DESIGN OF A WATER TOWER ENERGY STORAGE SYSTEM

A Thesis
Presented to
The Faculty of Graduate School
University of Missouri - Columbia

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
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MAY 2013
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ACKNOWLEDGEMENT

I would like to express my appreciation to my thesis advisor, Dr. Noah Manring, for his constant guidance, advice and motivation to overcome any and all obstacles faced while conducting this research and support throughout my degree program without which I could not have completed my master’s degree. Furthermore, I extend my appreciation to Dr. Roger Fales and Dr. Robert O’Connell for serving on my thesis committee. I also would like to express my gratitude to all the students, professors and staff of Mechanical and Aerospace Engineering department for all the support and helping me to complete my master’s degree successfully and creating an exceptional environment in which to work and study.

Finally, last, but of course not the least, I would like to thank my parents, my sister and my friends for their continuous support and encouragement to complete my program, research and thesis.
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ABSTRACT

This project is aimed at supporting the Mizzou Advantage strategic initiative in the area of Sustainable Energy. In particular, the project focuses on preparatory studies that will enable us to compete for national funding and recognition in the area of renewable energy resources.

The design and analysis of this project describes an idea for storing hydroelectric energy in municipal water towers that exist in abundance throughout the United States. The primary advantage of this idea is that it reduces the capital cost of construction to near about $200 per kWh. The second advantages include the ability to use renewable energy for providing municipal water pressure, and to leverage other common attributes that exist between water pressure and hydroelectric energy storage. Technical analysis shows that more than 2.05 GW of power can be stored and delivered throughout the United States using this method, which is the amount of power generated by a Hoover Dam!
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LIST OF VARIABLES

\( A \)  Area of water tower

\( d \)  Diameter of water tank

\( E \)  Energy storage capacity

\( g \)  Acceleration due to gravity

\( h_p \)  Height of the water tower

\( h_s \)  Height of the water level in water tank

\( N_p \)  Number of people

\( P \)  Pressure

\( P_{in} \)  Power input to the electric motor

\( Q \)  Flow rate

\( Q_{in} \)  Flow rate of water at inlet of water tank

\( Q_{power} \)  Flow rate of water supply to water turbine to generate electricity

\( Q_{use} \)  Flow rate of water supply for municipal purpose

\( t \)  Time

\( V \)  Volume of the water tank

\( V_{in} \)  Volume of water supplying to water tank

\( V_{use} \)  Volume of water used for municipal purpose

\( V_{power} \)  Volume of water used for power generation

\( \rho \)  Density of water
CHAPTER 1. INTRODUCTION

1.1 Background and Motivation

In an address to the nation in 1979, U.S. President Jimmy Carter impressed upon Americans, “The energy crisis is real. It is worldwide. It is a clear and present danger to our nation. These are facts and we simply must face them.” Thirty years later, the facts have taken on a harsher reality, and the energy landscape remains in constant turmoil and debate. Today, 85% of the energy consumed in the U.S. is produced from nonrenewable fossil fuels [1]. The U.S. imports 57% of its energy sources, 50% of the imports being from politically volatile countries in the Middle East, and the Energy Information Administration (EIA) projects that global energy consumption will have increased 44% by 2030 [2].

Moreover, while giving a campaign speech in New Hampshire in 2008, President Obama challenged the crowd, "…we can decide that solving our energy crisis will be one of the great projects of this generation." A change in the way the United States thinks and invests in energy is absolutely necessary, though the exact solution is unknown.

According to the national agenda for renewable energy that there is the desire to increase wind power from 3.5% to 20% by 2030. By this increase in percentage of renewable energy, the United States will achieve targeted regional economic development, enhance our power generation options, protect the local environment, and increase our energy and national security.

Even though Missouri is the nation’s largest importer of coal per capita and even though Missouri operates one of the 104 licensed nuclear reactors in the country, it is
poor in energy. In addition, the American Wind Energy Association has ranked Missouri’s wind resource 13th in the nation, and according to the National Renewable Energy Lab, these wind resources could provide over 9 times the state's current electricity needs. Moreover, the wind project in Missouri currently online is 459 MW [3]. The National Climate Data Center for the US Department of Commerce [4] identifies Missouri as only receiving 60% of the maximum annual amount of sunshine possible (Arizona receives 90%). Although Missouri has significant biomass resources, Forbes magazine has named North Dakota, Iowa, Mississippi, Georgia and North Carolina as the top five states for producing biomass feedback [5]. Missouri is not in the list. Again, the top 20 states for existing wind capacity include 4 of Missouri's neighbors, but not Missouri. In short, if the Midwest (and Missouri particular) is going to participate in the renewable energy agenda for the nation, we must find our renewable-energy niche and capitalize on our Midwest strengths. As an energy poor state, we believe our primary opportunities for leadership are in the area of utility-scale Energy Storage which is a critical technology for increasing the penetration of renewable energy.

According to Energy Information Administration Financial Statistics of Major U.S. Investor-Owned Utilities, the cost of hydroelectric is less that the cost of nuclear steam, fossil-fueled steam and Gas-turbine. The graph is shown in Figure 1-1. Thus, hydropower is more economical than the other energy storage options, and this is the main reason to give more importance and support to hydroelectric storage systems in this project which is definitely going to reduce the cost of energy storage system.
1.2 The Future of Wind Power in Missouri

Wind systems are ideal when used in conjunction with other power sources. Wind power systems can serve as a preferred source of power and can be “backed up” by conventional fossil fuel systems during times when winds are low. This strategy can be used to reduce current levels of fossil fuel use and conserve this finite resource while reducing the associated environmental issues inherent with fossil fuel systems.

Wind power systems have several advantages over other energy sources. The wind available worldwide as it is the product of natural global processes which will not run out like fossil fuels and so called renewable energy. Moreover, wind power is a clean source of power and operates without producing the air and water pollution associated with fossil fuels [6]. In 2002, the United States produced 52% of its electrical power needs by burning coal. In 1999 the state of Missouri derived 84% of electrical needs from
burning coal [7]. For Missouri almost all of this coal is imported from other states. Wind however, is available more near to the northwest area of the Missouri as shown in the Figure 1-2. The green area in the Figure shows that there is more wind speed availability than the white area at 50m height. Development of wind power would enable Missouri to retain a portion of the dollars sent to other states to purchase coal. In 1997 Missouri spent more than 635 million dollars importing coal to the state. The capital costs of wind turbines are much lower in the range of 5 to 6 cents per kilowatt-hour which is about 2 cents cheaper than coal fired electricity [8, 9]. So even if we spend some money locally produced energy sources, such as wind power, the benefit to Missouri’s economy could be significant.

Figure 1-2. Wind Availability in Missouri [7]
Developing wind power along with other clean power systems would allow Missouri to burn less coal. Missouri produces twice as much carbon dioxide as most of our neighboring states as a result of our higher state population and heavy reliance on coal [6]. Thus, if we enhance the production of wind energy, we could reduce the emissions of carbon dioxide according to the American Wind Energy Association [10].

1.2.1 Necessity of Storing Wind Energy

A common example of energy storage, the battery, which stores convertible chemical energy, can be found in many electronic devices. Other examples include hydroelectric dams storing gravitational potential energy, ice storage tanks storing thermal energy, and fossil fuels storing ancient energy from sunlight [11]. Perhaps one of the most important methods of energy storage, and the least thought of, is the energy stored in food. Energy storage is an integral part of living and integrating an effective storage method into wind energy operation is the step missing along the path to 20% wind capacity by 2030.

