hours storage can be obtained by applying increments/decrements at the rate of $1.75/kWh."
[6]Value from EPRI (2003)

Figure 2.22 Literature values for CAES costs
Source: (NREL)

According to the data given in the figure above, the power related cost the O&M cost is the same for all the geologies. The variable O&M cost of CAES plant is $5/MWh according to Energy Storage and Power LLC. The energy related capacity cost varies. The above figure provides the values for newly created limestone mines for the purpose of storing energy. The following figure provides the energy storage related capital costs for existing or abandoned limestone mines.

Formation Type	Air $/kWh ($2003)	Air $/kWh ($2008)	Air $/m³ ($2008)	Hydrogen $/kWh[1]
Solution-mined salt caverns[2]	1.00	1.20	2.88	0.02
Dry-mined salt caverns[2]	10.00	11.50	27.60	0.16
Rock caverns created by excavating comparatively impervious rock formations[2]	30.00	35.00	84.00	0.49
Naturally occurring porous rock formations (e.g., sandstone and fissured limestone) from depleted gas or oilfields[2]	0.10	0.12	0.29	0.002
Abandoned limestone or coal mines[2]	10.00	11.50	27.60	0.16
Geologic storage of hydrogen[3]	N/A	N/A	N/A	0.30

[1]Hydrogen storage cavern development cost is calculated assuming the same $/m³ as for CAES cavern development and energy density from Crotogino and Huebner (2008).
[2]Source: EPRI (2003) and Crotogino and Huebner (2008).
[3]Equation from H2A Delivery Scenario Analysis Model Version 2.02, for 41,000-kg usable storage capacity, www.hydrogen.energy.gov/h2a_delivery.html.

Figure 2.23 Costs for existing mines
Source: (NREL)

2.3.4 Existing CAES Mathematical Models

2.3.4.1 Vongmanee, Monyakul

The Vongmanee, Monyakul CAES model is described in the following figure:

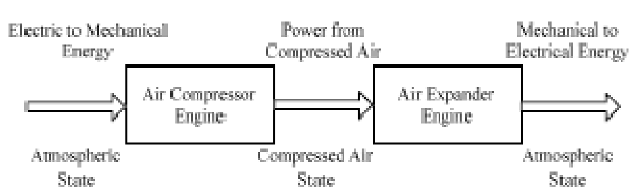


Figure 2.24 Vongmanee, Manyakul CAES Model

The model is developed in terms of three main components as the compressor, energy storage vessel and the compressed air generator. The electrical power from renewable energy resources is converted to mechanical power and provided to compressor which compresses the air from atmosphere and stores it in the storage vessel. This compressed air is used to turn the prime mover, which is coupled with generator, which converts mechanical power back to electrical power. The state of air changing in this system is shown in the diagram above.

The Vongmanee, Monyakul describes the compression process with the following equation:

$$P_c = P_1 Q(lnP_2 - lnP_1)$$

$$where$$

$$P_c = compression\,power\ (kW)$$

$$P_1 = pressure\ of\ air\ at\ inlet\ (bar)$$

$$P_2 = pressure\ of\ air\ at\ outlet\ (bar)$$

$$Q = air\ flow\ (m^3/s)$$

The expansion process is described by the same equation. The state of the stored air can be known through integrating the volumetric flow rate of air with respect to time.

The Vongmanee, Monyakul does not address the states of CAES completely. It has only one state which is the volumetric flow rate of air. The state of storage pressure, which is critical for CAES constraint analysis, is not included. The mass flow rate of air is commonly used as a parameter of air flow. This has also not been addressed in the model; instead volumetric flow rate is used.

The efficiency of compressor changes according to the input power levels. This has also not been addressed in this model. This model uses the model of an air expander, whereas the analysis require the model of gas turbine.

2.3.4.2 Rizzo, Marano

The compression process in Rizzo, Marano CAES model is given by the following equation:

$$P_c = \frac{1}{\eta_c}\dot{m}C_pT_{in}\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]$$

$where$
$P_c = input\ power\ to\ compressor$
$\eta_c = overall\ efficieny\ of\ compressor$
$\dot{m} = mass\ flow\ rate\ of\ air$
$p_2 = pressure\ at\ outlet\ of\ compressor$
$p_1 = pressure\ at\ inlet\ of\ compressor$
$k = specific\ heat\ ratio\ of\ air\ (C_p/C_v)$

The overall efficiency of compressor is a function of input power to the compressor according to the following figure.

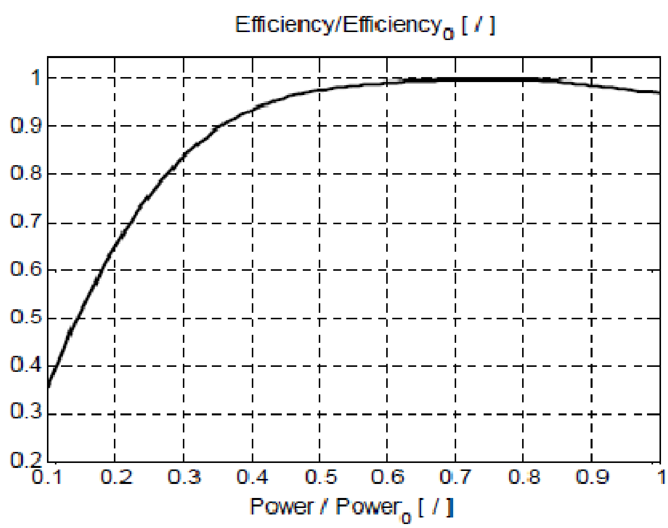


Figure 2.25 Relative variation of compressor efficiency vs. power

The mass flow rate at given power input levels is determined as follows:

$$\dot{m}_{compressor} = \frac{P_c}{C_p T_{in}\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]} \eta_c(P_c)$$

The air reservoir heat state equation is as follows:

$$\frac{dU}{dt} = \dot{m}_{compressor} h_{in} - \dot{m}_{turbine} h_{out}$$

$$where$$

$$U = internal\ energy\ (KJ)$$

$$\dot{m}_{compressor} = mass\ flow\ rate\ of\ air\ input\ to\ reservoir\ from\ compressor$$

$$\dot{m}_{turbine} = mass\ flow\ rate\ output\ from\ reservoir\ to\ gas\ turbine$$

$$h = enthalpy$$

The air reservoir pressure and temperature state equation is as follows:

$$\frac{d}{dt}\left(\frac{p}{T}\right) = (\dot{m}_{compressor} - \dot{m}_{turbine})\frac{R}{V}$$

$$where$$

$$R = gas\ constant$$

$$V = volume\ of\ storage$$

The air reservoir mass state equation is given as follows:

$$m_{stored} = \int_0^t (\dot{m}_{in} - \dot{m}_{out})dt$$

The resulting state equation becomes as follows

$$\frac{dp}{dt} = \left(m_{stored}\frac{dT}{dt} + \dot{m}_{in}T - \dot{m}_{out}T\right)\frac{R}{V}$$

$$T = \frac{pV}{m_{stored}R}$$

The reduced parameters for the turbine are as follows:

$$\dot{m}_{red,T} = \frac{\dot{m}_T}{p_{in,T}}\sqrt{T_{in,T}}$$

$$n_{red,T} = \frac{n_T}{\sqrt{T_{in,T}}}$$

The turbine operation state is given by the following equation:

$$\frac{\dot{m}_T}{\dot{m}_{T,0}} = \sqrt{1.4 - 0.4\left(\frac{n_T}{n_{T,0}}\right)}\sqrt{\frac{T_{in,T}}{T_{in,T,0}}}\sqrt{\frac{(\beta^2 - 1)}{({\beta_0}^2 - 1)}}$$

The efficiency is calculated as follows:

$$\frac{\eta_T}{\eta_{T,0}} = \left[1 - t\left(1 - \frac{n_{red,T}}{n_{red,T,0}}\right)^2\right]\left(\frac{n_{red,T}}{n_{red,T,0}} \times \frac{\dot{m}_{red,T,0}}{\dot{m}_{red,T}}\right)\left(2 - \frac{n_{red,T}}{n_{red,T,0}} \times \frac{\dot{m}_{red,T,0}}{\dot{m}_{red,T}}\right)$$

This model does not provide the similarity between the compression and gas turbine operations. The state of internal energy is also used which is usually not required for CAES analysis in terms of energy storage and power generation on hourly basis. There is an algebraic loop in the storage mathematical model. The turbine model is far more detailed as compared to the compressor model. The compression process is evaluated through adiabatic compression process and shaft speeds are not taken into consideration. The expressions used to calculate reduced parameters such as the mass flow rate and speed of the turbine are not balanced in terms of units. The expression used for calculating efficiency has the same issue.

The model also does not provide an expression between output power and the mass flow rate of air and fuel.

2.3.4.3 Dai, Das, Riaz

The state equations for the CAES model are given as follows.

$$\dot{m}_{A\_in} = \frac{P_c}{c_{p1}T_{in}\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

$$\gamma = C_{p1}/C_{v1}$$

The above equation indicates the charging operation of compressor. It provides the expression between the power to the compressor and the mass flow rate from the compressor which is fed to the storage. The mass flow rate and the power are the only variables. The input temperature and pressure ratio is assumed to be constant. The above equation is valid for single stage compressor.

$$\dot{m}_{A\_out} = \frac{P_{GT}}{\eta_M \eta_G c_{p2} T_2 \left(1 + \frac{\dot{m}_{A\_out}}{\dot{m}_{Fuel}}\right)\left(\frac{c_{p1}T_1}{c_{p2}T_2}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k_1-1}{k_1}}\right] + 1 - \left(\frac{P_b}{P_2}\right)^{\frac{k_1-1}{k_1}}\right)}$$

The above equation indicates the discharge operation of gas turbine. It relates the mass flow rate input to the gas turbine and the electric power produced by the turbine. These are the only two variables. The mechanical efficiency, electrical efficiency, input temperature to first and second stage and pressure ratios are kept constant.

$$m = \int \dot{m}_{A\_in}\, dt - \int \dot{m}_{A\_out}\, dt$$

The above equation indicates the state of charge in terms of the mass stored inside the storage. The mass flow rate input to the storage from the expression of compressor and the mass flow rate output from the expression of gas turbine are integrated and subtracted to calculate the net mass present in the storage.

$$p = \frac{R}{V}\left(\int \dot{m}_{A\_in}.T_{in}dt - \int \dot{m}_{A\_out}.T_{s}dt\right)$$

The above equation also indicates the state of charge, but in terms of pressure. Since pressure must be kept under the operational limits, it is an important state in CAES. The temperature of air flowing into the storage and flowing out of the storage is kept constant.

This CAES model assumes that the pressure ratio for compressor remains constant. This might not be true if compressor is directly coupled to the storage. Since the output of compressor is fed into the storage, and the input pressure is constant to be atmospheric pressure, the pressure ratio will change according to the pressure inside the storage. Also, compressors used in present CAES plants like Huntorf and McIntosh compose of more than one stage. The efficiency component for compressor is also not available. Since efficiency of compressor is not constant at all power conditions, it is an important factor to be introduced.

The electrical efficiency of electric generator changes with the load level according to the figure below. Since power mismatch is always changing on the grid, the gas turbine operates at different power conditions, it is important to take variable electrical efficiency into consideration.

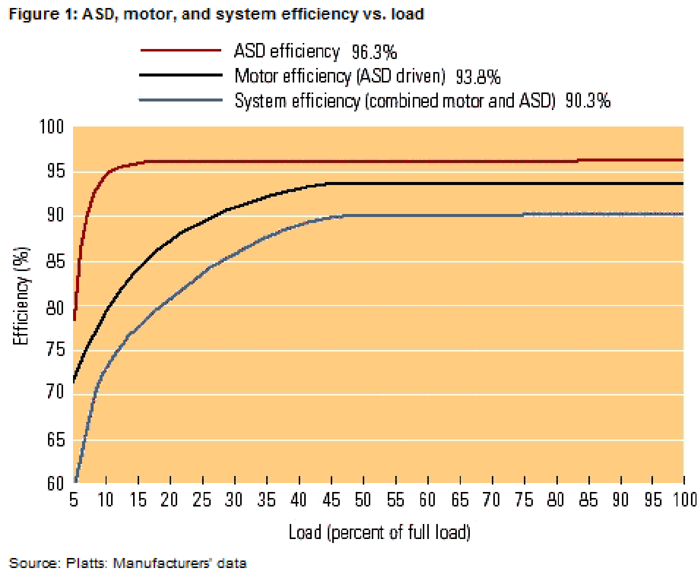


Figure 2.26 Electrical Efficiency vs. Load

Source: (Reliant Energy)

CHAPTER 3

COMPONENT MODEL DEVELOPMENT

3.1 Compressed Air Energy Storage

Following is the operational data for the Huntorf CAES plant in Germany.

Table 3.1 Operational data used in CAES simulation

Source: (BBC)

	Metric Units
Output	
turbine operation	290 MW
compressor operation	60 MW
Air mass flow rates	
turbine operation	425 kg/s
compressor operation	108 kg/s 50°C
air mass flow ratio in/out	1/4
Natural gas mass flow rates	
turbine operation	11 kg/s
Air caverns	2
total cavern volume	300,000 m^3
Cavern pressures	
minimum operational	46 bar
maximum operational	66 bar
pressure reduction rate	10 bar/h
Compressor Pressures	
Inlet	1 bar
Outlet	46-66 bar
Turbine Pressures/Temperatures	
1^{st} stage inlet	41 bar 550 °C
2^{nd} stage inlet	11 bar 825 °C
Startup times/ramp rate	
Turbine Startup time	11 min
Turbine Ramp rate for full load	88 MW/min
Compressor startup time	9 min

3.1.1 Compressor

There is large variety of compressors being used in the industry today. The compressors used in this design are centrifugal compressor and axial compressor. Centrifugal compressors are radial flow compressors (Dixon). It is recommended to use either radial or axial flow compressors for CAES (Alstom). A combination of axial flow compressor and centrifugal compressor is used in the design of Huntorf and McIntosh CAES plants. The centrifugal compressor and axial flow compressors can be evaluated using adiabatic compression process (McAllister).

The adiabatic compression process is given by the following equation which relates the power input to the mass flow rate (Arsie, Marano)

$$P_c = \dot{W} = \frac{1}{\eta_c}\dot{m}C_pT_{in}\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]$$

$where$

$P_c = input\ power\ to\ compressor$

$\eta_c = overall\ efficieny\ of\ compressor$

$\dot{m} = mass\ flow\ rate\ of\ air$

$p_2 = pressure\ at\ outlet\ of\ compressor$

$p_1 = pressure\ at\ inlet\ of\ compressor$

$k = specific\ heat\ ratio$

We can re-arrange the equation to solve for mass flow rate of air, since we know the input power. Therefore we can calculate the mass flow rate of air at different input power levels.

$$\dot{m} = \frac{P_c}{C_pT_{in}\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]}\eta_c$$

The pressure ratio (p_2/p_1) is defined as the amount of times the air is compressed from initial pressure to the final pressure. The process dependent constant, n depends upon the type of compression process that the compressor follows, e.g. adiabatic, polytropic or isothermal. The range of values of n varies from 1.0 to 1.4.

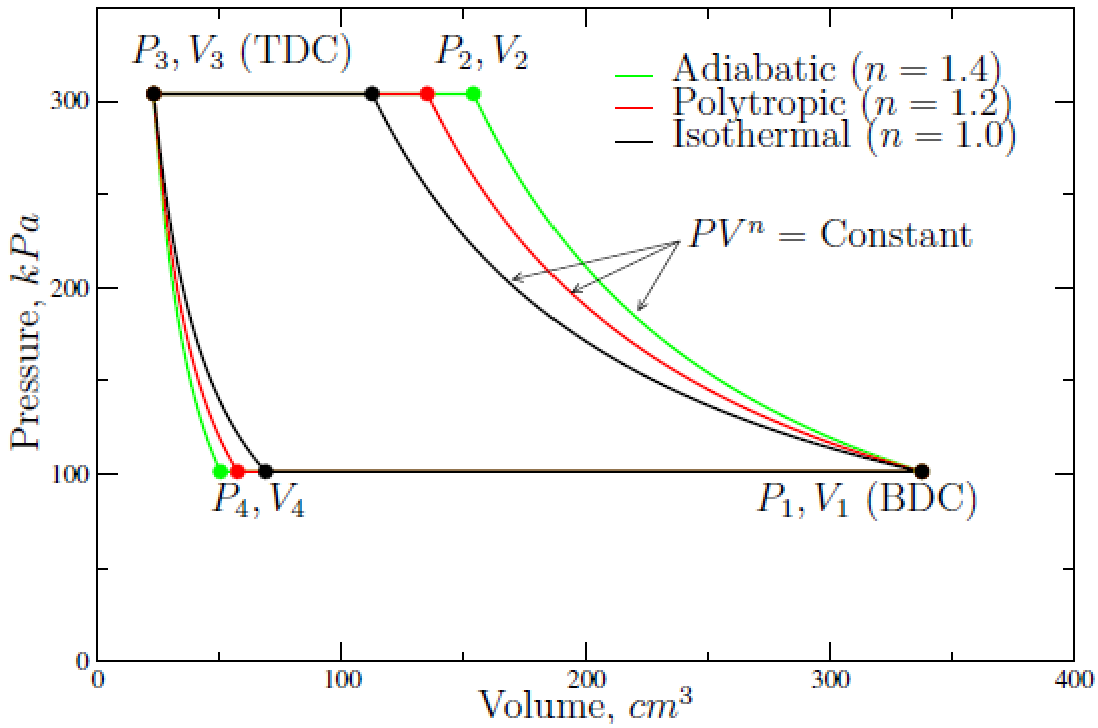


Figure 3.1 Process dependent constant at for different processes

Source: (Ueno, Hunter)

As shown in the figure above, when n is 1, an isothermal process occurs. An isothermal process is a kind of compression process in which the inlet and outlet temperatures remain same. Therefore we lose all heat during the isothermal compression process. Adiabatic process is the kind of compression process in which no heat is lost during the compression. Therefore this results in higher temperature at the outlet of the compressor. The polytropic compression process is type of process in which we lose heat but not all of it, during the compression process (Ueno, Hunter).

T_1 is the suction temperature at the inlet of the compressor which is typically taken as ambient temperature. The specific heat capacity of air at constant pressure (C_p) is 1.005 kJ/kgK (Jacobson). The value of power calculated would be in kW.

The overall efficiency of the compressor varies according to its size and design. It depends on the efficiency of electric motor that is coupled to the compressor and the efficiency of the compressor. Its value can be selected so that the performance of compressor matches to that of an industrial compressor. Typically, compressors are coupled together in different stages. Intercoolers are connected in between the stages to extract the heat from compressed air and make the compression process more efficient. CAES facilities like Huntorf and McIntosh use more than one stage for air compression. The two stage compressor equation can be written as follows using the given compressor equation.

$$\dot{m}_{in} = \frac{P_c}{C_p T_1 \left[\left(\frac{p_2}{p_{in}} \right)^{\frac{n-1}{n}} - 1 \right] + C_p T_2 \left[\left(\frac{p_{out}}{p_2} \right)^{\frac{n-1}{n}} - 1 \right]} \eta_c$$

$where$
$p_{in} = pressure\ of\ injected\ air\ at\ inlet\ of\ first\ stage$
$p_{out} = pressure\ of\ air\ at\ outlet\ of\ final\ stage$
$T_1 = temperature\ of\ air\ at\ inlet\ of\ first\ stage$
$T_2 = temperature\ at\ inlet\ of\ final\ stage$

The above expression provides the mass flow rate input to the storage. The pressure ratio of stage 1 is assumed to be constant. Since p_{in} is the atmospheric pressure it is assumed to be 1 bar. The output of compressor is assumed to be the input of storage, therefore, the output pressure, p_{out} of compressor is assumed to be the pressure of the storage which varies between 46 to 66 bars. Since no information is available on p_2, it is assumed to be 5.2 bars, which satisfies the criterion that first stage axial flow compressor has lower pressure ratio as compared to the second stage centrifugal compressor. Therefore the first stage axial flow compressor is assumed to have constant pressure ratio of 5.2 whereas the second stage centrifugal compressor is assumed to have variable pressure ratio between the ranges of 8.85

to 12.69. These numbers comply with the performance characteristics of both compressors as shown below.

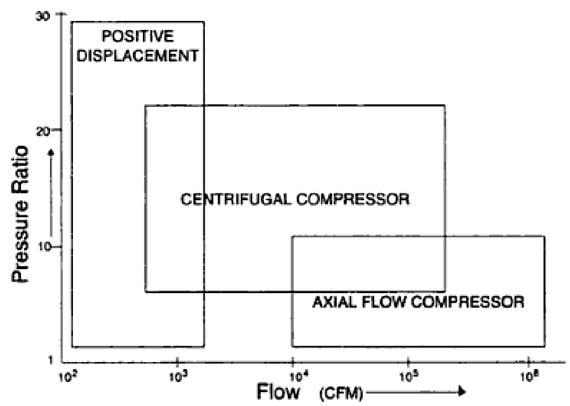


Figure 3.2 Performance characteristics of centrifugal and axial flow compressors

Source: (Boyce)

The inlet temperature of both stages, T_1 and T_2 is assumed to be constant.

The compression operation is supposed to be completely adiabatic i.e. lossless. For adiabatic process k for air is taken to be 1.4. C_p is the specific heat of air at constant pressure which is known to be 1.005 kJ/kgK. The input temperature of air to the first and second stage is assumed to be 289 K and 303 K respectively. Since the mass flow rate of air at full load is given as 108 kg/s, the efficiency of compressor at full load (60MW) can be calculated according to the following expression.

$$\eta_c = \frac{\dot{m}_{in}\left(C_p T_1\left[\left(\frac{p_2}{p_{in}}\right)^{\frac{n-1}{n}} - 1\right] + C_p T_2\left[\left(\frac{p_{out}}{p_2}\right)^{\frac{n-1}{n}} - 1\right]\right)}{P_c}$$

Using the above mentioned parameters, the full load operation efficiency is calculated as 0.91 according to the expression above.

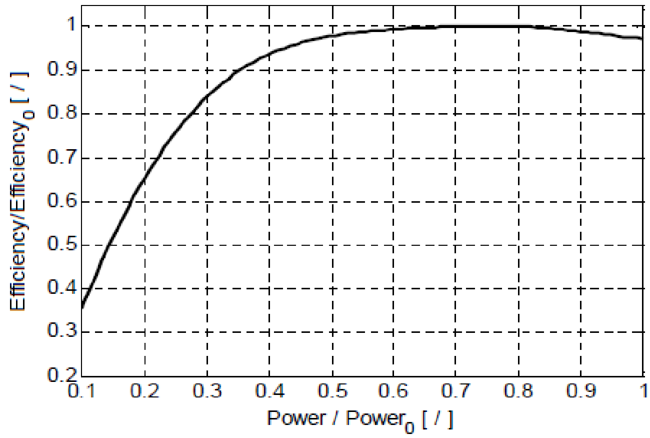


Figure 3.3 Compressor efficiency vs. power

The above figure shows the part-load operation of the compressor and its efficiency which is taken from existing CAES model for the component of compressor. Since our full load operation efficiency is 0.91, which is different than that of 0.97 in the figure, the given compressor profile is offset by -0.06. This provides us with values given in the following table.

Table 3.2 Compressor power vs. efficiency values

Power level (MW)	**Efficiency**
60	0.91
49.2	0.94
40.8	0.94
30	0.91
24	0.87
18	0.78
12	0.59
6	0.32

Using the values given in the table above, the efficiency profile is implemented according to piecewise linear approximation. The piecewise linear functions are given as follows.

Table 3.3 Piecewise linear functions for compressor power vs efficiency

Power (P) (MW) P(MW)=p(kW)e3	**Efficiency**
$49.2 \leq P \leq 60$	$-0.0278 \times 10^{-4}p + 1.0767$
$40.8 \leq P < 49.2$	0.94
$30 \leq P < 40.8$	$0.0278 \times 10^{-4}p + 0.8267$
$24 \leq P < 30$	$0.0667 \times 10^{-4}p + 0.71$
$18 \leq P < 24$	$0.15 \times 10^{-4}p + 0.51$
$12 \leq P < 18$	$0.3167 \times 10^{-4}p + 0.21$
$6 \leq P < 12$	$0.45 \times 10^{-4}p + 0.05$

The implementation of the above piecewise function is shown in the figure below.

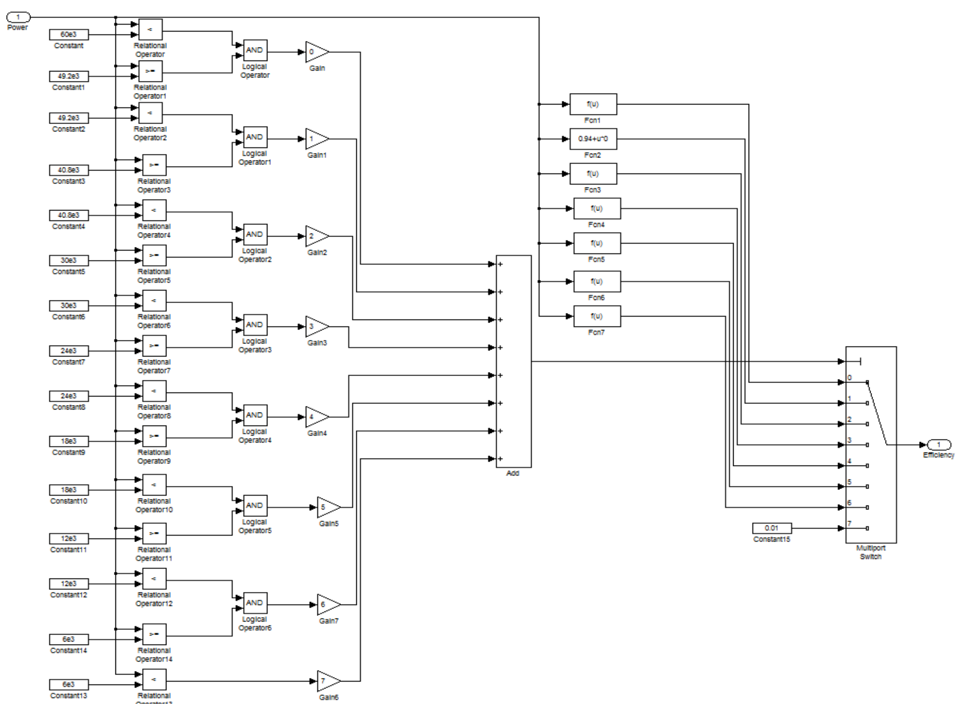


Figure 3.4 Piecewise linear implementation in Simulink

The power input is first compared with by the relational operators. There are two relational operators to compare the upper and lower limit of the power. The AND logic is applied to the upper and lower limit relational operators. A specific gain is assigned for each function. The output of AND gates with specific gain is added. Only one AND gate is enabled at a given time. The output of adder is fed to the multiport switch which then selects the piecewise linear function given at the ports according to the gain. Hence, this gives the efficiency for the corresponding power level at which the compressor operates.

For part-load operation, using the existing profile of compressor efficiency and power, we get the following relationship between the power of compressor and its efficiency with piecewise linear approximation.

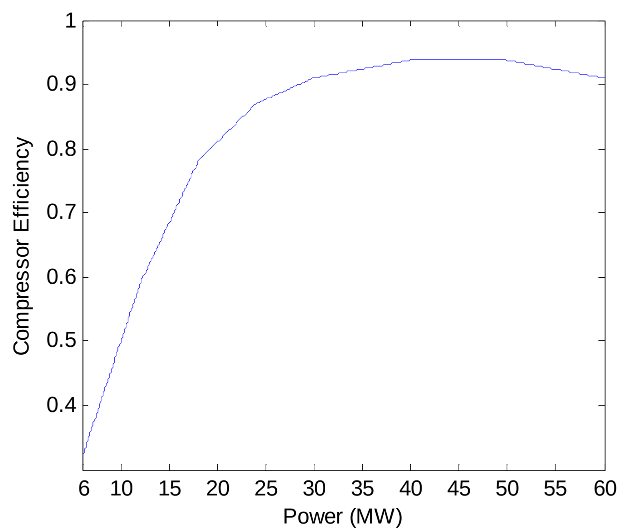


Figure 3.5 Simulation results for efficiency piecewise linear functions

The compressor model is shown in the figure below. Stage 1 refers to the expression $C_p T_1 \left[\left(\frac{p_2}{p_{in}} \right)^{\frac{n-1}{n}} - 1 \right]$. Stage 2 refers to the expression $C_p T_2 \left[\left(\frac{p_{out}}{p_2} \right)^{\frac{n-1}{n}} - 1 \right]$. The output pressure is assumed to be the same as that of the storage pressure.

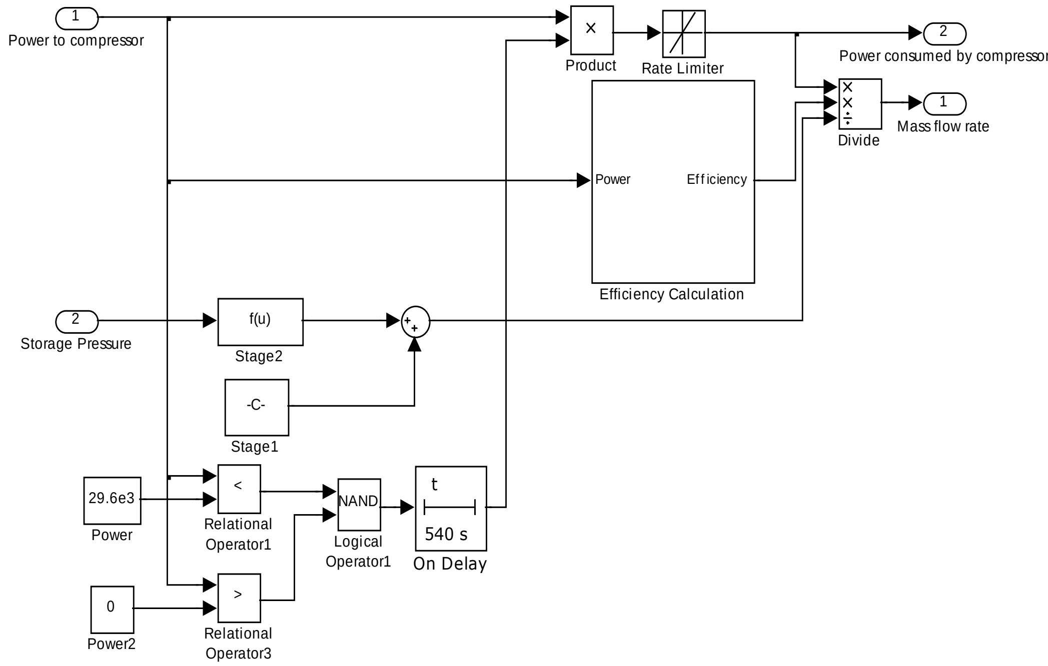


Figure 3.6 Compressor model for constant volume configuration

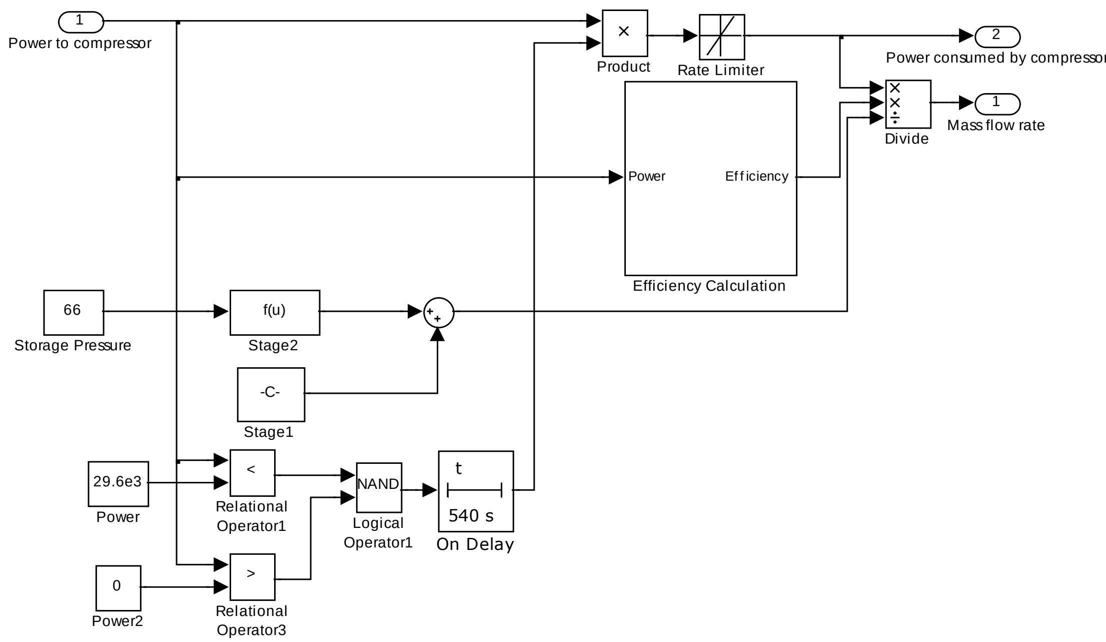


Figure 3.7 Compressor model for constant pressure configuration

The input power to the compressor above 29.6 MW, which is the operational requirement of the electric motor, is applied with a startup time of 540 seconds, which equals

9 minutes. This is implemented by comparing the input power to the compressor with relational operators. If the power is more than 29.6 MW the NAND output is true with an on delay of 9 minutes. This is multiplied by the input power and fed to the compressor equation with a ramp rate of 88 MW/min.

The power from the mismatch to compressor is controlled according to the pressure of the storage. If the pressure exceeds 66 bar, i.e. its operational limits, the compressors stops the operation. This is implemented in the following figure.

