Assessing the Costs of Dispatchable Wind Energy:
An Integrated Wind-Turbine and Energy Storage System

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1.0 Introduction

Increasing the use of renewable sources of electricity generation is an important component of energy and environmental policy. The intermittency of many of the potential renewable energy sources introduces new challenges in energy conversion and storage. Electric energy storage represents one potential strategy for addressing the resource variability challenge associated with some renewable energy sources like wind power.

This study explores renewable energy production possibilities from large-scale wind in Pennsylvania (PA). We examine cost and performance for large-scale wind generation (>100MW) coupled with on-site storage options for large-scale wind generation, using Northern PA as a case study. Compressed Air Energy Storage (CAES) or Pumped-hydro Storage (PHS) are possible energy storage methods because they are proven technologies that can store electrical energy on a large scale. Northern PA was chosen as the Greenfield site because it possesses some of the best wind speeds with nearby working energy storage sites. Economic and technical analyses were conducted to evaluate this Greenfield 100 megawatt (MW) commercial wind farm coupled with an energy storage facility. An analysis of the electricity prices, storage design and output of the Greenfield system was conducted to determine when wind with an energy storage system is economically advantageous.

Sensitivity analyses were conducted on the size of the storage system to maximize profits of the integrated wind generation and energy storage system as well as a stand-alone energy storage system. Two models representing these two systems were created. The Wind Integrated Storage System Model (WISSM) and the Stand-Alone Storage System Model (SASSM) enable us to determine the factors that influence profitability. These factors include capital costs, wind generation characteristics (variability), fuel costs, and market energy prices. The results of our analysis were used as a foundation for policy recommendations in the form of mandates, subsidies and carbon taxes.

2.0 Background

2.1 Renewable Energy Technologies

Renewable energy includes a diverse range of options for energy conversion and storage. Various options contribute to the total energy use for the state of Pennsylvania (PA); some are more economically, socially, and technically viable than others. The following sections describe energy generation and storage methods. For this study, we focused on Compressed Air Energy Storage (CAES) and Pumped-hydro Storage (PHS) because there are existing facilities in PA with these storage technologies, and they are scalable for a dispatchable wind generator at cost-competitive price compared to conventional generation sources.

2.1.1 Production Methods

There are multiple ways to produce energy, both from renewable and fossil-fuel based sources. The following are brief descriptions detailing the advantages and disadvantages related to generating electrical energy.

2.1.1.1 Wind

Wind energy is produced by way of turbines generating electricity from the force of the wind blowing against blades on a tower 30-100 meters in the air. Wind speeds over 11 mph are needed to generate electricity on a commercial scale and finding a good location is a difficult task. If a good location is determined with low intermittency, then producing wind energy is a promising way to provide commercialized energy. Wind energy is one of the largest growing renewable energy production methods in the world, and scientists are predicting it has the potential to produce 15%-20% of Pennsylvania's energy consumption in the next 20 years. Pennsylvania has average wind speed profiles, which make it possible to support commercial wind power production.

2.1.1.2 Solar

The sun emits radiation from its surface at about 6000K. This radiation reaches Earth's surface after passing through space and the atmosphere. It is useful both as a thermal energy source and as a driving force for electron emission in photovoltaic (PV) materials to create an electrical current. Large-scale solar thermal power plants are not feasible in Pennsylvania because they depend on the direct component of solar radiation, which is not consistently available in Pennsylvania [1]. PV costs are decreasing and approaching the point where these systems will be economically viable for average grid-tied homes [2] [3]. In a grid-tied scenario with real-time metering and time dependent pricing where the peak power loads are during the day when photovoltaics can be employed, photovoltaics are uniquely situated to produce power when the demand is at its peak [4]. While storage systems inherently help a power utility by enabling the storage of excess power during off-peak and dispatching it during peak, storage systems are not necessary for the utilization of grid-tied PV that produces during the peak hours [5].

2.1.1.3 Geothermal Energy: Ground Source, Direct Heat, Electricity Generation

There are three principal forms of geothermal energy production: ground source, direct heat, and geothermal electricity production. Ground source geothermal energy utilizes the Earth's natural ability to store heat in the upper layers of its crust. This heat is used to either transfer heat into the home, or, when it is warmer in the house, transfer heat out of the home. Ground source geothermal energy is typically not used for large-scale energy production. Ground source geothermal energy production is limited to residential scale installations and is not practical for utility scale energy production [6]. Direct heat geothermal energy production uses heat stored in geologic formations near the surface of the earth. The heat is transported to a heating system through a network of wells and pipes. The temperature of the geologic formations used for direct heat applications is not high enough to create the volume of steam necessary for electricity generation [7]. Geothermal electricity generation is performed by releasing steam from wells that exceed one mile in depth. The steam is used to drive a turbine connected to an electric generator. Current systems have the potential to generate electricity on the utility scale. Geothermal electricity production has little to no potential in Pennsylvania [8]

2.1.1.4 Hydrokinetic Energy Generation: Wave, Tide, and River Sources

Power generation from surface waterways, mainly rivers, in Pennsylvania (PA) has provided energy for rural and urban populations. This study originally considered several water-related energy sources for power generation using potential kinetic energy from waves, tides and river flows. Waves generate energy (electricity) from pressure differences from winds in a horizontal flow pattern. There are still difficulties with converting wave motion into electricity directly because wave motion is not constant or steady. Difficulties with generating electricity from tides are similar to wave generation. Energy production originates from vertical, slow-moving tides passing through a turbine or tidal barrage. With riverine power generation, energy is produced from the lateral flow of water through turbines below the surface, like miniature windmills along the river floor [9]. Streamflow speed and water depth are two necessary factors that determine if river hydrokinetic turbines are worth the investment. There is no existing project indicating there is consistent, strong streamflows at a suitable depth for a commercial river turbine site. Estimating total costs for construction, operation and maintenance for hydrokinetic energy generation is highly variable. There are no functioning large-scale projects utilizing wave, tide or river sources, and overall effects on the marine ecosystem are still unknown. Lack of profitable, working examples of large-scale energy production from water sources and additional maintenance challenges due to saltwater corrosion or strong currents that destroy turbine blades render hydrokinetic turbines as unfit to provide reliable electricity that is competitive with conventional sources. Thus, tidal, wave and river power sources are not scalable to provide dispatchable, base load electricity in PA.

2.1.1.5 Biofuels

Solid, liquid, or gaseous fuel that is derived from biological material is known as biofuel. Biofuels are differentiated from fossil fuels by the relatively short time span between the time of death and the time of use of the material. The best known forms of biofuel include wood vegetable oil, biodiesel, bioalcohols, bioethers, biogas, and syngas which are most typically used for burning to heat a space or for cooking food. The ability to dry solid biomass and gasify it enables the production of a syngas "consisting of a mixture of combustible gases including H_2, CO, CH_4, C_2H_4, and other minor constituents"[10]. Biofuel in the form of syngas can be utilized in natural gas turbines in conjunction with compressed air energy storage (CAES) systems [10].

2.1.2 Storage Methods

Along with various production methods to generate electricity, we also investigated a plethora of engineering techniques to storage energy, specifically on a utility scale.

2.1.2.1 Super Conductors

A super conductor is an element or compound that will conduct electricity without resistance at very low temperatures. One of the main benefits of super conductors storing energy is they have around 98% efficiency when it comes to releasing the stored energy. A super conductor offers no resistance to electron flow, so while the energy is being stored nothing is being lost. The only lost energy is associated with the cooling system needed for the material [11]. Super conductors are the basis behind Superconducting Magnetic Energy Storage (SMES). The size needed for commercial levels of storage would require a SMES loop 100 miles long. This size of superconductor would cause enormous electro-magnetic forces that may make it difficult to support a structure containing the SMES loop. Environmentalists are worried that large SMES systems may potentially alter the magnetic field of Earth, which would have an unknown impact on human life. Lastly, current SMES technologies can only provide storage in the order of megawatt-seconds. Since wind energy is intermittent, storage is needed for hours or longer. Storage time, size of SMES system, and environmental factors do not make this a likely candidate for wind energy [12].

2.1.2.2 Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) is a more recent method used for storing energy in the form of compressed air in a vessel, most often a cavern or salt dome in the ground. This air can then be released during peak hours to turn a turbine and reproduce energy with minimal efficiency losses. The efficiency of CAES systems is approximately 80%, due to losses of storing the air in a vessel, heat from the turbine, and using a fuel to heat up the air.. CAES turbines require an additional energy source that is usable within a short time frame without a major ramp-up time. Currently, natural gas is widely used as a fuel for these turbines; however, biofuels could also provide the required energy. An external fuel source, such as natural gas or biofuel, is necessary because the “magnitude of expansion envisioned in the CAES expander systems is such that the outflow of the turbine would be nearly cryogenic in nature, making the design of the turbines problematic” [13].

2.1.2.3 Flow Batteries

Flow batteries can be used on the utility scale and have been proven in several different applications where other storage options were not economically viable. However, the embodied energy in vanadium redox flow batteries from the manufacturing process is an order of magnitude higher than that of both pumped hydro storage and compressed air energy storage [14].

2.1.2.4 Pumped Hydro Storage

Pumped-hydro storage (PHS) is one potential energy storage method for Pennsylvania (PA) because it is a proven technology for storing electrical energy that can be controlled when generating electricity. Currently, there are two working sites that implement PHS with a nearby hydroelectric dam, Seneca Station (435 MW) in northwestern PA and Muddy Run (1,071 MW) alongside Conowingo Dam in southeastern PA. With PHS, there is a lower reservoir that pumps water up to an upper reservoir where water is held when electricity prices are low and/or demand is low. Water from the upper reservoir is released and pumped through underground or above ground piping that is pushed through turbines below. This process is done on a variable timescale, but optimally 8-10 hours of water stored in the upper reservoir during the night is released during the day when electricity prices and demand are high. Wind turbines would provide a carbon-free means for pumping water to the upper reservoir, which is likely done during the night when windspeeds are more consistent and stronger. PHS has approx. 75 % efficiency rate, and depending on the upper reservoir volume, is scalable to a 100MW Greenfield wind farm.

2.1.2.5 Supercapacitors

Capacitors consist of two parallel conductive plates separated by a dielectric insulator. Capacitors store energy in an electric field between the two parallel plates. The electric field is generated by separating oppositely charged ions toward the conductive plates by applying a DC voltage across the dielectric material. By using superconductive materials (carbon nanotubes or ceramics) for the conductive plates rather than the traditional metal construction, supercapacitors now have roughly four times the energy storage capacity of normal capacitors [15]. Supercapacitors can store energy efficiently for a short period of time and can be charged and discharged very quickly, and they have various practical applications from hybrid cars to portable electronics. However, charge leakage over long timescales and material costs for large-scale storage limit supercapacitors' potential for applications requiring long-term or large-scale energy storage [15].

2.1.2.6 Flywheels

Flywheels are currently not a beneficial way to store large amounts of energy, because their storage capacities are only in the range of batteries (3 kWh – 133 kWh). There is on-going research investigating how to improve bearings with the use of superconductors and developing high tensile strength materials that are able to withstand extremely high angular velocities. These two implementations could increase the effectiveness of the flywheel greatly. Current tensile strengths of the rotors are not strong enough to handle large loads required for commercial operations. When tensile strength is exceeded, the flywheel cannot store the energy, and it releases all of it at once, shattering the flywheel. When a flywheel breaks, it is essentially a grenade because high velocity shrapnel flies in all directions. Researchers are currently working on a compartment to safely house a flywheel. Despite research and development efforts, the main limitation for flywheels is the costs to properly design them with precision engineering so they operate efficiently [11].

2.1.2.7 Hydrogen

In a hydrogen fuel cell, hydrogen is the carrier medium used to produce electricity. Hydrogen gas acts as the "fuel" source from the anode side and oxygen is the "oxidant" from the cathode side [16]. A possible and common process used to isolate hydrogen is electrolysis, where an electrical current is passed through the water to separate the chemical bonds in the molecules [17]. Another method involves extracting hydrogen from fossil hydrocarbons [18]. The efficiency of storing energy using hydrogen is generally between 50-60%, while other storage methods like PHS and CAES are between 70-80% efficient [19]. Once the hydrogen is created, it can be passed through a fuel cell and combined with oxygen to produce electricity. Some water is left over while generating electricity within the fuel cell. This process is advantageous when the electricity comes from a renewable generation source, such as a hydropower plant or wind turbines, because it does not release pollution (carbon dioxide emissions) like hydrogen production using fossil fuels [20].