Wind energy, a clean and renewable energy source, is one of the most rapidly growing markets, increasing its presence in United State’s power generation portfolio by 51% in 2008, yet it still represents only 1.26% of all power generated [12]. New innovations within the industry and the domestic availability of the "fuel" has made wind only second to natural gas in terms of new power generation capacity added since 2005, as illustrated in Figure 1-3 [12]. Thus, it is necessary to store this wind energy which is available in abundant manner.
1.2.2 Benefits of Wind Energy Storage

The problem of wind speed variability and intermittence stands to be rendered obsolete by an effective storage application. Although prior to wind farm placement, the wind schedule, or regime, in a proposed site is meticulously modeled to the extent that wind pattern variation can be predicted within a 95% confidence interval [11]. The real benefit that can be derived from the storage of wind energy is when high wind speed does not coincide with high load demand. It is typical for average wind speed to be higher at night when load demand is lower [13]. Storage provides a practical solution to decrease variability from wind turbines by providing a means for storing excess energy and then restoring that energy to the grid when the wind turbine output drops off or load demand is higher than the output can serve. From the perspective of the wind operator, or the energy supplier to the grid, the day-ahead wind output commitment required by operators is more easily fulfilled. A stable source of supply is available to supplement the wind energy output, or lack thereof. From the demand side, or grid operator, the load is
balanced and demand is served. Periods of negative electricity prices can be reduced by the availability and usability of storage technology. Negative energy prices are not sustainable for long periods of time, yet they are a frequent occurrence as power companies producing renewable electricity refuse to shut down production even when supply is greater than load demand [13]. Why would power producers be willing to pay people to take electricity? As discussed earlier, owners of wind farms, and other renewable power sources, receive production tax credits provided by the government in the American Recovery and Reinvestment Act of 2009. Producers receive 2.1 cents per kWh of the electricity they generate from the government [14]. As long as the cost per kWh they are paying their customer to use the electricity is less than the government subsidy, the renewable producers make money. Having storage capabilities would allow producers to continue to generate electricity, earning the government subsidy, but save the power until it can be sold during times of high load demand instead of being needlessly wasted [14].

1.3 Midwest Energy Generation

There have been a number of studies of the availability of wind power across the United States. Most of these studies have concentrated on the wind at various heights which is useful for energy generation for wind turbines [15, 16]. The National Renewable Energy Laboratory has analyzed the wind climatology at advanced turbine hub heights based in data measured in existing tall towers in Central United States like in Kansas, Indiana, Minnesota and concluded that at the level of 50-100 m tall towers the wind in these are controlled by the strong southerly winds and with significantly higher shear exponent which is 0.143. The common range for shear exponents in 0.2-0.23; for
windiest sites, it is slightly lower from 0.18-0.20. This helps to prove beneficial to wind energy generation in the Midwest [15]. At levels closer to the earth’s surface, particularly in more urban areas, there is much more variability in wind speed as the influence of obstructions on wind flow and turbulence is significant. Therefore assessment of the impact of urban site selection on wind power generation performance is critical when considering implementation of local energy storage and utilization.

For Missouri the wind power resource is poorer than adjoining areas to the north and west, which means that Iowa and Kansas, in particular, have a competitive advantage because of having more wind availability compare to Missouri so they have more facilities for the development of large wind turbine [15]. Wind farms have been constructed in the northwest of the State of Missouri where good wind resources exist in areas adjacent to major transmission lines. On the other hand, southwest and mid-Missouri, in common with numerous areas nationwide, have a wind regime that can be exploited for smaller-scale applications as long as the energy can be stored and used when required.

The general spatial and temporal patterns of energy availability can be assumed from previous studies, and these show that in Missouri winds are strongest at night and through the cool season (November - May) [16, 17]. In general these are the times at which both energy and water consumption are low and this suggests that effective energy storage at the local level is an appropriate approach to maximizing the benefit of renewable installations. The wind patterns are also complementary to the solar power potential that is obviously at its best during the summer and daylight hours.
In order to accurately ascertain the impact of obstructions and surface conditions on the available energy that can be obtained by a wind turbine it is necessary to observe the wind at a representative location and height. Using the frequency distribution of wind speed observed it is then possible to calculate the output of different turbines based on their rating curves and find which produces the greatest energy per unit cost.

Therefore the aim is to determine the typical renewable energy resource available from wind source at a typical urban location. From this data we can assess the optimal configuration of wind energy generation that to the potential storage facilities. Using this information we would be able to calculate the cost per kWh of energy produced.

1.4 Midwest Energy Storage

Storage technologies provide synergies with wind power either by shifting electricity from periods of low demand to those of higher demand, or by damping out fluctuations in output. This process helps reduce stresses on other plants that would otherwise have to ramp up and down to compensate for the variations from the wind farms. The more wind installed in a system, the more valuable storage becomes—at higher penetrations, wind variations are larger and there is less balance-of-system to compensate [18]. According to the National Renewable Energy Laboratory (NREL), building the energy storage technologies have the important role for the successful renewable-energy [18]. This is due to the fact that renewable energy is produced in a stochastic manner and does not necessarily coincide with peak consumer demand. In other words, renewable energy that is produced during off-hours must be stored and delivered at a time when it is needed.
1.4.1 Previous and Existing Work

There are some previous energy storage solutions available to store the energy for some period of time so that is useful during the period when it is needed. Nowadays, there are different renewable energy storage technologies available or at an advanced stage of development, demanded by a new range of energy storage applications. These energy storage technologies are classified into two main categories, based in their discharge time.

1.4.1.1 Short-Term Discharge Energy Storage Devices

Short-term discharge energy storage device should be used to aid power systems during the transient period after a system disturbance, such as line switching, load changes and fault clearance.

Short-term discharge energy storage device use to getting common in power systems with important renewable energy penetration (like wind, for instance) and weak interconnections or in islands, avoiding temporary faults and contributing to the provision of important system services such as momentary reserves and short-circuit capacity [19]. The main short term discharge energy storage devices and their operation are presented below.

a) Flywheels

Flywheels store kinetic energy in a rotating mass. Such equipment has typically been used as short-energy storage devices for propulsion applications such as powering train engines and road vehicles, and in centrifuges. In these applications, the flywheel smoothes the power load during deceleration by dynamic braking action and then
provides a boost during acceleration [20]. Figure 1-4 shows the operating of a flywheel energy storage system.

Figure 1-4. Flywheel energy storage device operation diagram [59]

Flywheels store energy by accelerating a massive rotating cylinder to a high speed and maintaining that energy within the system as rotational energy. Operated in a low vacuum casing to reduce drag, the accelerating torque causes a flywheel to increase speed and store energy, while a decelerating torque causes a flywheel to slow down and energy to be extracted by the laws of energy conservation [21]. An example of a modern flywheel can be seen below in Figure 1-5. By manipulating the rotational acceleration, the flywheel is an exceptional tool for smoothing the volatility in the intermittence of wind generation. The flywheel has many advantages. The flywheel is already a highly developed and mature technology with efficiency between 80-90%, and it boasts a charge and discharge rate of mere minutes for over 100,000 life cycles [21]. Of course, the flywheel is limited to an average of 5-30 seconds of storage time, 15 minutes for an exceptional product, and it can only store up to 10 MW of electricity as opposed to the
100-300 MW the compressed air energy storage system is capable of storing [21]. Wind energy stored at night during higher average wind speeds could not be held for the hours required to make it to peak load demand during the day when wind is more likely to be dormant.