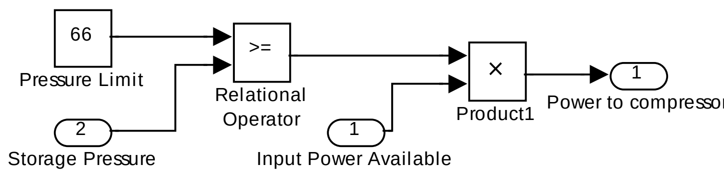


Figure 3.8 Compressor with storage pressure constraint

The implementation for constant pressure configuration is as follows.

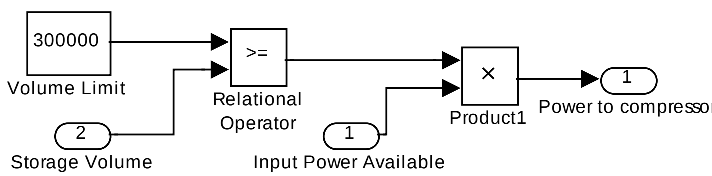


Figure 3.9 Compressor with storage volume constraint

3.1.2 Constant Volume Storage

We can write the ideal gas equation in the following manner (Moran, Shapiro):

$$PV = mRT$$

$$\begin{aligned} &where \\ &P = pressure\ in\ bars \\ &V = volume\ in\ m^3 \\ &m = mass\ in\ kg \end{aligned}$$

$$R = gas\ constant\ in \frac{m^3 bar}{kgK}$$
$$T = temperature\ in\ K$$

This equation can be modified as follows:

$$P = \frac{1}{V} mRT$$

$$\frac{dP}{dt} = \frac{1}{V} \frac{dm}{dt} RT$$

$$\frac{dP}{dt} = \frac{1}{V} \dot{m} RT$$

The overall mass flow inside the storage is the mass flowing in minus the mass flowing out. Therefore the equation becomes:

$$\frac{dP}{dt} = \frac{1}{V} (\dot{m}_{in} - \dot{m}_{out}) RT$$

$$P = \int_0^t \left[\frac{1}{V} (\dot{m}_{in} T_{storage} - \dot{m}_{out} T_{storage}) R \right] dt$$

V is the volume of storage in cubic meters which can be a volume of salt dome or aquifer. The value of universal gas constant R is given as (Monk):

$$83.145 cm^3 barmol^{-1} K^{-1}$$

We need to convert cubic centimeters in cubic meters and mol in kg. As we know

$$1cm^3 = \frac{1}{10^2 10^2 10^2} = 10^{-6} m^3$$

And

$$mole = \frac{mass}{molecular\ weight}$$

$$\begin{aligned}&where\\&mass\ is\ in\ kg\\&molecular\ weight = kg/mol\end{aligned}$$ (Atkins, Paula)

Molecular weight of air= 28.97 kg/kmol=0.02897kg/mol (Moran, Shapiro). Therefore from above equations the gas constant R can be written as

$$R = \frac{83.145}{10^6} \times \frac{1}{0.02897} m^3 bar kg^{-1} K^{-1} = 8.3145 \times 10^{-5} \frac{1}{0.02897} m^3 bar kg^{-1} K^{-1}$$

The mass inside the storage can therefore be calculated as:

$$\frac{dm_{stored}}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

$$m_{stored} = \int_0^t (\dot{m}_{in} - \dot{m}_{out}) dt$$

The input mass flow rate is calculated by the compressor equation (given in compressor section) while the compressor is running and is being fed to the storage. The output mass flow rate is calculated by the gas turbine equation while the turbine is running and is being fed to the turbine.

The storage temperature is assumed to be constant. The input mass flow rate is the mass flow rate calculated from the compressor expression. The output mass flow rate is obtained through the expression of gas turbine. R is the universal gas constant. It has a value of $287 \times 10^{-5} m^3 bar kg^{-1} K^{-1}$. T_{in} is the input temperature to the storage from the compressed air from compressor and is equal to 50+273 degrees kelvin as provided in the specifications of plant. The storage temperature is kept constant at 20+273 degrees kelvin because it only changes from 10 degree celcius to 35 degree celcius and does not has significant impact on results. Simulation results have shown that storage at 10 degrees celcius stores a maximum of 1227.53 MWh and storage at 35 degree celcius stores a maximum of 1227.51 MWh of energy. V is the volume of the storage which is given as 300,000 cubic feet. The figure below shows the implementation of storage pressure state.

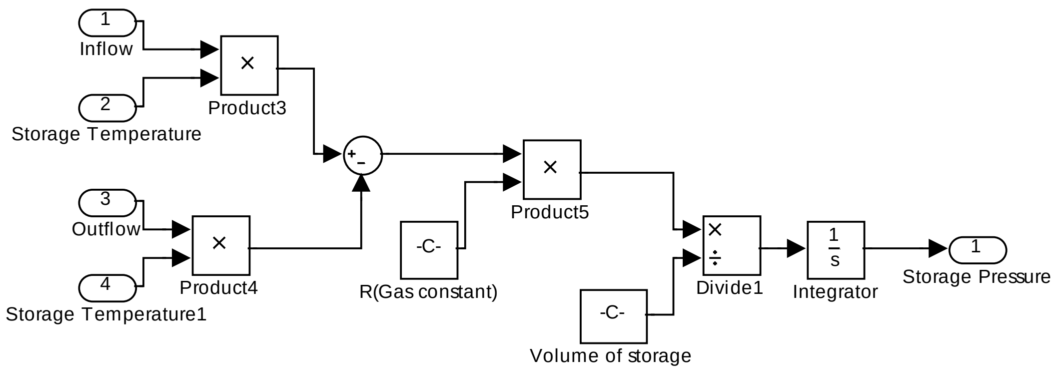


Figure 3.10 Constant volume storage model

The figure below shoes the implementation of storage mass state.

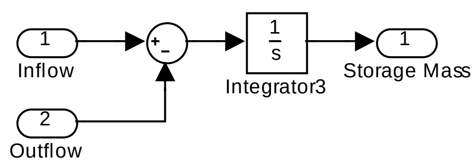


Figure 3.11 Mass of air in storage model

Following assumptions are made for the constant volume configuration

- Storage temperature remains constant
- Pressure ratio of first stage of compressor remains constant
- Pressure ratios of both stages of gas turbine remain constant
- Storage must discharge completely at the end of the day

- The output of compressor is assumed to be the input of storage, hence output pressure of second stage of compressor equals the storage pressure
- There is no daily and monthly allocation

3.1.3 Constant Pressure Storage

This ideal gas equation can be modified as follows for constant pressure configuration:

$$V = \frac{1}{P} mRT$$

$$\frac{dV}{dt} = \frac{1}{P}\frac{dm}{dt}RT$$

$$\frac{dV}{dt} = \frac{1}{P}\dot{m}RT$$

The overall mass flow inside the storage is the mass flowing in minus the mass flowing out. Therefore the equation becomes:

$$\frac{dV}{dt} = \frac{1}{P}(\dot{m}_{in} - \dot{m}_{out})RT$$

$$V = \int_0^t \left[\frac{1}{P}\left(\dot{m}_{in}T_{storage} - \dot{m}_{out}T_{storage}\right)RT\right] dt$$

V is the variable volume of storage in cubic meters which must be changed to keep the storage pressure constant. The storage temperature is assumed to be constant. Following figure shows the implementation of storage volume state for constant pressure storage.

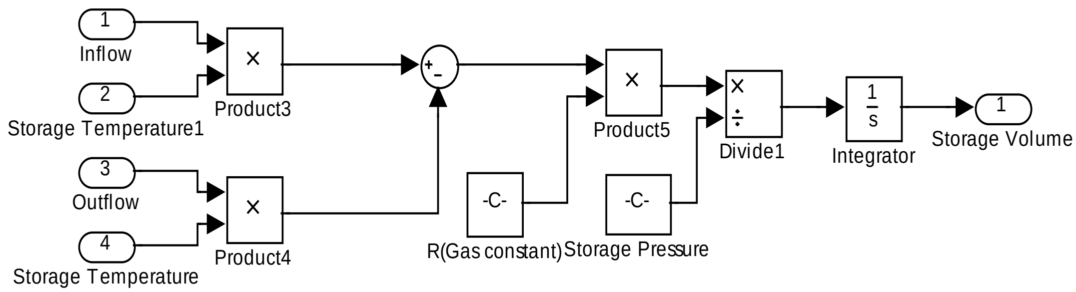


Figure 3.12 Constant pressure configuration storage model

Following assumptions are made for the constant pressure configuration

- Storage temperature remains constant
- Pressure ratio of first stage and second stage of compressor remains constant
- Pressure ratios of both stages of gas turbine remain constant
- Storage must discharge completely at the end of the day
- The output of compressor is assumed to be the input of storage, hence output pressure of second stage of compressor equals the storage pressure
- It can accommodate daily and monthly allocation

3.1.4 Gas Turbine

The gas turbine used in Huntorf CAES is a two stage turbine (Ter-Gazarian). The equation for the two stage turbine is stated below (Succar, Williams):

$$E_{GEN} = \eta_M \eta_G C_{p2} T_2 \left(1 + \frac{\dot{m}_{in,fuel}}{\dot{m}_{in,air}}\right) \int_0^t \dot{m}_{in,air} \left(\frac{C_{p1} T_1}{C_{p2} T_2}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n_1 - 1}{n_1}}\right] + 1 - \left(\frac{p_b}{p_2}\right)^{\frac{n_2 - 1}{n_2}}\right) dt$$

$where$
$\eta_M = mechanical\ efficiency$
$\eta_G = electric\ generator\ efficiency$
$C_p = specific\ heat\ capacity\ of\ air\ (KJkg^{-1}K^{-1})$
$p_1 = pressure\ at\ inlet\ of\ first\ stage\ (bar)$
$p_2 = pressure\ at\ input\ of\ second\ stage\ (bar)$

$p_b = barometric/atmospheric\ pressure\ (bar)$
$E_{GEN} = energy\ generated\ (kWH)$

To calculate for power the above equation can be re-arranged as follows. The ratio of mass flow rate of air to the mass flow rate of fuel is kept constant. Therefore:

$$E_{GEN} = \eta_M \eta_G C_{p2} T_2 \left(1 + \frac{\dot{m}_{in,fuel}}{\dot{m}_{in,air}}\right) \int_0^t \dot{m}_{in,air} \left(\frac{C_{p1} T_1}{C_{p2} T_2}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n_1-1}{n_1}}\right] + 1 - \left(\frac{p_b}{p_2}\right)^{\frac{n_2-1}{n_2}}\right) dt$$

Differentiating both sides with respect to time to obtain power

$$\frac{dE_{GEN}}{dt} = \eta_M \eta_G C_{p2} T_2 \left(1 + \frac{\dot{m}_{in,fuel}}{\dot{m}_{in,air}}\right) \frac{d}{dt} \int_0^t \dot{m}_{in,air} \left(\frac{C_{p1} T_1}{C_{p2} T_2}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n_1-1}{n_1}}\right] + 1 - \left(\frac{p_b}{p_2}\right)^{\frac{n_2-1}{n_2}}\right) dt$$

Since the derivative of energy is power

$$P_{GEN} = \eta_M \eta_G \left(1 + \frac{\dot{m}_{in,fuel}}{\dot{m}_{in,air}}\right) \dot{m}_{in,air} \left(C_{p1} T_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n_1-1}{n_1}}\right] + C_{p2} T_2 \left[1 - \left(\frac{p_b}{p_2}\right)^{\frac{n_2-1}{n_2}}\right]\right)$$

Re-arranging the equation to obtain expression for air mass flow rate.

$$\dot{m}_{in,air} = \frac{P_{GEN}}{\eta_M \eta_G \left(1 + \frac{\dot{m}_{in,fuel}}{\dot{m}_{in,air}}\right)\left(C_{p1} T_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n_1-1}{n_1}}\right] + C_{p2} T_2 \left[1 - \left(\frac{p_b}{p_2}\right)^{\frac{n_2-1}{n_2}}\right]\right)}$$

$$where\ \frac{\dot{m}_{in,fuel}}{\dot{m}_{in,air}} = constant = \dot{m}_{ratio}$$

This equation is used to calculate the input mass flow rate of air required to generate the power demanded. Since this is the mass flow rate required out of the storage $\dot{m}_{in,air}$ is denoted by $\dot{m}_{out}$ for clarity.

Therefore the equation for turbine becomes:

$$\dot{m}_{out} = \frac{P_{GEN}}{\eta_M \eta_G (\dot{m}_{ratio} + 1)\left(C_{p1}T_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n_1-1}{n_1}}\right] + C_{p2}T_2\left[1 - \left(\frac{p_b}{p_2}\right)^{\frac{n_2-1}{n_2}}\right]\right)}$$

The mass flow rate of air is estimated from this equation for each power generation level and the mechanical efficiency. This value of the mass flow rate of air is then fed back to the storage to calculate the new pressure due to the reduction in storage mass according to the equation provided in previous section. The generated power is the amount of power delivered, without violating the lower pressure limits of storage. The air-fuel ratio,$\dot{m}_{ratio}$, pressure ratios of both stages, inlet temperatures of both stages and electric generator efficiency are assumed to be constant.

The value for mechanical efficiency is not provided and hence is assumed to be 95%. The ratio of the mass flow rates can be calculated by the mass flow rate of air which is 425 kg/s and mass flow rate of natural gas which is 11 kg/s at rated power. Both of these values are given in the literature as operational values of Huntorf CAES.

$$\dot{m}_{ratio} = \frac{\dot{m}_{in,fuel}}{\dot{m}_{in,air}} = \frac{11}{425} = 0.0259$$

C_p is the specific heat of air at constant pressure which is known to be 1.005 kJ/kgK for both stages. Temperatures at the inlet of both the stages are available in the data specifications and are 550+273 and 825+273 degrees kelvin for first and the second stage respectively. The pressure at the inlet of first and second stages is provided as 41 and 11 bar respectively. The expansion process is assumed to be adiabatic since all of the stages are being analyzed separately. Therefore the value for n is kept at 1.4 for both stages.

The following figure provides the part-load operation of gas turbine for the Huntorf Germany CAES plant.

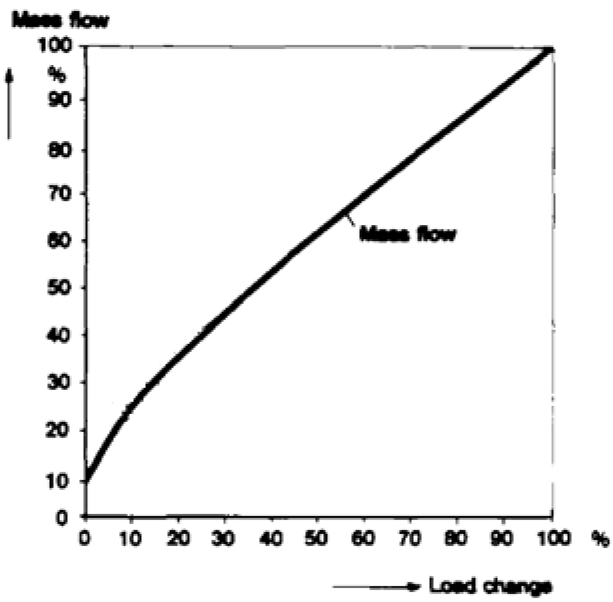


Figure 3.13 Operation of Huntorf CAES gas turbine
Source: (STYS)

The relationship between power and mass flow rate for the operation of Huntorf plant is not linear as shown in the figure above. The equation that we have used for the operation of gas turbine provides a linear relationship between the load power and mass flow rate.

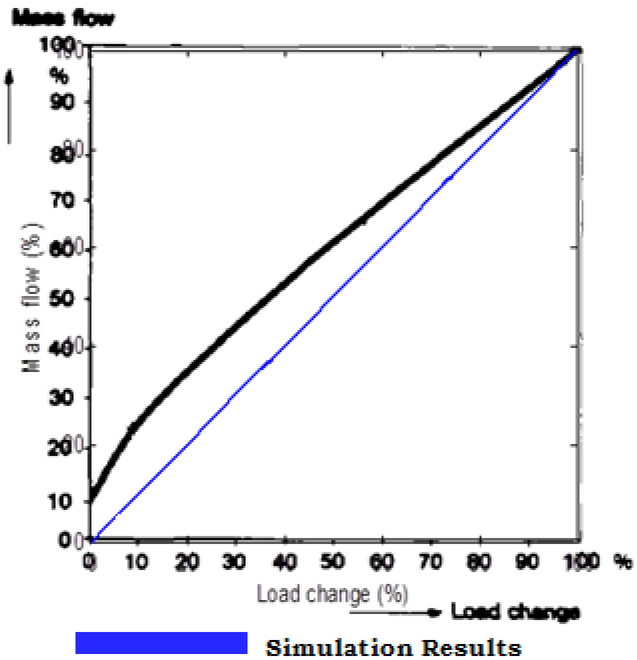


Figure 3.14 Simulation results for gas turbine with constant efficiency

Since this approximation does not match the operational part-load operation, the electrical efficiency, which varies according to the load level, is modeled as a variable. This electrical efficiency is implemented as a piecewise linear function such that the model is tuned according to the operational behavior of turbine. The data from the operational graph can be used to calculate the efficiency of turbine at each power level.

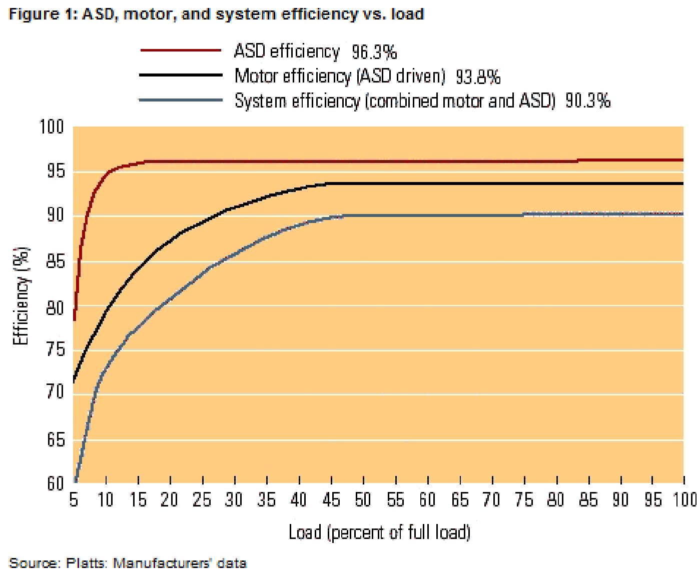


Figure 3.15 Electrical Efficiency vs. Load

Source: (Reliant Energy)

$$\eta_G = \frac{P_{GEN}}{\eta_M \dot{m}_{in,air}(1+\dot{m}_{ratio})\left(C_{p1}T_1\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n_1-1}{n_1}}\right]+C_{p2}T_2\left[1-\left(\frac{p_b}{p_2}\right)^{\frac{n_2-1}{n_2}}\right]\right)}$$

Table 3.4 Electrical efficiency of gas turbine generator at different load levels

Load (%)	**Mass flow(%)**	**Load (MW)**	**Mass flow (kg/s)**	**Electrical Efficiency (%)**
100	100	290	429.0316	86
85	90	246.5	386.1284	81.22
70	80	203	343.2253	75.25
60	70	174	300.3221	73.71
47	60	136.3	257.4190	67.37
35	50	101.5	214.5158	60.2
25	40	72.5	171.6126	53.75
14	30	40.6	128.7095	40.13
9.09	23	26.36	98.67726	33.99

Using piecewise linear approximation, following functions are obtained.

Table 3.5 Piecewise linear approximation for gas turbine generator efficiency

Power (P) (MW) P(MW)=p(kW)e3	Efficiency
$246.5 \leq P \leq 290$	$0.1099 \times 10^{-5}p + 0.5413$
$203 \leq P < 246.5$	$0.1372 \times 10^{-5}p + 0.4739$
$174 \leq P < 203$	$0.0531 \times 10^{-5}p + 0.6447$
$136.3 \leq P < 174$	$0.1682 \times 10^{-5}p + 0.4445$
$101.5 \leq P < 136.3$	$0.206 \times 10^{-5}p + 0.3929$
$72.5 \leq P < 101.5$	$0.2224 \times 10^{-5}p + 0.3762$
$40.6 \leq P < 72.5$	$0.4270 \times 10^{-5}p + 0.2280$
$26.36 \leq P < 40.6$	$0.4312 \times 10^{-5}p + 0.2262$

The piecewise linear function of load and electrical efficiency is given as follows.

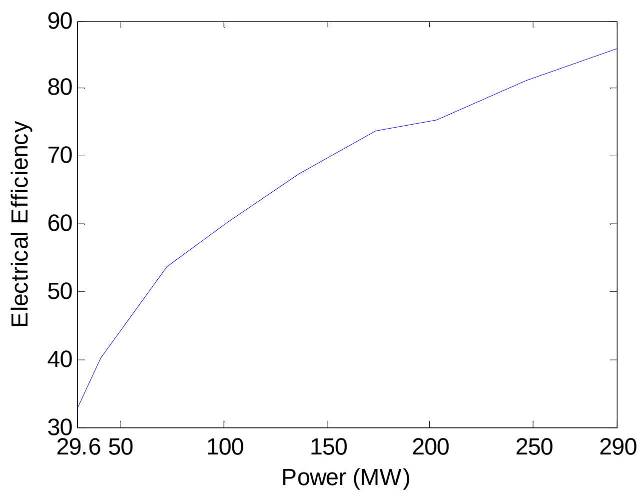


Figure 3.16 Electrical efficiency profile of gas turbine generator

The effieicncy calculation block in the following model includes the piecewise linear functions mentioned above. The simulation result for the tuned values is given as follows.

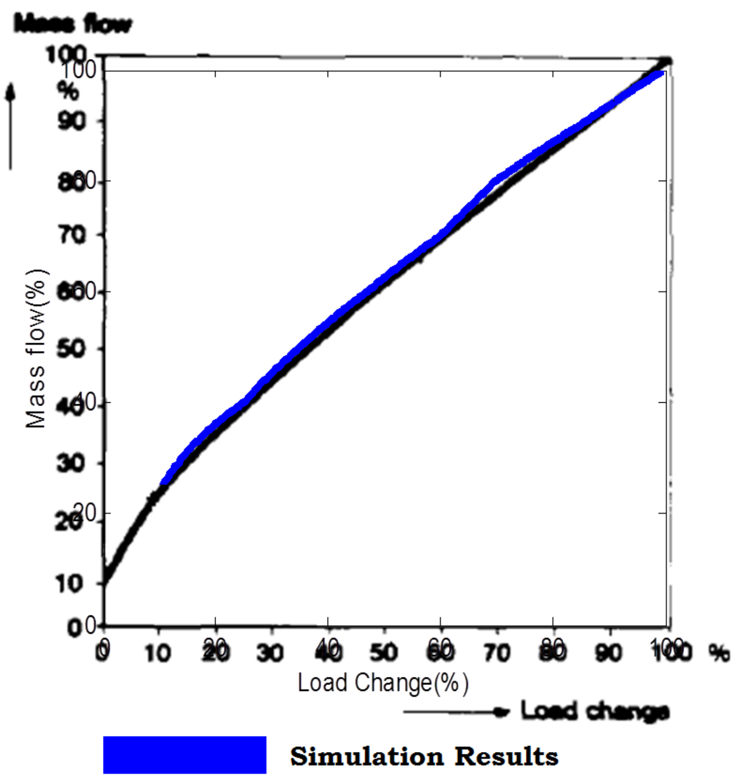


Figure 3.17 Simulation results of piecewise linear approximation of gas turbine generator efficiency

These are implemented in the same manner as that of the compressor. Stage 1 refers to $C_{p1}T_1\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n_1-1}{n_1}}\right]$ and stage 2 refers to $C_{p2}T_2\left[1-\left(\frac{p_b}{p_2}\right)^{\frac{n_2-1}{n_2}}\right]$.

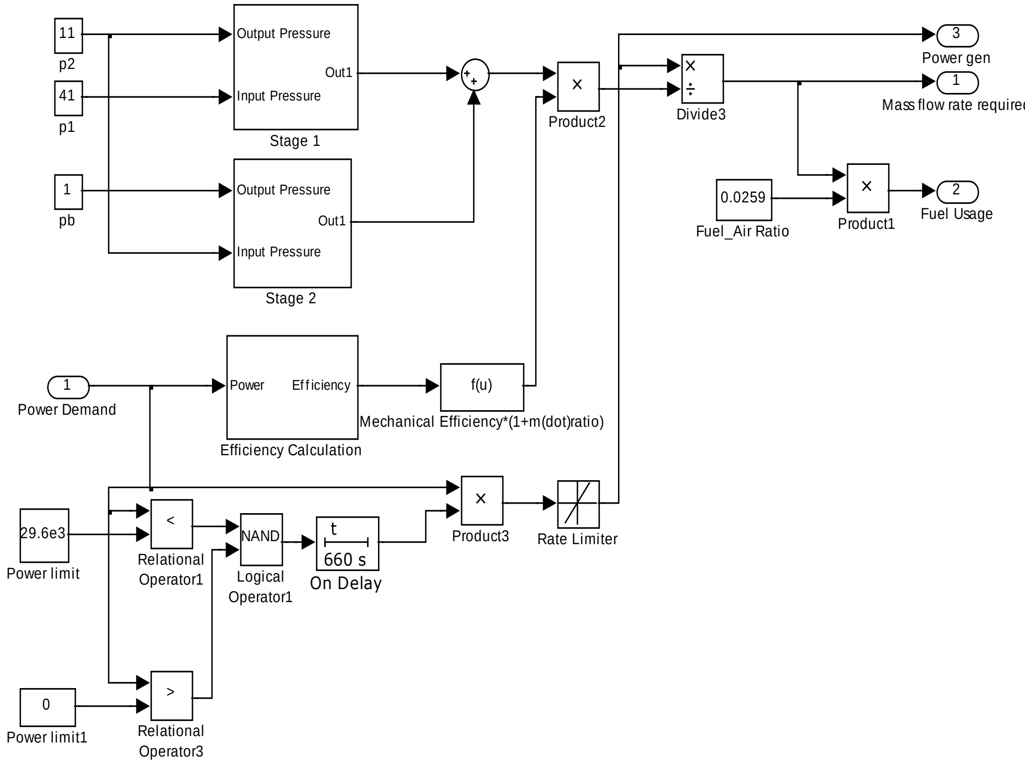


Figure 3.18 Gas turbine generator model

The input power to the turbine in the above figure must be above 29.6 MW for operation, which is the operational requirement of the electric generator. It is applied with a startup time of 660 seconds, which equals 11 minutes. This is implemented by comparing the power demand to the turbine with relational operators. If the power is more than 29.6 MW the NAND output is true with an on delay of 11 minutes. This is multiplied by the input power and fed to the compressor equation with a ramp rate of 88 MW/min. The turbine is only allowed to be operated when the pressure inside the storage is above its limits i.e. 46 bars. This is shown in following figure.

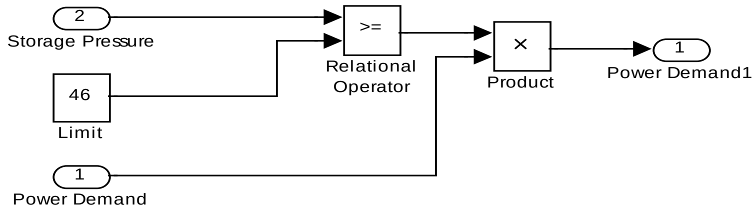


Figure 3.19 Storage pressure constraint model for gas turbine generator

The implementation for constant pressure configuration is as follows.

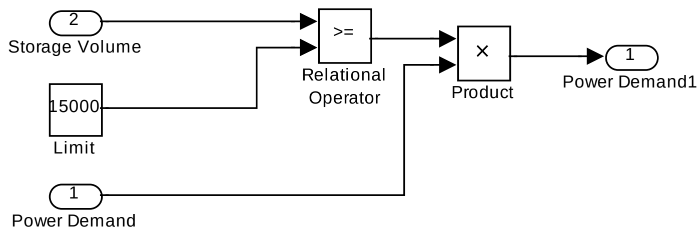


Figure 3.20 Storage volume constraint model for gas turbine generator

The CAES components are interconnected in the following figure. The power inputs to compressor and gas turbine are saturated from 0 to 60MW and 0 to 290MW respectively.

3.1.5 Energy Calculations

3.1.5.1 Storage Energy

Power calculations are done based on the pressure and mass stored at each instant of time. The calculations are made based on the power level. The mass flow rate of air is then calculated by the following equation:

$$\dot{m}_{out} = \frac{P_{rated}}{\eta_M \eta_G (1.0259)\left(C_{p1}T_1\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n_1-1}{n_1}}\right] + C_{p2}T_2\left[1-\left(\frac{p_b}{p_2}\right)^{\frac{n_2-1}{n_2}}\right]\right)}$$

As we know the mass of air in storage at each instant of time by following expression:

$$m_{stored} = \int_0^t (\dot{m}_{in} - \dot{m}_{out})dt$$

We can hence calculate the duration for which the storage would provide the demanded power from following expression:

$$Discharge\ Duration = \frac{m_{stored}}{\dot{m}_{out}}$$

The energy can hence be calculated by

$$E_{stored} = Discharge\ Duration \times P_{rated}$$

$$P_{rated} = 290MW$$

For constant volume storage, since we need to maintain lower limit for pressure, we wish to calculate the stored energy and duration according to this limit. The mass of air at the lower pressure limit can be calculated through ideal gas equation. We take this amount out of the mass stored and do our calculations from the following value:

$$m_{usable} = m_{stored} - m_{min}$$

$where$
$m_{usable} = amount\ of\ mass\ of\ which\ can\ be\ used\ to\ produce\ power$
$m_{min} = mass\ required\ to\ maintain\ minimum\ pressure\ in\ storage$

Therefore for constant volume configuration, the discharge duration is:

$$Discharge\ Duration = \frac{m_{stored} - m_{min}}{\dot{m}_{out}}$$

Since we need to know the mass of air stored at 46 bar so that we can make the stored power and energy calculations. Since we know that the volume of the storage is 300000 cubic meters. The pressure is 46 bars. R is $287 \times 10^{-5} m^3 bar kg^{-1} K^{-1}$. The storage temperature is 293 kelvin. Then from ideal gas law, we know

$$PV = mRT$$
$$m_{min} = \frac{PV}{RT} = \frac{46 \times 300{,}000}{287 \times 10^{-5} \times 293} = 1.6411 \times 10^7 kg$$

The ramp rate for the motor/generator was modeled with rate limiter. Since the ramp rate is in MW/min, it was converted to kW/sec, according to simulation requirements.

$$\frac{88MW}{min} = \frac{88{,}000kW}{60sec} = 1466.7kW/sec$$

The following figure shows the method used for calculating stored energy state. The stored energy is calculated at the rated power of gas turbine. When the rated power of gas turbine is fed to the turbine model, this provides the mass flow rate of air required to operate the gas turbine. The storage mass state is divided by the mass flow rate, which gives the hours for operation. The energy can hence be calculated by multiplying the hours of operation with rated power.

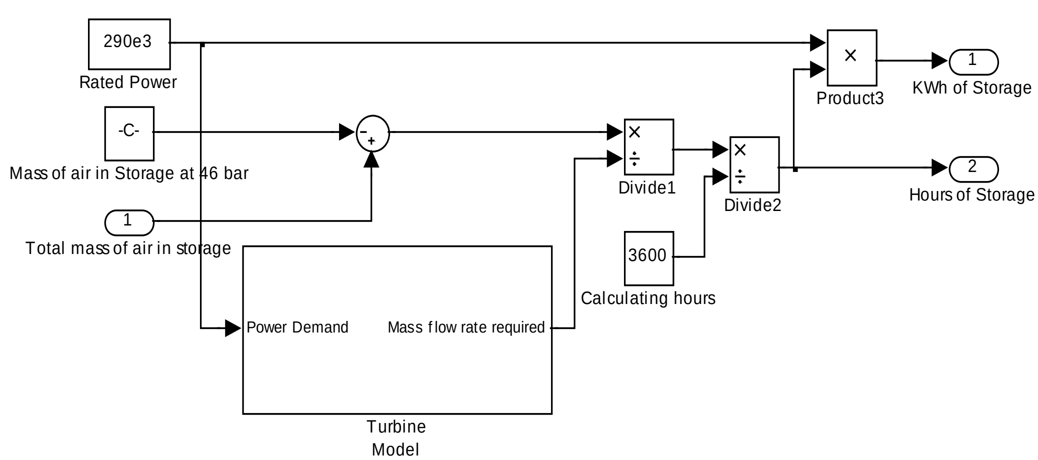


Figure 3.21 Storage energy state model for constant volume configuration

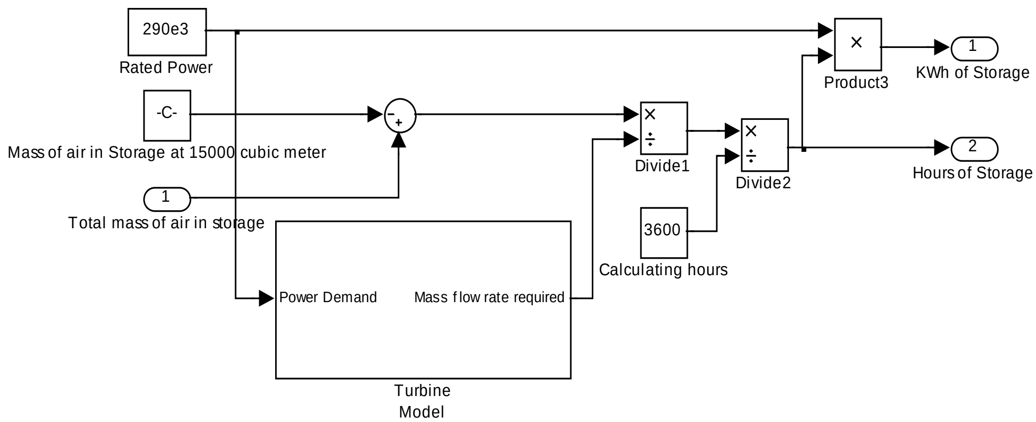


Figure 3.22 Storage energy state model for constant pressure configuration

Following constraints are employed for the CAES for both configurations:

- $29.6 < P_{GEN} < 290MW$
- $29.6 < P_C < 60MW$
- Ramp rate for generation: 88MW/min
- Ramp rate for compression: 88MW/min
- Storage pressure: $46 < p_{storage} < 66bar$ for constant volume configuration
- Storage volume: $15{,}000 < V_{storage} < 300{,}000m^3$ for constant pressure configuration

3.1.5.2 Rated power and hours of operation

The rated power of compressor operation on hourly basis can be calculated by intergrating the turbine energy. Since the model uses turbine energy in terms of KWs, it needs to be converted to KWh. The coversion involves a gain of 1/(3600*1000) to make this conversion. This is shown in the figure below.