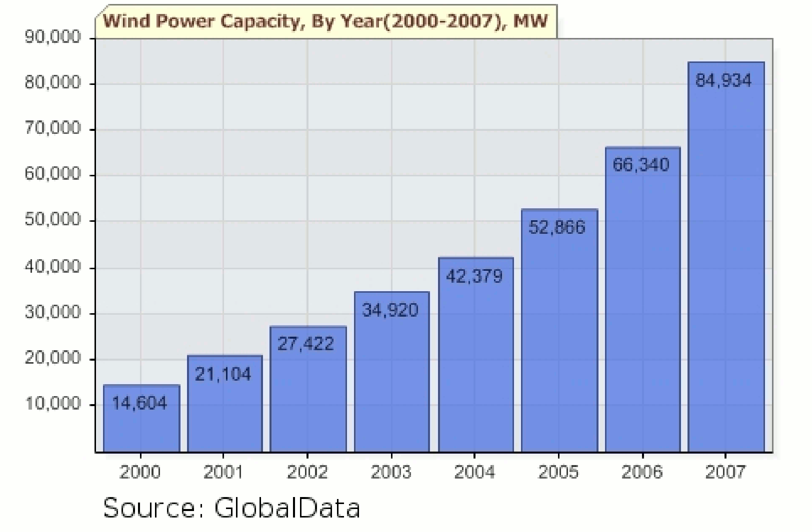
Energy storage via hydrogen struggles as the main storage facility for a dispatchable, integrated wind-storage system due to technical and sizing barriers. The materials needed to build and maintain a fuel cell and the electricity conversion loss described above present significant disadvantages. Platinum is a widely used material for the catalyst in the semi-permeable membrane within fuel cells. Researchers are investigating alternative catalyst choices such as nickel that are less expensive and scarce. An electrolyzer can be used to produce hydrogen gas by disassociating it from oxygen molecules in water. Platinum is also used as an electrode within an electrolyzer, but other metals such as nickel powder are also being investigated to attain higher conversion efficiency at a lower cost [21]. An on-site hydrogen fuel cell facility would be the most advantageous for the Greenfield site to bypass the cost and energy with transporting hydrogen in either tanks or pipes for example. However, there are no working, co-located projects in PA where hydrogen fuel cells have been shown to be a cost-effective method for storing electric energy for large-scale generators. Considerable research focuses on using a hydrogen fuel cell to power cars, since the required electricity output is more reasonable considering current technology capabilities [22].

2.2 Selected Energy Technologies

Pumped-hydro storage and compressed air energy storage were chosen specifically as cost-competitive and technically feasible storage options for a 100 MW Greenfield wind farm. These two technologies enhance the capacity and dispatchable nature for producing renewable electrical energy from utility-scale wind turbines (approx. 2 MW each).

2.2.1 Wind Electricity Generation

Wind power has been harvested and used over the past 1,100 years as a form of mechanical energy. The Persians were the first to use a functioning, practical windmill in 900 AD. These early stages of windmills were used to grind corn and draw water up from a nearby river or lake. Three hundred years later (1190 AD), northwestern Europe began using wind mills extensively to grind flour. Using wind to produce electricity was discovered early in the 20th century with small wind electric generators. The first significant US built wind turbine was constructed in 1930, and it was called the Smith Putnum machine. This turbine was the largest built in its time, featuring a 53.3 meter (m) diameter rotor that could produce 1.25 megawatts (MW) [23]. The widespread electrification in rural areas throughout the United States during the late 1930's led to a decline in the use of windmills for electricity production. In the 1970's, an oil shortage motivated researchers to investigate renewable energy options, such as wind energy. However, fossil fuels were widely abundant and cheap from the 1980's to the 1990's and less research and financial investment focused on wind energy. Wind energy has seen a resurgence within the last ten years, becoming a more attractive and cost-competitive power generation technology. Government incentives, growing environmental concerns, declining wind energy costs, improved wind turbine technology, and energy security concerns have specifically spurred interest in wind power. More recently, higher fossil fuel costs and the expectation of future carbon regulations have also contributed to the growth of wind energy production [24].



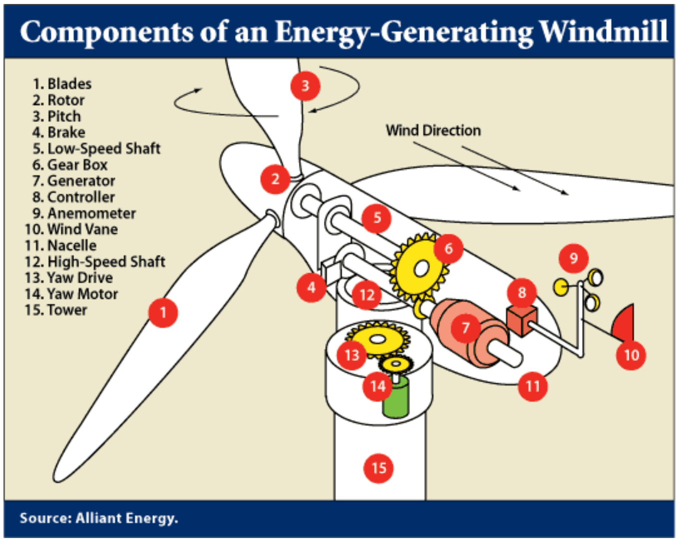
Source: GlobalData

Figure 1: Graph showing the growth in wind energy (MW) from 2000-2007 [23]

2.2.1.1 *Harvesting Wind Power*

Wind is produced from the uneven heating of the earth's atmosphere from the sun, rotation of the earth, and the irregularities on the earth's surface [25]. The total amount of economically usable power available from wind resources is almost seven times more than present human power use from all sources. Average global energy consumption is 15 TW, while total wind power potential on Earth could provide approximately 72 TW [26]. The basic mechanical process for wind generation involves wind turning turbines similar to the propeller blades on an airplane, and this turns an electric generator, which produces an electric current. Wind turbine components and selecting the proper placement for wind farms given the regional wind profile are two key aspects to consider when investing in this technology [24].

The most common type of wind turbine today is the horizontal axis wind turbine (HAWT). This turbine is named HAWT because its axis of rotation is parallel to the ground. The HAWT can be oriented with its rotors upwind or downwind and modern technologies are introducing mechanisms that rotate the turbine in the direction of the prevailing wind [23].



Components of an Energy-Generating Windmill

Source: Alliant Energy.

Figure 2: Image of turbine assembly showing all parts and make-up. This diagram shows the wind direction coming from upwind, but it is also possible for wind to turn the turbine from opposite directions (downwind). [24]

See Figure 2 for an assembly of a wind turbine and all of its features. The basic components of a HAWT are:

- Rotor and hub to support turbine
- Drive train, consisting of gearbox, shafts, generator, and mechanical brakes
- Turbine electrical switch box and control.
- Main frame and yaw system to house and orient systems necessary for turbine operations
- Tower and foundation
- Detached electrical system to transfer generated electricity [23].

The physics behind wind power generation is related to transforming the kinetic energy of the wind into mechanical energy, which translates into electrical energy for the grid. The power of the wind is used when it moves past the turning blades of the turbine, exerting a torque on the rotor. The power created is proportional to the wind speed, density of the air, and the area swept by the rotor. The equation for power production is:

$$P_w = \frac{1}{2}\rho A v^3$$

Equation 1: Power production in watts given the wind speed, density of the air, and the area. [27]

Using the above equation, the power in watts can be estimated for any wind turbine as long as the density of air (kg/m^3), cross-sectional area through which the wind passes (m^2), and the velocity of the wind (m/s) are known [27].

The final and most important factor in harvesting the wind is location. The first factor that influences the location decision is the availability of the wind. A general rule of thumb for placing wind turbines is to build where average wind speeds are 18 km/hr (5 m/s) or greater [27]. Meteorologists and government agencies have produced publicly accessible wind maps via the internet for almost every state. These wind resource maps provide a wind power class rating from one to seven based on the potential power in watts/m^2 that a turbine could produce. If any site is classified as a three or higher, the area is suitable for wind farm development. If the area has a class two rating, then it still has potential to run small wind generators [23]. An ideal location for a wind farm would be a ridge where the wind would have a near constant flow of non-turbulent wind, and not suffer from many powerful wind gusts [27]. Besides the availability of the wind, other factors contributing to location decisions include cost of the land, proximity to existing transmission lines, value of energy to be produced, land use considerations, and environmental impacts of building and operating the wind turbines [28].

2.2.1.2 Current Wind Generation Sites in PA

Wind power was the most rapidly growing alternative energy generation at the turn of the century. From 1999 to 2005, world-wide generating capacities quadrupled. The World Wind Energy Association (WWEA) predicted a growth rate around 15% per year. The United States is third in generation capacities behind Germany and Spain. These same growing trends on a global scale are also seen nationally throughout the U.S. Since 2005, wind turbines have been operating with a total capacity of 59,207 MW globally. By 2010, this capacity will increase to 136,543 MW [27].

Pennsylvania has several highly rated wind profile locations that favor large-scale energy production sites like commercial wind farms. The U.S. National Renewable Energy Lab (NREL) reports that the best wind resources east of the Mississippi River lie within Pennsylvania, New York, and West Virginia [29]. The wind resource map below indicates that about half of the land in Pennsylvania has a wind rating of three or higher.

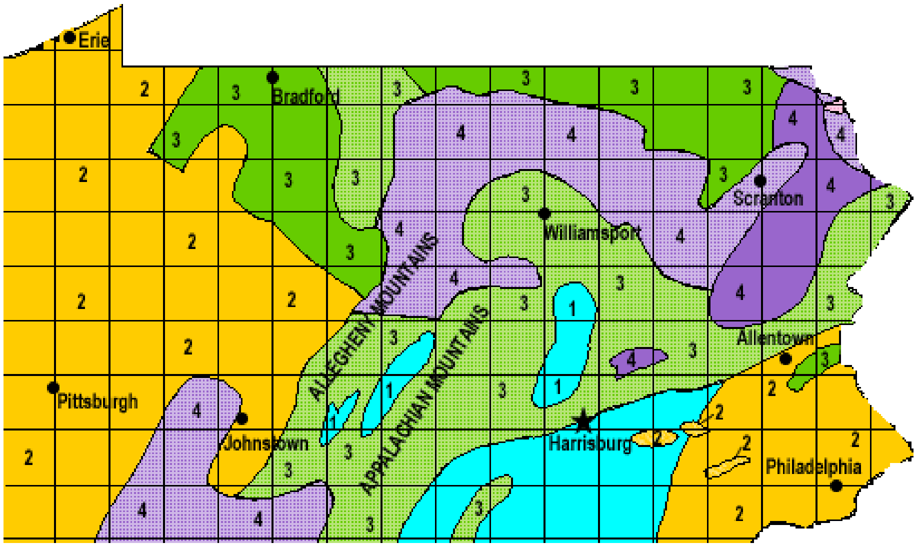


Figure 3: Wind resources in Pennsylvania. Ratings three or above have enough potential to produce wind energy on a commercial setting (WPPSEF).

PA has high wind profiles moving from the southwest up through the northeast through the Appalachian and Allegheny Mountains, continuing into Scranton (northeastern PA) Most wind farms in Pennsylvania are built and operating in this region.

Wind energy technology is a growing source for energy production, job growth, and rural economic developments. Advantages to constructing current and future wind turbines in PA are:

- Wind power in Pennsylvania can meet the full annual electric need of 1,000,000 homes.
- 5,000 workers are already employed and working in the wind production industry of PA, and with the increase in wind energy production, many more high-paying jobs will be introduced.
- Electricity from PA's wind farms increase electricity supply and help keep electric market prices affordable.
- Wind energy helps reduce the contribution of pollutants to the global warming problem. Nationally, Pennsylvania is the third highest producer of greenhouse gasses, such as methane and carbon dioxide. [29]

There are eight current wind farms in Pennsylvania. According to the map below, these eight wind farms are equally split across PA; four in the southwest and four in the northeast.

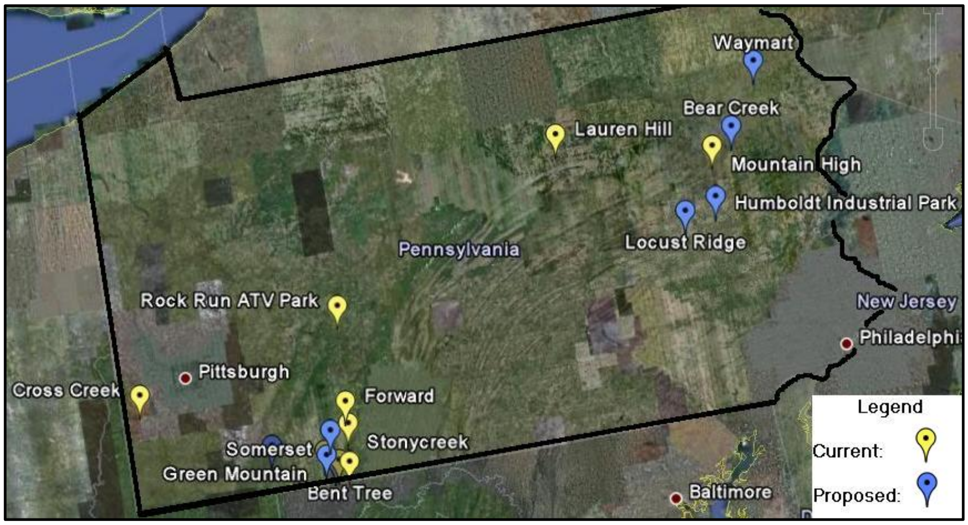


Figure 4: Current and future wind farms in Pennsylvania. Blue markers represent current wind turbine locations, and the yellow markers are projected wind farm areas.