![Flywheel Diagram](image)

Figure 1-5 Flywheel [21]

b) Supercapacitors

Supercapacitors are the latest innovative devices in the field of electrical energy storage. In comparison with a battery or a traditional capacitor, the supercapacitor allows a much more powerful power and energy density [22].

Supercapacitors are electrochemical double layer capacitors that store energy as electric charge between two plates, metal or conductive, separated by a dielectric, when a voltage differential is applied across the plates [23]. As like battery systems, capacitors
work in direct current. This fact imposes the use of electronic power systems, as presented in Figure 1-6.

Figure 1-6. Supercapacitor energy storage device operation diagram [59]

c) Magnetic Superconductor

Superconducting magnetic energy storage device store energy in the form of a magnetic field, through a direct current flowing in a superconducting coil. The alternate current from a power bus is converted to direct current and injected in the coil. When necessary, the stored energy can be released, through a direct current that is converted to alternate current and injected in the power bus [24]. The interface between the power bus and the superconducting coil uses power electronic convertors [25]. The Superconducting Magnetic Energy Storage (SMES) device operation diagram is shown in Figure 1-7.
The conductor for carrying the direct current operates at cryogenic temperatures where it behaves as a superconductor and thus has virtually no resistive losses as it produces the magnetic field. Consequently, the energy can be stored in a persistent mode, until required. The most important advantage of SMES device is that the time delay during charge and discharge is quite short. Power is available almost instantaneously and very high power output can be provided for a brief period of time [26].

1.4.1.2 Long-Term Discharge Energy Storage Devices

These storage devices known as a long-term discharge energy storage devices because of the capability to supply or absorb electrical energy during hours.

There are various long-term discharge energy storage technologies are already available today and their use is expected to rise in the next years because of the increasing integration of non-dispatchable renewable energy generation in the power
systems [27]. A brief description of the main long-term discharge energy storage technologies is presented below.

a) Batteries

A battery is a device that converts chemical energy directly to electrical energy. It consists of a number of voltaic cells; each voltaic cell consists of two half-cells connected in series by a conductive electrolyte containing anions and cations. One half-cell includes electrolyte and the electrode to which anions (negatively charged ions) migrate, i.e., the anode or negative electrode; the other half-cell includes electrolyte and the electrode to which cations (positively charged ions) migrate, i.e., the cathode or positive electrode. In the redox reaction that powers the battery, cations are reduced (electrons are added) at the cathode, while anions are oxidized (electrons are removed) at the anode. The electrodes do not touch each other but are electrically connected by the electrolyte. Some cells use two half-cells with different electrolytes. A separator between half-cells allows ions to flow, but prevents mixing of the electrolytes [28].

Batteries store energy in electrochemical form creating electrically charged ions. When the battery charges, a direct current is converted in chemical potential energy, when discharges, the chemical energy is converted back into a flow of electrons in direct current form [29]. The connection of the system to the grid, as shown in Figure 1-8, implies the use of power electronic converters in order to rectify the alternate current during the battery charge periods and to invert current drying the battery discharge periods.
Batteries are the most popular energy storage devices. However, the term battery comprises a sort of several technologies applying different operation principles and materials. And so, the distinction between two important battery concepts, electrochemical and redox-flow, is hereby emphasized.

*Electrochemical*

Electrochemical batteries use electrode both as part of the electron transfer process and store the products or reactants via electrode solid-state reactions [30].

There are a number of battery technologies under consideration for energy storage, the main being:

1) Lead acid
2) Nickel Cadmium
3) Nickel metal-hydride
4) Sodium sulphur
5) Lithium ion
Redox-Flow

Redox-flow batteries are storage devices that convert electrical energy into chemical potential energy by charging two liquid electrolyte solutions and subsequently releasing the stored energy during discharge [31].

The name redox-flow battery is based on the redox reaction between the two electrolytes in the system. These reactions include all chemical processes in which atoms have their oxidation number changed. In redox flow cell the two electrolytes are separated by a semi permeable membrane. This membrane allows ion flow, but prevents mixing of the liquids. Electrical contact is made through inert conductors in the liquids. As the ions flow across the membrane, an electrical current is induced in the conductors [32].

Over the past few years three types of redox-flow batteries had been developed up to the stage if demonstration and commercialization. These types are vanadium redox batteries (VRB), the polysulphide bromide batteries (PSB) and the zinc bromine (ZnBr) [32].

b) Compressed Air

Compressed Air Energy Storage (CAES) is a way to store energy generated at one time for use at another time. At utility scale, energy generated during periods of low energy demand (off-peak) can be released to meet higher demand (peak load) periods [33]. It is a device based on as gas turbine where the compression and the combustion processes are divided. During charging, the compressor is coupled to the electrical machine, working as a motor, compressing the air. After the compression, the air is stored into sealed underground carven. Discharging the device consists in generating power
through the coupling of the gas turbine with the electrical machine, working as generator, and supplying the stored compressed air to the combustion process [34]. A compressed air energy storage system operation diagram is presented in Figure 1-9.

Figure 1-9. Compressed air energy storage system operation diagram [59]

Three air reservoir types are generally considered: naturally occurring aquifers (such as those used for natural gas storage), solution-mined salt caverns, and mechanically formed reservoirs in rock formations. Main compressed air energy storage system implementation constraints are related with reservoirs achievement [35]. There are 3 ways in which a CAES system can deal with the heat. The air storage can be adiabatic, diabatic, or isothermal.

Adiabatic storage retains the heat produced by compression and returns it to the air when the air is expanded to generate power. The theoretical efficiency of adiabatic storage approaches 100% with perfect insulation, but in practice round trip efficiency is expected to be 70% [36, 37].

Diabatic storage dissipates the extra heat with intercoolers (thus approaching isothermal compression) into the atmosphere as waste. Upon removal from storage, the air must be re-heated prior to expansion in the turbine to power a generator which can be
accomplished with a natural gas fired burner for utility grade storage or with a heated metal mass [38].

Isothermal compression and expansion approaches attempt to maintain operating temperature by constant heat exchange to the environment [38].

c) Hydrogen Fuel Cell

A fuel cell is an energy conversion device that is closely related to a battery. Both are electrochemical devices for the conversion of chemical to electrical energy. In a battery the chemical energy stored internally, whereas in fuel cell the chemical energy (fuel and oxidant) is supplied externally and can be continuously replenished [39].

The overall reaction in a fuel cell is the spontaneous reaction of hydrogen and oxygen to produce electricity and water. During the operation of fuel cell, hydrogen is ionized into protons and electrons at the anode, the hydrogen ions are transported through the electrolyte to the cathode by an external circuit (load). At the cathode, oxygen combines with the hydrogen ions and electrons to produce water.

The hydrogen fuel cell system can be reversible, allowing electric power consumption for the production of hydrogen and that hydrogen can be stored for later use in the fuel cell [40]. The operation diagram of a hydrogen fuel cell energy storage system is presented in Figure 1-10.

Hydrogen volatility and its atoms reduced dimensions put the hydrogen storage reservoir as the critical element in this device. Last research place Metallic Hydrates as one of most efficient [41].
In the last years, hydrogen fuel cell systems become one of the most referred storage technologies to set up renewable energy integration issue. Price and charge/discharge efficiency about the 30% are its main constraints.

Figure 1-10. Hydrogen fuel cell energy storage system operation diagram [59]

d) Hydrogen Storage Technology

Hydrogen is also being developed as an electrical power storage medium. Hydrogen is not a primary energy source, but a portable energy storage method, because it must first be manufactured by other energy sources in order to be used. However, as a storage medium, it may be a significant factor in using renewable energies.