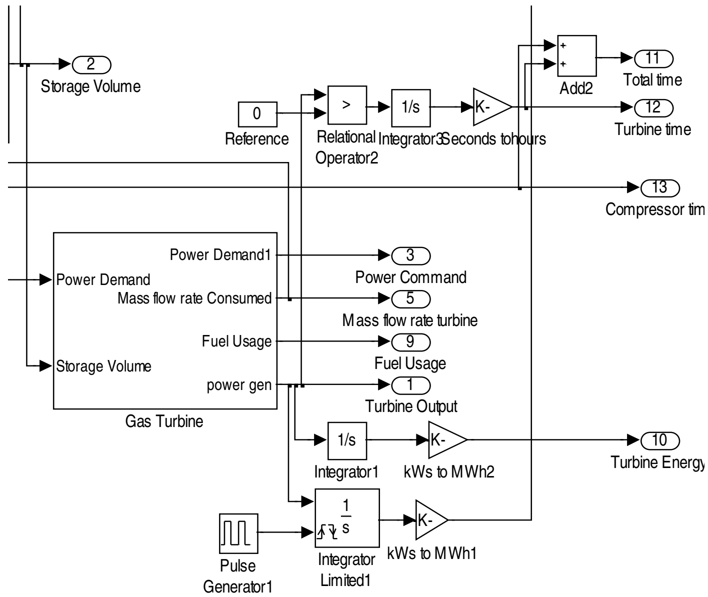


Figure 3.23 Model for evaluating energy consumed/provided per hour

The operation time can be calculated by integrating the time during which the power generated by gas turbine or absorbed by compressor is greater than zero. As shown in the figure above, the operation in hours is calculated by comparing the generated power at an instant to zero and the ourput is then applied to the integrator which gives the time of operation in seconds. The time in hours is calculated by applying a gain of 1/3600.

We also need to know the energy provided and consumed for each hour for economic analysis. This is evaluated by applying a pulse of period 3600*2 seconds with pulse width of 3600 seconds. This is applied to the external reset input of the continuous time integrator. The output gives energy consumed or provided in KWs. This is converted to MWh by applying a gain of 1/(3600*1000).

The average rated power for compressor or gas turbine for a day is hence calculated by dividing the energy consumed/provided by the time of operation. This is shown in the figure below.

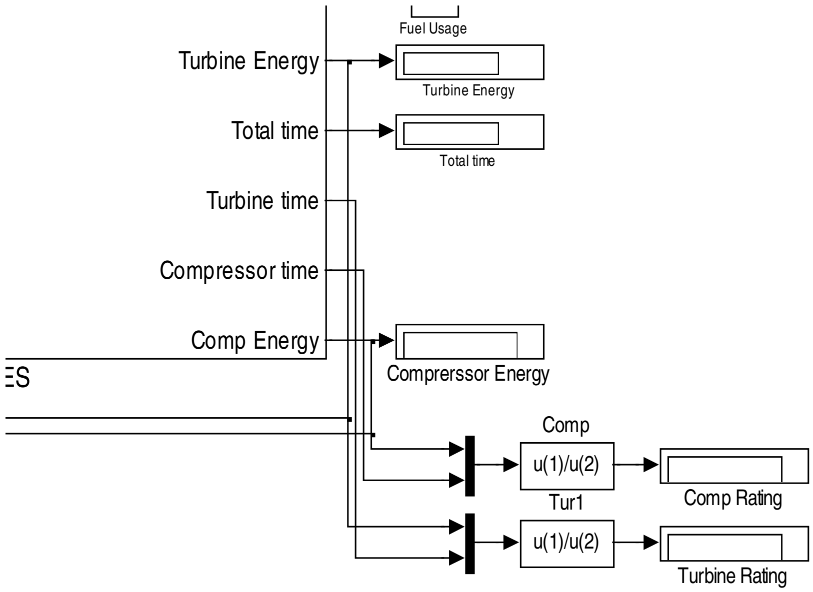


Figure 3.24 Model for computing compressor and turbine average power rating for hourly basis

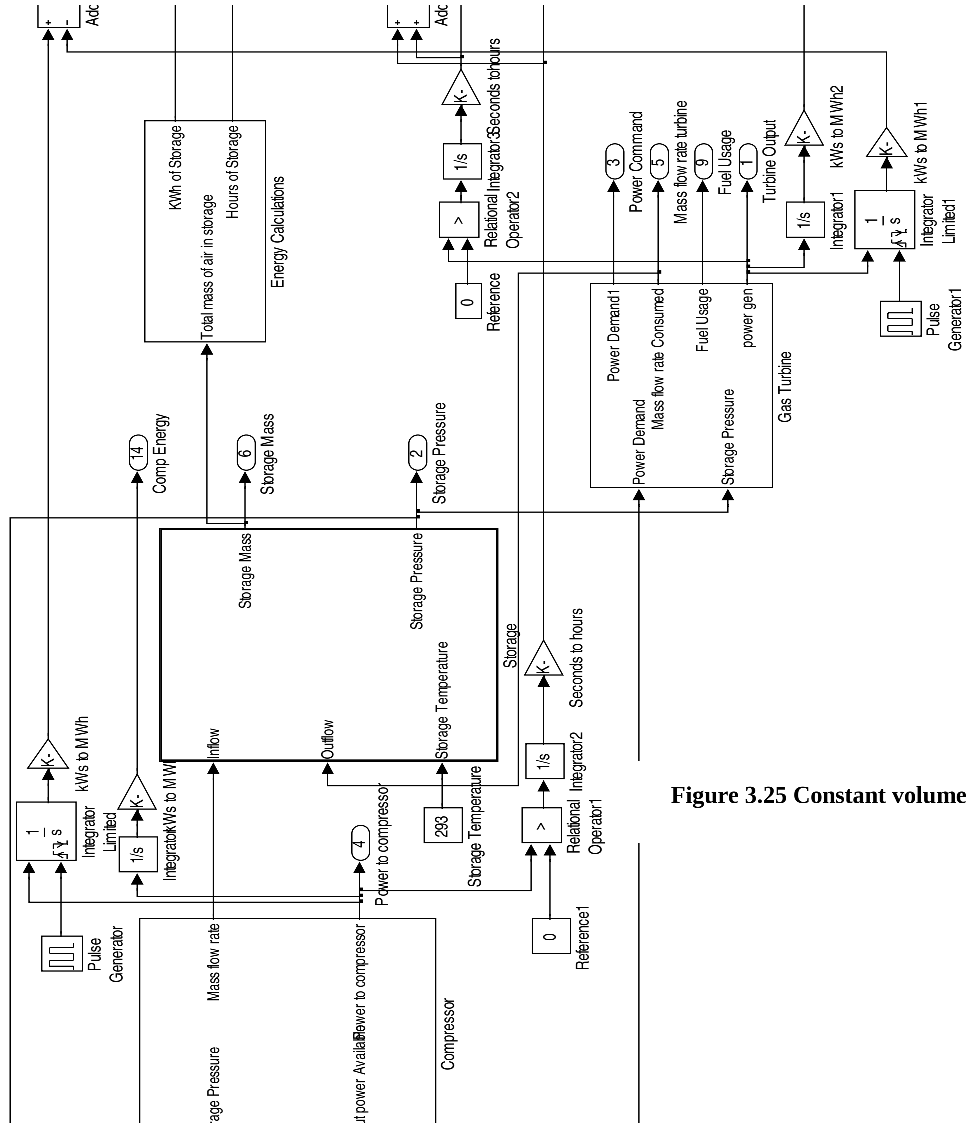


Figure 3.25 Constant volume CA

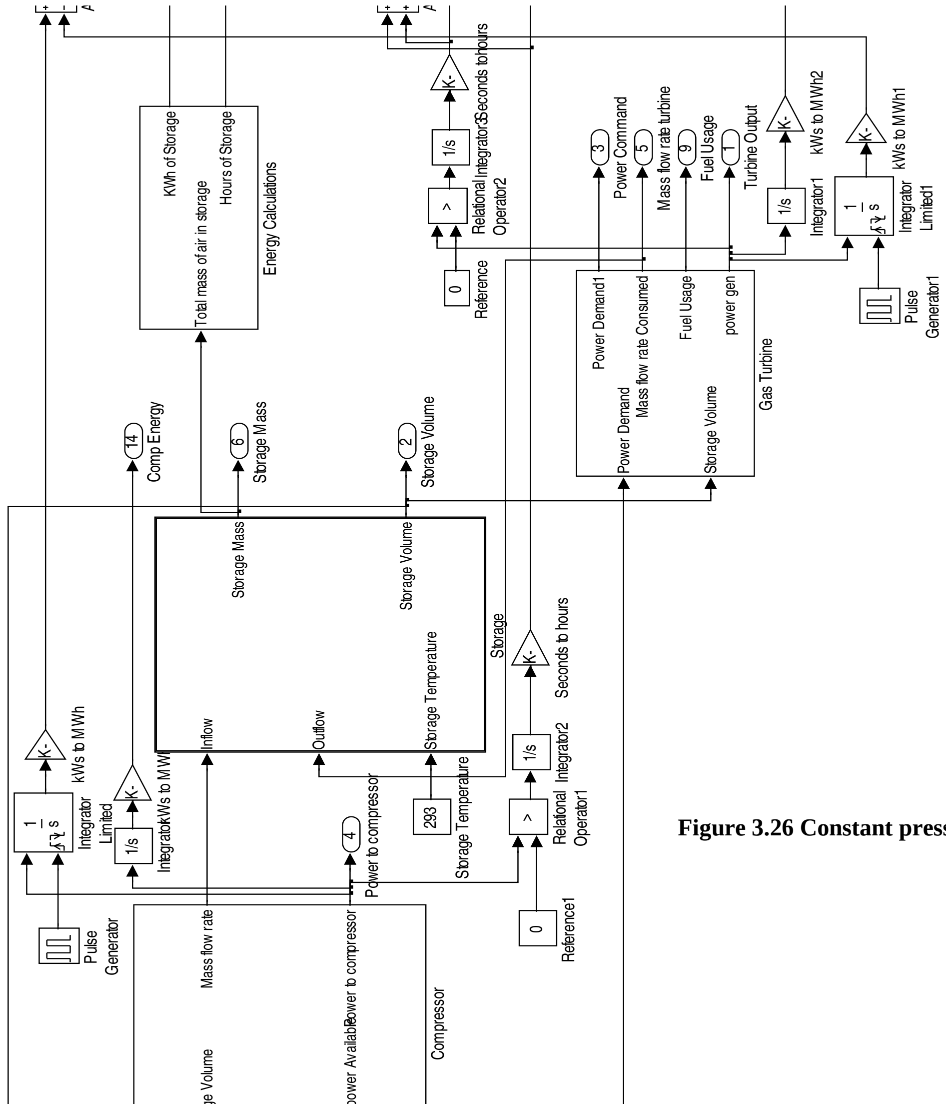


Figure 3.26 Constant pressure

3.1.6 CAES Model Verification

<u>3.1.6.1 Design Parameters</u>

The compressed air energy storage model described in the previous section was verified by comparing the simulation results with the performance parameters of two operational CAES plants. The main goal of verifying the result was to ensure that the simulation model charges and discharges at identical power ratings and provides accurate duration for these processes.

3.1.6.2 Simulation Results

The simulation model was given a power command to charge the storage from 46 bars to 66 bars at 60 MW for duration of 20 hours. The power command to discharge the storage from 66 to 46 bars to 290 MW was applied at hour 20 for duration of 7.78 hours. This is shown in the figure below.

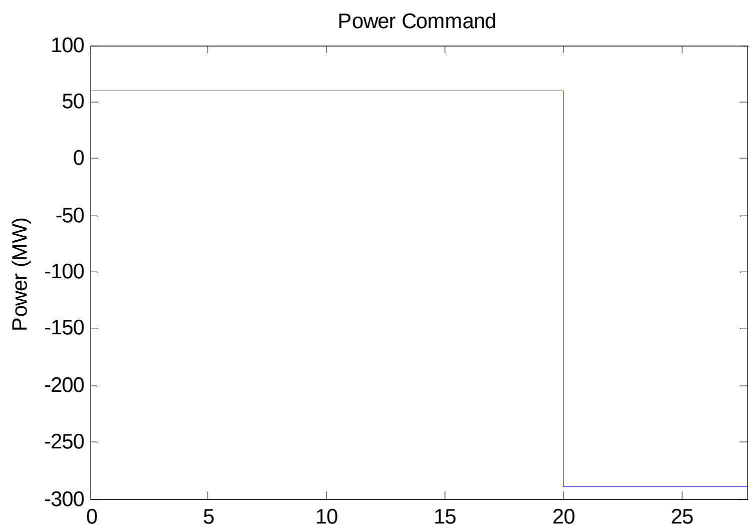


Figure 3.27 Power Command to CAES

The compressor operated for the duration of about 16.3 hours and charged the storage from 46 to 66 bars. Although the power command was provided for 20 hours, the compressor stopped at 16.3 hours because the pressure inside the storage reached its upper limit, i.e. 66 bars. During this operation, the mass flow rate of compressor changed from 118.8 kg/s initially to 104.4 kg/s finally whereas Huntorf's operating value is 108 kg/s. This is because initially the storage was charged at 46 bars. As the pressure inside storage increased, the more it opposed the mass flow rate from compressor. These results are illustrated in the following figure. A start up time of 9 minutes was also incorporated and the ramp rate of 88

MW/min which can be observed in the mass flow rate and compressor power graphs as it starts changing later than the power command to compressor.

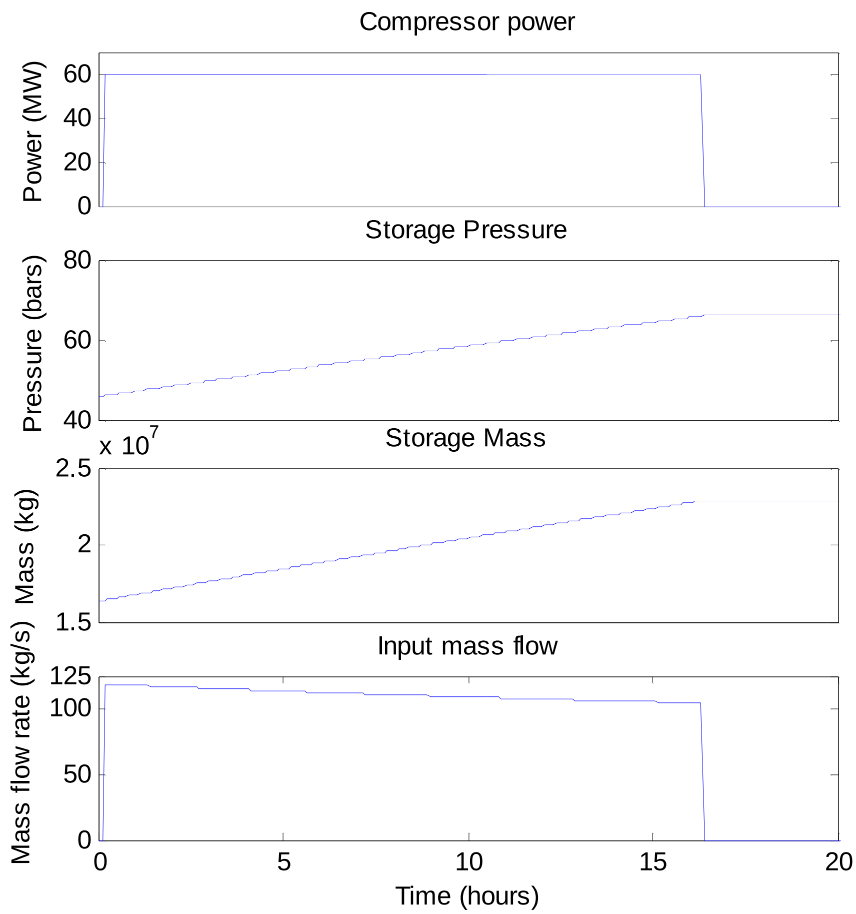


Figure 3.28 Compressor Operation

The discharging time of Huntorf CAES is approximately 4 hours. Since it has a ratio of 1 to 4 for charging and discharging, it must have a charging time of 16 hours, which is almost the same as in the simulation. Hence the compressor performance of simulation is very close to that of the plant. The compressor ramped up and ramped down between 0 to 60 MW in less than a minute, because the maximum ramp rate is 88 MW/min.

The storage simulation for charging cycle is verified according to the above results because it charges in about 16.3 hours which is the same as that of Huntorf CAES.

The discharging operational results for the gas turbine are shown in the figure below.

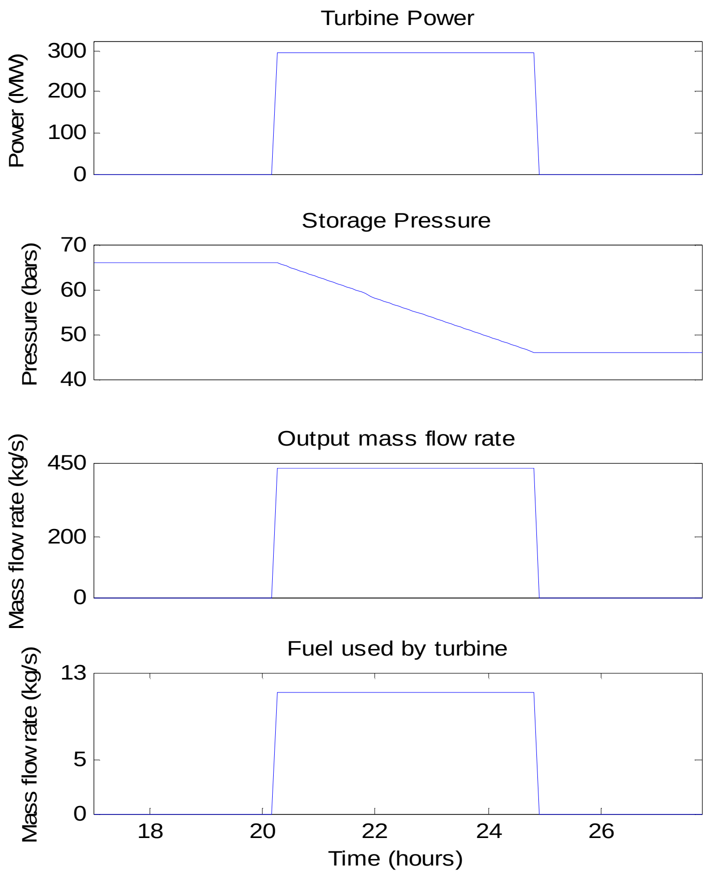


Figure 3.29 Turbine Operation

The gas turbine was scheduled to start at hour 20. It has a startup time of 11 minutes, which can be observed in the figure above. The gas turbine ramped up and down between 0 and 290 MW in about 4 minutes. This complies with the ramp rate limit of 88 MW/min. The mass flow rate of the air during 290 MW operation of the turbine was 429 kg/s which is very close to the operational value of 425 kg/s for the plant. It took about 4.5 hours for the storage pressure to decrease from 66 to 46 bars. This is also very close to the performance parameter of the plant.

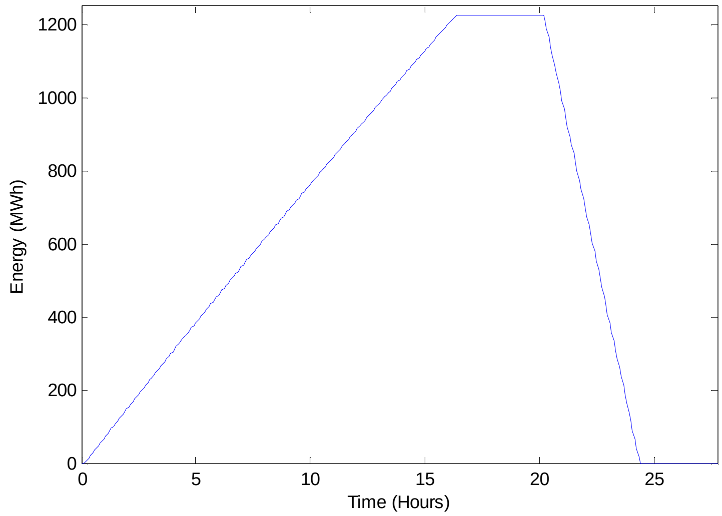


Figure 3.30 Amount of Energy Stored

The above figure shows the amount of energy stored at different times during charging and discharging. According to Huntorf CAES plant the storage must be able to deliver a maximum of 290 MW for 4 hours, which depicts that it can store a maximum of 1160 MWh. The simulation results show that the storage can hold a maximum of 1227 MWh.

3.2 Wind Turbine

Since the wind turbine produces power with the help of moving air, it uses the kinetic energy from wind. The kinetic energy can be given as:

$$K.E. = \frac{1}{2} m V^2$$

$$\begin{aligned} &where \\ &m = mass(kg) \\ &V = speed(m/s) \end{aligned}$$

Since we are interested in calculating power, we can re-arrange the above expression to calculate power. Since energy is the product of time and power. We get the following expression.

$$P = K.E./t = \frac{1}{2} m \left(\frac{d}{t}\right)^2 /t = \frac{1}{2} mA/t^3$$

Introducing density we get

$$P = \frac{1}{2} \times \frac{m}{d^3} \times A \times \frac{d^3}{t^3} = \frac{1}{2} \rho A V^3$$

The mathematical model for the wind turbine is defined by the following equation which includes the coefficient of performance, generator and gearbox/gearing efficiencies.

$$P = \frac{1}{2} \rho A C_p V^3 N_g N_b$$

$where$
$\rho = air\ density (kg/m^3)$
$A = rotor\ swept\ area\ exposed\ to\ wind\ (m^2)$
$C_p = coefficient\ of\ performance$
$V = wind\ speed\ (m/s)$
$N_g = generator\ efficiency$
$N_b = gearbox\ or\ gearing\ efficiency$ (AWEA)

The coefficient of performance is not constant for all wind speeds and has a maximum value of 0.59. Its value depends upon the wind speed. Following figure gives the illustration of changing levels of coefficient of performance at different wind speeds.

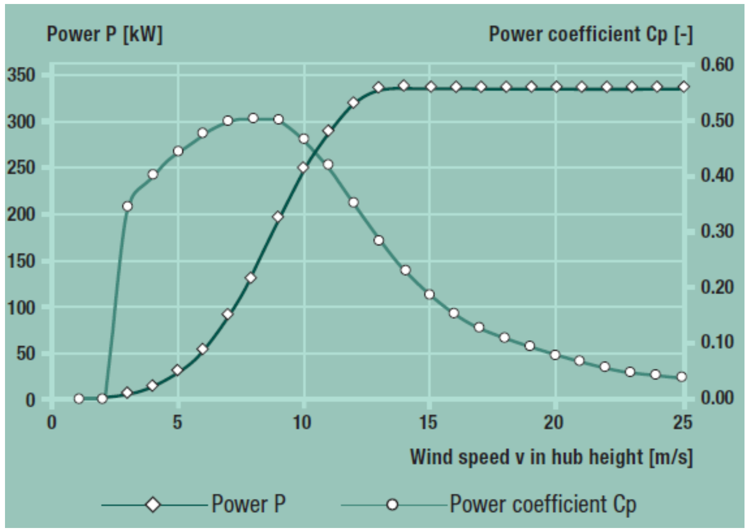


Figure 3.31 Coefficient of performance for Enercon E-33 330kW wind turbine

Source: (Enercon)

Since the load and wind data for Story County in the state of Iowa was available, the turbines used in Story County were chosen for analysis. These turbines are rated at 1.5 MW which are manufactured by General Electric. The equation mentioned above was chosen for simulating power from wind turbine at different wind speeds. Air density is known to be 1.225 kg/m^3. The rotor swept area exposed to wind for GE 1.5sle wind turbine is known to be 4657 m^2 according to the technical data provided by GE for this particular wind turbine. The generator efficiency and gearing efficiency were taken to be 80% and 95% respectively which are described as typical values for wind turbines according to AWEA. The graph that presents a relationship between wind speed and power for GE 1.5sle is shown as follows.

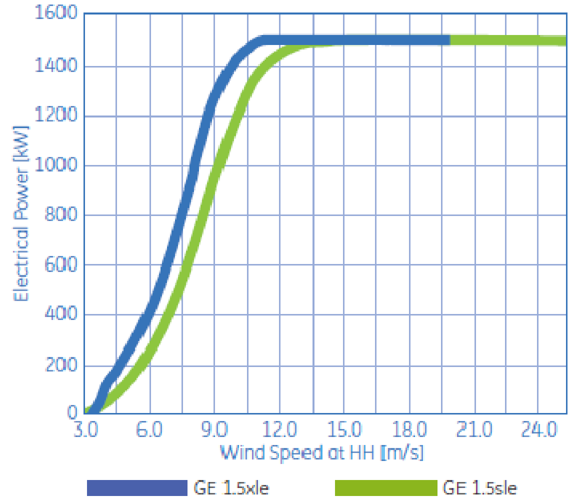


Figure 3.32 Electrical power and wind speed for GE 1.5sle wind turbine

Source: (GE Energy)

Since the coefficient of performance is not the same for all wind speeds, it needs to be known. The power equation of wind speed was used to calculate the coefficient of performance at different wind speeds for GE 1.5sle wind turbine using the above mentioned figure. The following expression which is the re-arranged form of power equation was used to calculate the coefficient of performance at different wind speeds.

$$C_p = 2P/\rho AV^3 N_g N_b$$

The given curve was divided into eight piecewise linear regions as follows.

Table 3.6 Calculated values of coefficient of performance for GE 1.5sle

Wind Speed (m/s)	**Power** (kW)	$\mathbf{C_p}$
3.5	20	0.2197
4.5	90	0.4651
6	230	0.5014
7.5	500	0.5581
9	900	0.593
10.5	1280	0.5207
12	1450	0.3951
14	1500	0.2574

The values for the coefficient of performance must be known between the speed intervals. To get piece wise linear equations for the wind speed and coefficient of performance curve the calculations regarding the gradients and y-axis intercepts were made. Since the equation of straight line is

$$y = mx + c$$

Y-axis is taken as coefficient of performance and X-axis as wind speed, m is the gradient of straight line and c is the y-intercept. The gradients can be calculated by the following expression where I corresponds to a particular interval.

$$m = (y_{i+1} - y_i)/(x_{i+1} - x_i)$$

After calculating the gradients from the intervals mentioned in the table above, the y-intercepts were calculated according to the following expression.

$$c = y_i - mx_i$$

The gradients and the y-intercepts calculated are given in the following table.

Table 3.7 Gradient and y-intercept calculations for coefficient of performance

Interval i	**Wind Speed** m/s	**Gradient** (m)	**y-intercept** (c)
1	0-3.5	undefined	undefined
2	3.5-4.5	0.2454	-0.6392
3	4.5-6.0	0.0242	0.3562
4	6.0-7.5	0.0378	0.2746
5	7.5-9.0	0.0232	0.3836
6	9.0-10.5	-0.0482	1.0268
7	10.5-12.0	-0.0837	1.3999
8	12.0-25	-0.0688	1.2213
9	25 & above	undefined	undefined

Since the GE 1.5sle is designed to work only in the range of 3.5 m/s and 25 m/s of winds, the values for gradients and y-intercepts are undefined for intervals which are outside the range of wind turbine operation. Now the coefficient of performance can easily be chosen at different wind speeds according to the following expression.

$$C_p = wind\ speed_i \times m_i + c_i$$

Since the coefficient of performance, C_p is a function of wind speed, we first calculate C_p from the corresponding wind speed. This is calculated by observing whether which interval does the wind speed fall. The equation for that specific interval is used to calculate C_p, for which the general form is given above.

Following figure shows the coefficient of performance for wind turbine at different wind speeds obtained from simulation.

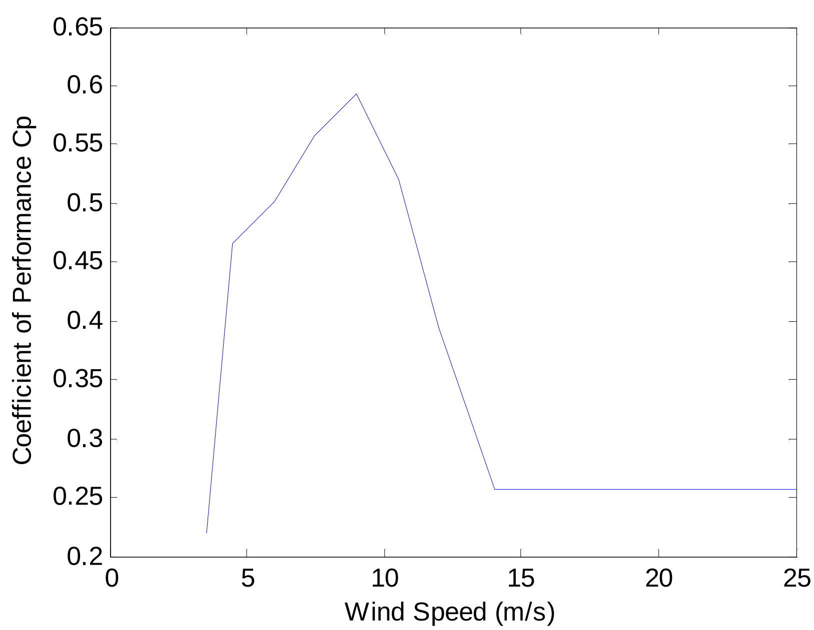


Figure 3.33 Simulation results for coefficient of performance

When C_p is obtained, it can be used to calculate the power. V in the equation corresponds to the wind speed. The coefficient of performance can hence be used to calculate the power from wind at different wind speeds from the wind power equation.

$$P = \frac{1}{2}\rho A C_p V^3 N_g N_b$$

The wind speed profiles are provided in the units of miles per hour. Since 1 mile per hour equals 0.44704 meters per second. This approximation is used. The following figure shows the implementation of the wind turbine model. The coefficient calculation block is implemented the same way as that of the compressor efficiency, using the piecewise linear functions for power and coefficient of performance obtained in this section. The input wind speed is saturated between 3.5 and 14 m/s, since 3.5 m/s is the minimum requirement to run the turbine and for speeds above 14 m/s, the coefficient of performance and power output remains the same. For speeds below 3.5 m/s and above 25 m/s, the relational operators and the AND logic outputs a zero which signifies the shutting down of wind turbine if wind speeds get out of range of operation.

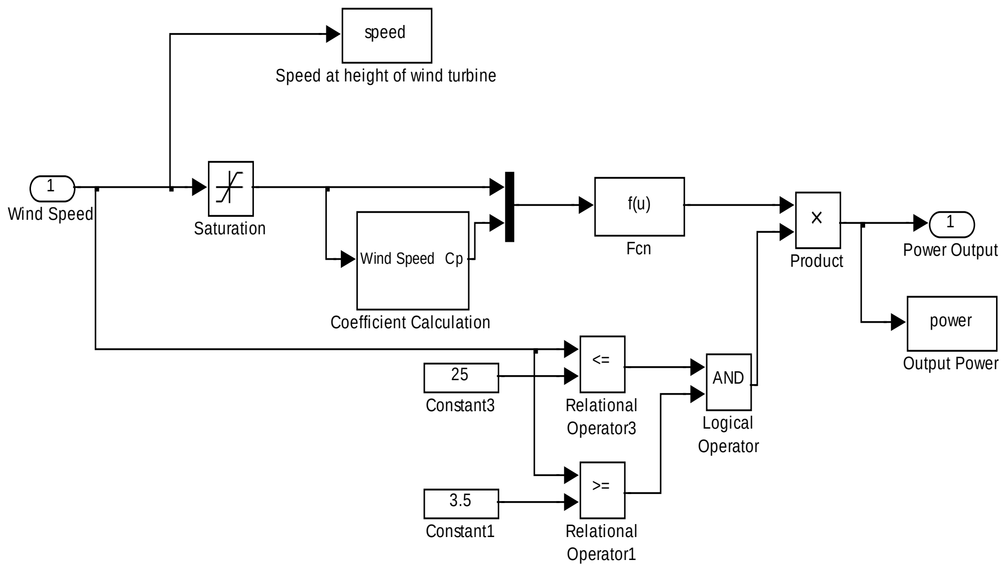


Figure 3.34 Wind farm model

3.2.1 Wind Turbine Model Verification

The verification of the model was performed by implementing the wind power expression for the combination of wind speeds and coefficient of performance, calculated in the previous section. Power was calculated at corresponding wind speeds. As shown in the following figure the simulation curve is quite identical to that of the actual curve of GE 1.5sle wind turbine. There are some discontinuities in the simulation curve because we are using piecewise linear approach. The results obtained are satisfactory and comply with the practical operation of GE 1.5sle in terms of wind speed and power.