The first wind energy production farm was in Humboldt Industrial Park (near Scranton, PA) and only has two established turbines. The site was founded in 1999 and has a capacity of 0.13MW. The largest wind farm in PA and second largest east of the Mississippi River is the Waymart Wind farm located in Wayne County. Waymart Wind farm consists of 48 wind turbines with a capacity of 64.5 MW. Below, is a summary table of the eight current wind farms in Pennsylvania (actionpa.org).

Table 1: Current Wind Farms in Pennsylvania. [30]

Wind Farm	Megawatts	County	Turbines	Online As Of
Humboldt Industrial Park	0.13	Luzerne	2	12/1999
Green Mountain	10.4	Somerset	8	5/2000
Somerset	9	Somerset	6	10/2001
Mill Run	15	Fayette	10	10/2001
Waymart	64.5	Wayne	43	11/2003
Meyersdale	30	Somerset	20	12/2003
Bear Creek	24	Luzerne	12	2/2006
Locust Ridge	26	Schuylkill	13	6/2007

Wind farms in PA are being built with newer technologies to help produce more energy. The newest set of turbines at Locust Ridge start generating electricity at 8 mph, which is equivalent to just a gentle breeze. New technologies have been developed in the blades and turbine that lowered the necessary wind speed down from older technology which required a minimum of 15 mph. John Hanger, chief executive of PennFuture, commented that "Pennsylvania is blessed with a good resource that can provide significant amounts of pollution free electricity to the state. That resource, if reasonably developed, will have the least environmental impact of any other way of making electricity." Pennsylvania's current generating capacity is 179 MW, which ranks it 13th nationwide. Of all the eastern states, only New York produces more wind energy. Lastly, Governor Rendell stated, "Wind energy is part of our future. It can do for Pennsylvania what coal and oil did for us in the '20s, '30s, '40s, and '50s." [31]

2.2.1.3 Future plans for PA and wind generation

Today, 0.1 percent of the United State's total power consumed is produced by wind power. This is a very small amount when compared to Denmark's 10 percent wind energy usage. In the next 10 years, the Department of Energy (DOE) wants to increase wind's contribution to US energy by 5 percent. One of the largest obstacles to overcome is the cost of wind electricity. The average cost to produce one kilowatt-hour of electricity using wind is three to five cents [32].

Many organizations advocate wind power in Pennsylvania, and currently, there are nine projected projects to be built in the near future. One of the main organizations supporting wind energy promotion is Community Energy, Inc. Recently, the council has announced 258 MW of new wind development, which will make PA the largest wind energy producer on the east coast when completed.

Over the past 20 years, wind energy cost has decreased 80 percent in Pennsylvania, and is almost as cost effective as coal and oil options. In the table below are the nine proposed wind farm locations [33].

Table 2: Proposed Wind Farms for Pennsylvania. Blank entries are still being discussed on land and location issues. [30]

Wind Farm Project	MW	County	Turbines
Stonycreek	45 – 64.8	Somerset	36
Keystone	25 -30	Somerset	16 – 30
Forward	30 – 36	Somerset	20
Mountain High	26 – 39.6	Luzerne	13
Brother’s Valley	15	Somerset	
Bent Tree		Somerset	
Rock Run Park	up to 400	Cambria	up to 200
Laurel Hill	up to 54	Lycoming	up to 54
Cross Creek	50	Washington	25

2.2.1.4 Summary of Wind

Wind energy is the fastest growing renewable resource option in the world, but there is one considerable challenge. The intermittency of the wind resource is unpredictable and uncontrollable. When the wind stops blowing, a decrease in energy production is bound to happen. One way to counter this is to have large enough wind farms separated by miles to capture various wind speeds. Distance may help to mitigate intermittency by reducing correlations in wind fluctuation [28]. The second option to counteract this challenge is to store the wind energy created during non-peak hours. Two possible ways to store the wind energy is through pumped-hydro storage and compressed air energy storage.

2.2.2 Pumped-hydro Storage

2.2.2.1 Definition and Background

One of two storage options investigated in this paper includes a pumped-storage hydroelectric system or pumped-hydro storage (PHS). This system consists of a main pipe (or piping) that is used to transfer water from a low elevation to high elevation into a reservoir. Having two reservoirs in close proximity with a high elevation gain is best, but the reservoir construction can vary. A PHS unit can be built near a pre-existing dam where the dam acts as a reservoir. Water from the lower reservoir is pumped to and stored in the upper reservoir when peak demand is low. When demand is high, water is released through the piping to the dam turbines below for power generation. The benefit of releasing water during periods of high electricity demand is electricity prices are highest then and the system increases revenue. High elevation is crucial to maximize the potential energy of water, yet height varies widely per reservoir. It is difficult to quantitatively determine what is the sufficient height for maximum electricity production because both sufficient and maximum are ambiguous words. Both pump-storage sites that are examined in this study are located at relatively high elevation sites near preexisting hydroelectric dams. [34]

2.2.2.2 Pumped-hydro storage (PHS) sites

Currently, there are two working PHS sites in Pennsylvania (PA).. Muddy Run pumped storage in southeastern PA is located in Drumore Township along the Conowingo Dam in Maryland (MD). In the opposite direction of Warren, PA, Seneca Station uses pumped storage as means to regulate peak electricity load and is located near one of other larger hydroelectric dams, Kinzua Dam. Muddy Run Reservoir is 1,000 acres (4 km^2) with an elevation of over 500 feet (152 m) and a capacity of 1,071 Megawatts (MW) [35]. The Seneca Station uses the Allegheny Reservoir, a 25 miles (40 km) lake located near the Kinzua Dam that produces 435 MW [36]. Seneca Station sits atop a ridge with an elevation gain of approx. 750 feet (ft) (Allegheny Reservoir approx. 1330 ft and Seneca Station approx. 2080 ft) [Figure 5].

Having an on-site energy storage is beneficial because it does not require substantial transmission wires and the cost associated with this investment. Assessing how close the energy storage unit should be to the wind turbines is beyond the scope of this research; however, it should be noted that additional transmission wires can present cost and interconnection barriers, and overall location for the energy storage site and a prospective wind farm influence technical feasibility and cost-competitiveness.

Figure 5 Google Earth™ image for Kinzua Dam and Seneca PHS Station (2080 ft) near Allegheny Reservoir (1330 ft) below

2.2.2.3 Feasibility and economic characteristics

Determining if pump-hydro storage (PHS) is a feasible storage option requires efficiency rates and costs. An additional comparison with other technologies that have the ability to act as a storage resource, such as open-cycle natural gas turbines, further distinguishes PHS as a feasible and competitive storage option. As mentioned later, CAES was also selected as a cost-competitive and technically feasible storage method for this research.

Three crucial factors are needed to study the feasibility and cost-competitiveness of pumped-hydro storage: power capacity mega-watt (MW) and energy capacity mega-watt per hour (MWh), and roundtrip efficiency (%). As mentioned, Seneca Station PHS has 438 (MW) of power capacity, while Muddy Run has 1,071(MW) .

On average, pumped-hydro storage energy capacity can "accommodate a full day's peak demand period of 8 hours; and, in some cases, have been built with more than 20 hours of discharge capacity" [37]. At the upper range, PHS devices have an approximately 75% roundtrip efficiency or a 20% conversion loss [37] [38]. Efficiency is a measure of electrical energy output (MWh) divided by the primary energy input (MWh), and efficiencies (%) vary depending if the system is a conventional fossil fuel or renewable energy source [39]. The duration (hours) for how much energy (MWh) can be stored and produced for a PHS unit varies depending upon several constituents, such as type of pump device, piping (underground or above ground), elevation, turbines, maximum reservoir volume etc. Thus, storage capacity (MWh) for PHS is approx. greater than 6,880 MWh.

The PHS characteristics for Seneca Station will be used in the engineering and economic analyses. Pump and energy generation characteristics relevant to this study were obtained from interviewing senior engineers at Kinzua Dam. These characteristics may provide useful estimations for Muddy Run at Conowingo Dam in the future, but currently there are no publicly accessible data for this site to conduct a confident assessment of this PHS site. These characteristics are used to provide a basic example for how a PHS unit is designed (reservoir volume, pump and elevation and utilized

At Seneca Station near Kinzua Dam in Warren, PA, the PHS unit pumps 6,500 cubic feet per second up to a reservoir that can hold two billion gallons of water. The pump to energy generation ratio from the turbines is 1.3-1.35 where 440 MW are used to pump water into the upper reservoir. Thus, the turbines generate approx. 340 MW of energy(440MW/1.3). With an efficiency rate ranging from 70-80%, the electrical conversion loss for a maximum 440 MW power capacity is equal to the energy capacity of 340 MW (.7 of 440 MW≈ 340 MW). The reservoir is 0.5 miles in diameter and 55 feet at an elevation of approx. 700 feet above the lower reservoir [40]. A minimum 15 feet of stored water is maintained throughout the day, releasing on average 40 cubic feet when peak demand is high. Water is generally pumped to the Seneca Station reservoir during the night using energy (electricity) from the grid. At nighttime, electricity prices and demand are low while wind generation is at its height. Wind power could be used to pump water into the reservoir to be stored during the night, since wind speeds are stronger during the night. Specifications for PHS system at Seneca Station/Kinzua Dam will provide a base estimate for the PHS unit used at Muddy Run/ConowingoDam [41].

The duration for how long electricity can be generated from the stored water in an upper reservoir is also important from engineering and economic perspectives. The total sum hours electricity can be produced from water that is released at a PHS site describes the maximum size for a energy storage facility, or, in this case, the volume of water that can be stored when an wind generator is not producing electricity directly to the grid. This can be translated into how many hours of electricity can be dispatched when there is no available wind and when it would be advantageous to use stored electricity because prices are higher. Thus, an integrated wind-PHS system is optimal when the volume of stored water can be drained for approximately eight hours to cover peak electricity demand during the day and earn the highest profits.

2.2.2.4 Wind potential and PHS

High wind intensity sites are located in central/northern, along the Appalachian Mountains and the east/northeastern areas of PA [Figure 3][Figure 4]. Cost of wind-generated electricity varies from $37 per MWh to $68 per MWh [34]. These estimates depend upon the type of installed wind turbines, and, although these cost figures are for the Alberta electrical grid, they provide a general pricing range for this study.

The largest dams are located in the southeastern corner of the state, stretching along the border with Maryland [42] [Figure 6]. For the purpose of this study, the engineering and economic analyses will focus on the established PHS site at Seneca Station and a possible extension of this study could be a comparison using Muddy Run storage site. North central PA has geographical promise as a Greenfield location because it possesses fairly decent wind speed and would utilize grid-connected electrical energy generated from Seneca Station at Kinzua Dam. This study is unique because we have not chosen a topography with an excellent wind resource (rated a 4-7), such as Wyoming or the greater central plains in the United States. Rather, we are assessing the impact of energy storage in a terrain with mediocre wind, ranging from a 2-4 rating. As explained later, the wind data used in this project was extrapolated from low height (<50 meters) weather data, when wind data is more accurate collected at 50-100 meters [27]. Thus, improving the capacity and dispatchability of a wind farm with data reflecting *average* consistency and strength of windspeeds via energy storage provides vital insight into how an integrated wind-energy storage system is applicable to other states with less attractive wind potential.

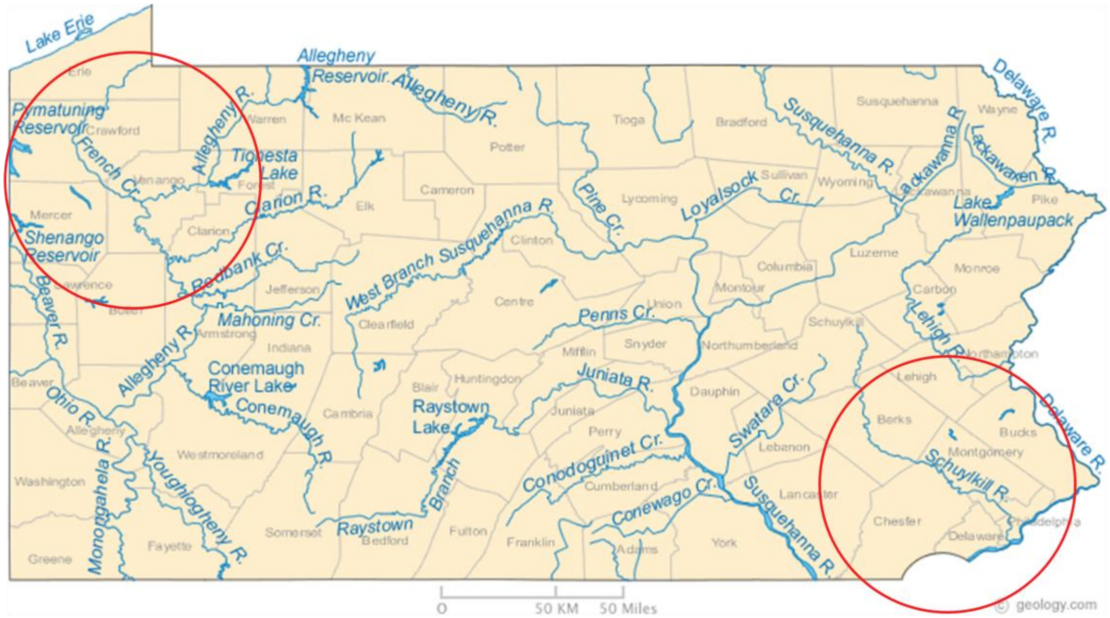


Figure 6 Pumped-hydro storage locations in PA: Seneca Station in NE and Muddy Run in the SE (Courtesy Geology.com)

There are other challenges associated with selecting a 'good' wind location and economically feasible energy storage site (like Seneca station), such as social, geographic and environmental barriers. There are not ample hydro power plants with pre-existing pump-storage units or available land for a new reservoir in PA. Essentially, a "traditional hydropower plant may be enhanced by pumped hydro storage" to balance wind intermittency and store energy during low peak electricity demand periods [34]; yet, significant elevation gain by many dams in PA coupled with large power capacity and nearby space to consider creating a new reservoir are needed to invest in a PHS system. This reality should be considered when choosing the type of energy storage system and designing the storage size for a large-scale wind farm looking to control electricity output as a base load generator.