Underground hydrogen storage is the practice of hydrogen storage in underground caverns, salt domes and depleted oil and gas fields. Large quantities of gaseous hydrogen are stored in underground caverns for many years without any difficulties [42]. The storage of large quantities of hydrogen underground can function as grid energy storage.
which is essential for the hydrogen economy. By using a turbo expander, the electricity needs for compressed storage at 200 bars amounts to 2.1% of the energy content [42].

With intermittent renewable such as solar and wind, the output may be fed directly into an electricity grid. At penetrations below 20% of the grid demand, this does not severely change the economics; but beyond about 20% of the total demand, external storage will become important [43]. If these sources are used for electricity to make hydrogen, then they can be utilized fully whenever they are available, opportunistically. Broadly speaking, it does not matter when they cut in or out, the hydrogen is simply stored and used as required. A community based pilot program using wind turbines and hydrogen generators is being undertaken from 2007 for five years in the remote community of Ramea, Newfoundland and Labrador [43].

Apart from this, there are some energy losses involved in the hydrogen storage cycle of hydrogen production for vehicle applications with electrolysis of water, liquification or compression, and conversion back to electricity [44], and the hydrogen storage cycle of production for the stationary fuel cell applications like microchip at 93% [45] with biohydrogen or biological hydrogen production, and conversion to electricity.

Again, to produce a kilogram of hydrogen, about 50 kWh (180 MJ) of solar energy is required, so the cost of the electricity clearly is crucial, even for hydrogen uses other than storage for electrical generation. At $0.03/kWh, common off-peak high-voltage line rate in the United States, this means hydrogen costs $1.50 a kilogram for the electricity, equivalent to $1.50 a U.S. gallon for gasoline if used in a fuel cell vehicle [44]. Other costs would include the electrolyze plant, hydrogen compressors or
liquefaction, storage and transportation, which will be significant. Thus this method is too costly.

e) Biofuel Storage Technology

Biofuel is one of the energy storage technology in which various biofuels such as biodiesel, straight vegetable oil, alcohol fuels, or biomass can be used to replace hydrocarbon fuels. Various chemical processes can convert the carbon and hydrogen in coal, natural gas, plant and animal biomass, and organic wastes into short hydrocarbons suitable as replacements for existing hydrocarbon fuels. Examples are Fischer-Tropsch diesel, methanol, dimethyl ether, or syngas. This diesel source was used extensively in World War II in Germany, with limited access to crude oil supplies. Today South Africa produces most of the country's diesel from coal for similar reasons [46]. A long term oil price above US$35/barrel may make such synthetic liquid fuels economical on a large scale. Some of the energy in the original source is lost in the conversion process. Historically, coal itself has been used directly for transportation purposes in vehicles and boats using steam engines. And compressed natural gas is being used in special circumstances fuel, for instance in busses for some mass transit agencies [46].

f) Thermal Storage Technology

Thermal storage is the temporary storage or removal of heat for later use. An example of thermal storage is the storage of solar heat energy during the day to be used at a later time for heating at night. The thermal reservoir may be maintained at a temperature above (hotter) or below (colder) that of the ambient environment. The applications today include the production of ice, chilled water, or eutectic solution at night, or hot water which is then used to cool / heat environments during the day [47].
g) Grothe Power Tower Technology

Grothe Power Tower is a sustainable energy storage device for homes and local communities using surplus energy from solar panels and wind turbines, stored in water tower like devices, and converted by hydrogen fuel cells into electricity for nights or windless days [48].

Grothe Power Tower receives surplus energy from a renewable energy source like solar or wind through a common electrical connection. Using a hydrogen fuel cell the power is converted and stored as a gas in a water tower like device called a Grothe Power Tower. Using the same fuel cell we convert the stored energy (gas) in the power tower back into an on-demand electrical load ready for home or local community when the sun isn't shining or the wind blowing. Making the Grothe Power Tower an ideal energy storage solution for renewable energy devices [48].

h) Pumping Hydro Energy Storage

In pumping hydro energy storage, a body of water at a relatively high elevation represents a potential or stored energy. When generation is needed, the water in the upper reservoir is lead through a pipe downhill into a hydroelectric generator and stored in the lower reservoir. To recharge the storage system, the water is pumped back up to the upper reservoir and the power plant acts like a load as far as the power system is concerned [49, 51].

Pumping hydro energy storage system is constituted by two water reservoirs, an electric machine (motor/generator) and a reversible hydro pump-turbine unit. The System can be started-up in few minutes and its autonomy depends on the volume of stored water.
There are three possible configurations for the pumping hydro systems. The first one, the pure pumping hydro, corresponds to a power plant that is specifically set-up for storage, where the only turbinated/pumped water is the one stored in the upper and lower reservoirs. The second configuration corresponds to a reservoir hydro power plant, integrated in a river course, equipped with a lower reservoir and reversible pump-turbine unit. The third configuration corresponds to a cascade of hydro power plants, where some reservoirs act simultaneously like upper and lower reservoir for the different power plants [49].

In second and third configuration, the most common, the power plant operation is more complex because of the coordination of the different power plants and the reservoir inflows resultant from the river [49]. The operation of a pumping hydro system is presented in Figure 1-11.

![Diagram of Pumping Hydro System Operation](image)

Figure 1-11. Pumping hydro system operation diagram [59]
1.4.2 Power Generation System using Water Tower

A patent is available for power generation system which gives the idea of generating electricity using a water tower. The design of this system is shown in Figure 1-12 which gives the detailed orientation of the system [50].

![Diagram of power generation system using water tower](image)

Figure 1-12. Design of power generation system using water tower [50]

The heart of this design and its working principle is shown in Figure 1-13. The reservoir includes a bottom surface (21). The water tower also includes the recirculating passageway (60) friendly connected to the reservoir. This recirculating passageway includes a first end (61) connected to and located near or below the bottom surface of the reservoir, and second ends (27b) and (27c) connected to the reservoir above the bottom surface (21) of the reservoir. The reservoir also includes the water pump (63) located in the recirculating passageway (60) and configured to pump fluid through the recirculating
passageway, and fluid-driven energy generating device (41) and (42) fluidly connected to the recirculating passageway. At least a portion of fluid directed through the energy generating device is directed through the recirculating passageway. In this way, energy is generated using energy generating device and transmitted to the grids for use [50].

Figure 1-13. Working principle of power generation system [50]

The major disadvantage of the system discussed above is that the design of the system is very complicated and thus expensive. Therefore it is necessary to design a particular energy storage system which is simple in design and construction. Thus, the aim of this project is to design the water tower energy storage system which is simple, less expensive and which reduces the cost of storing electricity.

Today, the water towers are only use to store the water and supply it to the public use. In this project, the main intention is to use these available water towers as energy
storage system. The concept proposed here is most similar to pumped hydroelectricity storage; however, it does not depend upon unique geological formations nor does it require the special construction of reservoirs.

Municipal and other types of water towers may include pumps for pumping water into the water towers, but using electricity of pump the water into the water towers requires substantial expenses. At night, when the demand for water typically is less, the rates for purchasing power from the electric power grid frequently are off-peak and lower. Therefore, pumping water into the water towers during off-peak times may reduce the cost of running the pumps.