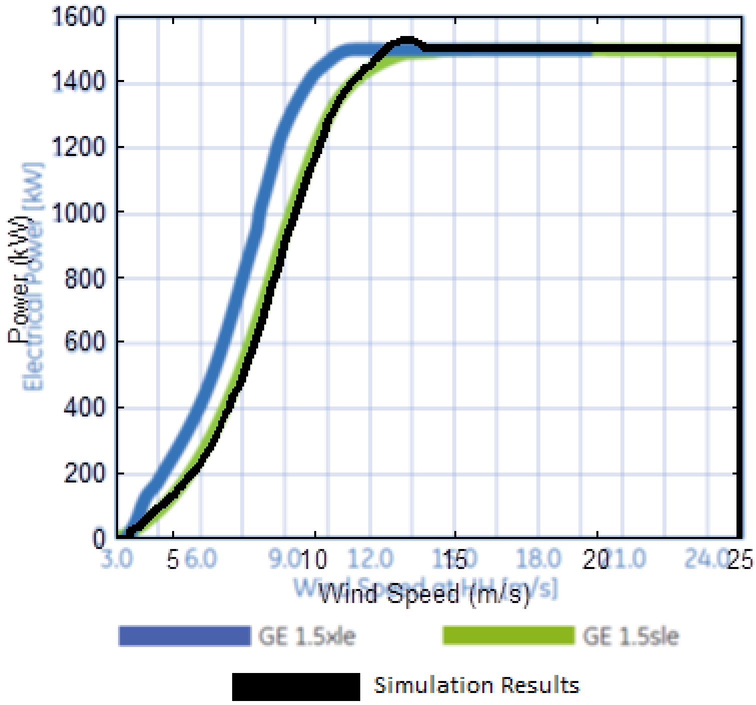


Figure 3.35 Verification of simulation results for wind turbine

CHAPTER 4

SYSTEM MODEL DEVELOPMENT

The hybrid wind system was developed by coupling the compressed air energy storage to the wind farm discussed in the previous sections. The main purpose of the system is to analyze the performance of CAES having different configurations. This analysis would provide useful information whether what kind of location needs what size of CAES and which configuration is best suitable for which location. An existing wind farm was chosen for the analysis. Wind profile from a particular location where this wind farm is present was used to find the generated power from wind farm. A load profile of a location near the existing wind farm was used, and CAES was charged and discharged according to the mismatch between the wind generation and the load.

Following figure shows the implementation of the power command to CAES. Power mismatch is calculated by subtracting the load profile from wind power. The power mismatch is then fed to the relational operators. There would be instances when we would need to limit the amount of energy charged or discharged in 24 hours to keep the storage energy balanced. The relational operated are used to compare the limits of energy being used or produced during the day. If the power mismatch is positive, the positive mismatch is routed to the compressor block when the compressor charge and turbine discharge limits are met and vice versa.

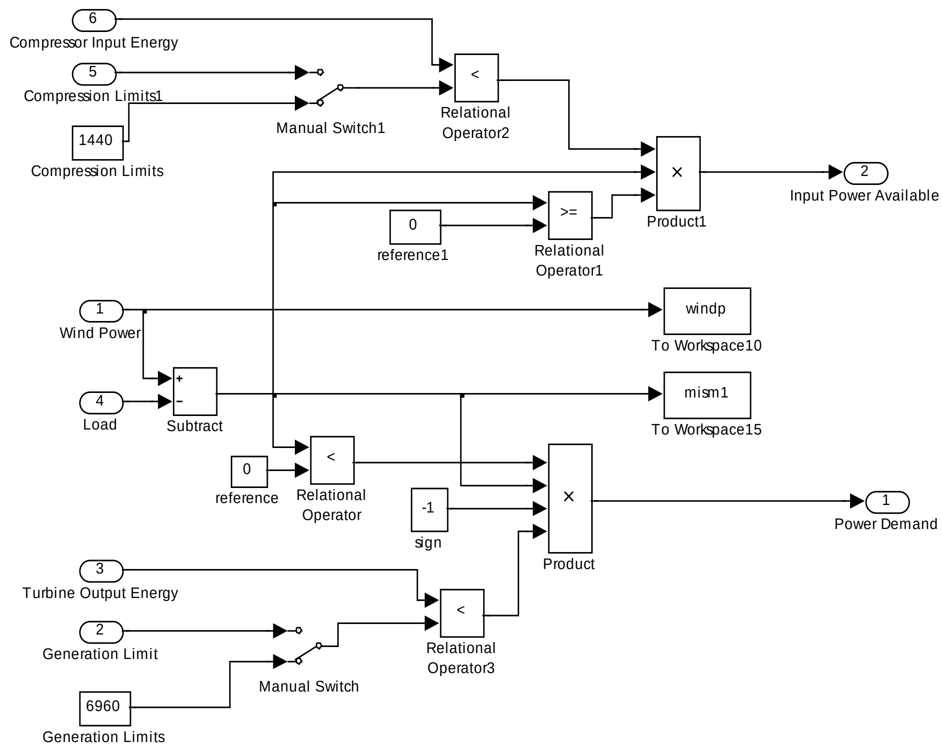


Figure 4.1 CAES power command model

The wind farm chosen for analysis is the Story County I and II Wind Energy Center in the state of Iowa. The wind farm has 200 GE 1.5sle wind turbines. Since the performance of the wind turbine was verified with the GE 1.5sle in the previous section. There are also many prospects for hard rock and aquifer CAES storage in this area as it is ideal for installation of both configurations as discussed in the literature review.

Wind profile for this area was obtained for typical days in summer and winter, since winds in winter are very high as compared to summer and would also provide an opportunity to look into storing energy in terms of seasons.

Wind speed is not the same at different heights. Therefore the wind that is measured and used for the analysis was measured at different height than the height of the wind turbine. The following expression provides the relationship of wind speeds between two heights. It is known as the power law wind profile.

$$V = V_o \left(\frac{H}{H_o}\right)^{\alpha}$$

$$\begin{aligned} &where \\ &V = speed\ at\ height\ H \\ &V_o = speed\ at\ height\ H_o \\ &\alpha = windshear\ exponent \end{aligned}$$

(Gipe)

Alpha is the wind shear exponent which depends on the atmospheric stability. Typical value for alpha for areas, which are not near sea is approximately 0.143 (Hsu). The wind profile for this wind farm was taken from KAMW Ames airport in Iowa. The wind measurements provided were made by a sensor mounted at about 8 feet from the ground. Therefore H_o for our case is 8 feet. The GE 1.5sle wind turbines are designed to be mounted 162 feet above the ground. Therefore H is 162 feet in the above expression. Following is the wind profile for a summer day of June for Ames.

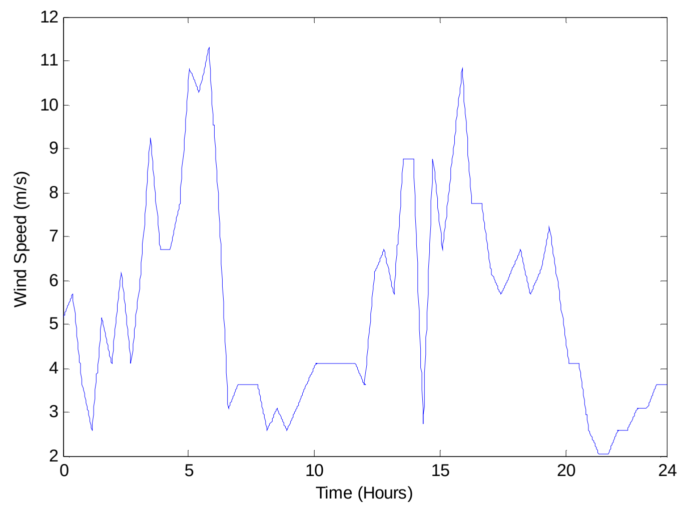


Figure 4.2 Wind profile of Ames at 8 ft. of height

Zero and twenty four hours refer to the midnight in the above figure. Since this profile is at the height of 8 ft., profile for 162 feet was obtained by using the power law wind profile. This is shown is the figure below.

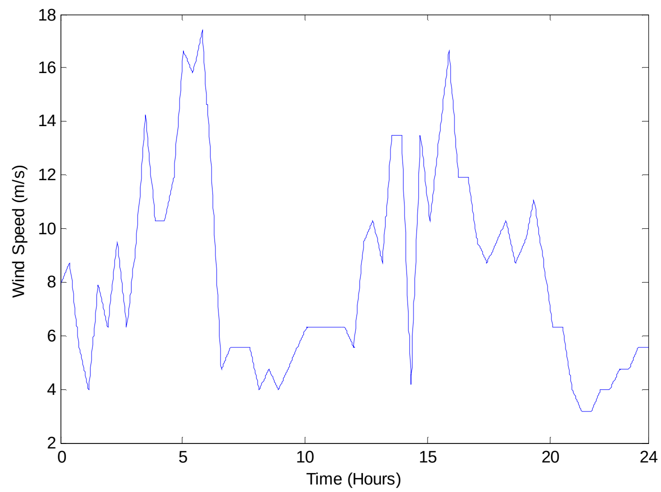


Figure 4.3 Wind profile of Ames at 162 ft. of height

Source: (KAMW Ames Airport)

Every wind turbine has a range of wind speeds with which it operates. The minimum wind speed required to operate the GE 1.5sle is 3.5 m/s and the maximum is 25 m/s. The wind farm is designed to operate in this range and it would stop producing power when this limit is violated. This would be useful to analyze whether CAES can be used to supply power to the load when the wind farm goes out of service for a while due to any reason.

The load profile that was used to do the analysis belonged to the city of Ames, which is one of the nearest cities to the wind farm. The hybrid wind farm was supposed to be taken as the only source of power for the city. This was done to study the power delivery performance of hybrid wind farm as a standalone source of power. Since the world is becoming more and more dependent upon renewable energy resources day by day, this analysis would give a deep insight to the potential of wind energy resources coupled with different CAES configurations.

The load profile for the city of Ames for a summer day of June is as follows.

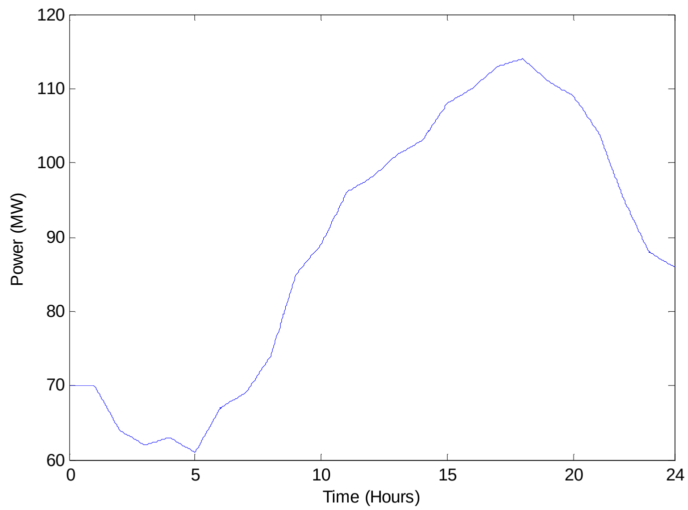


Figure 4.4 Load profile of the city of Ames

Source: (Ames Cohousing)

Since we have a variety of power mismatch levels between the load and the power generated from wind farm, we need to fix the minimum and maximum operating limits for CAES plant. The minimum and maximum operating limits are not provided for Huntorf CAES, whereas these limits are provided for CAES McIntosh plant. The motor/generator of CAES Huntorf operates between 10 MW and 110 MW. This means that it can operate at a minimum of 9.09% of full load conditions. Therefore CAES Huntorf would be operated at a minimum of 26.36 MW for simulation purposes.

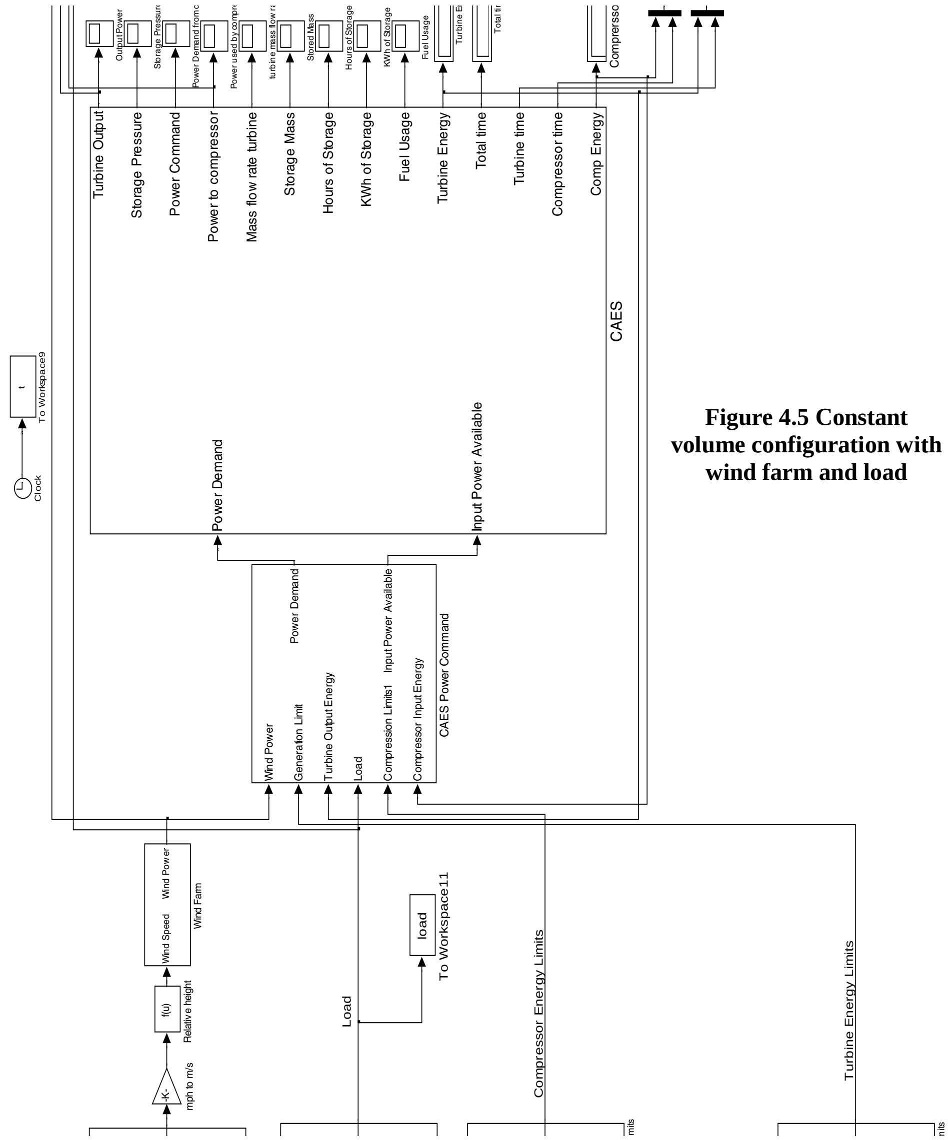


Figure 4.5 Constant volume configuration with wind farm and load

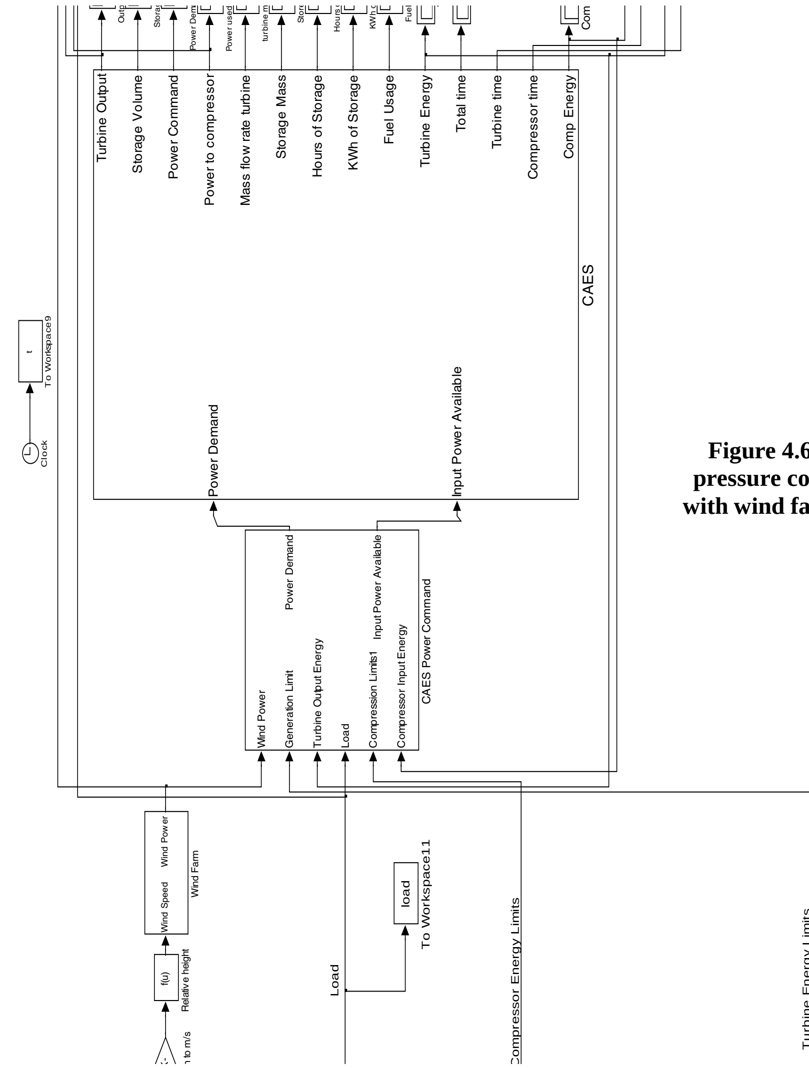


Figure 4.6 Constant pressure configuration with wind farm and load

CHAPTER 5

RESULTS/ANALYSIS

5.1 Hourly Basis

5.1.1 150 MW Wind farm

The verified CAES model of the Huntorf CAES was used together with the wind farm to do the analysis for constant volume CAES configuration. Since there is no existing constant pressure CAES plant, for the purpose of fair comparison, Huntorf CAES was supposed to be a constant pressure CAES configuration by maintaining the pressure of 66 bars inside the storage. This configuration was also analyzed with the same wind profile and load profile. The wind farm was first directly related to the load. Following results were obtained.

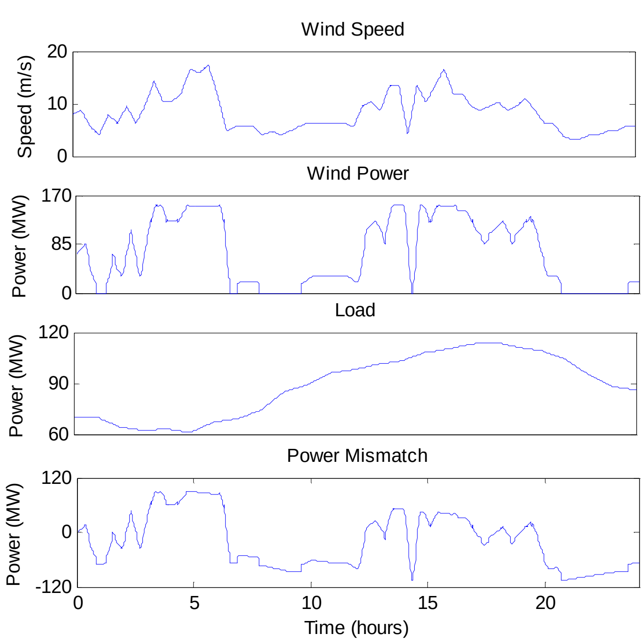


Figure 5.1 150 MW Wind farm Serving Load without CAES

The above figure shows the comparison between wind speed, power generated by wind farm, the load and the mismatch between powers generated and demand. The power mismatch is positive when generation is higher than the demand and vice versa. Since the minimum wind speed required to operate the wind turbine is 3.5 m/s, wind farm has no generation for wind speeds below 3.5 m/s. The power mismatch at these situations goes as low as -104.94 MW. At times wind power is much higher than the load; the power mismatch goes as high as 91.08 MW. These results clearly show that there needs to be a storage device that charges during excess wind power generation and discharges during low wind power generation to meet the demand of the load. Winds have often very irregular behavior on hourly basis. Being one of the major renewable energy resources, such methods must be used which make it more reliable on hourly basis.

Wind profile of January is assumed to be identical to that of December. Assuming constraints according to December. The wind profile of February is assumed to be identical to that of November. The wind profile of March is assumed to be identical to that of April.

5.1.1.1 Constant Volume Configuration & Wind Farm

The 290 MW Huntorf CAES model is coupled with this wind farm to meet the demands of this load. Following are the results for this scenario.

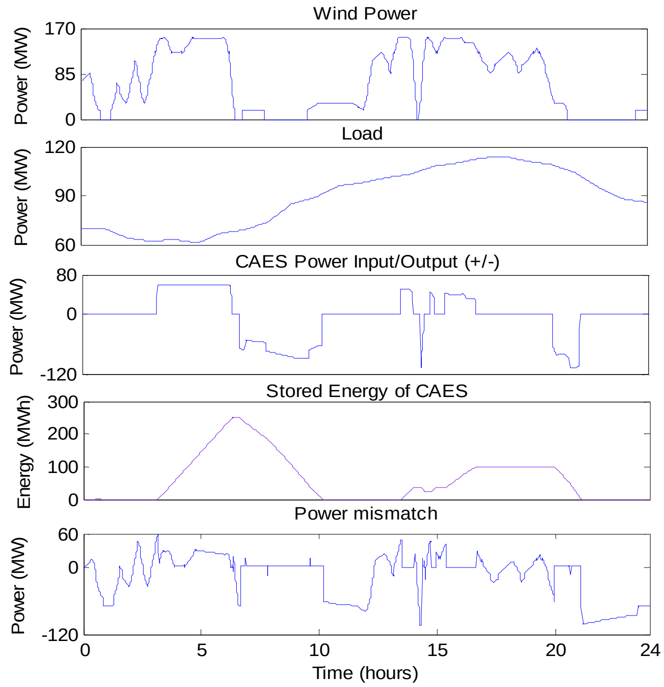


Figure 5.2 290 MW CAES with empty start

CAES plant was constrained to a ramp rate of 88 MW/min and startup time of 9 minutes for charging, and 11 minutes for discharging. Initially the CAES was not charged. Since there was negative power mismatch during this instant CAES was not able to deliver because it wasn't charged, the load demands were not met. CAES was charged from hour 3 to 7 when there was more wind power generated than demand. There was still a positive mismatch because CAES can take a maximum of 60 MW. Improvement was seen around hour 7 when there was no power generated from wind and the demand was met by CAES. This stored energy was later used for negative power mismatch to meet the demand loads from hours 6.5 to 10.2. The CAES could not meet the load demand after hour 10.2 due to being having no stored energy at this time. After hour 12.5, the CAES charged and discharged off and on but couldn't meet the demand of the load most of the times. CAES was charged after hour 14 but couldn't cater the load mismatches between hour 17 and 19 because this mismatch was below the operating range of 29.6 MW. Some spikes are also seen in the results which are either due to the start-up time constraint of CAES or minimum operation of 29.6 MW. The CAES only charges to a maximum of 296 MWh whereas the capacity of CAES is 1227 MWh. It also reaches zero state of charge at the end of the day.

The figure below shows the comparison between the power mismatch without CAES and with CAES.

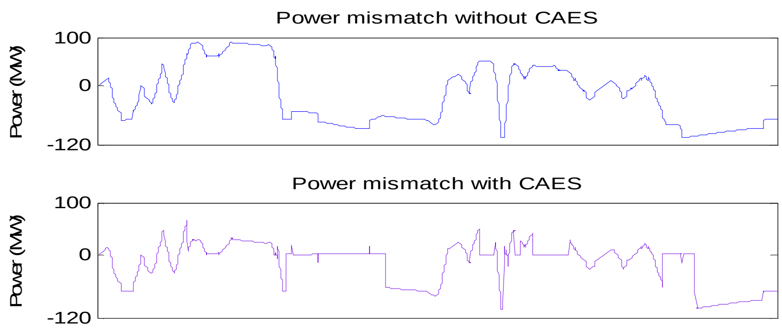


Figure 5.3 Power mismatch comparison

Although CAES was not charged in the beginning but the power mismatch seems to have been improved with the introduction of CAES. Some of the long duration high power positive and negative power mismatches have been removed.

The analysis with CAES initially fully charged to 66 bars and 1227 MWh of energy was done. The simulation results during our verification for the model showed that CAES stores air of mass 2.2884e7 kg when fully charged. This is our initial condition for the mass stored inside the storage. The initial condition for the pressure is 66 bars. Following are the results for starting the CAES at full charge.

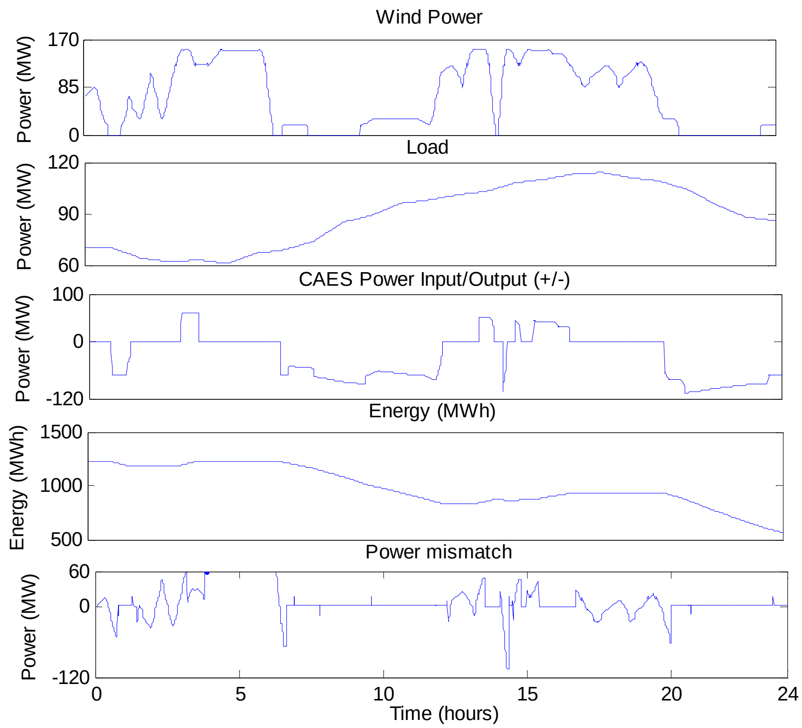


Figure 5.4 290 MW CAES with full start

The storage was able to cater the negative power mismatch greater than 29.6 MW initially because it was charged and the load demands met. Some spikes are seen in the power mismatch which is due to the start-up time constraint of CAES or the requirement of minimum operation of 10% of full load. The CAES is configured to start after 9 minutes for charging operation and 11 minutes for discharging operation after the instant, power mismatch goes out of the range of 29.6 MW. This is why for rapidly changing power mismatch; CAES was not able to deliver short duration power. The CAES was not able to remove the positive mismatch during hours 4 to 6, because it was completely charged. The maximum capacity of CAES is 1227 MWh. It reaches to the energy level of 564.74 MWh at the end of the day.

The figure below shows the comparison between the power mismatch without CAES and with CAES with empty start and full start.

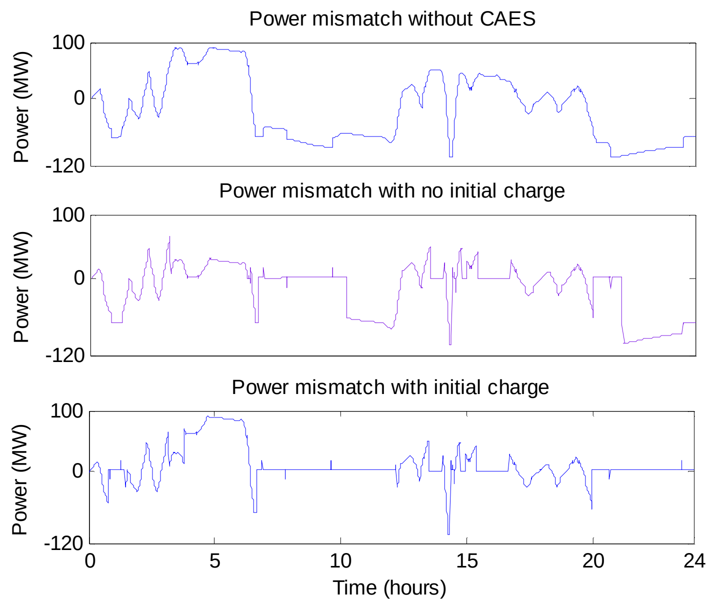


Figure 5.5 Power mismatch comparison

It is evident from the figure above that CAES should be charged to some extent at all times. The power mismatch between the wind generation and the load can change any time and there must be some level of energy maintained in CAES for emergency situations. This fact is evident as the CAES caters the load between hours 10 to 12.5 and 21.5 to 24. This load is not served by CAES which was not initially charged.

CAES should also not be completely charged at all times during the day. It was observed in the simulation results of fully charged CAES that it was not able to accept the available energy, since it was already charged and hence this energy was spilled.

On the other hand there are some short term power mismatch peaks that even the fully charged CAES is not able to cater. This is because CAES is not a fast responding storage technology especially at moments when there is a sudden change in load or wind. High power, fast responding storage technologies can be coupled with hybrid wind farms to address this issue.

Since we are not storing energy on daily and monthly basis for this configuration, the energy discharge and charge after each day needs to be balanced, i.e. for hourly basis, the state of charge of storage at the start of the day must be equal at the end of the day. This means that for hourly basis, we charge the storage during the day and discharge it on the same energy level that it was at the start of day. For this we need to introduce the following constraints:

- $E_{comp} < C_{limit}$
- $E_{turbine} < T_{limit}$

E_{comp} is the energy consumed by compressor for the whole day for hourly basis and $E_{turbine}$ is the energy provided by the gas turbine for the whole day for hourly basis. These correspond to the compressor and turbine energy limits given in CAES model. C_{limit} and T_{limit} is chosen through hit and trial iterative method in such a way that the initial state of charge is equalized to the final state of charge. Since it is assumed that there is no monthly and daily allocation for the constant volume configuration, we analyse a typical load and wind profile for a day of each month of the year.

Table 5.1 CAES charge and discharge energy constraint

Month	**Charge Constraint (Compression)** (MWh/day)	**Discharge Constraint (Generation)** (MWh/day)
January	≤243	≥180
February	≤81	≥51
March	≤182	≥134.55
April	≤210	≥73.92
May	≤88	≥159.5
June	≤309	≥67.7
July	≤188	≥47.93
August	≤14	≥11
September	≤187	≥152
October	≤158	≥112
November	≤80	≥52
December	≤220	≥161

The simulation results for the month of June are given as follows:

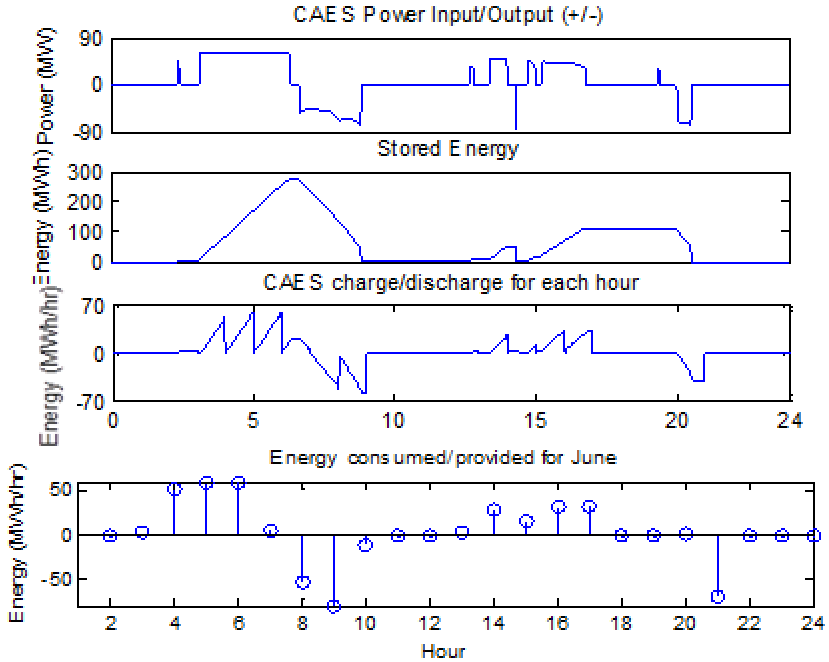


Figure 5.6 Hourly basis operation for typical day of June

5.1.1.2 Constant Pressure Configuration

The 290 MW CAES plant is analyzed as constant pressure configuration. Since there is no operational plant regarding this configuration, due to its similarity to pumped hydro storage technology, parameters like maximum water flow rate and the amount of volume that water is used in pumped hydro to occupy would rather decide whether filling in a certain volume of storage with water is feasible or not.

The 479.3 MW Bath County Pumped Storage System in the state of Virginia is one of the largest in United States. The downhill water flow rate during generation is as high as 852 cubic meters per second. The lower reservoir has an area of about 2.25 square kilometers and the water fluctuates 18 meters during operation. Therefore the total volume of water that fluctuates is 18*2,250,000 cubic meters which is about 40,500,000 cubic meters (Dominian).

The constant pressure reservoir used for analysis is only 300,000 cubic meters. Therefore it is feasible to fill storage of 300,000 cubic meters of volume. A minimum of 5 percent (15,000 cubic meters) of total volume would be reserved for air at all times and would hence be used for analysis. The discharging operation would be used to determine the maximum volumetric rate of change input to the water reservoir. The charging operation would be used to determine the maximum volumetric rate of change out from the water reservoir.