Potential advantageous sites for building a reservoir for pump-hydro services, either by an established hydro power plant or another existing body of water such as a lake, may not be feasible since land in PA is already appropriated for farms, private ownership or is federally protected. Pennsylvania will not be heavily investing in new hydroelectric dams, as they are costly (infrastructure and maintenance), time consuming to build and must abide by several land, water and wildlife protection laws to meet competing uses (agriculture, recreational, municipal uses) and preserve the downstream ecosystem. However, the efficiency loss (70-75%), minimal to no carbon emissions and ability to provide electricity on a large-scale from multiple waterways in PA are compelling features for PHS as a storage option [38].

2.2.3 Compressed Air Energy Storage

One of the few, currently known energy storage technologies with the potential to be competitive on the scale necessary for large electrical power systems is Compressed Air Energy Storage (CAES). CAES is performed by using airtight geologic formations or manmade containers to store gas at a high pressure. A compressor uses energy to compress gas and inject it into the containing facility. In most CAES systems, a motor draws electrical power to compress air and inject it into a geological storage system. The energy stored in the compressed air is retrieved through turbines. Currently existing CAES systems utilize gas turbine technology to convert the stored energy into mechanical torque to turn an electrical generator. The turbine consists of two components, a combustor and an expander. The air is heated at constant pressure (isobaric heating) in the combustor, and then energy is extracted at constant entropy in the expander and is used to produce mechanical torque.

When compared to a typical gas turbine powered electricity generation facility, a CAES system can be described as interrupting the gas turbine cycle after the compression stage. In a gas turbine, air is compressed and fed directly into a combustor to be heated and expanded through the expander. In the expander, the energy contained in the high pressure, hot air is converted into mechanical torque, which turns an electromagnetic generator and produces electrical current. The stages of a typical gas turbine are shown in Figure 7. CAES interrupts this cycle by sequestering and storing the compressed air for a period of hours or days before it is fed to the compressor. A typical CAES system is described in Figure 8.

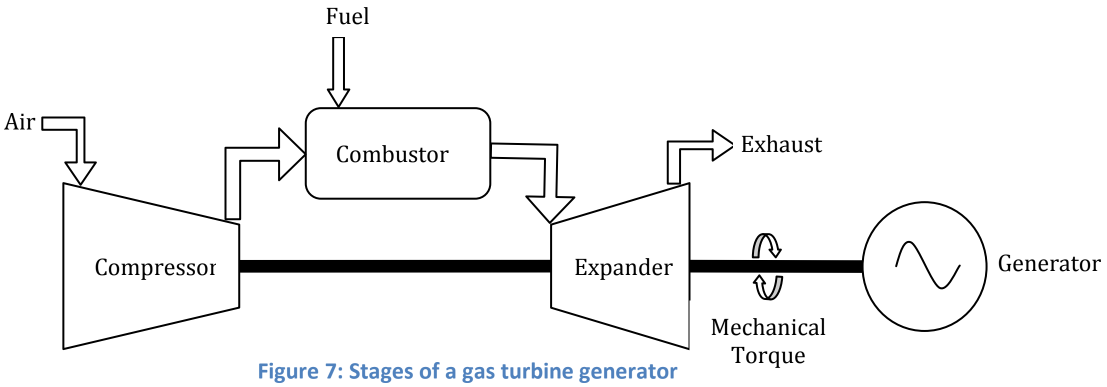


Figure 7: Stages of a gas turbine generator

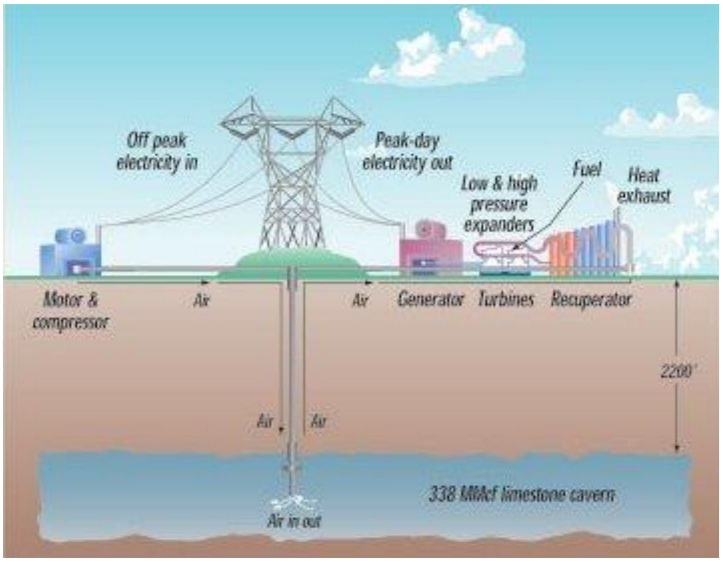


Figure 8: CAES Facility [43]

Energy is stored in the air that is compressed and sequestered in either geological or manmade containers. Theoretically, manmade containers are possible, but the abundance of suitable geologic formations and the costs associated with fabricating a container on the necessary scale make the construction of manmade containers for CAES impractical. That said, it is possible to use manmade underground caverns for CAES, such as abandoned mine shafts.

There are several natural geologic formations that are suitable for CAES. Depleted gas fields, aquifers, and salt caverns are a few examples of the geologic formations that possess characteristics necessary for compressed air storage. Figure 9 shows that approximately 85% of the continental United States contains one or more geological formations suitable for CAES [44]. Figure 10 outlines the three principle techniques for compressed air storage depending on the formation containing the air [44].

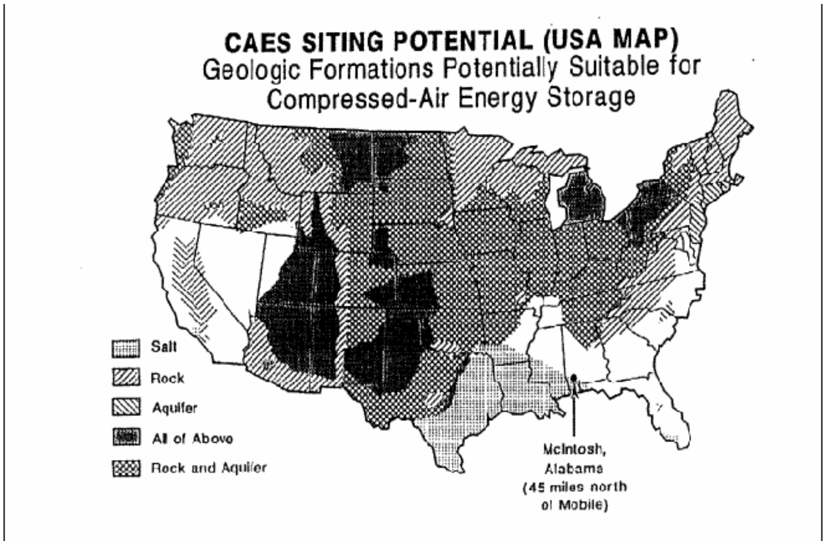


Figure 9: Regions of the US suitable for CAES [45]

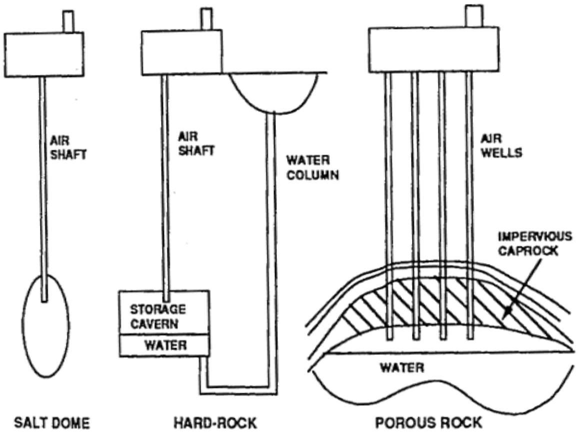


Figure 10: Air Storage Schematics [44]

The simplest technique is used for static volume caverns, such as salt domes. Salt domes are evacuated using water for solution mining, and once evacuated, air can simply be injected into the salt dome.

Depleted gas fields and underground aquifers do not require mining for the purpose of air storage. However, due to the porous rock within these formations, multiple air wells are usually required to provide adequate air percolation on the necessary time scale.

Abandoned mines used for air storage are typically the most expensive of the three techniques. In order to maintain a constant pressure in the cavern, a column of water is fed to the bottom of the storage cavern, reducing the cavern volume.

While CAES is principally an energy storage system, the extraction of energy is typically done using gas turbines, which require an external fuel source. Thus, the CAES system is potentially a generation system as well as a storage system. Modern single cycle combustion turbines have efficiencies in the range of 30%-40% [46]. By replacing a compressor on a traditional gas turbine with the compressed air stored within the CAES facility, the efficiency of the gas turbine is greatly increased. Approximately 4500 kJ of fuel are needed for each KWh of electrical energy produced by the gas turbine as opposed to the typical heat rate for a natural gas turbine of 11,500 kJ [10], [47]. The CAES compressors that replace the compression cycle in the gas turbine require about 0.8 KWh of electricity input per 1 KWh that is output by the gas turbine [44].

Advanced-Adiabatic CAES (AA-CAES) has been proposed as a system that stores the heat created by compressing the air in an underground thermal energy storage system [48]. Using the stored thermal energy to heat the input air for the expanders effectively eliminates the need for a combustion cycle and thus an external fuel input. The entire system yields a lower electricity output than traditional CAES but also has zero CO_2 emissions.

There exist several CAES facilities worldwide, the first is a 290 MW plant that was constructed in Huntorf, Germany in 1978 and has been operating reliably ever since. The U.S. saw the construction of its first CAES facility in 1991 when the Alabama Electric Cooperative built a 110MW plant in Macintosh, Alabama [46]. In 1997 a 35 MW plant was built in Sunagawa, Japan [44]. The Iowa Stored Energy Park has proposed a 200-300MW CAES facility in conjunction with a wind farm that is scheduled to be built in 2011 [49]. The economic and technical success of existing CAES facilities proves that the technology is a viable energy storage technique. The abundance of feasible locations, storage capacity, charging time and ramp rate of CAES systems make them a good match to several existing renewable energy production technologies.

3.0 Methods

The following analysis focuses on the profitability of energy storage for use in conjunction with large scale wind electricity generation. We design storage systems for integrated use with a wind generation facility and for stand-alone use. A sensitivity analysis maximizes profits by varying the design parameters of the storage system. We adjust the cost structure to determine the conditions under which such a system becomes profitable.

3.1 Designing a Greenfield System

A Greenfield system describes a hypothetical new installation of the selected technologies at a specific geographic location. The goal was to determine the viability of a system in a real-world setting.

3.1.1 Site Selection and System Sizing

The first step in the analysis was finding an area in Pennsylvania that can generate electricity from wind profitably, and has the land to build enough turbines to produce approximately 100 MW. A 2 MW wind turbine is the typical size used in Pennsylvania, and would need to be placed 50-100 meters off the ground for adequate wind speeds. Since Pennsylvania has plans on building wind farms ranging from 80-150 MW in the near future, we chose a 100 MW farm. Using this number we would need to do an analysis to figure out the size of storage needed for our system.

The site we chose was in north eastern Pennsylvania near Scranton. This area was chosen because the wind has a class rating of four, and has other growing wind farms currently surrounding this location. Mountains surrounding the area provide access to the high winds. On the northern side of Pennsylvania there are also depleted salt domes that could be used for CAES. Once the location was chosen, wind data had to be collected around the area to ensure the choice of sizing, and to see if the area was suitable for a large scale wind project.