Thus, there are lots of energy storage systems available in this world but the design of the energy storage technology using the water tower is making this project innovative and different from other storage technologies as we are using these water tower itself as a storage device which will definitely save a lot of money compare to the other technologies discussed above. These water towers are already present abundantly throughout the nation and the main objective of this project is to use these water towers not only for the supply of water to municipal purpose but also for storing electricity.

Today, there is 21 GW of utility–scale electric storage in the United States, most of which is Pumped Hydroelectric Storage (PHS) like the Taum Sauk Hydroelectric Power Station in Missouri (as shown in Figure 1-12) which is capable of generating about 450 MW of electricity [52]. These energy storage resources are inadequate for achieving the long term goals of renewable energy penetration, primarily due to their cost of construction.
One of the largest economic barriers for energy storage systems (including PHS) is that their construction costs are too high per kWh. Today, a storage system costs about $1000 per kWh to build and this cost needs to be reduced to near about $200 per kWh [53]. It is believed that this technology can be developed to provide renewable energy storage solution that cost near about $200 per kWh to build.

1.5 Goals and Objectives

The primary goal of this project is a idea of storing hydroelectric energy in existed municipal water towers by the combination of the electrical and fluid power components with typical water tower system. Firstly, the overall system will be mathematically modelled and then basic components will be selected based on the requirements and calculated results.
1.6 Description of Water Tower Energy Storage System

Figure 1-15 shows a traditional water-tower with a wind turbine standing alongside. It should be noted that the wind turbine can be mounted to the top of the water tower for additional wind availability. The wind turbine represents a device that can be used for capturing renewable energy and can easily be replaced by a set of solar panels or another renewable energy source without changing the function of the wind tower. The water tower has two levels of water: 1) the water level $h_p$ is used for establishing the necessary water pressure traditionally generated by the water tower and 2) the water level $h_s$ is used to store the energy in the form of pumped hydroelectric energy.

Figure 1-15 shows the discharge water line which divides the water supply for residential and commercial purpose and for generating electricity. The bottom of the Figure shows a power management system which pumps water in and out of the tower to replenish the water supply and extract power. This power management system utilizes a hydraulic pump driven by an electric motor which is powered by a renewable energy source itself like wind turbine. The pump fills water from the reservoir into the water tower. The output side of the power management system is a water turbine that drives a single-phase electric generator. This turbine is utilized to draw hydroelectric energy from the tower during times of peak power demand. This hydroelectric energy will then supply to the power grid or to the houses. The water used for driving the turbine is then go through the water filtration system (not shown in figure) and recycled by directing its discharge flow back into the reservoir from where the pump draws its water. This closed system prevents the waste of water and contains the power management system within
the overall water-tower design. The only water leaving the system is water that is used for municipal water supply.

Figure 1-15. Water Tower Energy Storage (WTES) System
2.1 Introduction

The design of water tower energy storage system is presented within chapter 1-section 1.6. The analysis of this system is provided in this chapter which gives the electricity generation capacity of single water tower energy storage system under section 2.2. Moreover, section 2.3 and 2.4 gives the electricity generation capacity for all water towers present in Missouri and United States respectively.

2.2 Technical Analysis

The Water tower shown in Figure 1-15 will be used for preliminary analysis of this concept. In this analysis, it will be shown that both the traditional need for water pressure and the new need for energy storage can be facilitated within a single water tower system.

First, it is well known that the water pressure at the base of a traditional water-tower is directly proportional to the height of the water column in the tower. The pressure is given by,

\[ p = \rho gh \]  

(1)

Where, \( \rho \) is the density of water, \( g \) is the gravitational constant, and \( h \) is the height of the water level in the tower. If we assume that the water level above a certain height \( h_p \) is sufficient for generating the needed municipal water-pressure, then anything in excess of
$h_p$ may be used for storing hydroelectric energy. In the other words, energy may be extracted from the water level that exists above $h_p$.

Second, it can be shown that the power required to pump fluid into the water tower is given by the following expression:

$$P_{in} = \frac{dE}{dt} = pQ \quad (2)$$

Where $E$ is energy, $t$ is time, $p$ is fluid pressure at the base of the water tower, and $Q$ is the volumetric flow rate of the fluid into the tower. Following the previous discussion, the fluid pressure at the bottom of the tower is given by,

$$p = \rho g (h_p + h_s) \quad (3)$$

If we assume that the fluid is incompressible, the volumetric flow rate may be written as

$$Q = \frac{dv}{dt} = A \left( \frac{dh}{dt} \right) \quad (4)$$

Where $A$ is the cross-sectional area of the tower shown in Figure 1-15. Substituting Equations (3) and (4) into the Equation (2) produces the following expression for the amount of stored hydroelectric energy in the tower:

$$\int_0^E dE = \int_0^{h_s} \rho g (h_p + h_s)A dh_s$$

$$E = \rho g A \left( h_p h_s + \frac{1}{2} h_s^2 \right) \quad (5)$$
If we use the following values for the water tower design [58]: $\rho = 1000 \text{ kg/m}^3$, $g = 9.81 \text{ m/s}^2$, $A = 113 \text{ m}^2$ (a 12 meter diameter tank), $h_p = 40 \text{ m}$, $h_s = 10 \text{ m}$ then we get,

$$E = 1000 \frac{kg}{m^3} \times 9.81 \frac{m}{s^2} \times 113 m^2 \times \left( 40m \times (10m) + \frac{1}{2} (10m)^2 \right)$$

\[\therefore E = 1,108,530 \frac{kg \cdot m}{s^2} \times (450)m^2\]

\[\therefore E = 498.83685 \times 10^6 \frac{kg \cdot m^2}{s^2}\]

\[1 \frac{kg \cdot m^2}{s^2} = 1 \text{ Joule} = 2.7778 \times 10^{-7} \text{ kWh}\]

\[\therefore E = 498.83685 \times 10^6 \times 2.7778 \times 10^{-7} \text{ kWh}\]

\[\therefore E = 139 \text{ kWh}\]

This storage capacity of 139 kWh is for full volume of water store in the tank. But it is considered that, the only half amount of water is extracting from tank to generate electricity and half will be used for supplying water for municipal purpose which means only half volume is using for storing energy. Therefore, the actual storage capacity for single water tower is,

$$E = \frac{139 \text{ kWh}}{2}$$

\[\therefore E = 69.5 \text{ kWh}\]
So the energy storage capacity for the single water tank is 69.5 kWh. If it is assumed that energy discharge over a 7 hour period,

\[
\therefore \text{Power} = \frac{69.5\text{kWh}}{7h}
\]

\[
\therefore \text{Power} = 10\text{kW}
\]

So the power provided by this stored energy is 10 kW. This may not seem like much storage; however, this number needs to be scaled by the national opportunity that is available in municipal water towers.

2.3 Storage Capacity of Water Towers in Missouri

According to the data collected from Missouri Department of Natural Resources [54], it indicates that there are 3880 water storage systems available in Missouri which include storage system like water tower storage system, ground storage system, clear well storage system, pressure tank storage system and much more. Within this storage systems, there are 2060 storage systems are Water Tower storage systems available to supply water for municipal and commercial purpose [54]. So we can use these water towers to store the electricity using the WTES technology.

As we discussed earlier in preliminary technical analysis that, we can store 10 kW of electricity from one water tower, then if we calculate the storage capacity of 2060 water towers then we get,

\[
\text{Power} = 10\text{kW} \times (2060 \text{ Water Towers})
\]

\[
\therefore \text{Power} = 20600\text{kW}
\]

\[
\therefore \text{Power} = 20.6\text{MW}
\]
Thus, it concludes that the energy storing capacity for cumulative water towers present in the Missouri is 20.6 MW.