The constant pressure configuration was analyzed by operating at pressures of 46 and 66 bars. The simulation results for constant pressure CAES configured at 66 bars are given in the following figure. The initial conditions for this configuration are calculated as follows.

$$initial\ volume = 15000\ m^3$$
$$pressure = 66\ bar$$
$$gas\ constant\ R = 287 \times 10^{-5} m^3 bar kg^{-1} K^{-1}$$
$$T = 293\ K$$
$$m = \frac{PV}{RT} = \frac{66 \times 15{,}000}{287 \times 10^{-5} \times 293} = 1.1773 \times 10^6\ kg$$

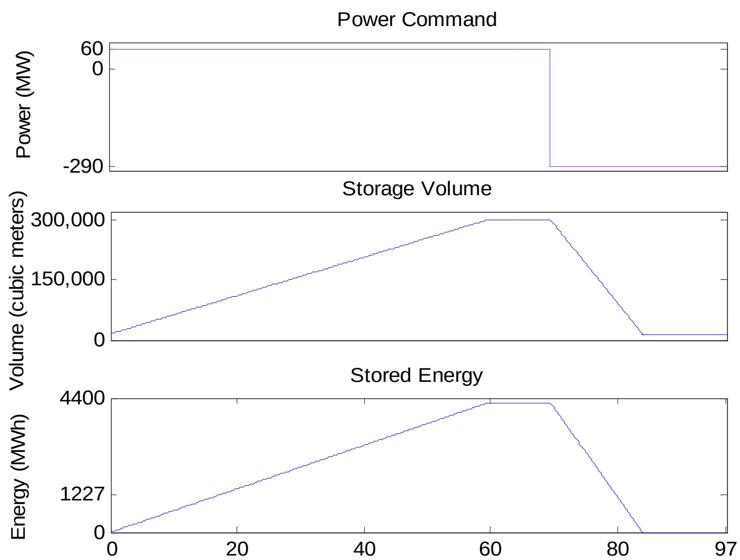


Figure 5.6 Constant pressure configuration (66 bars)

According to the figure above, the maximum inflow of water in the reservoir required is 4786.8 cubic meters per hour which is equal to 1.3297 cubic meters per second. The maximum outflow of the water out of the water is required to be 19,630 cubic meters per hour, which is equal to 5.45 cubic meters per second. These water flow rates are very low as compared to that of pumped hydro storage and hence are considered in feasible range.

As compared to constant volume configuration, constant pressure configuration has the potential of storing a lot more energy. Simulation results have shown that constant pressure configuration only stores about 1227 MWh of energy, for operating between 46 to 66 bars of pressure for a 300,000 cubic meter of storage volume. The constant volume configuration can store up to 4240 MWh of storage, for operating between volumes of

15,000 cubic meters to 300,000 cubic meters at a pressure of 66 bars. This is because the constant pressure configuration makes use of large amount of air which is used to maintain a pressure of 46 bars inside the constant volume configuration.

Since the mass flow rate of air from compressor depends upon the pressure inside the storage, maintaining the pressure at lower requirement of 46 bars would charge the storage much faster. The initial conditions for this configuration are calculated as follows.

$$initial\ volume = 15000\ m^3$$
$$pressure = 46\ bar$$
$$gas\ constant\ R = 287 \times 10^{-5} m^3 bar kg^{-1} K^{-1}$$
$$T = 293\ K$$
$$m = \frac{PV}{RT} = \frac{46 \times 15{,}000}{287 \times 10^{-5} \times 293} = 8.2054 \times 10^5\ kg$$

The simulation results shown in the figure below show that a constant pressure configuration of 66 bars provides more energy but rather takes more time to charge as compared to the constant pressure configuration of 46 bars. The constant pressure configuration with 46 bar of pressure can store up to 2955 MWh of storage, for operating between volumes of 15,000 cubic meters to 300,000 cubic meters.

According to the figure below, the maximum inflow of water in the reservoir required is 6867.3 cubic meters per hour which is equal to 1.9076 cubic meters per second. The maximum outflow of the water out of the water is required to be 21,510 cubic meters per hour, which is equal to 5.975 cubic meters per second. Therefore the 46 bar configuration has more volumetric rate than 66 bar configuration.

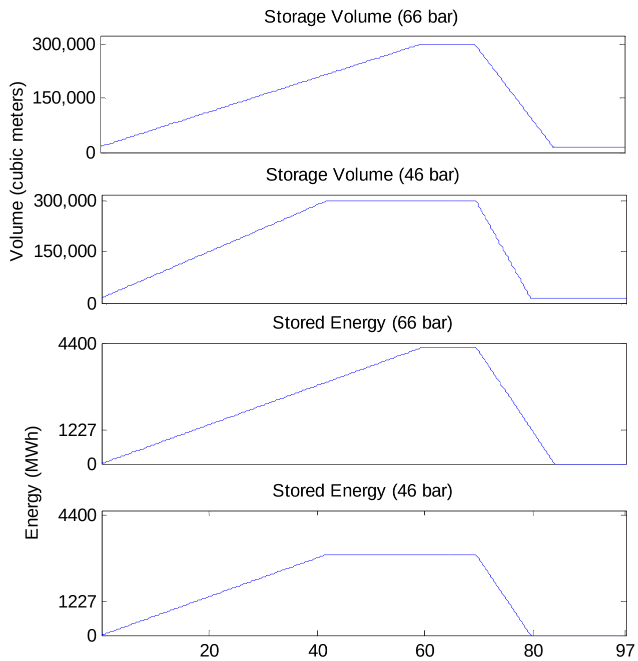


Figure 5.7 Comparison of 46 bar and 66 bar CAES

5.1.2.3 Constant pressure configuration with wind farm

The constant pressure configuration with 66 bar of operating pressure can store more energy than constant volume configuration and constant pressure configuration with 46 bar of operating pressure. Hence this configuration will be used for further analysis. The constant pressure configuration was coupled with the same wind farm as that which has been used in the previous analysis. The CAES was configured to maintain a pressure of 66 bars and initiated with the same amount of mass that constant volume storage at 46 bar has, which is 1.6411e7 kg. The results will help in comparing the two technologies in terms of state of charge of the storage, the units of charge being kg. The initial conditions for this configuration are as follows:

$$initial\ mass = 1.6411 \times 10^{7}\ kg$$
$$pressure = 66\ bar$$
$$gas\ constant\ R = 287 \times 10^{-5} m^{3} bar kg^{-1} K^{-1}$$

$$T = 293\ K$$
$$V = \frac{RTm}{P} = \frac{287 \times 10^{-5} \times 293 \times 1.6411 \times 10^{7}}{66} = 209{,}090\ m^3$$

The results for the simulation are in the following figure. The constant pressure configuration seems to have a very high energy stored at the amount of mass of air, which is stored in the constant volume configuration to maintain its lower pressure limit of 46 bar.

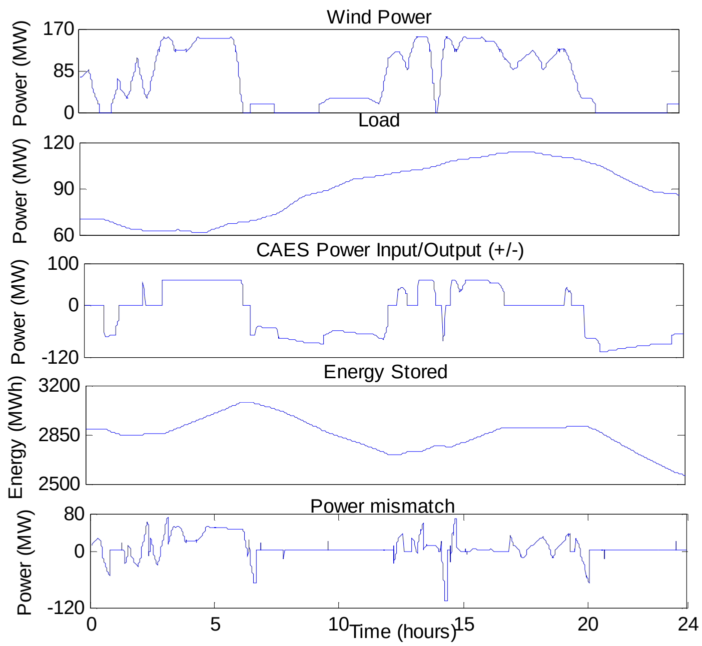


Figure 5.8 Constant Pressure CAES with wind farm

The CAES is already charged up to 2887 MWh having this mass of air at 66 bars. It's availability to load that has ramp rate less than 88 MW/min or is over 29.6 MW is above 95%. It has positive mismatches because of its ability to only charge at a maximum of 60 MW. Larger mismatch occurs where the turbine or the compressor turns on after being completely shut down. Since the compressor takes 9 minutes and gas turbine takes 11 minutes to charge after the moment power mismatch goes below or above 19.6 MW, these zones occur. To compensate for this limitation of CAES high power and fast response storage devices are required.

The constant pressure CAES in contrast with constant volume CAES proved better in terms of available energy and the ability to charge in periods of positive power mismatch. The energy stored in constant pressure storage having 1.6411e7 kg of air is about 2887.5 MWh whereas constant volume CAES has none. Also during this demanding summer day the storage was able to save 2559.3 MWh, whereas constant volume storage charged to full storage energy of 1227 MWh was left with only 564.74 MWh. This is because the constant volume CAES could not take the opportunity of charging when there was positive mismatch since it was already fully charged. This led to a net loss of more energy which was spilled due to this fact. The final state of energy of constant volume was 662.26 MWh below the initial state, whereas for constant pressure, it was 328.2 MWh. This depicts that constant pressure CAES has more versatile range of operation than constant volume CAES.

5.1.2 205.5 MW Wind farm

According to our simulation results for constant pressure CAES in the previous section; without compression and generation energy constraints, lost 328.2 MWh at the end of the day after hourly operation. It might not be affordable to lose 328.2 MWh after a day because we might need this energy on following days. On the other hand this generation per day, during months of low winds couls cause CAES to lose all of its energy allocated on daily and monthly basis. We have seen in simulation results that it is not optimal for CAES to have low energy during the high energy demand days.

The 205.5 MW wind farm consisting of 137 1.5MW wind turbines is coupled with the high energy rating CAES configuration, which is the constant pressure configuration. This is because 100 MW wind farm cannot operate on daily and monthly basis. This is shown in the next section where generated energy per month is lower than the energy consumed by the load for every month. Following is the simulation result of 205.5 MW wind farm without CAES.

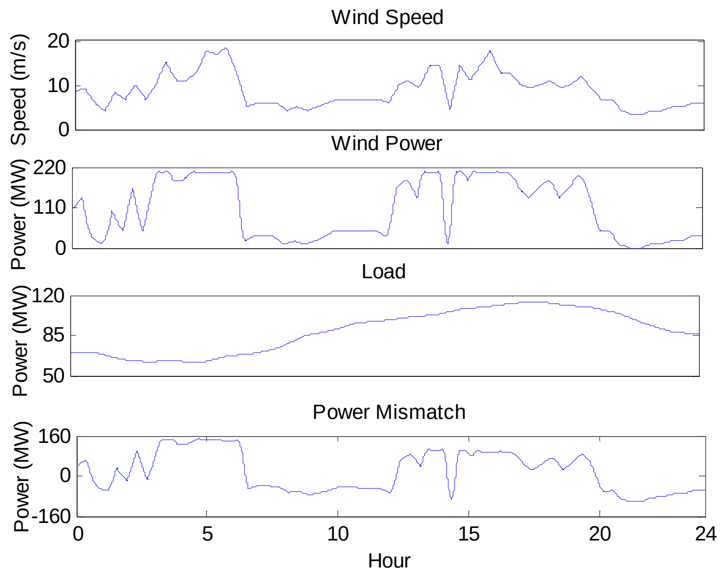


Figure 5.9 Power mismatch for 205.5MW wind far mand load

The hourly basis operation of CAES is assumed to operate such that the initial and final state of storage energy remain the same. The energy consumed and provided by CAES for this operation is constrained by the following constraints, for each day of the month, which are given in the table on next page:

Table 5.2 CAES charge and discharge constraint with loss factor

Month	**Charge Constraint (Compression)** (MWh/day)	**Discharge Constraint (Generation)** (MWh/day)	**Net Energy used for hourly operation** (MWh/day)	**Loss Factor**
January	135	66	69	0.49
February	28.33	14.29	14.04	0.51
March	168.33	112.14	56.19	0.67
April	197.3	136.49	60.81	0.692
May	333.83	214.01	119.82	0.641
June	582.58	376.56	206.02	0.646
July	597.06	424.16	172.9	0.710
August	209.06	138.42	70.64	0.662
September	249.33	179.64	69.69	0.720
October	113.33	70.65	42.68	0.623
November	57.33	29.77	27.56	0.519
December	133.32	91.54	41.78	0.687

The net energy used for hourly operation in the day occurs because CAES is not 100% efficient. It depends on the rating of the turbine and compressor that how efficiently the storage charges and discharges. If CAES is operated below its rated conditions it becomes less efficient. The loss factor is hence the ratio of actual energy delivered to the actual energy consumed from the grid. The loss factor would be used to analyse the charge and discharge of CAES on daily and monthly basis.

The hourly operation of constant pressure CAES is given in the figure below. Since CAES is also charged on daily basis we assume that there is some energy present in the storage at the beginning of the day. The figure below shows that during hour 10 to hour 15, the storage energy falls below the initial state, since during the day CAES charges at the end. We need to make sure that energy is present from daily and monthly allocation for months of such days. The following figure shows that for June, the storage energy goes below 324 MWh from its initial state near hour 12.

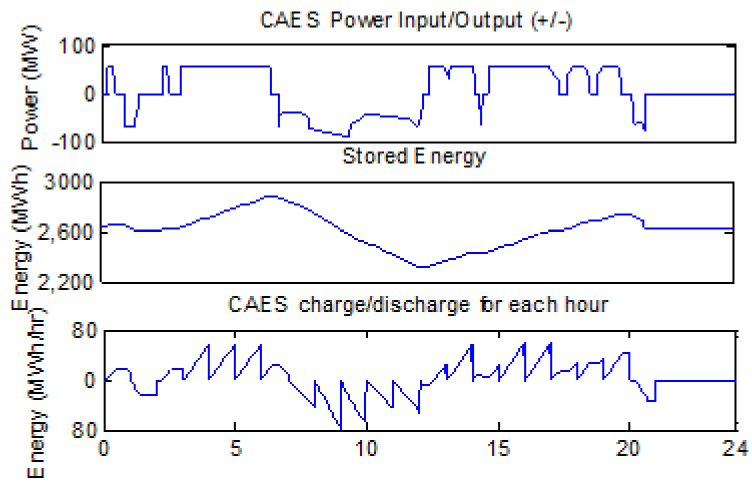


Figure 5.10 CAES operation on hourly basis for day of June

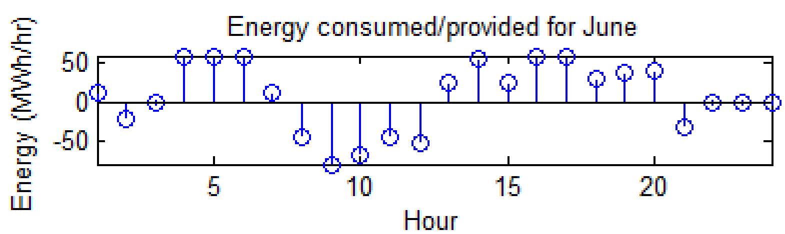


Figure 5.11 CAES energy consumed and provided for day of June

The months of days having the storage energy falling below the initial value are May, June, July, August and September. Following is the amount of energy that goes below the initial value for the following months.

Table 5.3 Energy below initial state of charge for hourly basis

Month	**Energy below initial state** (MWh)
May	317
June	324
July	678
August	264
September	46

This is not an issue for other months, since their energy doesnot fall below the initial state as shown in the figure below for January.

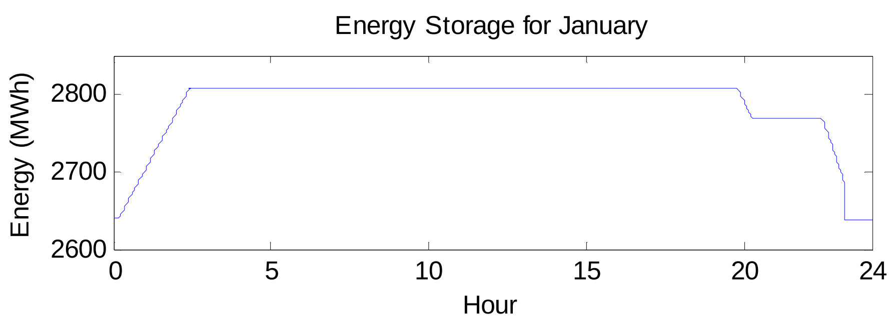


Figure 5.12 Storage energy hourly profile with energy constraints

We also need to accommodate some portion of energy for the hourly operation so that the daily charge doesnot completely fill the storage which could hinder in the charging or discharging of hourly operation. For this purpose, we look at the maximum amount of energy stored at an instant during a day of any month. Simulation results show that the storage is charged to a maximum of 262.54 MWh for hourly basis operation in September. This is shown in the figure below.

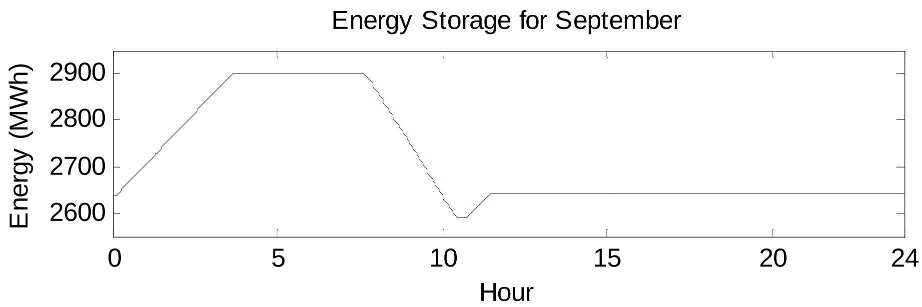


Figure 5.13 Storage energy hourly profile with wind energy constraints

5.2 Monthly and Daily Basis

To operate CAES on long term basis, the maximum energy that can be stored in CAES is divided into two parts.

1. Energy allocated for hourly basis
2. Energy allocated for daily and monthly basis

The storage energy allocated for hourly basis is charged and discharged in such a way that the initial energy state of the storage remains the same as the final. This is the normal operation of CAES and has been discussed in previous section.

The typical profiles of wind and load on monthly and daily basis are used to schedule the operation of CAES on monthly and daily basis. This portion of storage energy was used to store energy during months and days having positive energy mismatch (low demand, high generation) and deliver energy during months and days having negative energy mismatch (high demand, low generation).

The typical profiles of wind and load on daily basis were used to schedule the operation of CAES on daily basis. This portion would be used to store energy during days having net positive mismatch for a day and deliver energy during days having net negative mismatch for a day.

To analyze the CAES on monthly basis, a typical wind and load profiles for a year are required. Following is the annual load data for the city of Ames and the wind data for the Story County 150 MW wind farm used for analysis.

Table 5.4 Energy consumption and production on monthly basis

Source: (Ames Electric Department, Iowa Energy Center)

Month	**System Load** (kWh/month)	**Energy produced per month from wind farm** (kWh/month)
January	49,859,059	36,546,164
February	42,883,150	32,157,689
March	45,463,929	38,499,976
April	43,904,475	37,947,645
May	45,800,744	31,823,868
June	52,512,764	26,347,567
July	52,799,277	20,613,517
August	54,738,126	18,690,942
September	48,785,669	23,084,596
October	45,378,395	29,805,560
November	42,776,739	33,608,552
December	48,334,050	35,324,638

It can be observed that there is a lot of difference between generation and the system load. This configuration of wind farm is hence not adequate for the given load. Following is the figure that shows the wind generation and load demand for the data given above.

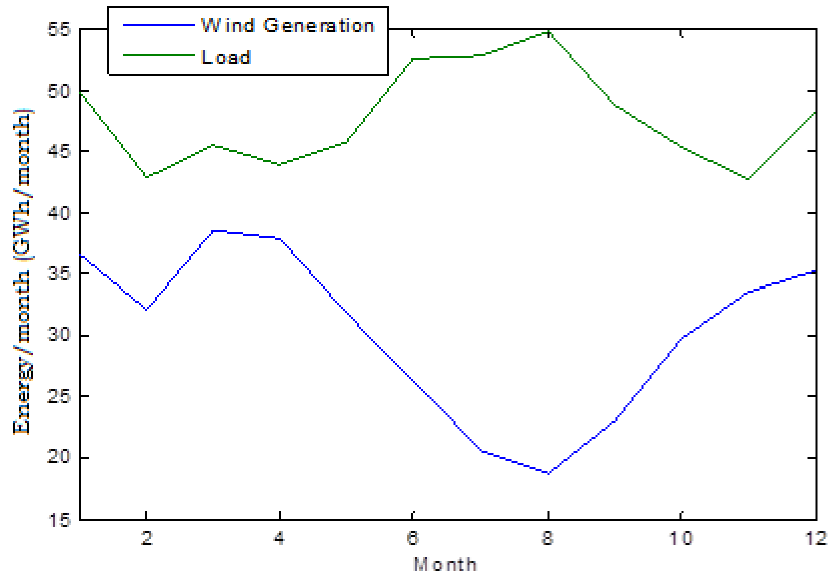


Figure 5.14 150MW Wind Generation and city of Ames load

The wind farm size for constant pressure configuration was chosen to be 205.5 MW to meet the needs of the load on daily and monthly basis. The energy produced by 205.5 MW wind plant per month and energy consumed by load per month is given in the following table.

Table 5.5 205.5 MW Wind Generation and load

Source: (Ames Electric Department, Iowa Energy Center)

Month	**System Load** (kWh/month)	**Energy produced per month** (kWh/month)
January	49,859,059	49,702,783
February	42,883,150	43,734,456
March	45,463,929	52,359,967
April	43,904,475	51,608,797
May	45,800,744	43,280,461
June	52,512,764	35,832,692
July	52,799,277	28,034,383
August	54,738,126	24,419,681
September	48,785,669	31,395,051
October	45,378,395	40,535,562
November	42,776,739	45,707,631
December	48,334,050	48,041,508

The data provided in the above table is given in the figure below.

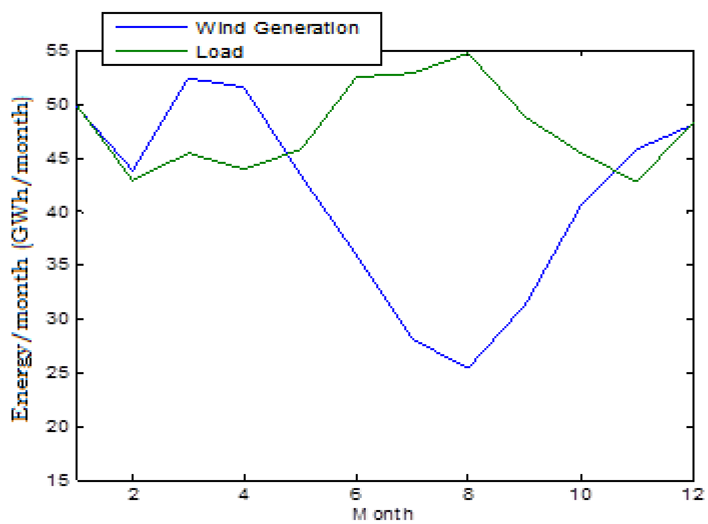


Figure 5.15 205.5 MW Wind Generation and city of Ames load

According to the figure above, it is evident that the mismatch between load and generation occurs on monthly basis as well. The energy portion allocated for monthly and daily basis operation of CAES would be used to minimize this mismatch. The regions where wind generation line is above the load line, we have extra energy, the regions where wind energy line is below load line, this is the deficiency of energy.

The energy mismatch per month for the figure above is provided in the following table.

Table 5.6 Energy mismatch on monthly basis

Month	**Energy Mismatch** (GWh/month)
January	-0.1563
February	0.8513
March	6.8960
April	7.7043
May	-2.5203
June	-16.6801
July	-24.7649
August	-29.3184
September	-17.3906
October	-4.8428
November	2.9309
December	-0.2925

The data given in the table above is plotted as follows.

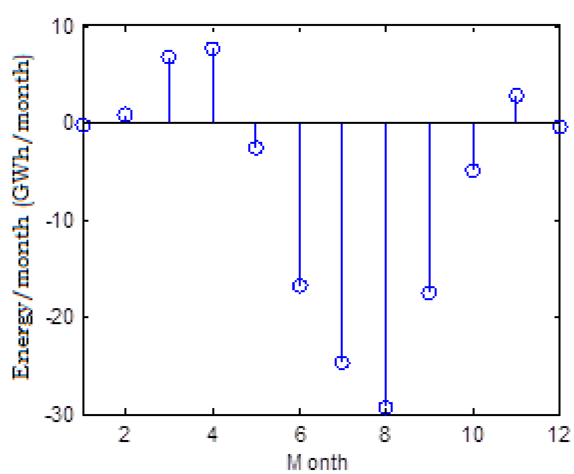


Figure 5.16 Energy Mismatch on monthly basis

Since CAES has a limited amount of energy storage, it cannot capture and deliver all of the energy provided in the figure above. Also, we need to consider the fact that CAES operates according to the power mismatch on hourly basis. If the hourly power mismatch is below rated values of compressor and turbines, CAES is not going to charge at its maximum rate.

Therefore for analyzing energy charge and discharge for CAES for monthly and daily basis, we need to use the hourly basis simulation results. The amount of energy that CAES would be able to charge on each day depends on the following:

- Size of Storage
- Average power rating of hourly basis compression during a typical day of particular month
- Duration of hourly basis compression operation
- Average power rating of hourly basis generation during a typical day of particular month
- Duration of hourly basis generating operation.

We configured the CAES on hourly basis allocation to charge and discharge completely. In the previous section we observed from the simulation results that hourly basis allocation was charged to a maximum of 262.54 MWh. From this result we allocate 450 MWh of energy storage for hourly operation. The total energy that constant pressure CAES can store is 4240 MWh. Therefore we are left with 3790 MWh of energy allocated for daily and monthly basis. The simulation on hourly basis provides the following results for typical days of each month.

Table 5.7 Summary of hourly basis operation

Month	Compressor Operation Average Rating		Turbine Operation Average Rating		Total Operation
	(MW)	(Hours)	(MW)	(Hours)	(Hours)
January	59.69	2.27	54.69	1.22	3.48
February	59.56	0.48	30.19	0.47	0.96
March	59.75	2.82	54.26	2.1	4.9
April	59.79	3.3	57.58	2.37	5.67
May	58.78	5.66	51.27	4.17	9.83
June	57.24	10.18	57.74	6.51	16.68
July	53.96	11.06	62.92	6.74	17.81
August	49.27	4.24	69.84	1.98	6.23
September	59.01	4.23	63.99	2.81	7.03
October	46.75	2.42	45.09	1.57	3.99
November	59.28	0.97	31.51	0.95	1.91
December	59.69	2.23	57.08	1.60	3.83

Since, CAES is not 100% efficient, the generation energy is always lower than the energy consumed during compression. The following table from the previous section provides the amount of energy used for generation and compression during a typical day of each month.

The daily amount of energy that CAES can charge and discharge per day for daily and monthly allocation for a typical day of each month is calculated by the following expression.

$$C_{limit,i} = P_{c,i} \times (24 - h_{c,i} - h_{gen,i})$$
$$D_{limit,i} = P_{gen,i} \times (24 - h_{gen,i} - h_{c,i})$$

where
$C_{limit,i}$ = *charging limit in MWh/day for month i*
$D_{limit,i}$ = *discharging limit in MWh/day for month i*
$P_{c,i}$ = *average operating power of compressor per day of month i*

$P_{gen,i} = average\ operating\ power\ of\ generator\ per\ day\ of\ month\ i$
$h_{c,i} = average\ hours\ of\ compressor\ operation\ per\ day\ of\ month\ i$
$h_{gen,i} = average\ hours\ of\ generating\ operation\ per\ day\ of\ month\ i$

The charge and discharge limits during a day for each month are calculated using the above expression and the hourly basis operation data as follows.

Table 5.8 Energy constraints for charging and discharging on daily basis

	Charge/Discharge Limits for daily operation (MWh/day)	
January	1224.2	-1121.7
February	1372.9	-695.88
March	1140	-1035.3
April	1095.95	-1055.44
May	832.91	-726.49
June	418.42	-422.07
July	334.55	-390.10
August	876.02	-1241.75
September	1000.80	-1085.27
October	935.46	-902.25
November	1308.90	-695.74
December	1203.94	-1151.30

Although the energy storage charges and discharges completely during the day, the CAES actually consumes some form of energy. Therefore we do not deliver the complete amount of energy. Since we measure the storage energy with gas turbine design, we assume that during charging, the total energy consumed does not completely get stored in the storage but some amount of ratio which we call the loss factor. The loss factor for a typical day of each month is provided on the basis of hourly operation. This is provided as follows.

Table 5.9 Loss factor on hourly basis operation

Month	Charge (Compression) (MWh/day)	Discharge (Generation) (MWh/day)	Net Energy used for hourly operation (MWh/day)	Loss Factor
January	135	66	69	0.49
February	28.33	14.29	14.04	0.51
March	168.33	112.14	56.19	0.67
April	197.3	136.49	60.81	0.692
May	333.83	214.01	119.82	0.641
June	582.58	376.56	206.02	0.646
July	597.06	424.16	172.9	0.710
August	209.06	138.42	70.64	0.662
September	249.33	179.64	69.69	0.720
October	113.33	70.65	42.68	0.623
November	57.33	29.77	27.56	0.519
December	133.32	91.54	41.78	0.687

The amount of energy consumed would be multiplied by this loss factor and would be used to measure the amount of energy actually going into the storage after the loss.

Following is the energy mismatch for each day of the year starting from November.

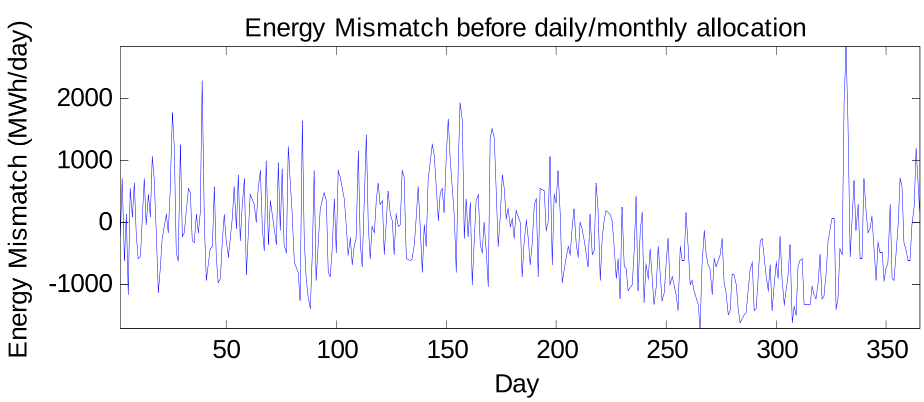


Figure 5.17 Energy mismatch on daily basis

We need to know which amount of energy can CAES consume or serve on each day. We assume that the net energy used on hourly basis operation would not be recovered. Therefore on the days having positive energy mismatch, the energy that would be available to charge CAES on daily basis would be actual energy mismatch less the net energy consumed for hourly operation on that day. Similarly on the days having negative energy mismatch we assume that CAES only delivers the difference of actual negative energy mismatch to the amount of energy consumed for hourly basis. This would provide us the actual amount of energy mismatch that CAES can use for charging or deliver by discharging.

We also need to consider the generation and compression limits for the day. These limits are evaluated in the previous table. The actual cmount of energy would be compared with these limits. If the limits are violated, the values of limits are take, otherwise we make no changes. This would give us actual amount of energy available after hourly operation loss and charging and discharging constraint for a day.

The available energy is then added to the amount of energy already available inside the storage. Since we are taking negative values The storage limits are checked. The algorithm for this process is shown in the flow chart on next page.