3.1.2 Obtain Data

Good wind data collected at heights over 150ft is very difficult to obtain because of the inherent value of such information. However, there are many data sets, collected by both professionals and amateurs, at a 15-30ft height across the United States. Extrapolations of low height data to higher heights are not accurate, yet can be very good indicators of the variability of speed as well as the quality. For this study, wind data collected by the Newton Township weather station at Clarks Summit, PA at a height of approximately 20ft was the closest wind data to the desired location of our Greenfield system. Using wind speed scaling factors with respect to height and the surrounding environment and further scaling the results appropriately to match the profitability of currently installed utility scale wind farms around Pennsylvania has led to a derived wind speed data set that produces similar yearly wind output as other installations in PA.

Electricity price data was collected through the Independent System Operator (ISO) for the region that includes the Greenfield site. PJM is the ISO that encompasses Pennsylvania, New Jersey, Maryland, Virginia, Delaware, and parts of West Virginia, Ohio, Indiana and Illinois. PJM publishes the monthly results of the day-ahead auction for hourly electricity prices. The day-ahead auction is an electricity market that determines the market price for electricity 24 hours before it is generated. We were able to combine 12 months of data to generate one complete year of electricity prices. After determining the site for the Greenfield system, we determined the nearest high voltage (>110kV) substation. Using the yearly day-ahead price information at that substation, we were able to extrapolate the series to match the 15 minute interval wind data.

3.1.3 Levelized Costs of Energy

In order to determine the differences between the various energy generation and storage options, the costs must be converted to comparable units. For this study, all costs were derived from capital cost, total energy production per year, and the life span of each technology. These costs were then levelized to dollars per kilowatt-hour [$/kWh] using Equation 2. Operating and maintenance (O&M) costs, with the exception of fuel costs, were omitted to obtain an overnight cost for simplification of the comparison.

$$\frac{Capital\ cost/kW}{Energy * Life * CapacityFactor} + Fuel\ cost/kW = \left[\frac{\$}{kWh}\right]$$

Equation 2

Table 3: Levelized Costs of Energy Production and Storage Technologies[1]

Energy Generation or Storage Option	Levelized Cost of Energy [$/kWh]
Pumped-hydro Storage (PHS)	$0.010/kWh
Compressed Air Energy Storage (CAES)	$0.034/kWh
Wind Generator	$0.026/kWh
Natural Gas Non-Peaking Generator	$0.038/kWh
Coal Generator	$0.045/kWh
Natural Gas Peaking Generator	$0.387/kWh

3.1.4 Operating Characteristics

The algorithm that models the operating characteristics of the storage system incorporates examples from existing PHS and CAES installations. Figure 11 shows the energy flow of an integrated energy storage and generation system.

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[1] See Appendix A

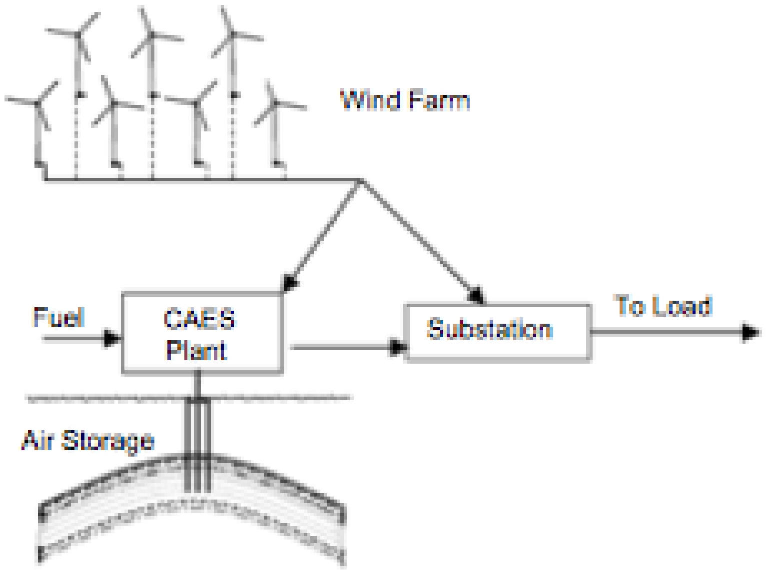

Figure 11: Schematic of Wind Integrated CAES System [10]

3.1.4.1 Wind Integrated Storage System Model

The wind integrated storage system model (WISSM) represents a system that stores and sells energy created by a wind installation of 100MW based on electricity prices at the time of generation. If electricity prices are low and the wind generator is operational, the energy is stored using a CAES facility. If prices are high, the energy produced by the wind generator is sold straight to the grid and the storage system outputs energy for sale to the grid. The price threshold for sale and storage of energy is set by the levelized cost of the storage facility. The capital cost of $700/kWh and fuel cost of $0.0298/kWh are used along with a plant lifetime of 40 years in calculating the levelized cost of energy. In previous calculations of levelized costs for CAES systems, we had assumed a standard operating characteristic based upon the properties of a CAES system and typical operating characteristics of existing PHS systems. When coupled with wind generation, the operating characteristics are a function of the output of the wind generators; and, thus levelized cost depends upon the wind data. The operation of the WISSM depends upon four key input parameters:

- Levelized cost of storage ($/kWh)
- Market electricity price ($/kWh)
- Wind generator output (kWh)
- Capacity of storage system (kWh)

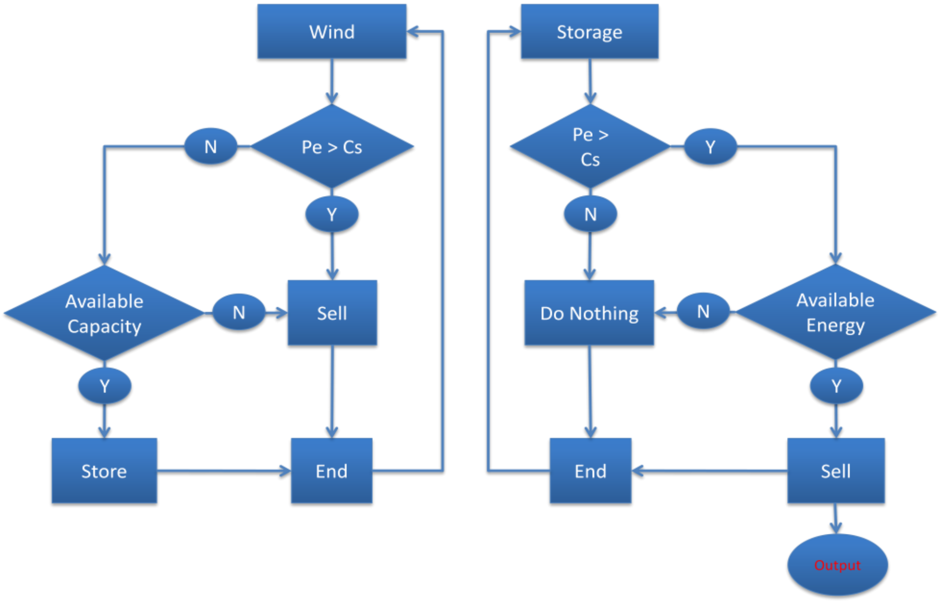

Figure 12: Activity Diagram for Wind Integrated Storage System Model (WISSM)

Using these input parameters, the WISSM operates according to the activity diagram in Figure 12. When the market electricity price (P_e) is higher than the levelized cost of CAES (C_S), the system uses its capacity for generation, both directly from wind generators and from the energy stored in the CAES facility to sell energy onto the grid. Conversely, when the market electricity price is below the levelized cost of CAES, the system uses its wind generation capacity to charge the storage system in order to sell the energy at a later time and higher price.

Using the output from the WISSM, we were able to conduct a sensitivity analysis on the size of the storage system. The size of the storage system consists of two primary components. First, is the amount of energy that the facility can store, which in the case of CAES, is analogous to the volume and pressure of the container in which air is compressed. The second component is the rated output of the electricity generator, which depends upon the gas turbine included in the system. We determined that the output of the system was most sensitive to the size of the storage facility rather than the output of the generator. After determining a generator size of near optimal value, we were able to design the system to optimize profits. By varying the size of the storage facility, we were able to run a sensitivity analysis to determine the optimal size of the storage system.

3.1.4.2 Stand-Alone Storage System Model

The WISSM output is a function of the storage facility design and the wind energy generation coupled to the system. In order to determine the profitability of the storage system itself, it is necessary to simplify the system. By decoupling the wind generation and storage system, a model can be created that determines the profitability of storage based upon the electricity market and the levelized costs of a storage facility. The Stand-Alone Storage System Model (SASSM) represents a stand-alone CAES facility. The operation of the model is consistent with the operating characteristics of existing CAES and PHS facilities. The system operates based on the assumptions that it can discharge for 10 hours and recharge in 2 hours. Using these assumptions, the system determines the 2 hours that typically represent the lowest market electricity prices and charges the system during that time. Likewise, the system discharges and sells electricity during the 10 hours of highest electricity prices daily. Figure 13 shows the times when the SASSM charges and discharges by buying and selling electricity. The upper dotted line represents the threshold above which the SASSM sells energy and the lower dotted line is the threshold below which the system buys energy.

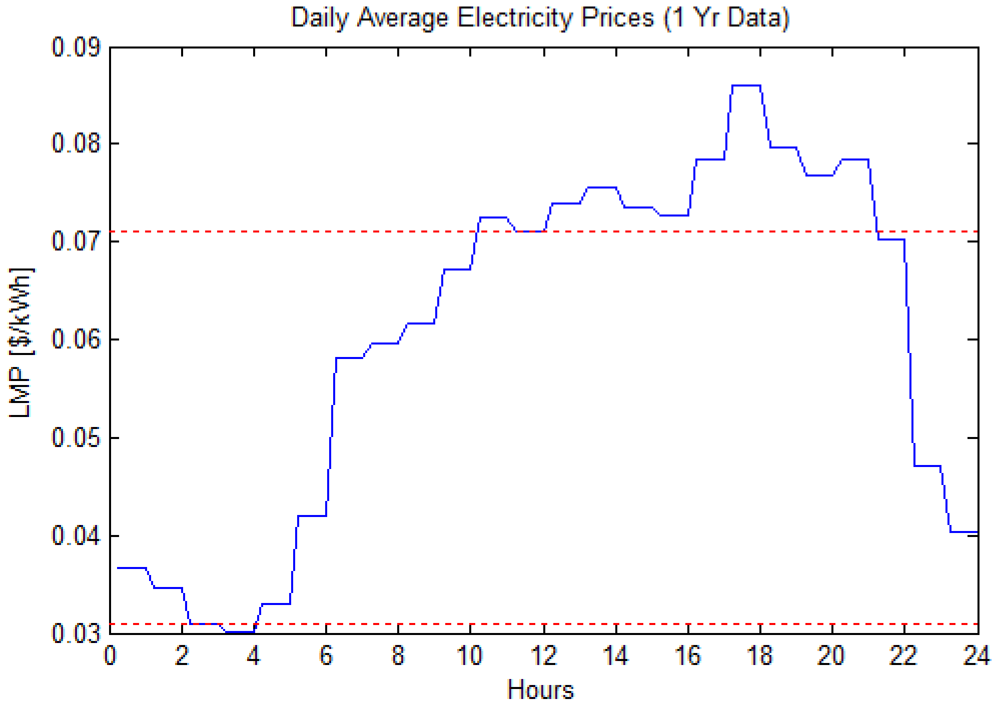

Figure 13: Charge-Discharge Times for Stand-Alone Storage System Model (SASSM)

As with the WISSM, a sensitivity analysis is necessary to determine the size of the storage facility that optimizes profits. However, because the operation of the SASSM is not variable, the storage system size does not have to be decomposed into two components. In this case, the turbine output rating, and the storage capacity can be combined into one simple storage size variable. By varying the storage size we were again able to maximize profits considering system output and levelized costs.

3.2 Greenfield Outputs

We considered the following outputs of the system models in conjunction with energy prices to determine the value of the system.

3.2.1 Energy Output

The operating characteristics of a 100MW wind farm consist of fifty 2MW generators that utilize intermittent wind generation in conjunction with a utility scale storage facility, driven by maximization of revenues influenced by selling electricity at peak electrical demand and storing energy during periods of low demand. Electricity price fluctuates with demand. As demand increases during the daylight hours, the prices increase, and as demand decreases during the night, the price decreases. If electricity is being generated by the wind turbines during a period of high demand, the electricity will be sold directly to the grid. If it is generated during a period of low demand, the energy will be placed in storage until the price has increased to a level that is profitable.

3.2.2 CO_2 Outputs

When sizing the integrated wind-energy storage site, carbon emissions were calculated to better understand the overall costs, economic and environmental, associated with renewable energy and conventional generation sources, such as natural gas. No carbon dioxide (CO_2) is released with a wind-PHS generator because hydropower generation backing up wind turbines is inherently emissions-free. Different carbon content is emitted when burning purely natural gas (combined-cycle natural gas turbine), CAES, and for a natural gas plant. The heat rate for each component technology was multiplied by the amount of emitted CO_2 when burning natural gas, 117 lbs of CO_2 for every Billion BTUs burned [42].[2]

Carbon emissions provide another criterion for evaluating the cost-effectiveness of wind-storage electricity generation system compared to traditional generation sources in PA. Examining carbon emissions within the economics of the Greenfield site includes environmental quality as a key parameter rather than an externality. Hence, including carbon emissions as a cost factor extends our study beyond a basic evaluation for improving the power capacity of wind generation via storage because we are considering how the overall energy-environmental system is impacted. We are investigating how PA's natural resources like wind can be harnessed and used with the in-place transmission grid to supply electricity with minimal greenhouse gas emissions (GHG). The system also is designed around existing energy storage sites within the chosen geography (north/central PA) and supports current legislation to invest in more PA wind power. Thus, the innovative merit and social relevance for this Greenfield system are that it is feasible from engineering and economic perspectives and that it strives to adopt global carbon abatement goals via a carbon tax. A further assessment of the effects of a carbon tax will help elucidate how and when an appropriately sized integrated wind-energy storage system would be more advantageous than conventional use of natural gas in PA.