2.4 Storage Capacity of Water Towers in United States

According to the data collected from Missouri Department of Natural Resources, there are 3880 water storage systems in Missouri. The population of Missouri is 6 million. It means 3880 water storage systems use to provide water to 6 million people. Amongst these 3880 water storage systems there are 2060 water towers storage systems which indicates that only 53% people of Missouri served by water from 2060 water tower systems. It means only 3.1 million people in Missouri takes the advantage of 2060 water towers [54].

Research shows that the population of United States is near about 308 million. If, 3.1 million people require water form 2060 water towers then 308 million people require near about 204,671 water towers.

\[
\text{i.e. No. of water towers in US} = \left(\text{2060 water towers} \times \text{308 million}\right) / (3.1 \text{ million})
\]

No. of water towers in US = 204,671 water towers

Again if we calculate the storage capacity for whole Unites States it gives,

\[
\text{Power} = (10 \text{ kW/watertower}) \times (204,671 \text{ watertowers})
\]

\[
\therefore \text{Power} = 2,046,710 \text{ kW}
\]

\[
\therefore \text{Power} = 2.05 \text{ GW}
\]

Thus, we can store 2.05 GW of energy in the water towers of United States which is amounts to the power produced by a Hoover Dam!
2.5 Summary

It is concluded that, the electricity generation capacity is 10kW for single water tower, 20.6MW for 2060 water towers in Missouri, and 2.05GW for 204,671 water towers in United States. Thus, the generation capacity for whole nation's water towers is almost equal to the amount of generation capacity of a Hoover Dam which implies that this design of water tower energy storage system will definitely help the nation to improve the economy in the area of renewable energy by reducing the cost of construction of electricity storage system. The design and modeling of this system is discussed in the next chapter.
3.1 Introduction

As discussed in Chapter 2, research shows that there are 2060 water towers present in Missouri and 204,671 water towers present in whole nation. The important goal of this project is to use these abundantly existing water towers not only for the use of supplying water to municipal purpose but also for generating of electricity. So, for the generation of 10kW of electricity from single water tower, we have to design the typical system of water tower with standard specification used for existed water towers. According to the research, the design specifications used for standard water tower system are with the height of 40m, and the area of water tank is about 113m² (12m diameter tank) [58] and from technical analysis discussed in chapter 2, it concludes that single water tower can generate 10kW of electricity using these standard specifications for water tower system.

In this chapter, the volume capacity of water tank, flow rates required for generating electricity and for supplying water to the municipal purpose, number of people serve by water tank, power needed to run the water pump, and the required basic components is discussed.

3.2 Volume Capacity of a Water Tower

As discussed in Chapter 2, water tank having an area of 113 m². It is necessary to calculate the volume capacity of this water tank which gives a idea of volume of water
required for generating electricity and volume of water required for supplying to municipal purpose.

Figure 3-1 shows the typical water tower which has a volume capacity $V$. It is assumed in project that half amount of volume of water $V_{\text{power}}$ use for generating electricity and other half $V_{\text{use}}$ for supplying water for municipal purpose.

![Typical water tower diagram](image)

Figure 3-1. Typical water tower
Now, Volume of tank $V$ is given by

$$V = \frac{\pi d^2}{4} (h_s)$$

$$V = \frac{\pi (12m)^2}{4} (10m)$$

$$V = 1131 \text{ m}^3$$

We know that,

$$1 \text{ m}^3 = 264 \text{ US Gallons}$$

$$\therefore V = 1131 \times 264$$

$$\therefore V = 298,584 \text{ US Gallons}$$

Thus, volume of the water tower $V$ is 298,584 US Gallons of which half amount is use to generate electricity and other half will be use for municipal purpose. Therefore it is necessary to calculate the flow rates of water through the inlet pipe and outlet pipe which will be discussed in following sections.

3.3 Flow Rate of Water at Outlet of the Water Tank

The outlet of this water tank is mainly divided into two ways, one way is to supply water for generating electricity and other way for municipal purpose. Therefore it is necessary to calculate the flow rates for both outlets.
3.3.1 Flow Rate of Water Use for Municipal Purpose

As discussed in section 3.2, it is assumed that half amount of volume of water is used for supplying water for municipal purpose. It is needed to calculate the flow rate of water \( Q_{use} \) to municipal purpose as shown in Figure 3-1. Before that, it is necessary to compute the volume of water use for municipal purpose. It is considered to use half amount of water in water tank for municipal purpose:

\[
\therefore V_{use} = \frac{298,584}{2} \text{ US Gallons}
\]

\[
\therefore V_{use} = 149,292 \text{ US Gallons}
\]

Therefore, 149,292 US Gallons of water can be use for municipal purpose.

Thus, the flow rate of water use for municipal purpose for 12 hours is

\[
Q_{use} = 3.46 \text{ Gallons/sec}.
\]

3.3.2 Flow Rate of Water Use for Generating Power

The half amount of water (149,292 US Gallons) in the tank is using for generation of electricity and water is extracting for 7 hours. Therefore, flow rate of water use for generating power is \( Q_{power} = 5.92 \text{ Gallons/sec} \).

3.4 Flow Rate of Water at Inlet of the Water Tank

It is considered that pumping water in to the water tank will be done during night for 12 hours and the volume of water is 298,584 US Gallons.
Therefore, Inlet Flow rate is given by,

\[ Q_{in} = \frac{298,584}{12 \times 60 \times 60} \text{ Gallons/sec} \]

\[ \therefore Q_{in} = 6.912 \frac{\text{Gallons}}{\text{sec}} = 0.026 \frac{m^3}{\text{sec}} \]

Thus, the flow rate of water at inlet of water tank is \( 0.026 \text{m}^3/\text{sec} \).

3.5 Number of People Served by the Water Tower

The main goal of this project is to use existed water towers not only to use for generation of electricity but also to use for supplying water for municipal purpose, therefore, it is also needed to calculate the number of people serves by the amount of water \( V_{use} \), but before that, it is necessary to calculate the average use of water per person per day which will be discussed in this section.

**Average use of water per person per day**

According to United States Geological Survey (USGS), it has calculated that, each person uses about 80-100 gallons of water per day. This analysis is shown in Table 3-1 [55].
Table 3-1. Analysis for average water use per person per day [55]

<table>
<thead>
<tr>
<th>Activity</th>
<th>Water Use at Home per Person per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bath</td>
<td>A full tub is about 36 gallons.</td>
</tr>
<tr>
<td>Shower</td>
<td>2 gallons per minute. Old shower heads use as much as 5 gallons per minute.</td>
</tr>
<tr>
<td>Teeth brushing</td>
<td>&lt;1 gallon, especially if water is turned off while brushing. Newer bath faucets use about 1 gallon per minute, whereas older models use over 2 gallons.</td>
</tr>
<tr>
<td>Hands/face washing</td>
<td>1 gallon</td>
</tr>
<tr>
<td>Face/leg shaving</td>
<td>1 gallon</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>4 to 10 gallons/load, depending on efficiency of dishwasher</td>
</tr>
<tr>
<td>Dishwashing by hand</td>
<td>20 gallons. Newer kitchen faucets use about 2.2 gallons per minute, whereas older faucets use more.</td>
</tr>
<tr>
<td>Clothes washer</td>
<td>25 gallons/load for newer washers. Older models use about 40 gallons per load.</td>
</tr>
<tr>
<td>Toilet flush</td>
<td>3 gallons. Most all new toilets use 1.6 gallons per flush, but many older toilets used about 4 gallons.</td>
</tr>
<tr>
<td>Glasses of water drunk</td>
<td>8 oz. per glass</td>
</tr>
<tr>
<td>Outdoor watering</td>
<td>5 to 10 gallons per minute</td>
</tr>
</tbody>
</table>