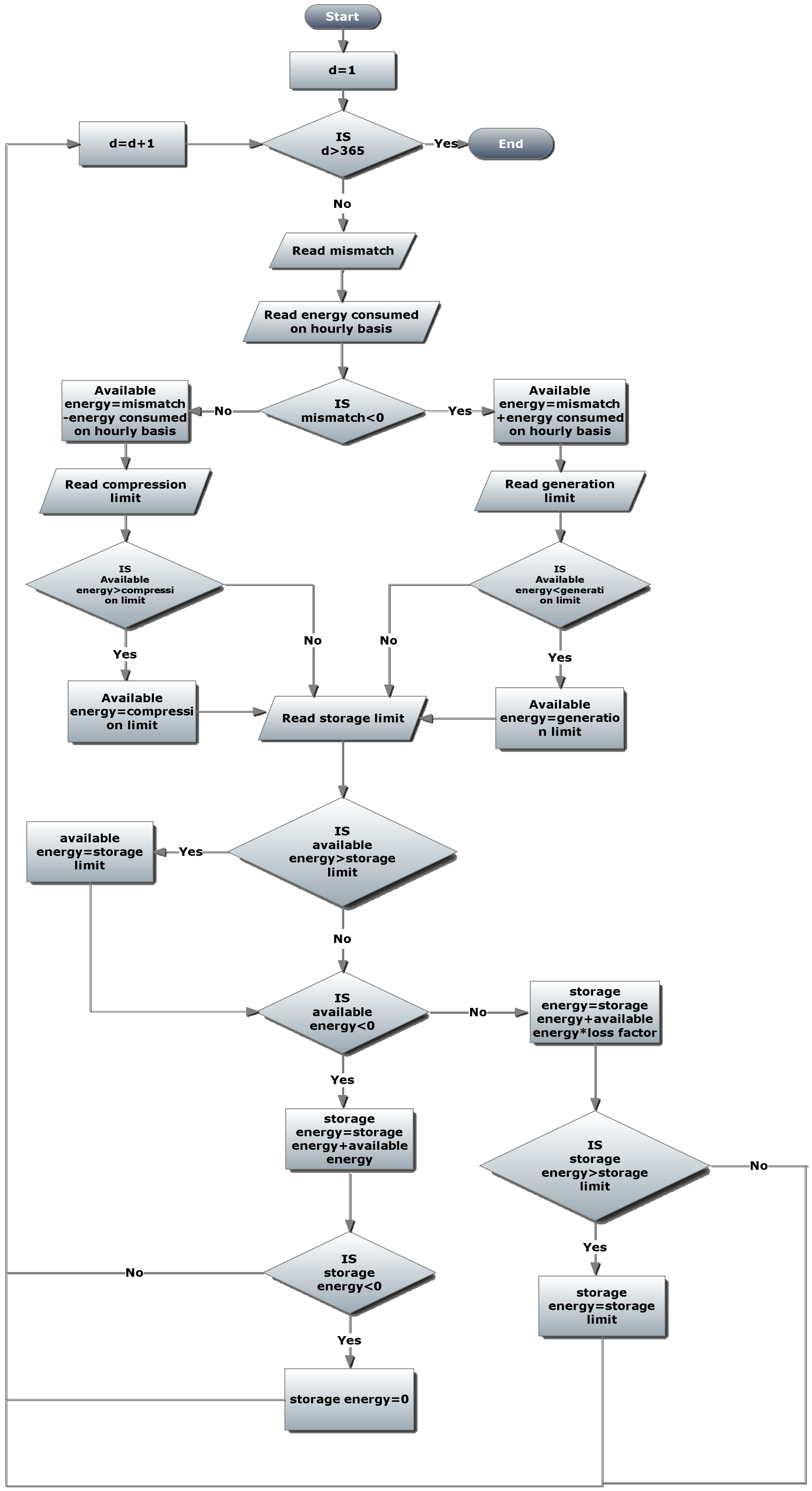


Figure 5.18 Flow chart to determine state of charge on daily basis

The amount of energy consumed and provided during each day can be found through the state of charge evaluated from the algorithm. This can be done by subtracting the state of charge of a particular day with the previous day.

$$charge(i) = SOC(i) - SOC(i-1)$$
$$where\ i = day$$
$$SOC = state\ of\ charge$$

The initial state of charge is assumed to be constant. The updated mismatch can hence be calculated by adding the amount of energy consumed and provided during each day.

$$umis(i) = mis(i) + charge(i)$$
$$where$$
$$umis = energy\ mismatch\ after\ daily/monthly\ allocation\ per\ day$$
$$mis = energy\ mismatch\ per\ day$$

Using above expressions we obtain the following results.

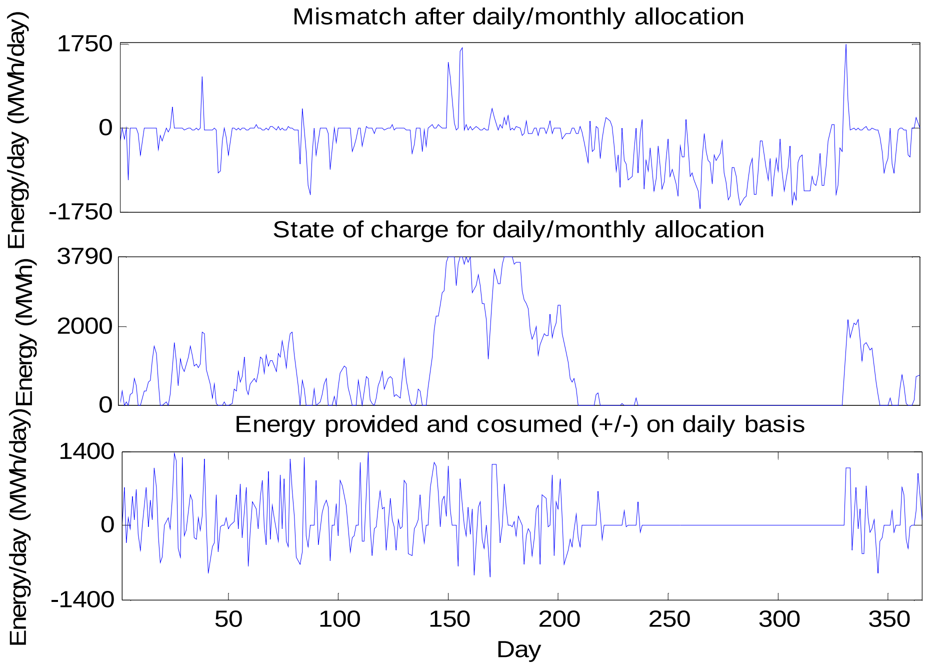


Figure 5.19 Simulation results for daily allocation

The storage energy in the figure above charges and discharges simultaneously from November to April. In May the storage discharges to zero and there no energy available for the months of June, July, August and partly September. We need to tune the values for the energy discharge limits per day. The discharge per day constraint for months of May , June, July and August is tuned in such a way that energy is provided according to the energy mismatch of each month.

We discussed in the hourly operation that the months of days having the storage energy on hourly basis falling below the initial value are May, June, July, August and September. We must have following amount of energy at all times during the following months to ensure the initial state os storage energy for hourly operation.

Table 5.10 Energy constraint on hourly basis for reserve operation

Month	**Energy below initial state** (MWh)
May	317
June	324
July	678
August	264
September	46

The tuned values for energy discharge per day are given as follows.

Table 5.11 Tuned constraints for daily basis

Month	**Energy Mismatch** (GWh/month)	**Discharge constraint Tuned Values** (MWh/day)
May	-2.5203	-8.81
June	-16.6801	-28.65
July	-24.7649	-39.8
August	-29.3184	-45.2
September	-17.3906	-29.52

Following are the results after using the tuned values. The storage is now able to serve the load for the months it was not able to with the constraints used previously.

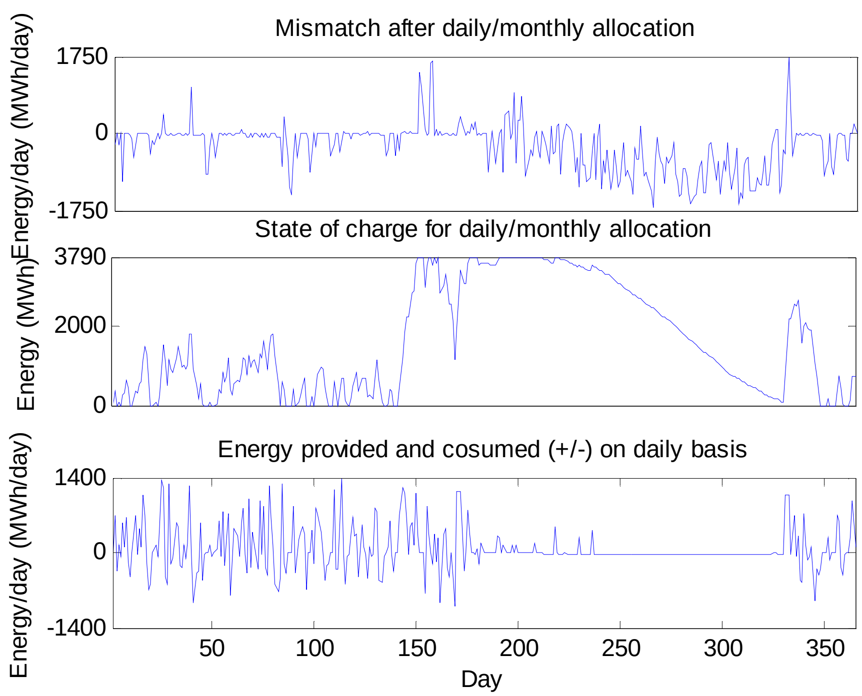


Figure 5.20 Simulation results for daily basis operation with tuned constraints

The state of energy is 997.39 MWh at the end of the year after the month of October.

CHAPTER 6

COST ANALYSIS

The results from the previous sections show that constant pressure configuration provides a wide range of operation due to its energy rating. To evaluate the economic benefits of the 150 MW wind farm with constant volume CAES and 205.5 MW wind farm with constant pressure CAES, we perform the cost analysis. We also need to consider whether CAES provides more economic benefit without being integrated a wind farm.

The capital cost of the CAES configurations is evaluated by taking in consideration the two main components of CAES.

- Power related cost
- Energy capacity related cost

The power related cost is related to the power conditioning system of CAES. The energy capacity related cost is related to the storage.

On the other hand the operational costs include the cost of:

- Energy bought (compression)
- Generation
- Operation and maintainance costs

The revenues include:

- Energy sold (generation)

We have evaluated the energy consumption and generation profiles for hourly and daily basis. Hourly basis locational marginal prices are used to evaluate the cost of buying energy. The cost of generation includes the variable operational and maintainance costs and the cost for buying the natural gas.

6.1 150 MW wind farm with constant volume storage

The huntorf CAES is based on the salt geology. We assume that the constant volume storage that is being used is based on a salt dome. According to NREL, the power related cost for this geology is 350 $/kW. Our CAES plant is 290 MW. Therefore the power related cost is as follows:

$$power\ related\ cost = 350\,\$/kW \times 290000kW = \$101{,}500{,}000$$

The energy related cost for salt geology is 1.2$/kWh according to NREL. The constant volume configuration can store up to 1227 MWh of energy. Therefore the energy related cost is as follows:

$$energy\ related\ cost = 1.2\$/kWh \times 1{,}227{,}000 = \$1{,}472{,}400$$

The total capital cost for the project is as follows:

$$capital\ cost = power\ related\ cost + energy\ related\ cost$$

$$capital\ cost = \$102{,}972{,}400$$

The heat rate of the generating plant is used to calculate the cost of generation. Heat rate is the measurement of how efficiently a generating plant uses heat energy. The average heat rate for Huntorf Germany plant is 5563.98 KJ/kW according to Succar. Since 1 Btu is equal to 1055 J, we get the heat rate of Huntorf Germany plant as 5563.98 Btu/kWh. The cost of electricity generated can be found by using the following expression.

$$Cost\ of\ generation(\$/kWh) = cost\ of\ fuel(\$/Btu) \times H_R(Btu/kWh) + variable\ O\&M\ cost$$

H_R is the heat rate of the plant. The cost of fuel is assumed to be 4.35 $/MCF according to EIA. The units for the average monthly cost of natural gas are provided in terms of $/MCF. Since 1 MCF=1.026 MMBtu=1.026e6 Btu, this provides the cost of generation for each month to be 4.24 $/MMBtu. The variable O&M cost according to Energy Storage & Power LLC is 5 $/MWh. The cost of generation is evaluated as follows:

$$cost\ of\ generation(\$/MWh) = 4.24\$/MMBtu \times 5563.98/(1000 \times 1000)MMBtu/MWh + 5\$/MWh$$

$$cost\ of\ generation = 28.59\$/MWh$$

The LMP profile on hourly basis for a typical day of April, May and June for the wind generation MISO node ALTW.WOLFWIND is as follows.

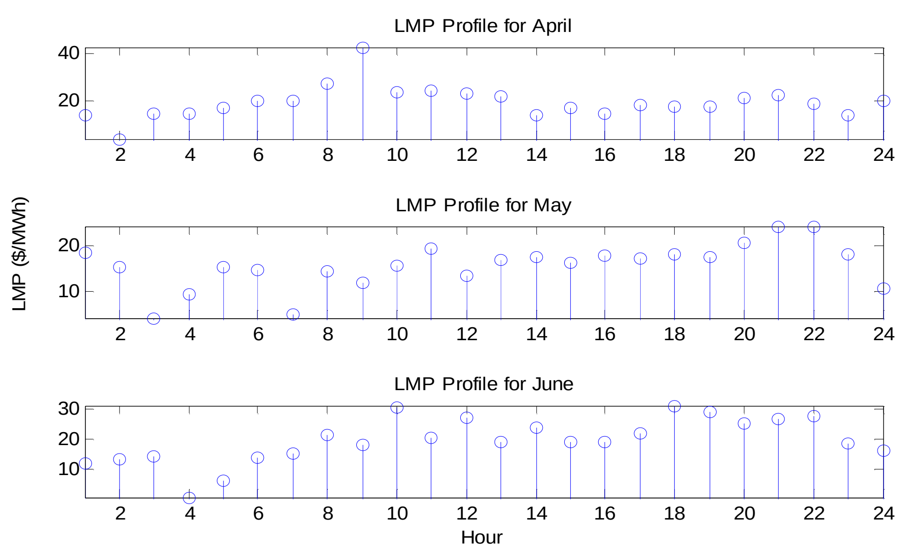


Figure 6.1 LMP profile for wind node

The amount of energy consumed and generated on hourly basis from the simulation results in previous sections is as follows.

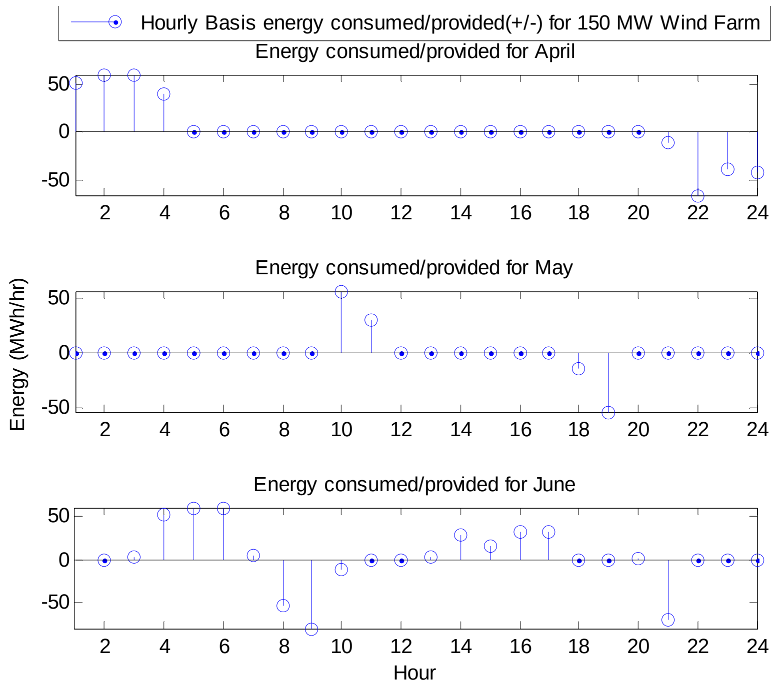


Figure 6.2 Energy consumed and provided by CAES on hourly basis

The charging cost for a day is evaluated by taking a product of LMP with the amount of energy used to charge the storage for each particular hour. These are the charging costs for each hour. Then this cost is added to obtain the total cost of charging during the day.

$$charging\ cost(\$/day) = \sum_{i=1}^{24} E_i(MWh/hr) \times LMP_i(\$/MWh) \qquad E_i > 0$$

$$\begin{aligned} &where \\ &E_i = amount\ of\ energy\ consumed\ during\ hour\ i \\ &LMP_i = locational\ marginal\ price\ during\ hour\ i \end{aligned}$$

Similarly the discharging revenue is evaluated by taking a product of LMP with the amount of energy discharged for each particular hour. These are the discharging renvenues for each hour. Then this cost is added to obtain the total revenue obtain from discharging during the day.

$$revenue\ from\ discharging(\$/day) = \sum_{i=1}^{24} -E_i(MWh/hr) \times LMP_i(\$/MWh) \qquad E_i < 0$$

$$\begin{aligned}&where\\&E_i = amount\ of\ energy\ generated\ during\ hour\ i\\&LMP_i = locational\ marginal\ price\ during\ hour\ i\end{aligned}$$

The sum of amount of discharge energy for each day can be multiplied by the generation cost per MWh, evaluated in this section. This would provide the cost of generation.

$$cost\ of\ generation(\$/day) = \sum_{i=1}^{24} -E_i(MWh/hr) \times 28.59\,\$/MWh \qquad E_i < 0$$

$$\begin{aligned}&where\\&E_i = amount\ of\ energy\ generated\ during\ hour\ i\end{aligned}$$

The revenues generated per day can hence be calculated as follows:

$$revenue(\$/day) = revenue\ from\ discharging(\$/day) - charging\ cost(\$/day) - cost\ of\ generation(\$/day)$$

The revenue per month is calculated by multiplying the days of particular month with the revenue per day.

$$revenue\ per\ month\ i = revenue\ per\ day\ month\ i \times no.of\ days\ of\ month\ i$$

The above evaluations for constant volume CAES with 150 MW wind farm are summarized in the table below.

Table 6.1 Casflow for constant volume configuration

Month	Charge (Buying) ($/day)	Generation Cost ($/day)	Discharge (Selling) ($/day)	Revenue ($/day)	Revenue ($/month)
January	5724.496	5081.87	4885.57	-5920.79	-183,545
February	842.7684	1445.28	1060.82	-1227.23	-34,362.4
March	1528.3064	3816.79	2855.98	-2489.11	-77,162.6
April	2414.5499	4560.96	2939.62	-4035.89	-121,077
May	1460.9927	1930.96	1191.30	-2200.66	-68,220.4
June	3669.03488	6095.67	4777.77	-4986.93	-149,608
July	2995.1744	4321.6	2509.91	-4806.92	-149,015
August	336.49121	297.32	250.45	-383.353	-11,883.9
September	2447.6357	4323.66	2905.19	-3866.1	-115,983
October	2565.7042	3053.15	2696.46	-2922.4	-90,594.3
November	1304.2962	1476.38	461.41	-2319.27	-69,578.2
December	4547.1766	4588.98	7664.00	-1472.16	-45,636.9
TOTAL					**-$1,116,667**

Following figure shows the cashflow for the project. The project is assumed to operate for 40 years according to Sioshansi.

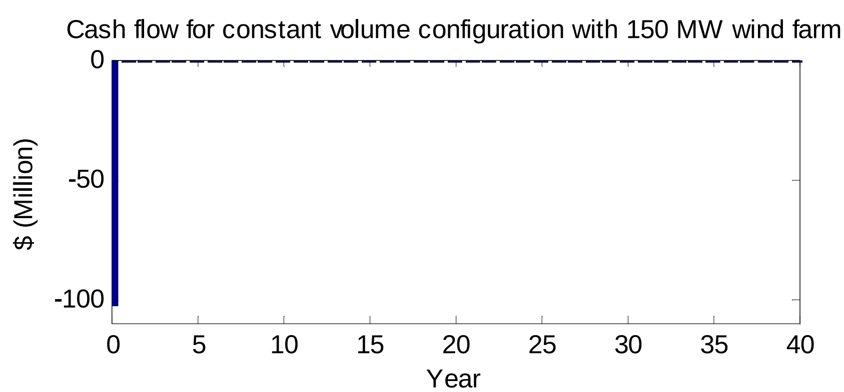


Figure 6.3 Cash flow for constant volume configuration

Since the annual revenues are negative, no rate of return exists.

6.2 205.5 MW Wind farm with constant pressure configuration

6.2.1 Hourly Basis Operation

The constant pressure configuration is assumed to be based opon the limestone geology. We assume that the constant pressure storage that is being used is based on a limestone mine. According to NREL, the power related cost for this geology is 350 $/kW. Our CAES plant is 290 MW. Therefore the power related cost is as follows:

$$power\ related\ cost = 350\,\$/kW \times 290000kW = \$101{,}500{,}000$$

The energy related cost for storage based on existing limestone mine geology is 11.5 $/kWh according to NREL. The constant pressure configuration can store up to 4240 MWh of energy. Therefore the energy related cost is as follows:

$$energy\ related\ cost = 11.5\$/kWh \times 4{,}240{,}000 = \$48{,}760{,}000$$

The total capital cost for the project is as follows:

$$capital\ cost = power\ related\ cost + energy\ related\ cost$$

$$capital\ cost = \$150{,}260{,}000$$

The heat rate of the generating plant is used to calculate the cost of generation. Heat rate is the measurement of how efficiently a generating plant uses heat energy. The average heat rate for Huntorf Germany plant is 5563.98 KJ/kW according to Succar. Since 1 Btu is equal to 1055 J, we get the heat rate of Huntorf Germany plant as 5563.98 Btu/kWh. The cost of electricity generated can be found by using the following expression.

$$Cost\ of\ generation(\$/kWh) = cost\ of\ fuel(\$/Btu) \times H_R(Btu/kWh) + variable\ O\&M\ cost$$

H_R is the heat rate of the plant. The cost of fuel is assumed to be 4.35 $/MCF according to EIA. The units for the average monthly cost of natural gas are provided in terms of $/MCF. Since 1 MCF=1.026 MMBtu=1.026e6 Btu, this provides the cost of generation for each month to be 4.24 $/MMBtu. The O&M cost according to NREL is the same for limestone mine and salt geologies. The cost of generation is evaluated as follows:

$$cost\ of\ generation(\$/MWh) = 4.24\$/MMBtu \times 5563.98/(1000 \times 1000)MMBtu/MWh + 5\$/MWh$$

$$cost\ of\ generation = 28.59\$/MWh$$

The LMP profile on hourly basis for a typical day of April, May and June for the wind generation MISO node ALTW.WOLFWIND is as follows.

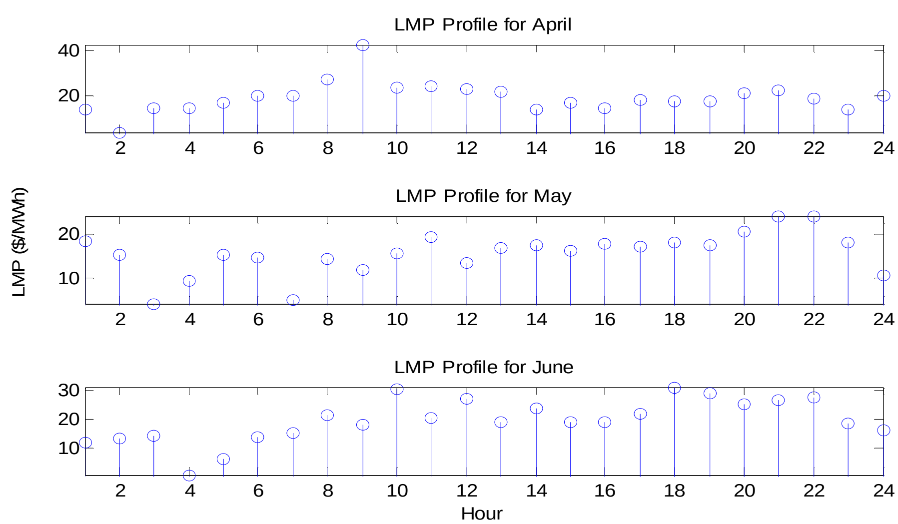


Figure 6.4 LMP profile for wind node

The amount of energy consumed and generated on hourly basis from the simulation results in previous sections is as follows.

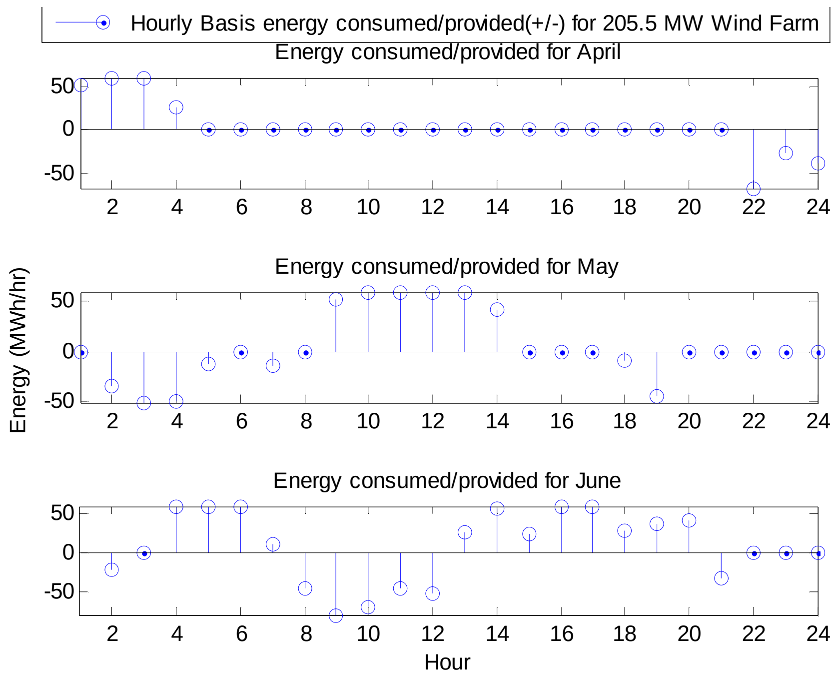


Figure 6.5 Energy consumed provided by constant pressure CAES

The charging cost for a day is evaluated by taking a product of LMP with the amount of energy used to charge the storage for each particular hour. These are the charging costs for each hour. Then this cost is added to obtain the total cost of charging during the day.

$$charging\ cost(\$/day) = \sum_{i=1}^{24} E_i(MWh/hr) \times LMP_i(\$/MWh) \qquad E_i > 0$$

$$where$$
$$E_i = amount\ of\ energy\ consumed\ during\ hour\ i$$
$$LMP_i = locational\ marginal\ price\ during\ hour\ i$$

Similarly the discharging revenue is evaluated by taking a product of LMP with the amount of energy discharged for each particular hour. These are the discharging renvenues for each hour. Then this cost is added to obtain the total revenue obtain from discharging during the day.

$$revenue\ from\ discharging(\$/day) = \sum_{i=1}^{24} -E_i(MWh/hr) \times LMP_i(\$/MWh) \qquad E_i < 0$$

$$\begin{aligned} &where \\ &E_i = amount\ of\ energy\ generated\ during\ hour\ i \\ &LMP_i = locational\ marginal\ price\ during\ hour\ i \end{aligned}$$

The sum of amount of discharge energy for each day can be multiplied by the generation cost per MWh, evaluated in this section. This would provide the cost of generation.

$$cost\ of\ generation(\$/day) = \sum_{i=1}^{24} -E_i(MWh/hr) \times 28.59\ \$/MWh$$

$$\begin{aligned} &where \\ &E_i = amount\ of\ energy\ generated\ during\ hour\ i \end{aligned}$$

The revenues generated per day can hence be calculated as follows:

$$revenue(\$/day) = revenue\ from\ discharging(\$/day) - charging\ cost(\$/day) - cost\ of\ generation(\$/day)$$

The revenue per month is calculated by multiplying the days of particular month with the revenue per day.

$$revenue\ per\ month\ i = revenue\ per\ day\ month\ i \times no.of\ days\ of\ month\ i$$

The above evaluations for constant pressure CAES with 205.5 MW wind farm are summarized in the table below.

Table 6.2 Cashflow for hourly basis operation

Month	Charge (Buying) ($/day)	Generation Cost ($/day)	Discharge (Selling) ($/day)	Revenue ($/day)	Revenue ($/month)
January	16339.1	9916.73	13706.2	-12549.6	-389,038
February	21249.78	9941.03	6265.22	-24925.6	-697,917
March	5978.982	3969.44	1941.22	-8007.2	-248,223
April	3074.977	4840.86	5362.76	-2553.07	-76,592.2
May	1354.791	2019.88	901.702	-2472.97	-76,662.2
June	701.9834	851.124	481.976	-1071.13	-32,133.9
July	1423.06	2573.96	1004.15	-2992.87	-92,778.9
August	1824.375	1902.75	1328.18	-2398.94	-74,367.2
September	396.9033	408.551	210.349	-595.106	-17,853.2
October	1661.374	3159.48	2150.74	-2670.11	-82,773.4
November	2690.949	3744.43	2058.55	-4376.83	-131,305
December	9581.7	6114.94	6524.17	-9172.47	-284,347
TOTAL					**-2,203,990.16**

Following figure shows the cashflow for the project. The project is assumed to operate for 40 years according to Sioshansi.

Since the annual revenues are negative, no rate of return exists.

6.2.2 Daily Basis Operation

The daily average LMP profile for the year of 2009 for wind generation MISO node ALTW.WOLFWIND is as follows. The profile in the following figure starts from November and ends at October.

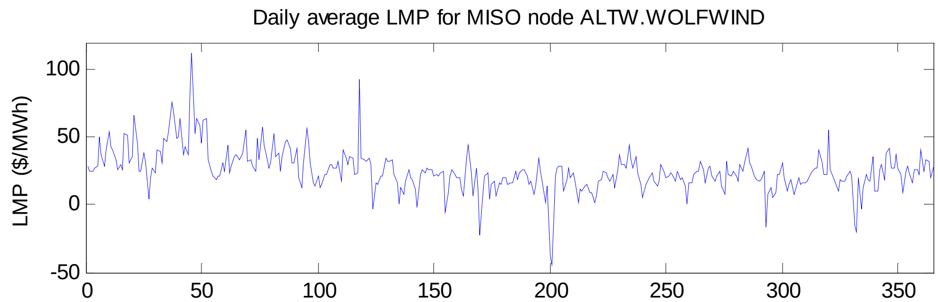


Figure 6.6 LMP on daily average for wind node

The amount of energy consumed and generated on daily basis from the simulation results in previous sections is as follows.

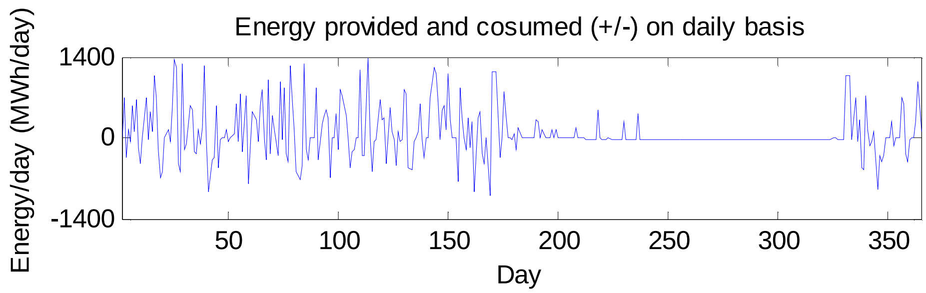


Figure 6.7 Energy consumed and provided by CAES on daily basis

The charging cost for a year is evaluated by taking a product of LMP with the amount of energy used to charge the storage for each particular day. These are the charging costs for each day. Then this cost is added to obtain the total cost of charging during the year.

$$charging\ cost(\$/month) = \sum_{i=n}^{m} E_i(MWh/day) \times LMP_i(\$/MWh) \qquad E_i > 0$$

$$\begin{aligned}&where\\&E_i = amount\ of\ energy\ consumed\ during\ day\ i\\&LMP_i = average\ locational\ marginal\ price\ of\ day\ i\end{aligned}$$

Similarly the discharging revenue is evaluated by taking a product of LMP with the amount of energy discharged for each particular day. These are the discharging renvenues for each day. Then this cost is added to obtain the total revenue obtain from discharging during the year.

$$revenue\ from\ discharging(\$/month) = \sum_{i=n}^{m} -E_i(MWh/day) \times LMP_i(\$/MWh) \qquad E_i < 0$$

$$\begin{aligned}&where\\&E_i = amount\ of\ energy\ generated\ during\ day\ i\\&LMP_i = average\ locational\ marginal\ price\ of\ day\ i\\&n\ is\ the\ first\ day\ of\ month\\&m\ is\ the\ last\ day\ of\ month\end{aligned}$$

The sum of amount of discharge energy for the year can be multiplied by the generation cost per MWh, evaluated in this section. This would provide the cost of generation.

$$cost\ of\ generation(\$/month) = \sum_{i=n}^{m} -E_i(MWh/day) \times 28.59\,\$/MWh \qquad E_i < 0$$

$$\begin{aligned}&where\\&E_i = amount\ of\ energy\ generated\ during\ day\ i\\&n\ is\ the\ first\ day\ of\ month\\&m\ is\ the\ last\ day\ of\ month\end{aligned}$$

The revenues generated per year can hence be calculated as follows:

$$\begin{aligned}revenue(\$/month) &= revenue\ from\ discharging(\$/month) - charging\ cost(\$/month)\\&- cost\ of\ generation(\$/month)\end{aligned}$$

The above evaluations for constant pressure CAES with 205.5 MW wind farm are summarized in the table below.

Table 6.3 Cash flow for daily basis operation

Month	Charge (Buying) ($/month)	Generation Cost ($/month)	Discharge (Selling) ($/month)	Revenue ($/month)
January	292,135.92	131,593.84	195,348.73	-228,381.03
February	202,040.41	89,923.02	108,321.05	-183,642.39
March	190,898.18	75,041.41	67,375.58	-198,564.01
April	55,857.85	136,244.44	94,359.60	-97,742.69
May	23,204.97	4,573.98	3225.34	-24,553.61
June	25,460.55	20,503.89	14,276.49	-31,687.94
July	0	34,640.70	25,606.81	-9,033.88
August	0	40,060.30	27,352.29	-12,708.01
September	17,945.87	21,684.51	16,016.75	-23,613.63
October	84,401.24	119,638.78	124,319.60	-79,720.42
November	322,329.81	111,220.60	115,979.08	-317,571.33
December	223,603.58	121,046.10	205,289.92	-139,359.76
TOTAL				**-1,310,687**

The total revenue for daily and hourly basis operation is as follows:

$$total\ revenue = revenue\ from\ daily\ basis + revenue\ from\ hourly\ basis$$
$$total\ revenue\ per\ year = -\$3{,}514{,}677$$

Following figure shows the cashflow for the project. The project is assumed to operate for 40 years according to Sioshansi.