4.0 Results and Discussion

Results from the analyses of the WISSM and SASSM models show the maximized profits and optimal storage sizing for the Greenfield site.

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[2] CAES: 4265 BTU/kWh × 117lbs CO2/ billion BTUs = 0.00050 lbs CO2/kWh [10]
NG Turbine Generator: 11459 Btu/kWh × 117lbs CO2/billion BTUs = 0.00134 lbs CO2/kWh [42]
CCNG: 7445 BTU/kWh ×117lbs CO2/ billion BTUs = 0.00087 lbs CO2/kWh [42]

4.1 Design

The results of WISSM show that for the 100MW wind installation used in the Greenfield system, the considered costs of a CAES facility always outweigh the revenues produced by the system. The optimal choice for sizing a storage facility is to not build any storage at all. The costs dominate the revenues such that the costs, which are linearly increasing with size, create a linearly decreasing profit function as the size of the storage facility increases. Figure 14 shows the results of the WISSM sizing sensitivity analysis. The brief positive portion of the figure represents the profits produced from the wind installation when the storage system is small and cheap enough that its costs do not completely offset revenues.

The wind data used to determine the output of the wind installation plays a significant role in the unprofitable project. More accurate wind data may yield slightly different results. Our data has several long periods with no wind output. This may be due to the fact that the scaling factor that was used to account for the height difference between data collection and generation does not account for the fact that when there is no wind velocity at collection height. There may be a wind velocity present at generation height of approximately 80m. The large periods with zero wind velocity skew the results since the storage system is missing out on several periods of extremely high market electricity prices. In order to produce a profitable system, wind output characteristics would have a much shorter variability scale. Instead of calm periods lasting days or weeks, it is necessary to have windy periods present in most every day, and preferably most of the time. The system does not need constant wind, but, as a minimum, the system needs regular variable winds in order to be profitable.

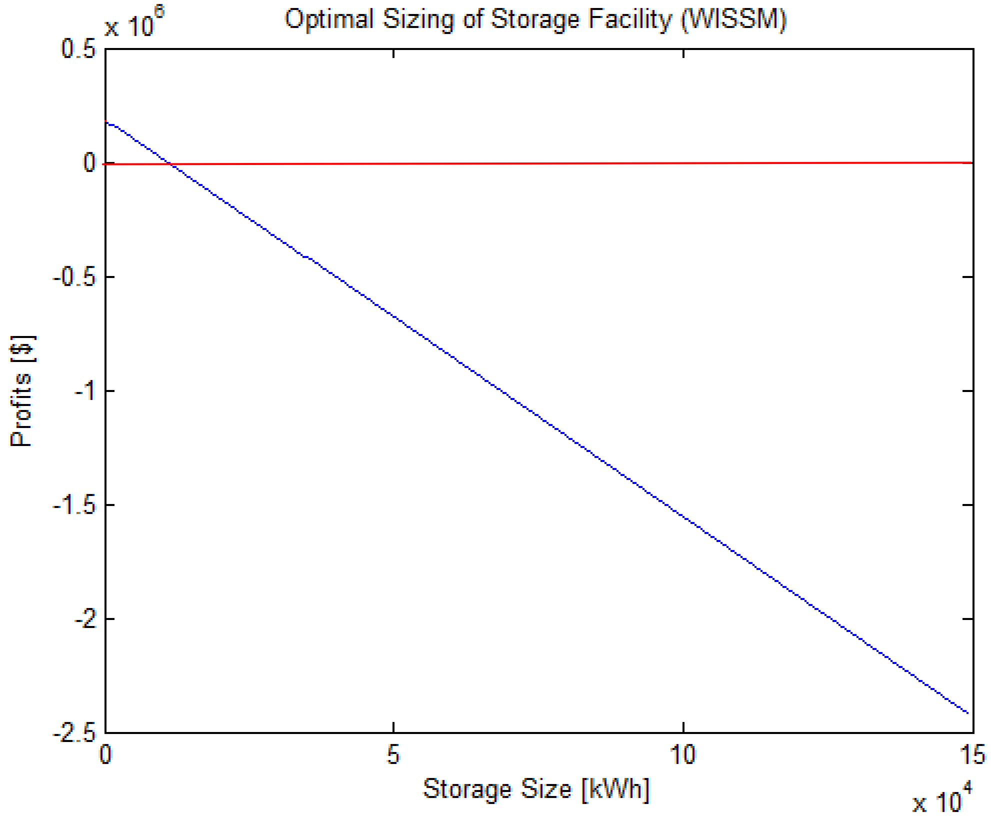


Figure 14: Sensitivity Analysis Results for Sizing of WISSM

By removing the potentially bad wind data from the analysis, the SASSM should produce results that indicate the profitability of the storage system. The results of the SASSM sizing sensitivity analysis are similar to the results of the WISSM sizing results. Again, the profitability of the system is hindered due to the dominant costs of the CAES system. Figure 15 shows the results of the sizing sensitivity analysis on the SASSM. Unlike the WISSM, there exists no positive profit in the SASSM results. This is due to the removal of the potentially profitable wind farm from the system. The negative profits rendered from this analysis show that the costs of CAES must be reduced in order for this technology to be profitable. Our analysis has also shown that the cost figure is dominated by the capital costs of the system and not the operating/fuel costs.

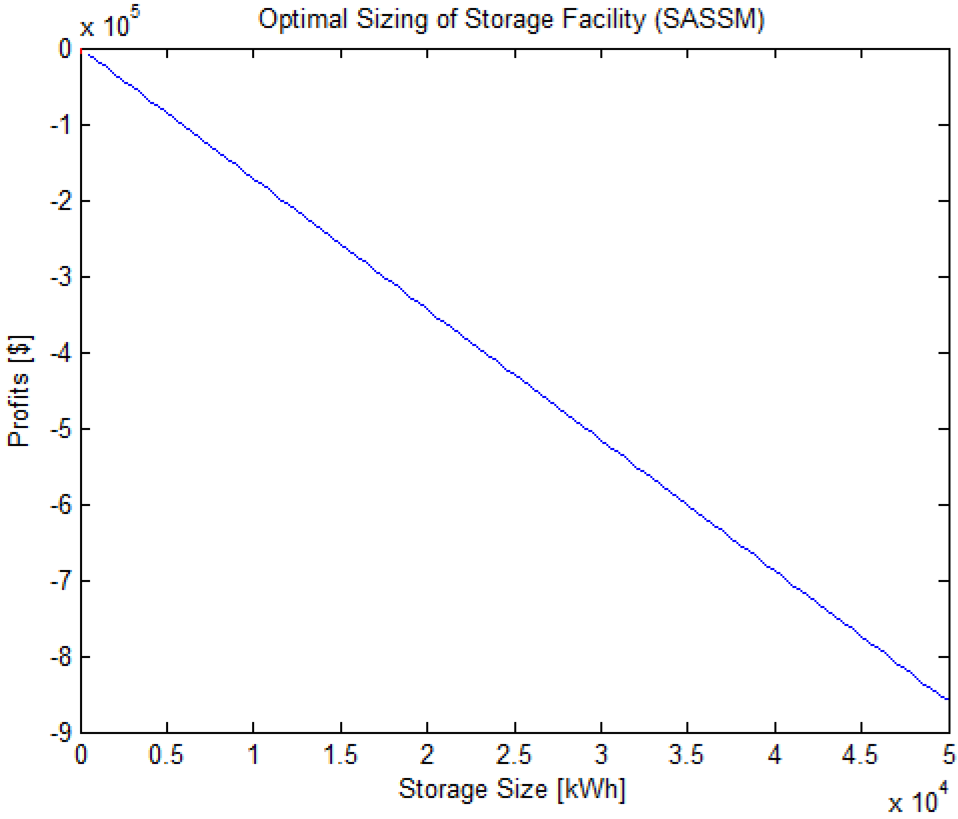


Figure 15: Sensitivity Analysis Results for Sizing of SASSM

4.2 CO_2 Outputs

Below are the carbon emissions for a wind turbine and co-located CAES system and two different natural gas generators [42] [14].

Table 4: Carbon Emissions

Carbon emissions (lbs/kWh) for integrated wind-storage system and conventional generation sources in PA	
Component	GHG emissions rate (lbs CO2/kWh)
Wind turbine with CAES storage (2MW)	0.00050
Natural Gas (NG) Turbine Generator	0.00134
Combined Cycle NG (CCNG)	0.00087

4.3 Policy Suggestions

As the penetration of intermittent renewable electricity generation increases, storage becomes a necessary asset to ensure reliability. In order to make these renewable energy storage solutions viable, policy must be established to account for the real cost of nonrenewable energies. This includes the development of emissions penalties that reflect the environmental costs, subsidies for the installation cost of new storage facilities, and mandates that require the installation of storage in conjunction with new wind turbines. If these policies can be established, nonrenewable generation methods will face increased costs, which will increase electricity prices and improve the competitiveness of renewable energy storage.

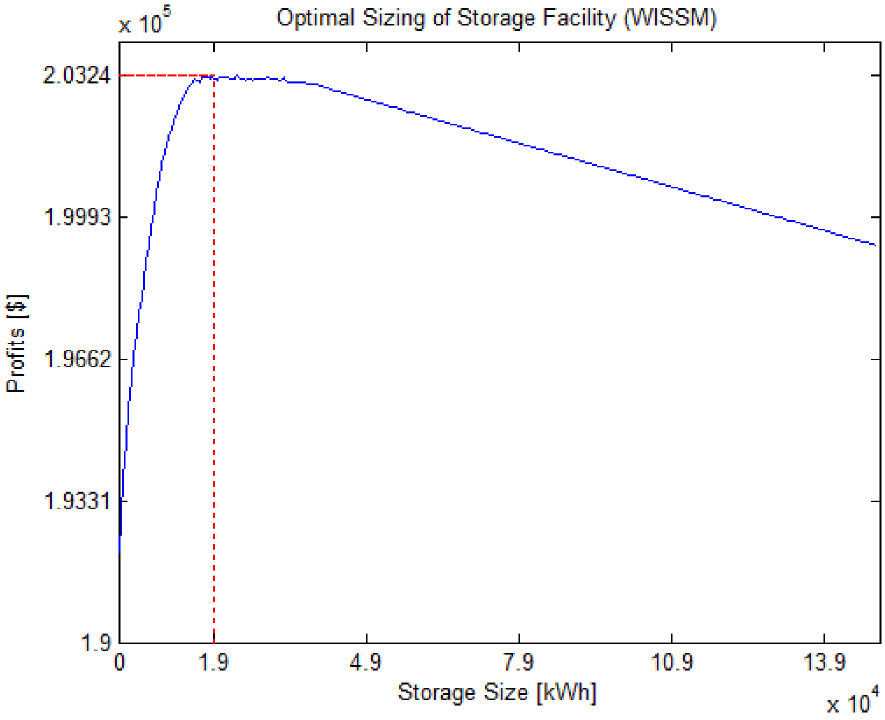


Figure 16: Optimal Sizing of WISSM under Reduced Costs

By reducing the costs associated with the CAES facility we are able to size the storage facility to optimize profits of the WISSM. The results in Figure 16 indicate that the storage facility should be sized at 19MWh per installed 2MW wind turbine, or 950MWh in the case of our 100MW Greenfield wind installation.

Figure 17 shows that under the reduced cost structure the optimal storage system sizing for the SASSM is 32MWh per 2MW of installed wind generation.