Thus, average water use per person per day is 100 gallons. Therefore, the number of people \( N_p \) feed by 149,292 US Gallons of water is given by;

\[
\therefore N_p = \frac{149,292}{100}
\]

\[
\therefore N_p = 1493 \approx 1500 \text{ People}
\]

Thus, 1500 people can be served by the use of 149,292 US Gallons of water.
3.6 Amount of Power Required to Run the Water Pump

During this project, a wind turbine is used for generating some amount of electricity to run the electric motor which runs the water pump to pump water at the height of 40m. Therefore, it is necessary to calculate the amount of electricity needed to run the water pump which will helps to decide the size of wind turbine require for this project. Therefore, power required for the water pump to pump water into the water tank is given by,

\[ WHP = \frac{Q_{in} \times h_p}{3960} \]

Where, \( WHP \) = Water horsepower

\( Q_{in} \) = flow rate in Gallons/min = \( 414.72 \) Gallons/min

\( h_p \) = head in foot = \( 131.2 \) foot

Now, power required for water pump to pump water into the water tower is,

\[ WHP = 13.74 \text{ HP} = 10.24 \text{kW} \]

Therefore, power required for water pump to pump water into the water tower is \( 10.24 \text{kW} \).

3.7 Basic Components

In this project, we need few basic components because of already existed water tower structure and its relevant components like electric motor, water pump, water filtration system and sensor for maintaining water level in the tank are already available with the water tower system which will definitely saves the cost of purchasing them. The basic components required for this project are discussed below.
1) Wind Turbine

A wind turbine as shown in Figure 1-15 is a device that converts kinetic energy from the wind, also called wind energy, into mechanical energy; a process known as wind power. If the mechanical energy is used to produce electricity, the device may be called wind turbine or wind power plant. If the mechanical energy is used to drive machinery, such as for grinding grain or pumping water, the device is called a windmill or wind pump. Similarly, it may be called wind charger when it is used to charge batteries [56].

In the project, by taking the advantage of height of the water tower, it is decided to place the wind turbine on the roof of the water tank which helps to reduce the height and thus cost of the wind turbine. Moreover, as discussed in section 3.6, the amount of power required to run the water pump at the head of 40m is 10.24 kW which implies that the wind turbine required for this project should have the capacity to generate a very small amount of electricity of at least 10.24 kW which also reduces the size and thus cost of the wind turbine required for this project.

Calculations for Wind Turbine

According to the discussion in Chapter 2, Section 2.2, single water tower can store 139kWh of energy by using full volume of water. Moreover, wind turbine is running during night to run the water pump and full up the tank with water. So it is considered that the wind turbine will run for 12 hrs per day. This information will help to calculate the required power output capacity for wind turbine as discussed below.

\[
(Turbine \text{ Power output}) \times 12 \text{ hr} = 139 \text{ kWh}
\]

\[
\therefore \text{ Turbine Power output} = \frac{139 \text{ kWh}}{12 \text{ hr}}
\]
Therefore, the project needs a wind turbine having a capacity to generate 11.6 kW of electricity.

After a survey with the Qingdao Windwings Wind Turbine Co. Ltd. which is wind turbine manufacturing company, a wind turbine model number FZY10KW which having a capacity to generate 15kW of electricity, voltage range from 220-240V, AC, 50/60 Hz frequency and is suitable wind turbine for this project with having cost of $16,308 [68].

2) Turgo Turbine, Generator, and Control Valve Unit

Turgo turbine is developed in 1919 by Gilkes as a modification of the Pelton wheel, the Turgo has some advantages over Francis and Pelton designs for certain applications. First, the runner is less expensive to make than a Pelton wheel. Second, it doesn't need an airtight housing like the Francis. Third, it has higher specific speed and can handle a greater flow than the same diameter Pelton wheel, leading to reduced generator and installation cost [57].

The Turgo turbine is an impulse water turbine designed for medium head applications. Operational Turgo Turbines achieve efficiencies of about 85%. In factory and lab tests Turgo turbines perform with efficiencies of up to 90%. It works with net heads between 15 and 300 m. The actual Turgo turbine and generator unit where water turbine and generator coupled with each other to make a single unit. Turgo operate in a head range where the Francis and Pelton overlap. While many large Turgo installations exist, they are also popular for small hydro-power projects, where low cost is very important. Like all turbines with nozzles, blockage by debris must be prevented for
effective operation. A Turgo runner looks like a Pelton runner split in half. For the same power, the Turgo runner is one half the diameter of the Pelton runner, and so twice the specific speed. The Turgo can handle a greater water flow than the Pelton because exiting water doesn't interfere with adjacent buckets [57]. The specific speed of Turgo runners is between the Francis and Pelton. Single or multiple nozzles can be used. Increasing the number of jets increases the specific speed of the runner by the square root of the number of jets (four jets yield twice the specific speed of one jet on the same turbine) [57].

Theory of Operation

As shown in Figure 3-2, the Turgo turbine is an impulse type turbine; water does not change pressure as it moves through the turbine blades. The water’s potential energy is converted to kinetic energy with a nozzle. The high speed water jet is then directed on the turbine blades which deflect and reverse the flow. The resulting impulse spins the turbine runner, imparting energy to the turbine shaft which helps to generate electricity of 10kW using generator. Water exits with very little energy because Turgo runners are extremely efficient [57].

Figure 3-2. Theory of operation [57]
In this project, the inlet flow rate of the water is 5.97 gallons/sec and the net head is 40m, therefore the Turgo turbine and generator can generate near about 7-8kW of electricity [67]. This little power loss is because of efficiency of the turbine which is 85%. After a survey for the cost of this unit with Suzhou Yueniao Machinery and Electronics Imp and Exp Company Limited which is the manufacturers of turbines and generator unit for such hydropower projects, it discovered that the cost of the unit is $6,466 and the model number is T30-10SCT4/-Z [64]. This unit also includes the control valve, and electronic load controller to control the output voltage and frequency.

3) Electric Motor and Water Pump

An electric motor is an electromechanical device that converts electrical energy into mechanical energy. In an electric motor the moving part is called the rotor and the stationary part is called the stator. Magnetic fields are produced on poles, and these can be salient poles where they are driven by windings of electrical wire [61]. Electric motors are found in applications as diverse as industrial fans, blowers and pumps, machine tools, household appliances, power tools, and disk drives.

A pump is a device that moves fluids (liquids or gases), or sometimes slurries, by mechanical action. Pumps can be classified into three major groups according to the method they use to move the fluid: direct lift, displacement, and gravity pumps. Research says that, centrifugal pumps is mostly used in water tower systems which has the voltage range from 220-240V, AC, 50/60 Hz frequency [62,65,66] which completely matches with the output of the wind turbines selected for this project.

In this project, the electric motor use to run the water pump. Research shows that this electric motor coupled with water pump is already equipped with water tower system
as shown in Figure 1-15. Therefore, it not necessary to purchase the electric motor and water pump for the project and thus, it helps to avoid the cost of purchasing them.