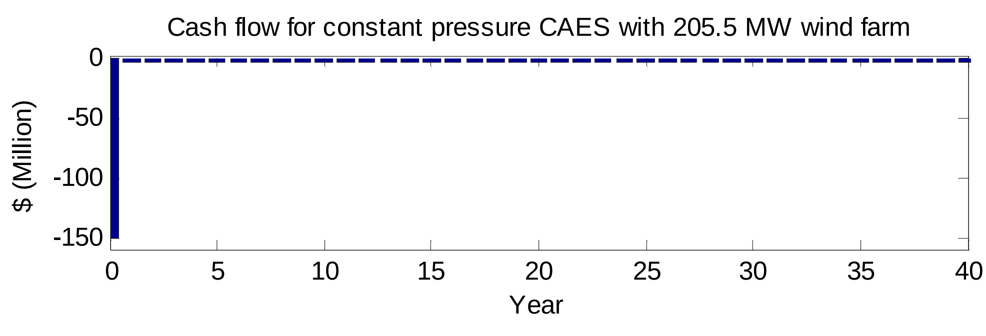


Figure 6.8 Cash flow for constant pressure CAES with wind farm

Since the annual revenues are negative, no rate of return exists.

6.3 Independent Operation of Constant pressure CAES with loadzone

The independent operation of constant pressure CAES is assumed to free of energy constraints which were due to the hybrid operation with wind farm. The storage is assumed to be connected to the MISO AECI.ALTW loadzone. The charging and discharging limits for the day are fixed according to the mean LMP of the month. Six months having low LMP are chosen for charging and other six months having relatively high LMP are chosen for discharging operation. January, March, May, June, August and September are months which have relatively low LMP. These months are chosen to charge CAES. February, April, July, October, November and December are months of relatively high mean LMP. These months are chosen for discharge purpose.

The total energy that constant pressure configuration can store is 4240 MWh. This is divided on the month of 31 days, for charging or discharging purposes, it comes out to be 136.77 MWh/day.

If charging or discharging months occur simultaneously, the charging or discharging would occur on the basis of mean LMP. The amount of charge limit for consecutive months of May and June is taken identical because their mean LMP is almost the same. Same is the case with the months of August and September. The discharge limit for October November and December is chosen as follows.

$$charge\ limit\ of\ day\ of\ month\ i = \frac{mean\ lmp\ of\ month\ i}{sum\ of\ mean\ lmp\ of\ consecutive\ months} \times 136.77 MWh/day$$

The charging and discharging limits based on above criterion are given as follows.

Table 6.4 Daily charging and discharging limits

Month	**Mean LMP** ($/MWh)	**Charging/discharging limits** (MWh/day)
January	24.92	136.77
February	34.51	-136.77
March	28.31	136.77
April	39.11	-136.77
May	24.23	68.39
June	24.35	68.39
July	29.11	-136.77
August	22.33	68.39
September	22.51	68.39
October	42.06	-44.21
November	50.41	-54.87
December	35.96	-37.70

Hourly LMP profile for a typical day of a month is provided with LMP limits such that it charges according to the above schedule. The model is shown in the figure on the next page.

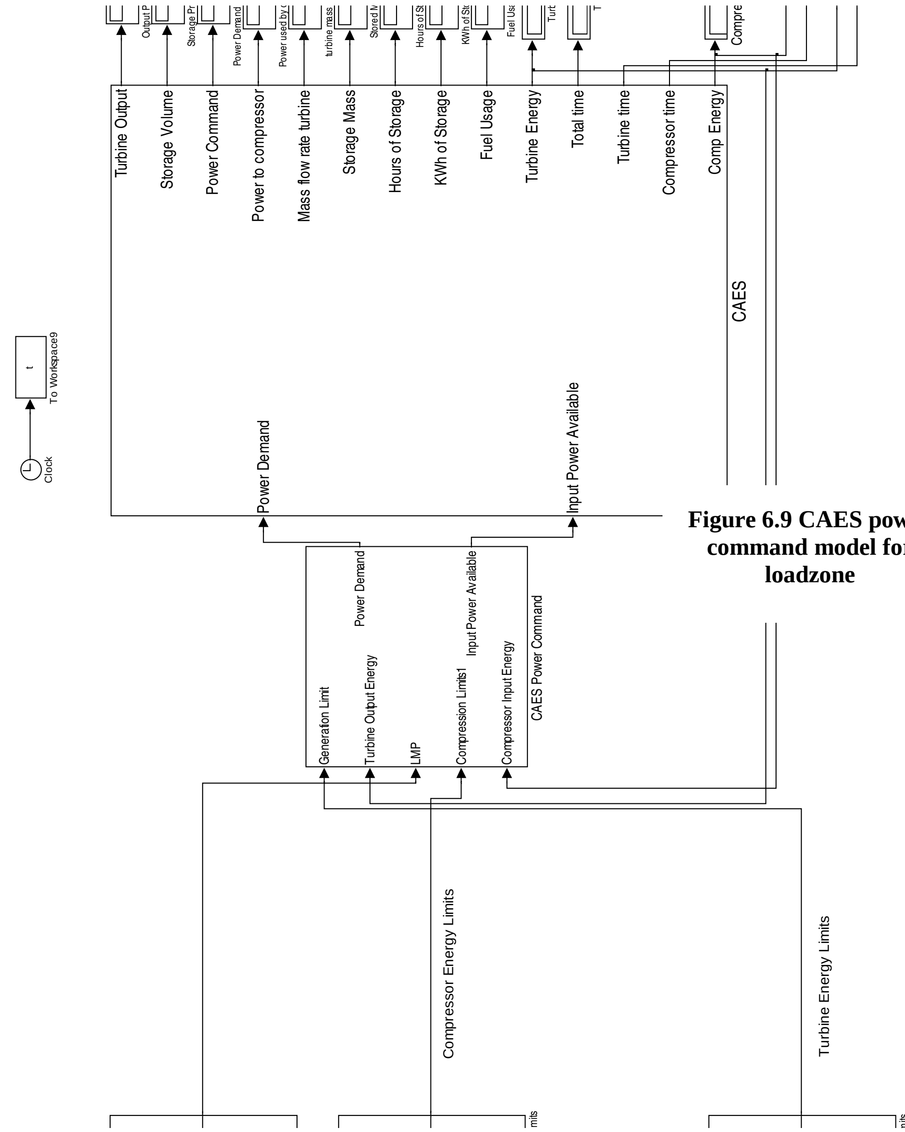


Figure 6.9 CAES power command model for loadzone

Figure 6.10 CAES power command model for loadzone

Following are the simulation results for the LMP constraints which charge the storage on daily basis according to the schedule.

Table 6.5 CAES LMP constraints

Month	Charge Constraint ($/MWh)	Discharge Constraint ($/MWh)	Charging/discharging simulation results (MWh/day)
January	LMP≤18	LMP≥49.8	136.45
February	LMP≤18	LMP≥50.9	-135.46
March	LMP≤18	LMP≥61.7	136.83
April	LMP≤18	LMP≥73.92	-136.63

May	LMP≤13.57	LMP≥48	68.63
June	LMP≤17.29	LMP≥48	68.79
July	LMP≤18	LMP≥47.93	-136.28
August	LMP≤13.31	LMP≥45	68.30
September	LMP≤11.52	LMP≥44	68.61
October	LMP≤19	LMP≥80.6	-44.64
November	LMP≤19.3	LMP≥112	-54.68
December	LMP≤19.3	LMP≥67.48	-37.85

The revenues are hence found using the expressions provided in the previous section.

Table 6.6 Cashflow for CAES with loadzone

Month	Charge (Buying) ($/day)	Generation Cost ($/day)	Discharge (Selling) ($/day)	Revenue ($/day)	Revenue ($/month)
January	3,145.9	3,890.14	6,382.3	-653.7	-20,264.7
February	664.2	6,771.06	11,830.8	4,395.5	123,074
March	4,637.9	8,864.8	19,192.51	5,689.8	176,383.8
April	2,436.8	15,711.1	40,940	22,792.1	683,763
May	1,339.1	4,698.29	6,336.8	299.4	9,281.4
June	3,961.3	14,191.1	21,494.8	3,342.4	100,272
July	5,031.1	17,418.3	29,188.2	6,738.8	208,902.8
August	2538.7	6,625.9	9,458.2	293.6	9,101.6
September	1808.5	3,468.6	4,632.3	-644.8	-19,344

October	4,362.6	12,160.3	39,394.4	22,871.5	709,016.5
November	5,897.4	16,582.2	62,847.7	40,368.1	121,1043
December	2,467	5,955.93	12,856.7	4,433.7	137,444.7
TOTAL					**3,328,674**

The internal rate of return can be evaluated from the following expression.

$$NPV = CF_o + \sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} = 0$$

$where$
CF_o $is\ the\ capital\ investment$
CF_t $is\ the\ annual\ return$
$IRR\ is\ the\ internal\ rate\ of\ return$
$NPV = net\ present\ value$

(Finnerty)

The internal rate of return for a project life-time of 40 years is -2%, which means it is not feasible according to the capital investment. The net present value from the above equation is evaluated at the desired rate of return of 7%. The net present value comes out to be $98,956,156. This means that in order to achieve the 7% rate of return we need to lower our capital investment cost from $150,260,000 to $98,956,156.

CHAPTER 7

CONCLUSION & FUTURE WORK

7.1 Conclusion

Storage volumes are often limited in terms of availability. Salt domes, aquifers and rock mines suitable for underground air storage are not abundantly available for use. Large amount of investment is required to create the storage through the process of mining. Hence volume is expensive and therefore optimizing its use is very important in order to make a reasonable rate of return on the investment.

In this thesis

- CAES configuration has been developed which improves the energy rating of CAES.

The decision variables that govern the amount of storage that can be stored in a given storage volume are pressure and the mass of air. These decision variables characterize both, the configuration and operation of CAES. Pressure and volume characterize the configuration of CAES. Pressure and mass characterize the operation of constant volume configuration. Volume and mass characterize the operation of constant pressure configuration.

Methods have been developed

- To determine the operational and economic benefits of low energy rating CAES configuration with relatively small wind farm to store energy on hourly basis.

- To operate high rating CAES configuration with relatively large wind farm on monthly and daily basis
- To determine the operational and economic benefits of high energy rating CAES configuration to store energy on hourly basis.

These methods are applicable to constant volume and pressure configuration having energy rating of more than 1160 MWh with 10% to 100% of full load conditions. Present CAES plants operate on minute by minute basis. The wind does not only change on hourly basis, but also on daily and monthly basis. Since the CAES energy rating has been improved and coupled with the large wind farm in such a way that it surpasses the requirements of hourly operation, it also needs to be operated on daily and monthly basis according to the daily and monthly wind profiles. These analyses were used to determine the requirements for storage of energy required for operation on hourly basis. These analyses were also used to determine the rate of discharge of energy for CAES for a particular year, month and days.

1. *Comparison of configurations:*
    a. Constant pressure configuration can store more energy than constant volume configuration for the same amount of pressure, mass and total storage volume
    b. The more the operating pressure of constant pressure configuration, the more energy it can store.
    c. Constant volume configuration has more charging/discharging rate relative to maximum capacity than constant pressure configuration.

d. In order to minimize the energy mismatch during the day, state of storage energy must either not be completely full, neither empty.

2. *Operation on daily basis:* Storage in this section refers to the portion of energy rating of CAES allocated for storage on daily basis.

   a. To ensure that storage energy must neither be completely full not empty, the amount of energy used for hourly basis to charge and discharge the storage during the day must be constrained.

3. *Economic analysis of storing energy on hourly basis (150 MW wind farm with constant volume CAES:*

   a. Monthly returns are negative, hence annual return is also negative which means that this combination does not make revenues.

   b. The cost of generation was higher than the selling price for the days of all the months except December.

   c. The cost of buying energy was higher than the revenues made through selling energy for the days of months of January, May, July, August and November.

4. *Economic analysis of storing energy on hourly basis (205.5 MW wind farm with constant pressure CAES:*

   a. Monthly returns are negative, hence annual return is also negative which means that this combination does not make revenues.

   b. The cost of generation was higher than the selling price for the days of all the months except January, April and December.

c. The cost of buying energy was higher than the revenues made through selling energy for the days of all months except April, October and December.

5. *Economic analysis of storing energy on daily basis (205.5 MW wind farm with constant pressure CAES:*

   a. Monthly returns are negative, hence annual return is also negative which means that this combination does not make revenues.

   b. The cost of generation was higher than the selling price for the days of all the months except January, February, October, November and December.

   c. The cost of buying energy was higher than the revenues made through selling energy for the days of all months except April, July and August.

6. *Economic analysis of constant pressure CAES with independent operation*

   a. Monthly returns are positive for the days of all months except January and September.

   b. The cost of generation was lower than the selling price for the days of all the months.

   c. The cost of buying energy was lower than the revenues made through selling energy for the days of all months.

   d. The internal rate of return was -1% for a duration of 40 years.

   e. The net present value at 7% desired rate of return is 65.8% the capital cost.

The constant pressure CAES proved better than the constant volume CAES in terms of operational performance for the same size of storage volume available. The mismatch between generation and load changes instantaneously. If CAES is completely charged it cannot exploit the advantage of capturing excess amount of energy available. On the other hand if it is completely discharged, it cannot deliver at the times when it is required. Therefore some portion of stored energy must be kept as a reserve.

The constant volume CAES has less energy rating then constant pressure CAES. If some part of storage energy is used as a reserve for emergency purposes, this would limit the energy rating of CAES further more. Hence the energy rating of CAES was increased for the same amount of volume by storing the air at constant pressure. A portion of constant pressure CAES energy rating was kept for hourly basis operation. This was done to avoid the interruption on hourly based operations of CAES.

The CAES proved to be relatively beneficial when it is operated independently with a loadzone. Since its operation with the wind farm is constrained by the energy mismatch between wind generation and load, it cannot be independently operated to make profits based on LMPs. On the other hand, it is not always the case to have low LMP during positive energy mismatch(charging cycles) and high LMP during negative energy mismatch(negative cycles). With having it operated independently, we can buy energy whenever the LMP are low and sell when these are high. This proves that the hybrid operation of wind farm and CAES is not profitable with the real-time wind LMP profile used in the simulations.

7.2 Future Work

Compressed Air Energy Storage is not a completely renewable resource of energy, since it makes use of natural gas to generate electricity. Efforts are being made to make CAES completely renewable, hence making the wind hybrid system completely renewable. This renewable operation of CAES is known as advanced adiabatic CAES (AA CAES). Since we observed that a lot of cost is spent on generation, we can avoid this cost by making CAES completely renewable. Most of the AA CAES require a heat storage facility to heat the compressed stored air before entering the expansion stages. This would change the energy rating of CAES since it would also depend on the state of charge of heat storage.

Since CAES is one of the major storage technologies on which wind energy relies on, it is becoming very important to make it completely renewable.

CHAPTER 8

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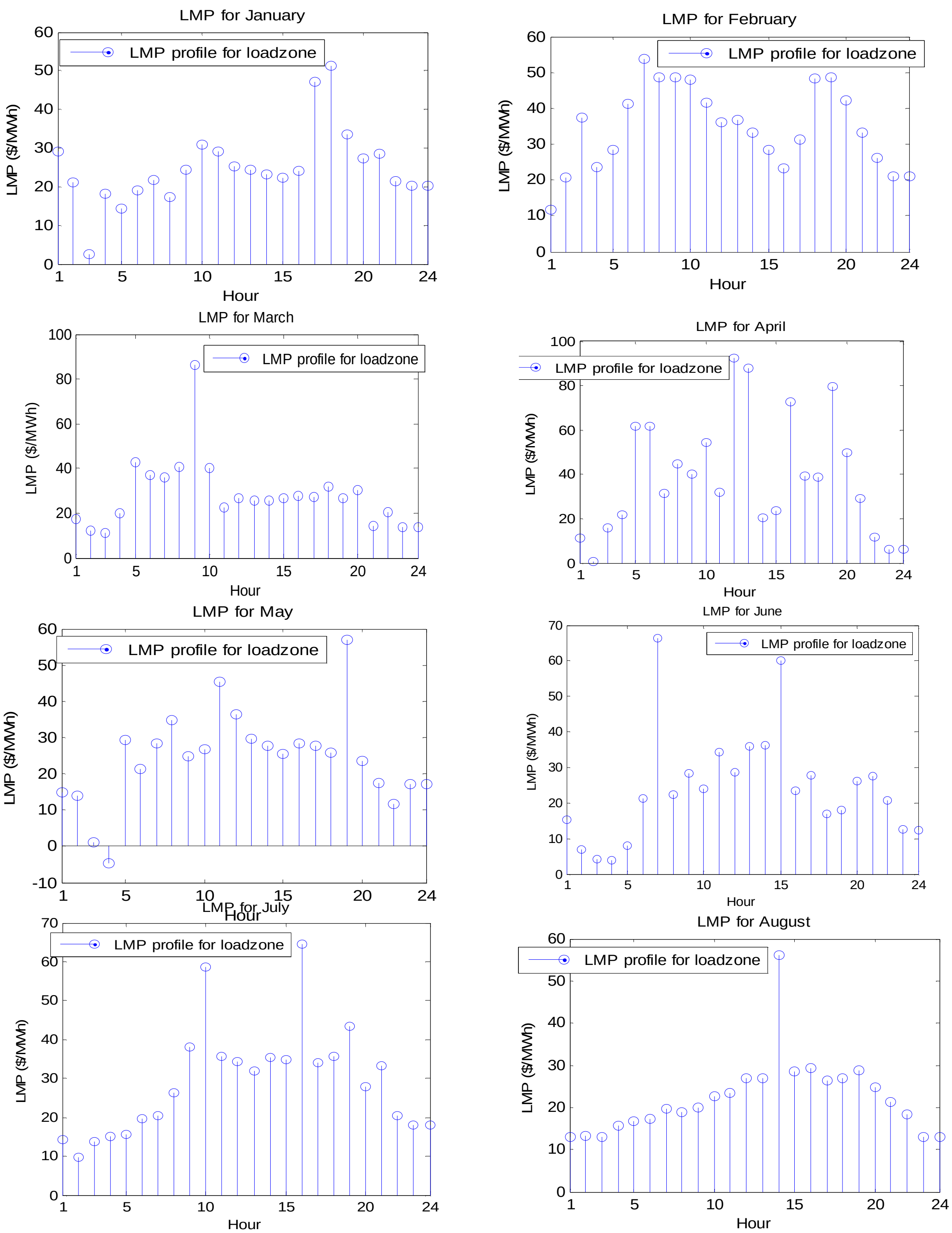
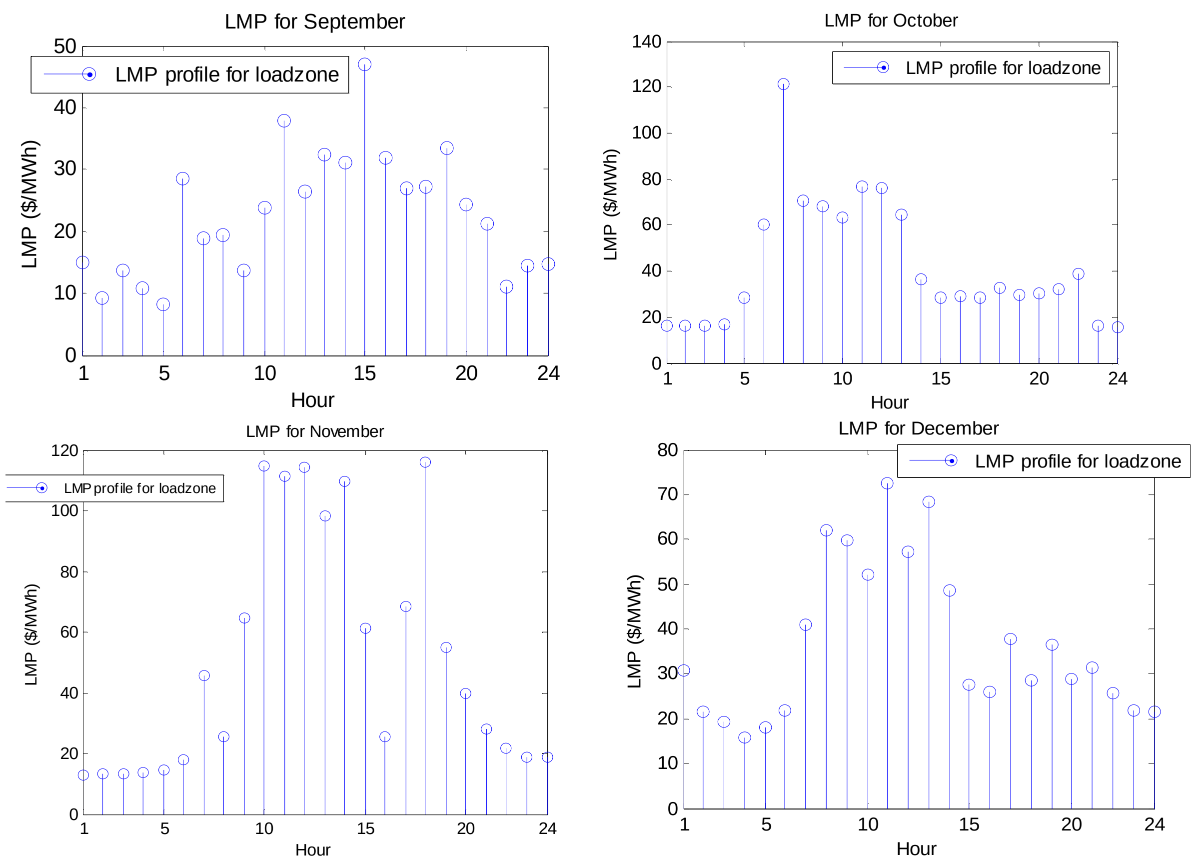
APPENDIX A

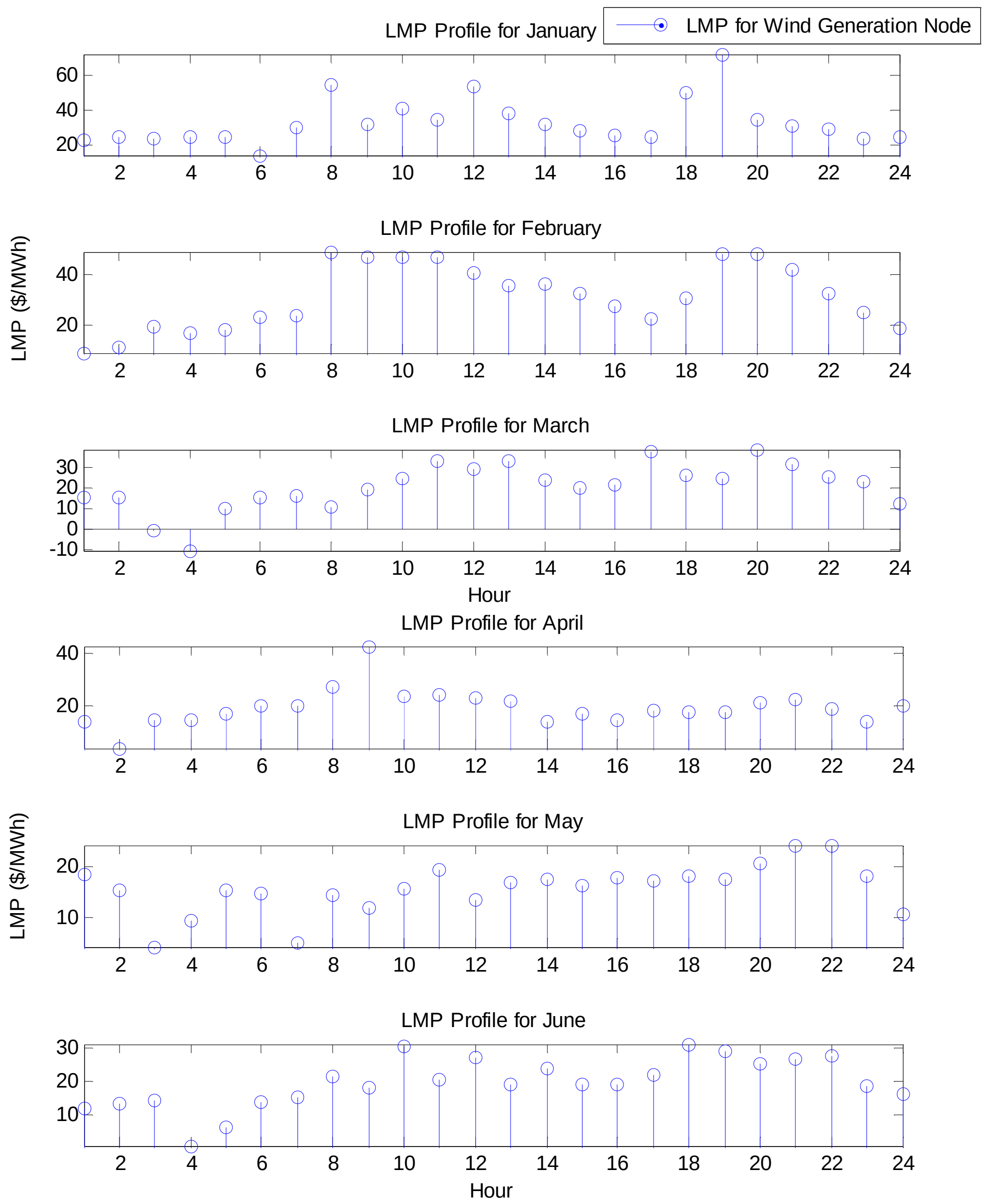
LMP PROFILE FOR MISO LOADZONE AECI.ALTW

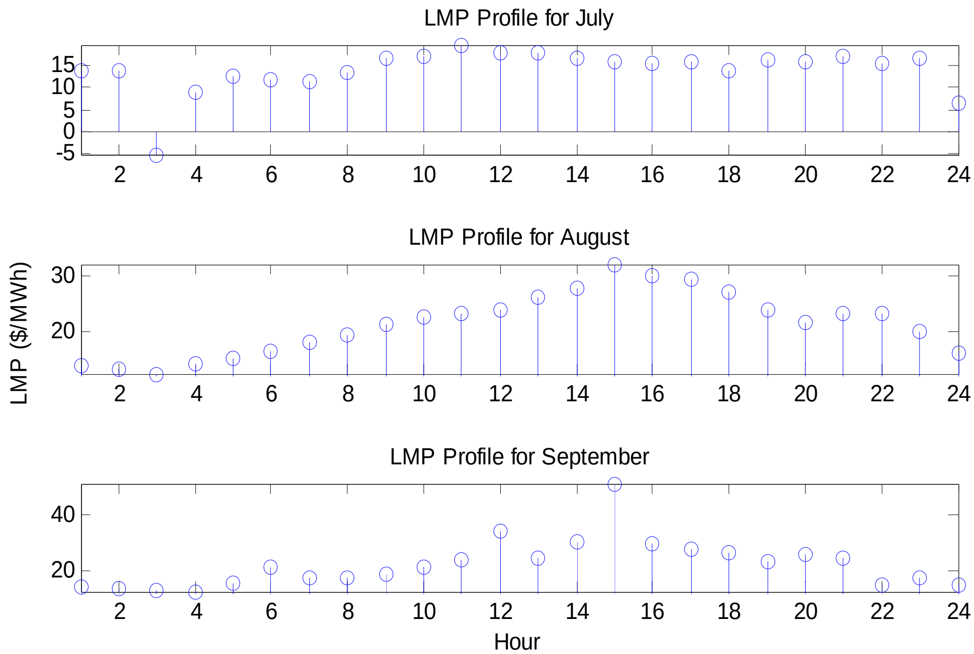



LMP for September
LMP profile for loadzone
LMP ($/MWh)
Hour
LMP for October
LMP profile for loadzone
LMP ($/MWh)
Hour
LMP for November
LMP profile for loadzone
LMP ($/MWh)
Hour
LMP for December
LMP profile for loadzone
LMP ($/MWh)
Hour

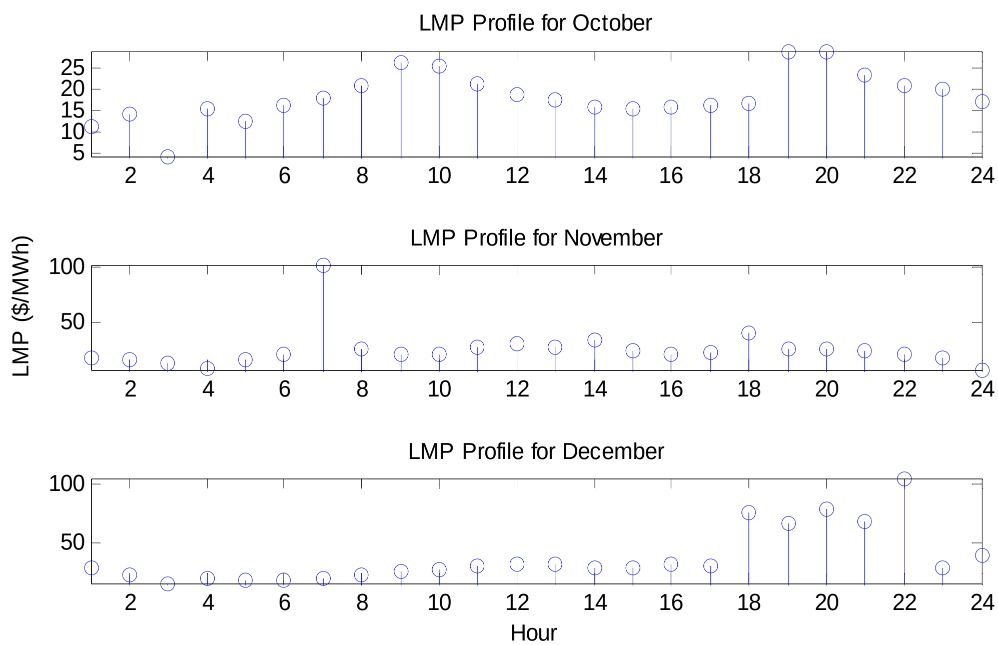
APPENDIX B

LMP PROFILE FOR MISO WIND NODE ALTW.WOLFWIND





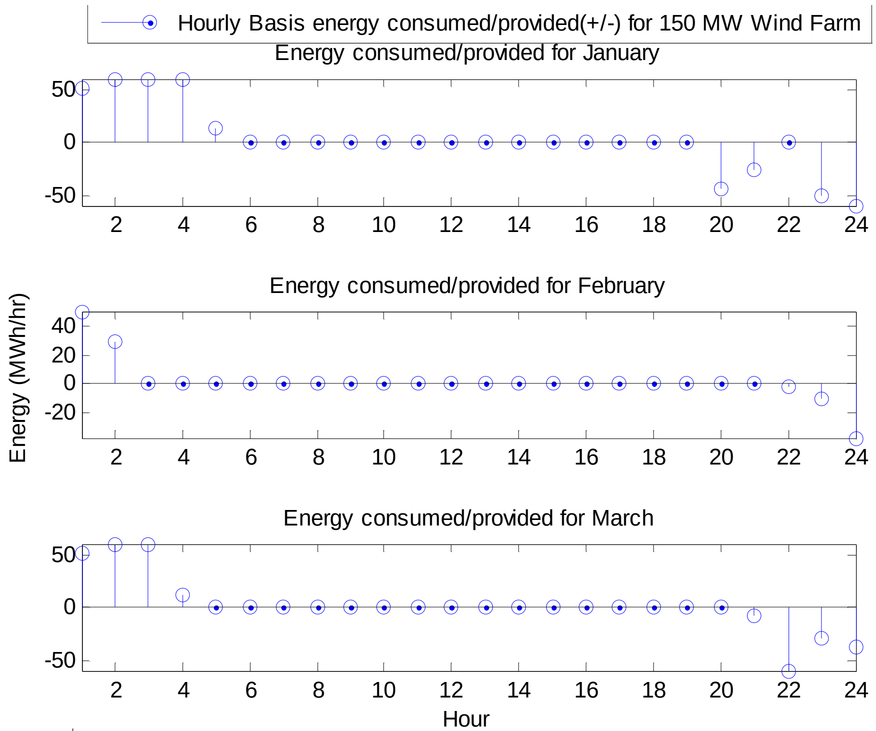
LMP Profile for July
LMP Profile for August
LMP Profile for September
LMP ($/MWh)
Hour