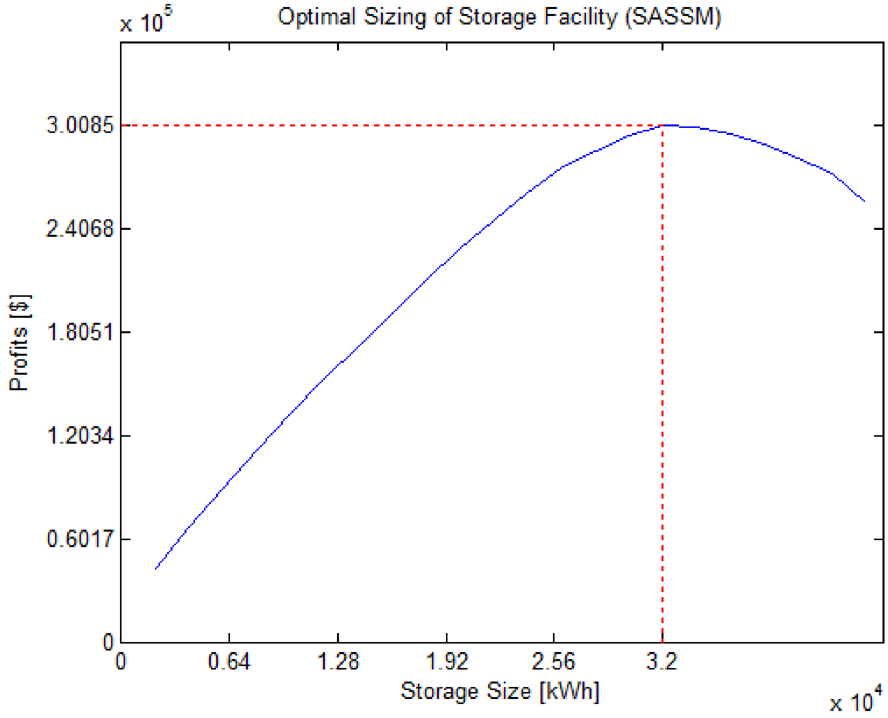


Figure 17: Optimal Sizing of SASSM under Reduced Costs

5.0 Conclusion

The survey of storage technologies and their application in Pennsylvania (PA) were explored to better understand the current and future energy storage potential in PA and the use of storage with intermittent renewable energy. Compressed Air Energy Storage (CAES) and Pumped-hydro storage (PHS) were selected as suitable storage technologies in PA since there are pre-existing PHS sites generating positive revenues and both are scalable to utility-size electricity production. Northern PA was chosen as a case study for a 100 MW Greenfield site due to its geographic location. The site was chosen as an area with 'good' wind characteristics (rating 2-4) and close proximity to salt domes and caverns necessary for storing compressed air. Storing energy via an existing PHS site is also a currently viable option for PA. However, the land requirements, costs and watershed issues associated with building new reservoirs limits the future for PHS in PA. The scale of CAES and number of geologic locations that are suitable makes CAES the most promising energy storage technology for PA.

The inherent variability of wind requires energy storage to allow for dispatchable electricity production. We concentrated on energy storage for the 100 MW Greenfield site. We developed two models to analyze profitability with respect to various storage facility sizes. The first assessed a wind-integrated storage system (WISSM) and the second examined a stand-alone storage system (SASSM). Our goal was to determine maximum profits for a given storage size. Revenues included energy output, electricity prices and total cost. WISSM incorporated wind variability into profit maximization and SASSM investigated optimal profits for a stand-alone storage site. PHS characteristics were reflected in the energy output and time cycle for running the storage unit, but CAES was used as the template storage technology because it was our preferred technology for new installations. Analyzing the economic feasibility for WISSM showed that revenues are linearly decreasing and at no point does storage increase profits. Analysis of SASSM decoupled the wind generation from the storage, demonstrating that the storage facility itself was not profitable. We assumed constant fuel price ($7/ million BTU) with a capital cost ($700/kWh) and varying electricity prices. Capital costs proved to be the most influential variable affecting total profits.

In order for storage to become profitable, mandates or subsidies would be necessary. We suggest a mandate that would require storage to be built in conjunction with utility-scale wind farms, mitigating wind variability and ensuring reliability of the electrical system. Subsidies would also incentivize investment in storage because capital costs would be reduced. A carbon tax was also considered because it seeks to reduce carbon emissions while promoting renewable energy. A wind-integrated storage system benefits from a carbon tax because the emissions from wind generation are substantially less than fossil-fuel based generation. Carbon taxes increase the costs of generation from fossil fuels; thus, the price of electricity will increase. Increased electricity prices will increase the profits of wind generators and promote investments.

This project provided a solid foundation into investigating how intermittent technology can theoretically benefit from energy storage. More accurate wind data (at 80 meters) would enhance the model output and allow us to size an energy storage facility that would obtain maximum profits. Other parameters, such as fuel price, may be varied to reflect a more accurate analysis of total profits for WISSM or SASSM. More precise data and variable parameters (energy output and cost figures) affecting total profits would greatly improve and extend this study to better understand how intermittent power generation sources coupled with energy storage can provide reliable electricity in PA.

6.0 Appendix A – Levelized Costs of Energy Calculations

$$\frac{Capital\ cost/kW}{Energy * Life * CapacityFactor} = \left[\frac{\$}{kWh}\right]$$

PHS:

$$\frac{\$1600/kW}{300\left[\frac{\cancel{cycles}}{\cancel{yr}}\right]*10\left[\frac{hr}{\cancel{cycle}}\right]*70[\cancel{yrs}]*0.75} = \$\mathbf{0.01016/kWh}$$

CAES:

$$\frac{\$700/kW}{300\left[\frac{\cancel{cycles}}{\cancel{yr}}\right]*10\left[\frac{hr}{\cancel{cycle}}\right]*40[\cancel{yrs}]*0.80} + fuel\ cost = \frac{\$0.00729}{kWh} + \frac{\$0.0266}{kWh} = \$\mathbf{0.0339/kWh}$$

Wind: with capacity factor of 35%.

$$\frac{\$1600/kW}{365\left[\frac{\cancel{cycles}}{\cancel{yr}}\right]*24\left[\frac{hr}{\cancel{cycle}}\right]*0.35*20[\cancel{yrs}]} = \$\mathbf{0.0261/kWh}$$

Coal:

$\$0.0304/kWh + \cancel{\$0.0047/kWh} + \$0.0145/kWh = \$\mathbf{0.0449/kWh}$
Capital O&M Fuel
Source: EIA

Natural Gas Non-Peaking:

$\$0.0114/kWh + \cancel{\$0.0014/kWh} + \$0.0266/kWh = \$\mathbf{0.0380/kWh}$
Capital O&M Fuel
Source: EIA

Natural Gas Turbine Peaking Plant:

$0.565/kWh for the total cost including Fuel and O&M
Breaking this down a bit gives:
$\$0.36/kWh + \$0.0266/kWh = \$\mathbf{0.387/kWh}$
Capital Fuel
Using $15/MCF = $14.59/MMBtu

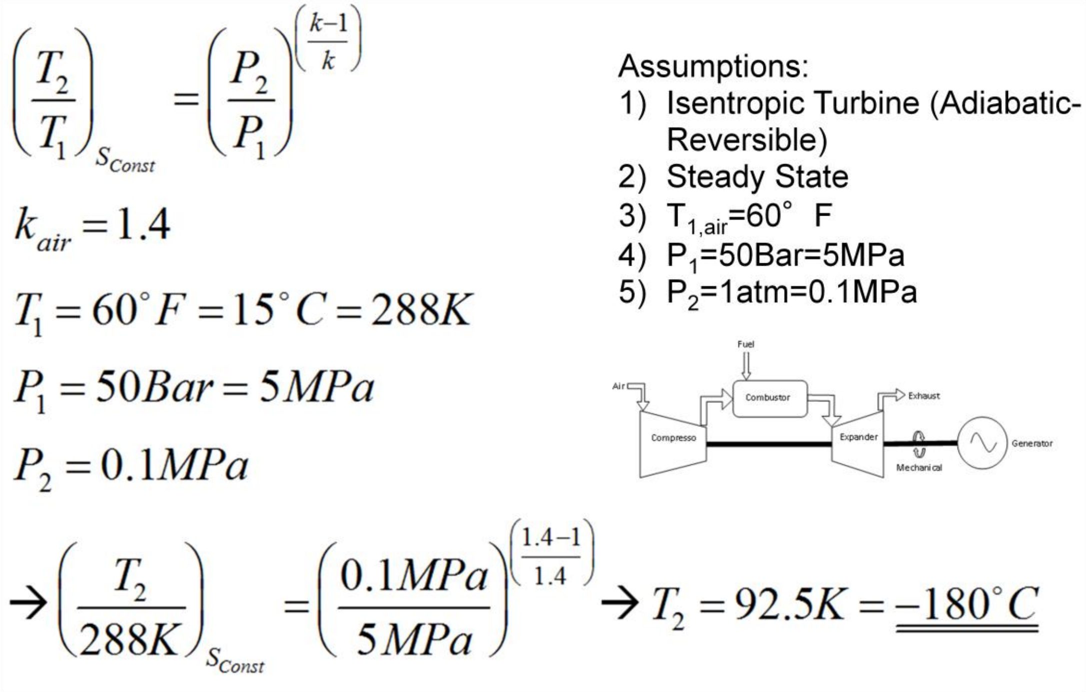
Source: The Costs, Air Quality, and Human Health Effects of Meeting Peak electricity Demand with Installed Backup Generators. By Gilmore et.al. 21 Oct 2006

NOTE: Cost of Natural Gas Fuel

The cost of Natural Gas for the CAES, Natural Gas Peaking, and Natural Gas Non-Peaking is based on the most recent price of Natural Gas reported by the EIA at the end of 2008 of about $8/1000ft^3. This price will most likely increase over time resulting in an even shorter payback period for renewable options.

$$\frac{\$8}{1000ft^3} * \frac{1ft^3}{1027Btu} * \frac{3412Btu}{kWh} = \$\mathbf{0.0266/kWh}$$

7.0 Appendix B – Thermodynamic Calculations



$$\left(\frac{T_2}{T_1}\right)_{S_{Const}} = \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right)}$$

$$k_{air} = 1.4$$

$$T_1 = 60^\circ F = 15^\circ C = 288K$$

$$P_1 = 50Bar = 5MPa$$

$$P_2 = 0.1MPa$$

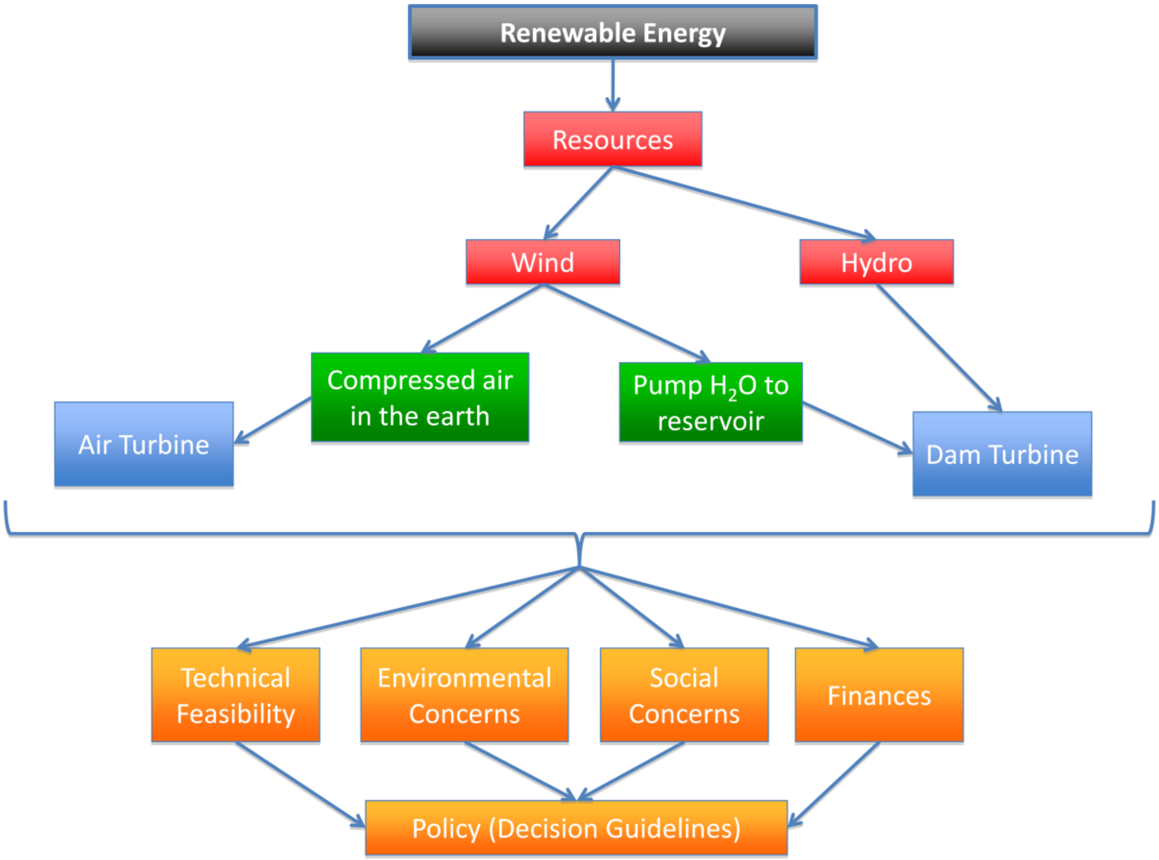
Assumptions:

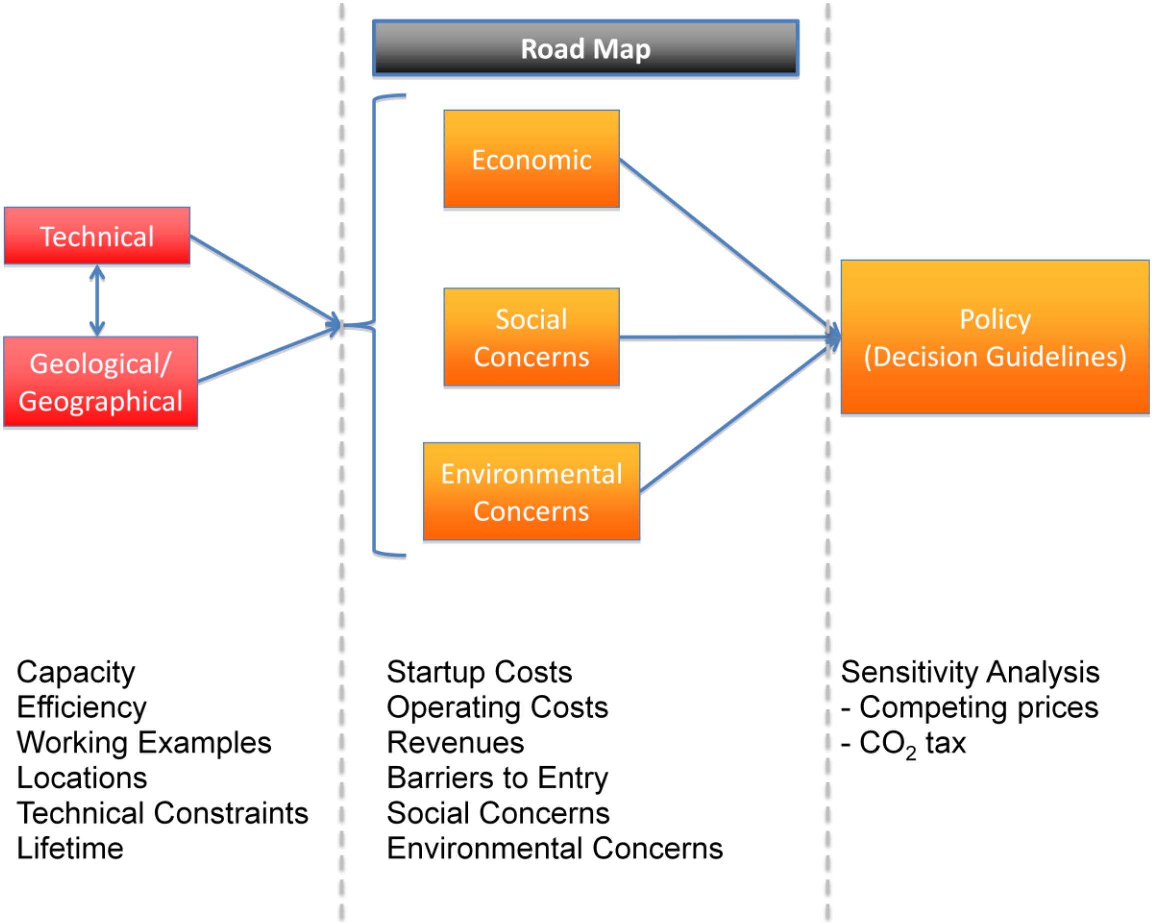
1) Isentropic Turbine (Adiabatic-Reversible)
2) Steady State
3) $T_{1,air}$=60° F
4) P_1=50Bar=5MPa
5) P_2=1atm=0.1MPa

$$\rightarrow \left(\frac{T_2}{288K}\right)_{S_{Const}} = \left(\frac{0.1MPa}{5MPa}\right)^{\left(\frac{1.4-1}{1.4}\right)} \rightarrow T_2 = 92.5K = \underline{\underline{-180^\circ C}}$$

8.0 Appendix C – Concept and Road Maps and Gantt Chart

The following concept and road maps and Gantt chart were guides used during the preliminary steps of this research project. They do not necessarily reflect the final methods and results presented in this paper.





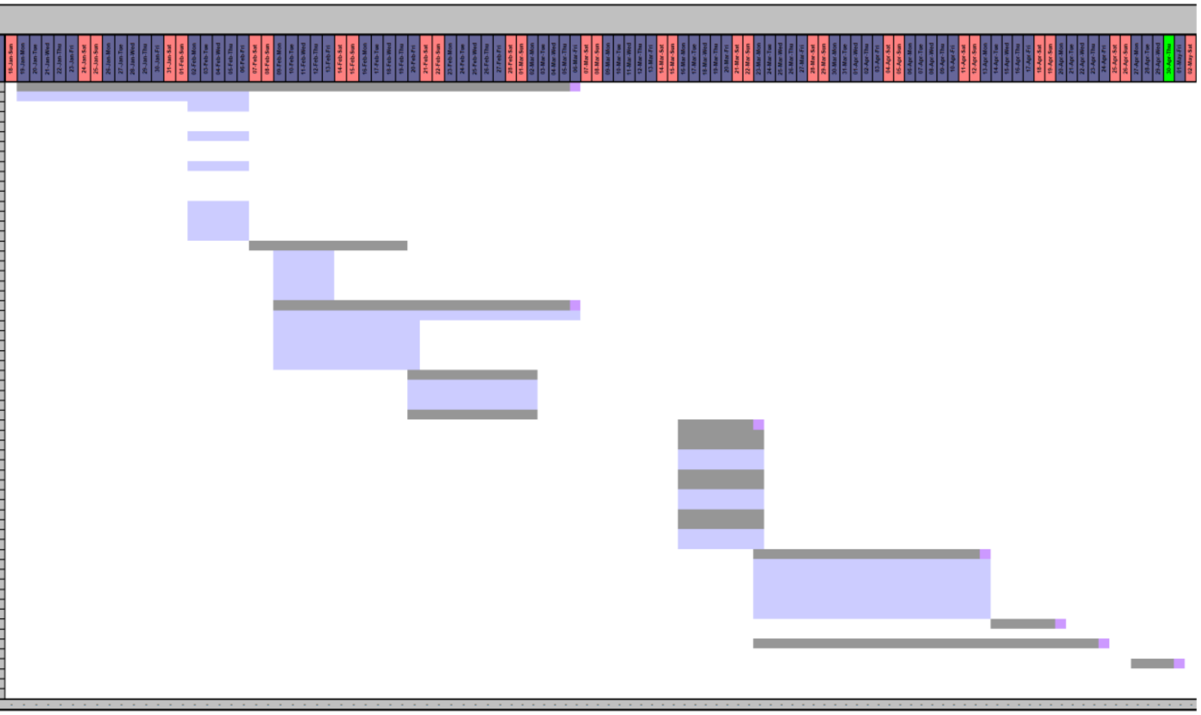
Capacity
Efficiency
Working Examples
Locations
Technical Constraints
Lifetime

Startup Costs
Operating Costs
Revenues
Barriers to Entry
Social Concerns
Environmental Concerns

Sensitivity Analysis
- Competing prices
- CO_2 tax

EME 580 - Storage Team Gantt Chart

Task Level	WBS	Tasks	39895	End dd/mmm mm/dd/yyyy	Calendar Days	Exclude Weekends	Gantt Color	Status
1	**1**	**Literature Review**	**19-Jan-Mon**	**06-Mar-Fri**	**47**	**35**	x	
2	**1.1**	**Ruled Out Alternatives**	**19-Jan-Mon**	**06-Feb-Fri**	**19**	**15**	.	-
3	1.1.1	Solar	02-Feb-Mon	06-Feb-Fri	5	5	.	-
4	1.1.1.1	Thermal and Molten Salt					.	
4	1.1.1.2	PV and Batteries					.	
3	1.1.2	Geothermal	02-Feb-Mon	06-Feb-Fri	5	5	.	-
4	1.1.2.1	Ground Source					.	-
4	1.1.2.2	Direct Heat					.	
3	1.1.3	Hydro	02-Feb-Mon	06-Feb-Fri	5	5	.	
4	1.1.3.1	Wave					.	
4	1.1.3.2	Tide					.	
4	1.1.3.3	River					.	
3	1.1.4	Biofuels	02-Feb-Mon	06-Feb-Fri	5	5	.	
3	1.1.5	Super Conductors	02-Feb-Mon	06-Feb-Fri	5	5	.	
3	1.1.6	Super Capacitors	02-Feb-Mon	06-Feb-Fri	5	5	.	
3	1.1.7	Flywheels	02-Feb-Mon	06-Feb-Fri	5	5	.	
2	**1.2**	**Selected Alternatives**	**07-Feb-Sat**	**19-Feb-Thu**	**13**	**9**	..	
3	1.2.1	Wind	09-Feb-Mon	13-Feb-Fri	5	5	.	
3	1.2.2	Hydro	09-Feb-Mon	13-Feb-Fri	5	5	.	
4	1.2.2.1	Current Resource	09-Feb-Mon	13-Feb-Fri	5	5	.	
4	1.2.2.2	Pumped Storage Hydro	09-Feb-Mon	13-Feb-Fri	5	5	.	
3	1.2.3	CAES	09-Feb-Mon	13-Feb-Fri	5	5	.	
1	**2**	**Engineering Analysis**	**09-Feb-Mon**	**06-Mar-Fri**	**26**	**20**	x	
2	**2.1**	**Technical Feasibility**	**09-Feb-Mon**	**06-Mar-Fri**	**26**	**20**	.	
3	2.1.1	Capacity	09-Feb-Mon	20-Feb-Fri	12	10	.	
3	2.1.2	Efficiencies	09-Feb-Mon	20-Feb-Fri	12	10	.	
3	2.1.3	Working Examples	09-Feb-Mon	20-Feb-Fri	12	10	.	
3	2.1.5	Technical Constraints	09-Feb-Mon	20-Feb-Fri	12	10	.	
3	2.1.6	Lifetime	09-Feb-Mon	20-Feb-Fri	12	10	.	
2	**2.2**	**Environmental Feasibility**	**20-Feb-Fri**	**02-Mar-Mon**	**11**	**7**	..	
3	2.2.1	Locations	20-Feb-Fri	02-Mar-Mon	11	7	.	
4	2.2.1.1	Geology	20-Feb-Fri	02-Mar-Mon	11	7	.	
4	2.2.1.2	Geography	20-Feb-Fri	02-Mar-Mon	11	7	.	
2	**2.3**	**Social Concerns**	**20-Feb-Fri**	**02-Mar-Mon**	**11**	**7**	..	
1	**3**	**Economic Analysis**	**16-Mar-Mon**	**23-Mar-Mon**	**8**	**6**	x	
2	**3.1**	**Startup Costs**	**16-Mar-Mon**	**23-Mar-Mon**	**8**	**6**	..	
3	3.1.1	Wind	16-Mar-Mon	23-Mar-Mon	8	6		
3	3.1.2	Pumped Storage Hydro	16-Mar-Mon	23-Mar-Mon	8	6	.	
3	3.1.3	CAES	16-Mar-Mon	23-Mar-Mon	8	6	.	
2	**3.2**	**Operating Costs**	**16-Mar-Mon**	**23-Mar-Mon**	**8**	**6**	..	
3	3.2.1	Wind	16-Mar-Mon	23-Mar-Mon	8	6		
3	3.2.2	Pumped Storage Hydro	16-Mar-Mon	23-Mar-Mon	8	6	.	
3	3.2.3	CAES	16-Mar-Mon	23-Mar-Mon	8	6	.	
2	**3.3**	**Revenues**	**16-Mar-Mon**	**23-Mar-Mon**	**8**	**6**	..	
3	3.3.1	Wind	16-Mar-Mon	23-Mar-Mon	8	6		
3	3.3.2	Pumped Storage Hydro	16-Mar-Mon	23-Mar-Mon	8	6	.	
3	3.3.3	CAES	16-Mar-Mon	23-Mar-Mon	8	6	.	
1	**4**	**Barriers to Entry**	**23-Mar-Mon**	**13-Apr-Mon**	**22**	**16**	x	
2	**4.1**	**Land Costs**	**23-Mar-Mon**	**13-Apr-Mon**	**22**	**16**	.	
2	**4.2**	**Competition**	**23-Mar-Mon**	**13-Apr-Mon**	**22**	**16**	.	
3	4.2.1	Current Energy Profile of PA	23-Mar-Mon	13-Apr-Mon	22	16	.	
3	4.2.2	Sensitivity	23-Mar-Mon	13-Apr-Mon	22	16	.	
4	4.2.2.1	Competing Prices	23-Mar-Mon	13-Apr-Mon	22	16	.	
4	4.2.2.2	CO2 Tax	23-Mar-Mon	13-Apr-Mon	22	16	.	
1	**5**	**Policy (Descision Guide)**	**14-Apr-Tue**	**20-Apr-Mon**	**7**	**5**	x	
4								
1	**6**	**Revisions**	**23-Mar-Mon**	**24-Apr-Fri**	**33**	**25**	x	
2							.	
1	**7**	**Final Oral Examination (Individual)**	**27-Apr-Mon**	**01-May-Fri**	**5**	**5**	x	
3								
3								
3							.	



XL Gantt

Project Title:	EME 580 - Storage
Project Manager:	Alisha, Brian, Clayton, Luke
Company:	Penn State University
Client:	
Last Update Date:	
Template Version:	XL-EasyGantt V2.4
Notes:	

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