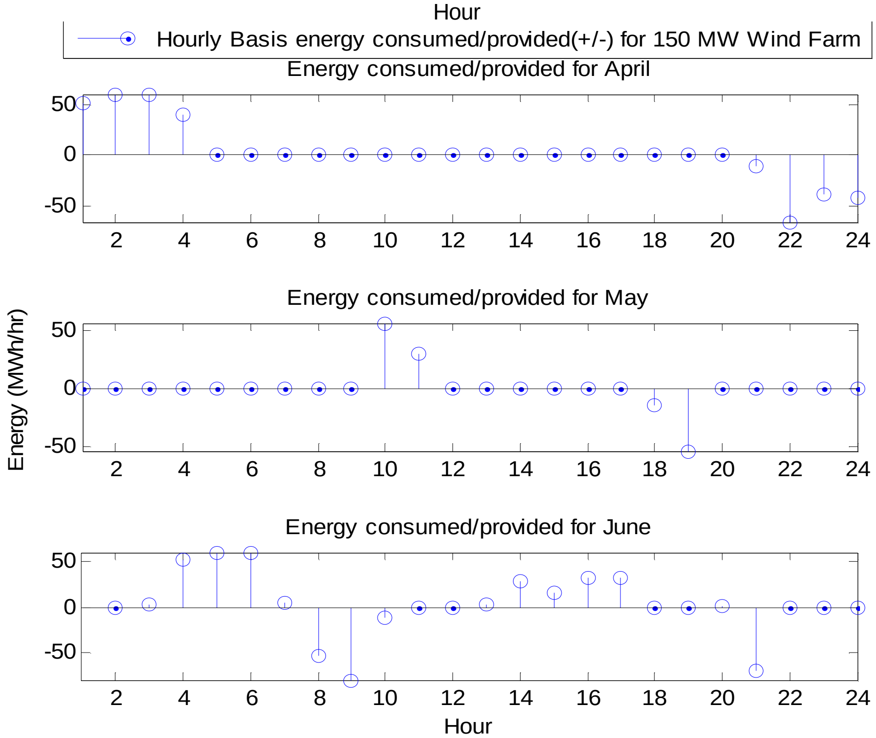


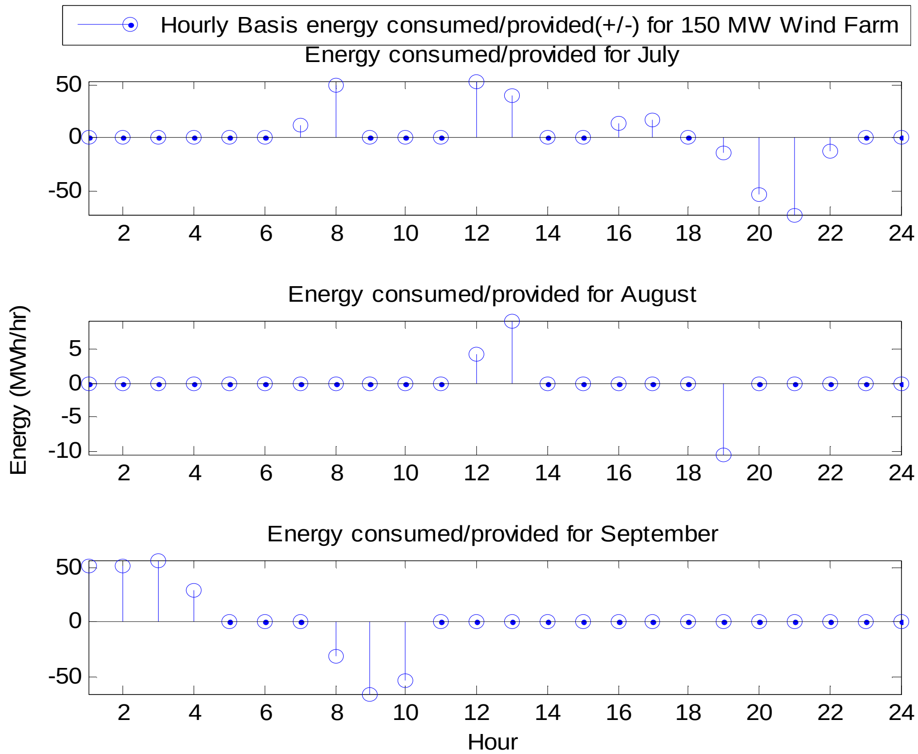
LMP Profile for October
LMP Profile for November
LMP Profile for December
LMP ($/MWh)
Hour

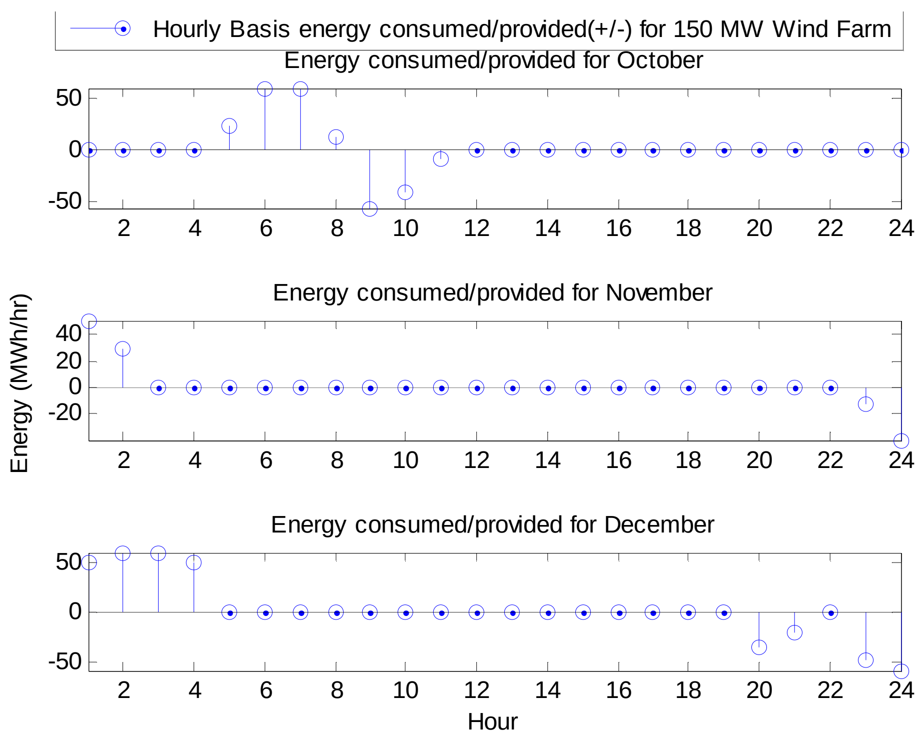
APPENDIX C

HOURLY BASIS OPERATION OF CAES WITH 150 MW WIND FARM



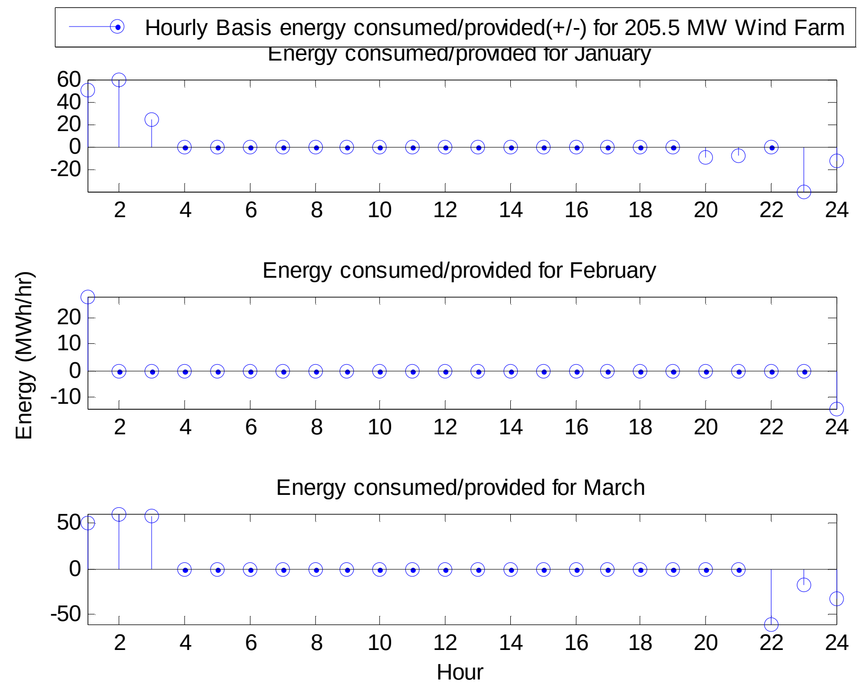


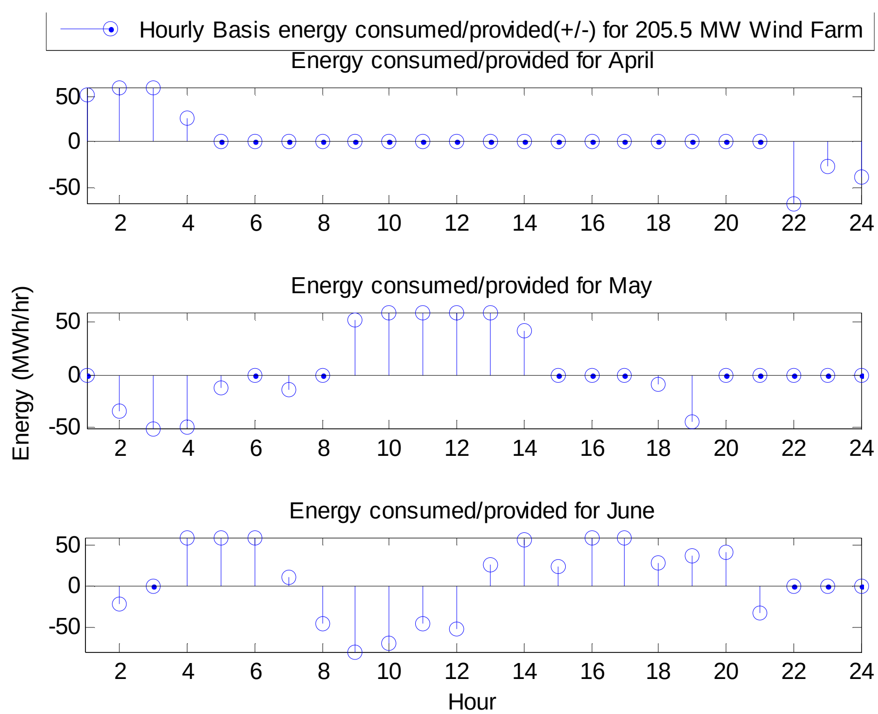

Hourly Basis energy consumed/provided(+/-) for 150 MW Wind Farm
Energy consumed/provided for July
Energy consumed/provided for August
Energy consumed/provided for September
Energy (MWh/hr)
Hour

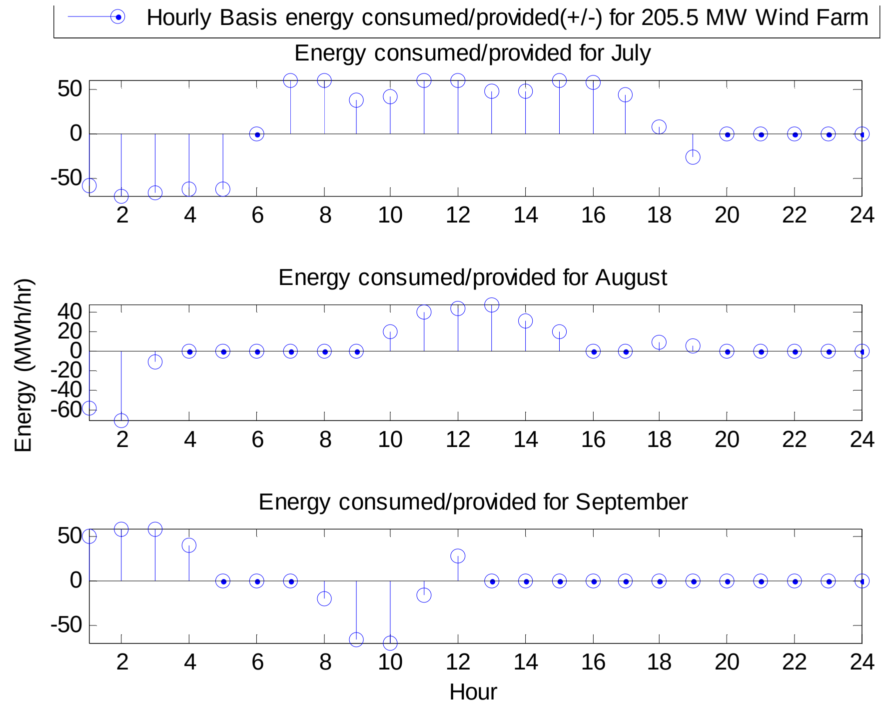

Hourly Basis energy consumed/provided(+/-) for 150 MW Wind Farm
Energy consumed/provided for October
Energy consumed/provided for November
Energy consumed/provided for December
Energy (MWh/hr)
Hour

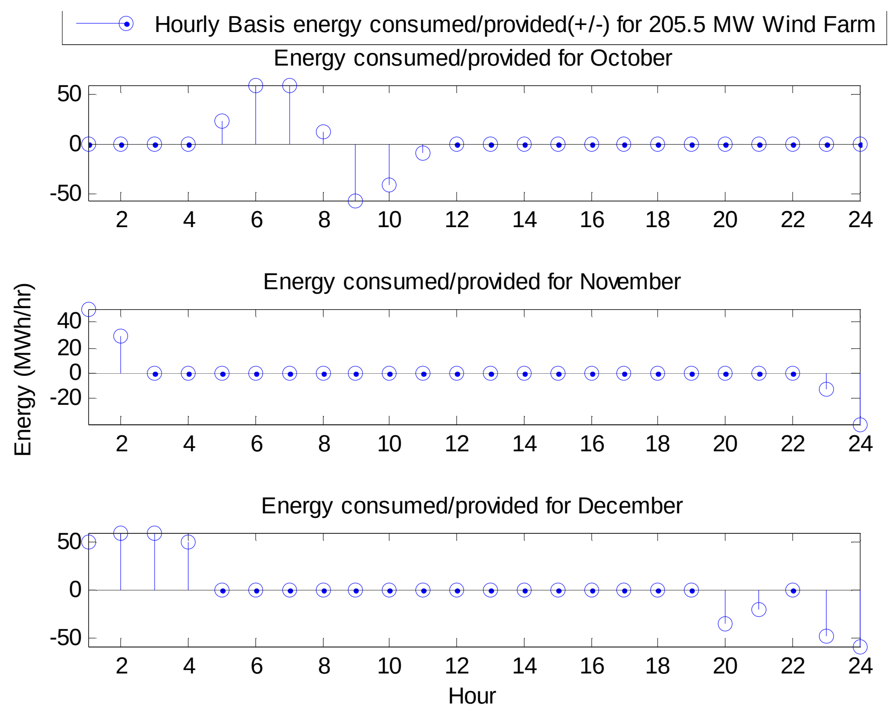
APPENDIX D

HOURLY BASIS OPERATION OF CAES WITH 205.5 MW WIND FARM



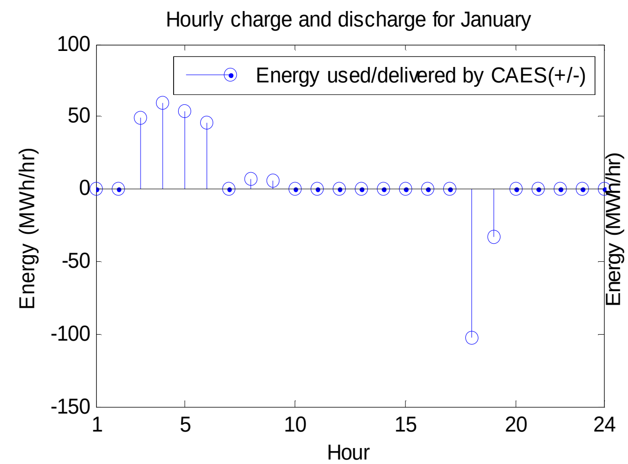


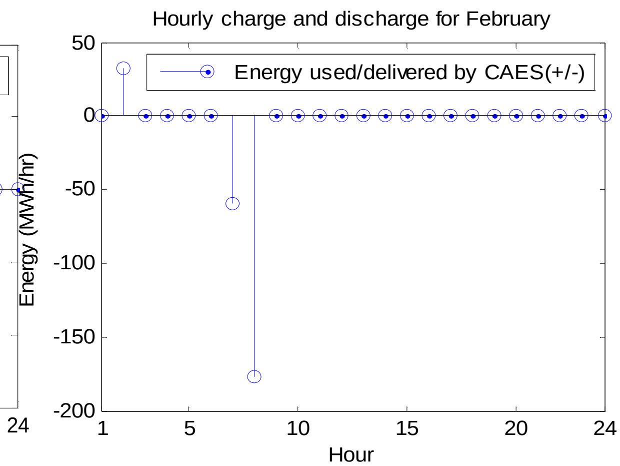

Hourly Basis energy consumed/provided(+/-) for 205.5 MW Wind Farm
Energy consumed/provided for July
Energy consumed/provided for August
Energy consumed/provided for September
Energy (MWh/hr)
Hour

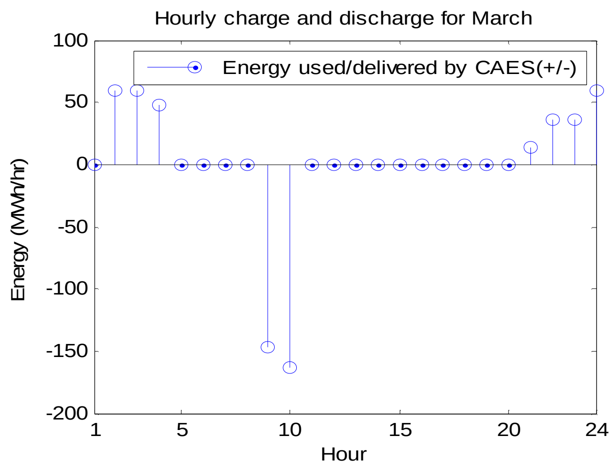

Hourly Basis energy consumed/provided(+/-) for 205.5 MW Wind Farm
Energy consumed/provided for October
Energy consumed/provided for November
Energy consumed/provided for December
Energy (MWh/hr)
Hour

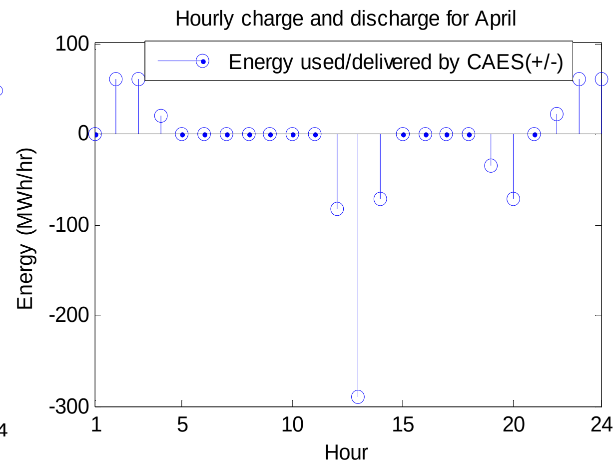
APPENDIX E

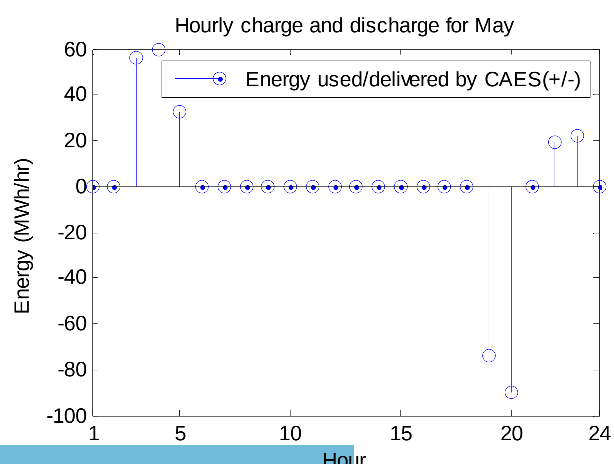
HOURLY BASIS INDEPENDENT OPERATION OF CAES WITH LOADZONE

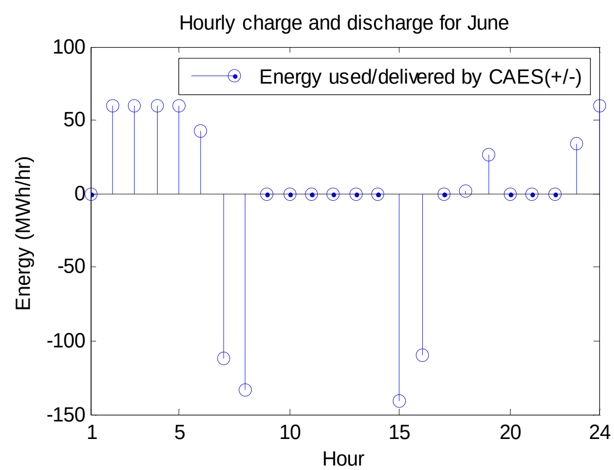


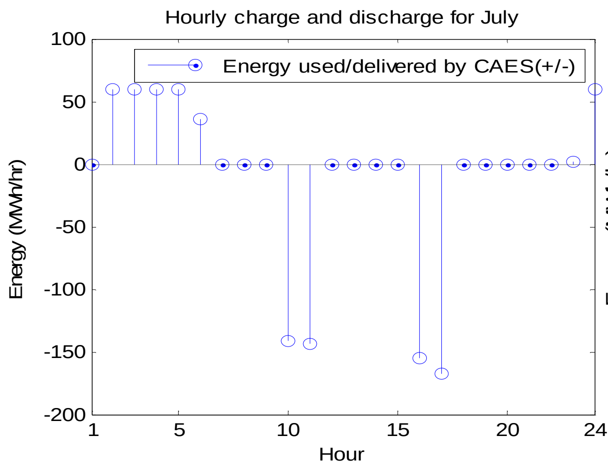


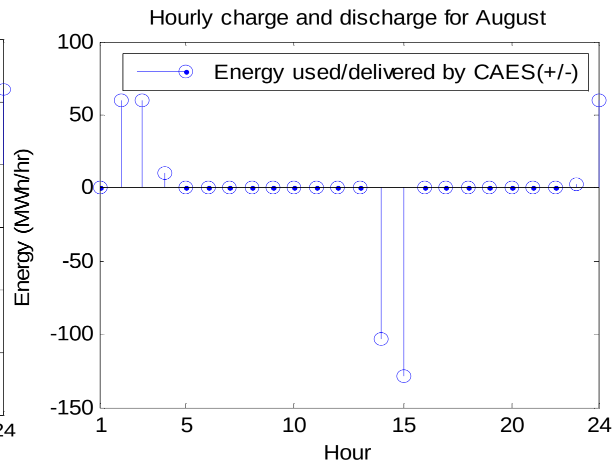


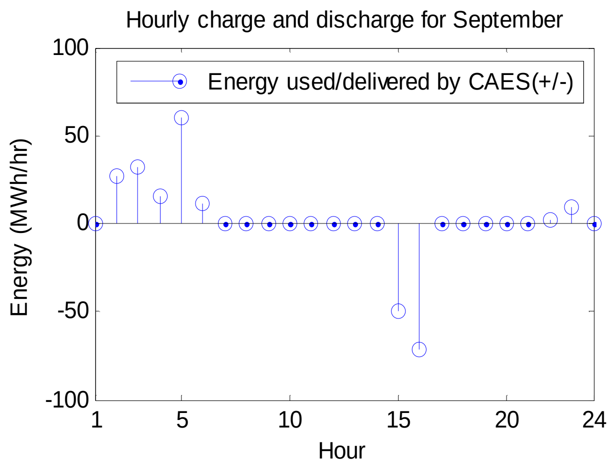


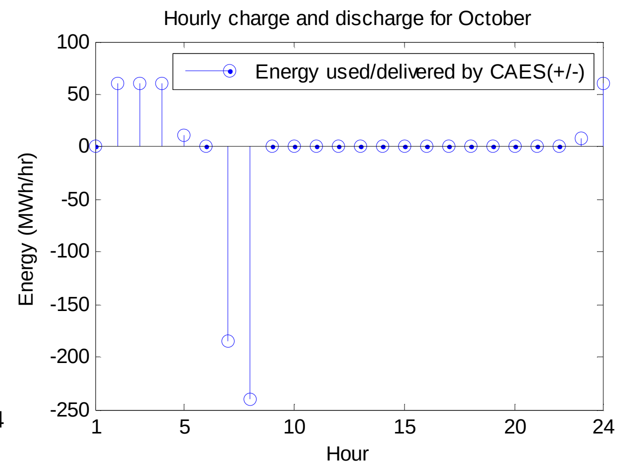


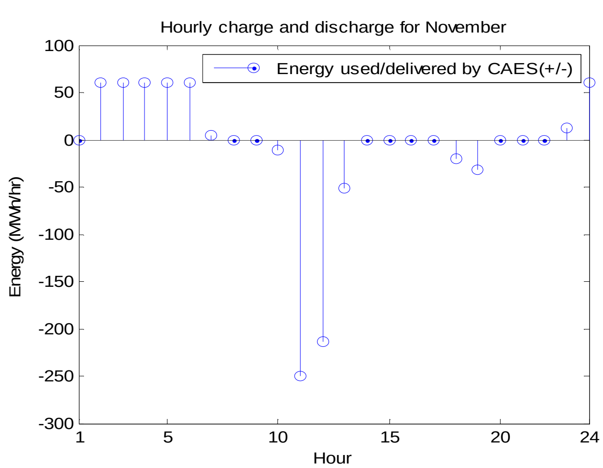


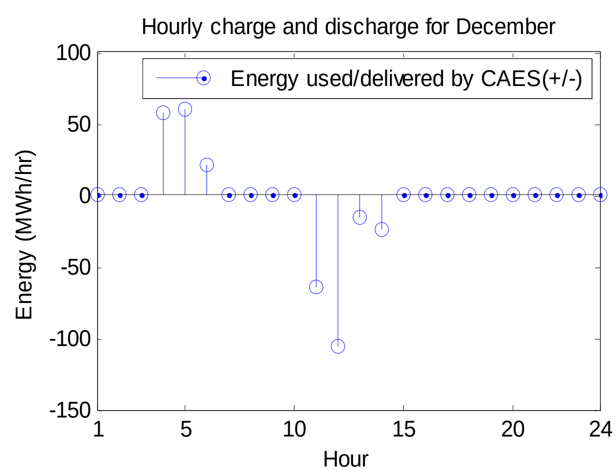

Hourly charge and discharge for July
Energy used/delivered by CAES(+/-)
Energy (MWh/hr)
Hour


Hourly charge and discharge for August
Energy used/delivered by CAES(+/-)
Energy (MWh/hr)
Hour


Hourly charge and discharge for September
Energy used/delivered by CAES(+/-)
Energy (MWh/hr)
Hour

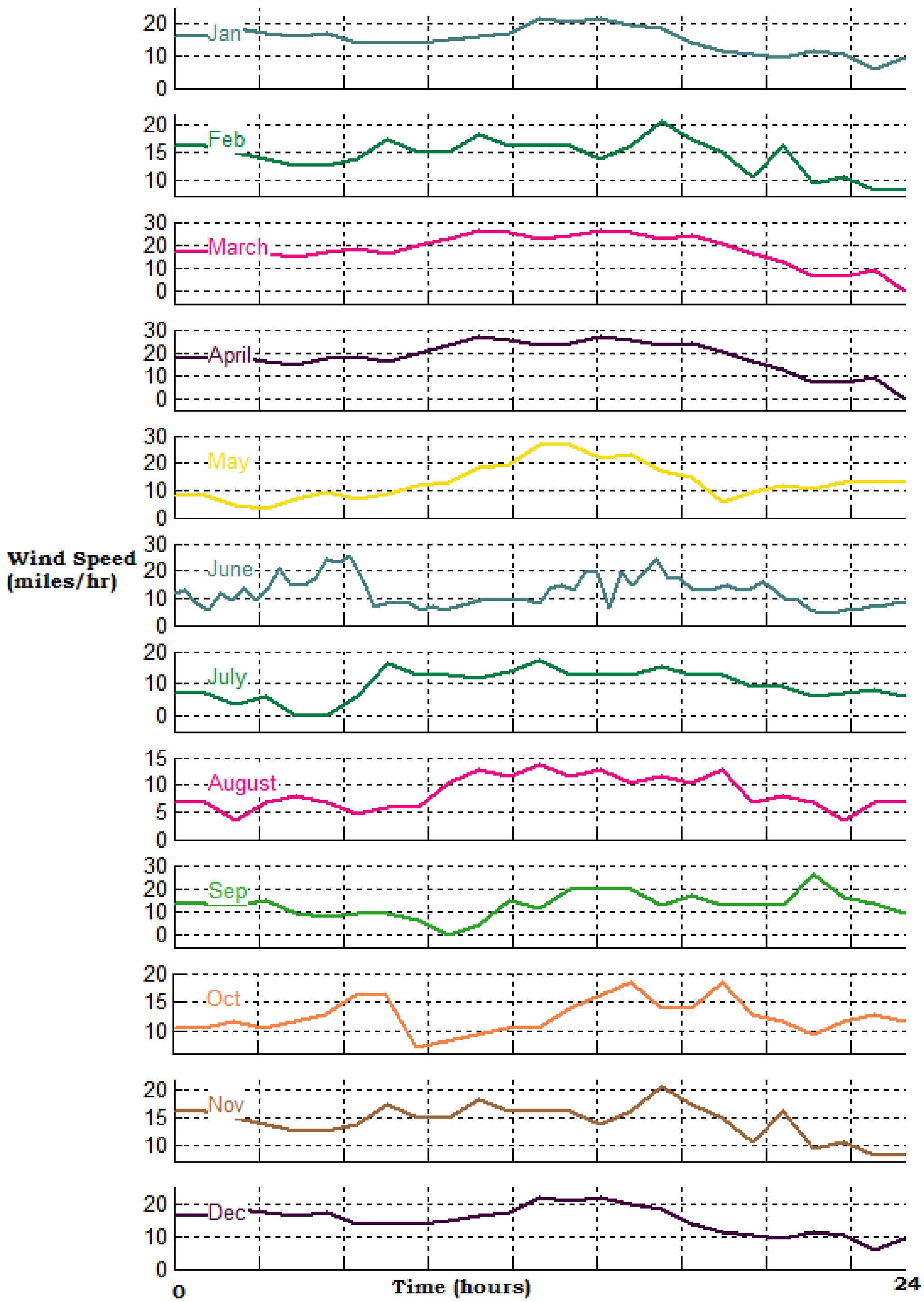

Hourly charge and discharge for October
Energy used/delivered by CAES(+/-)
Energy (MWh/hr)
Hour

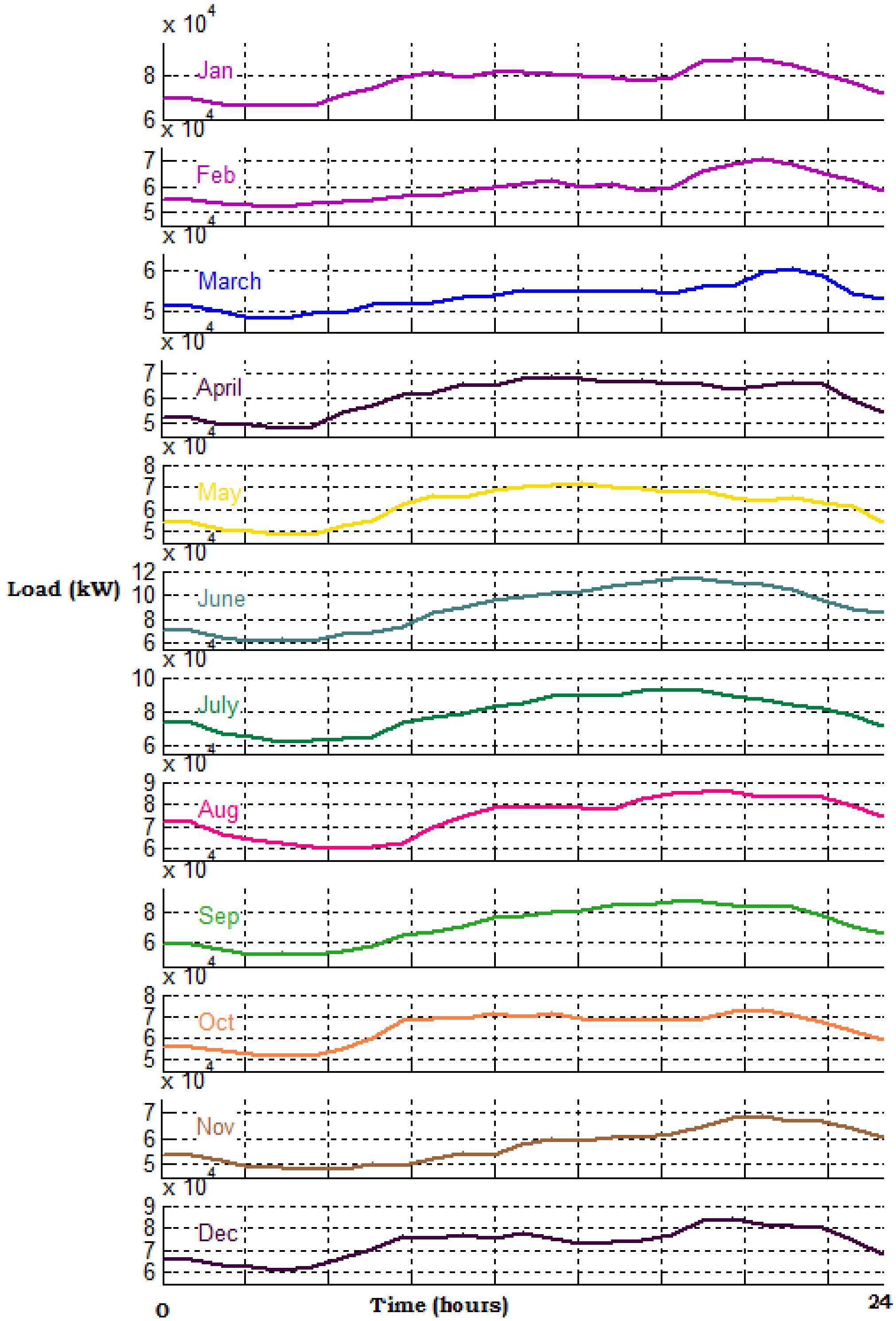

Hourly charge and discharge for November
Energy used/delivered by CAES(+/-)
Energy (MWh/hr)
Hour


Hourly charge and discharge for December
Energy used/delivered by CAES(+/-)
Energy (MWh/hr)
Hour

APPENDIX F

HOURLY BASIS WIND AND LOAD PROFILES FOR CITY OF AMES




Load (kW)
x 10^4
Jan
Feb
March
April
May
June
July
Aug
Sep
Oct
Nov
Dec
0
Time (hours)
24