4) Water Reservoir

A water reservoir is nothing but the source of water from where water is extracted to use for various applications. In this project, the water reservoir shown in Figure 1-15 is nothing but the source of water from where water tank is filled. The reservoir may be in terms of lake or river or any type of source of water which is easily available and very near to water tower system to fill up the tank by water. For instance, a Chicago water tower uses water from lake Michigan to fill up the tank [63]. Therefore, it is considered that each water tower system already has its own water reservoir to get water to fill in the tank.

5) Power Supply Automatic Controller Microcomputer Timer Switch

It is considered in the project that the wind turbine is running for 12 hours during night which runs the water pump to fill up the tank. During next 12 hours (daytime) the wind turbine power supply gets disconnected and grid will supply the power to run the water pump whenever necessary. As it is considered that the only half amount of water using for generating electricity during daytime. Therefore, to recover that amount of water in tank, grid power will supply the energy to run the pump for 6 hours only at the rate of 6.912 gallons/sec during the day period. To maintain this automatic transaction between two different power supply (wind turbine and grid) according to the specified timings, it is necessary to use a power supply automatic controller microcomputer timer switches which maintains this smooth transaction between power supply by wind turbine and grid. The switch model number KG316T with specifications 220V, 50/60Hz which
completely matches with the AC motor input use to run the water pump. Thus, we need two such switches, one for controlling the output of wind turbine and other for output of a grid as shown in Figure 1-15. This unit has a price of $19.20 each.

3.8 Summary

In this Chapter, other design quantities has been calculated such as volume capacity of water tower, inlet and outlet flow rated of water tank, number of people serves by this water tower. The calculated power required for water pump gives idea about the size of wind turbine needed for system to run the water pump. Moreover, the basic components required for this project has been discussed which decides the cost of project and consequently decide the energy storage cost per kWh which is discussed in next chapter.
CHAPTER 4. RESULTS AND DISCUSSION

4.1 Introduction

The energy storing and generation capacity of single water tower, towers in Missouri and in United States are presented in Chapter 2. Moreover, Chapter 3 gives the design and modeling of the water tower required for this project. It is also presented the quantities such as volume capacity, inlet and outlet flow rates, and number of people serves by the water tank that used for storing energy. Again, it is discussed the basic components required for this project. This chapter split into two sections: first Section 4.2, gives a summary of all results that obtained in previous chapters and second Section 4.3 presents the cost of the energy stored per kWh.

4.2 Results

A summary of results is given in Table 4-1. The result table starts with the design values of water tower, follows with energy storing and generation capacity of single water tower and generation capacity of towers in Missouri and United States, and then it gives brief summary of other quantities of water tank such as volume and flow rates.
Table 4-1. Result table

<table>
<thead>
<tr>
<th>Quantity:</th>
<th>Results:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of water tower ( h_p )</td>
<td>40 m</td>
</tr>
<tr>
<td>Height of water level in tank ( h_s )</td>
<td>10 m</td>
</tr>
<tr>
<td>Area of water tank</td>
<td>113 ( m^2 )</td>
</tr>
<tr>
<td>Storing capacity of single water tower</td>
<td>69.5 kWh</td>
</tr>
<tr>
<td>Capacity of single water tower</td>
<td>10 kW</td>
</tr>
<tr>
<td>Capacity of water towers in Missouri</td>
<td>20.6 MW</td>
</tr>
<tr>
<td>Capacity of water towers in United States</td>
<td>2.05 GW</td>
</tr>
<tr>
<td>Volume of tank</td>
<td>298,584 US Gallons</td>
</tr>
<tr>
<td>Number of people serves by water tower</td>
<td>1500 people</td>
</tr>
<tr>
<td>Flow rate of water used for inlet of water tank</td>
<td>6.912 Gallons / sec</td>
</tr>
<tr>
<td>Flow rate of water used for generating energy</td>
<td>5.92 Gallons / sec</td>
</tr>
<tr>
<td>Flow rate of water used for municipal purpose</td>
<td>3.46 Gallons / sec</td>
</tr>
<tr>
<td>Power required for pump</td>
<td>10.24 kW</td>
</tr>
</tbody>
</table>

4.3 Energy Storage Cost per kWh

By taking advantage of the fact of using the components those are already available with the existed water tower system, the number of basic component needed for this project become less. This also reduces the required cost of the project and consequently it helps to achieve the main goal of reducing the energy storage cost per kWh.
As discussed in Chapter 3 in Section 3.7, for this particular project, we need three main components such as wind turbine, water turbine and generator unit. The cost of these components presented in Table 4-2, gives the idea of cost required for this project and which helps to calculate the cost of energy storage per kWh.

Table 4-2. Total cost of the project

<table>
<thead>
<tr>
<th>Name of the component</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Turbine</td>
<td>$16,308</td>
</tr>
<tr>
<td>Water turbine and Generator unit:</td>
<td></td>
</tr>
<tr>
<td>Turbine</td>
<td></td>
</tr>
<tr>
<td>Generator</td>
<td>$6,466</td>
</tr>
<tr>
<td>Control Valve</td>
<td></td>
</tr>
<tr>
<td>Electronic load controller</td>
<td></td>
</tr>
<tr>
<td>Power Supply Automatic Controller Microcontroller Timer Switch (2 units)</td>
<td>$38.40</td>
</tr>
<tr>
<td><strong>Total cost of the project:</strong></td>
<td><strong>$22,812</strong></td>
</tr>
</tbody>
</table>

Thus, the total cost of the project is $22,812 and the storage capacity of single water tower is 69.5 kWh. Therefore, energy storage cost for 1 kWh is

\[
\text{Energy storage cost per kWh} = \frac{22,812}{69.5\text{kWh}}
\]

Energy storage cost per kWh = $328 / kWh
4.4 Summary

Thus, the results shows that energy storage cost per kWh is $328 which is far less than the current cost of storing energy that is $1000/kWh. Additionally, by using the wind turbine, project saves the expenses of electricity required to supply for water pump to pump water in the water tank. Therefore, it proves that the idea of storing energy using already existed municipal water tower structures is worth.
CHAPTER 5. CONCLUSION

5.1 Introduction

In this chapter, conclusions are made based and supported by the results discussed in the previous chapter. Section 5.2 lists these conclusions as well as summarizes this entire document. Finally, the last section, Section 5.3, recommends future endeavors to be taken to further the understanding and development of water tower energy storage system in this thesis.

5.2 Conclusions

Chapter 1 describes the need for more efficient energy storage system due to the higher cost of storing energy (near about $1000/kWh). There are lots of alternatives available to store energy in terms of short term and long term discharge energy storing technologies. Comparing to these existed storing technologies, the water tower energy storage system are shown to have a lower associated cost.

Chapter 2 gives the analysis of the single water tower energy storage system described in Chapter 1 and computes that the storage and generation capacity of single water tower are 69.5kWh and 10kW respectively. Moreover, it discussed the generation capacity for water towers present in Missouri and United States and assure the importance of project due to the high amount of power generation capacity (up to 2.05 GW) of the project near about 50MW more than the capacity of a Hoover Dam (up to 2GW).
Chapter 3 discussed the calculation of the other design values required to complete the modeling of the project and also tells about the basic components required for the project which helps to calculate the total cost of the water tower energy storage system.

Chapter 4 gives the brief discussion on the results got from Chapter 1 to 3. Moreover, it discussed about the energy storage cost per kWh of this water tower energy storage system which is $328/kWh. Again, by using the wind turbine, project assures the saving of cost of electricity required to run the water pump. Thus, because of less energy storage cost and saving in electricity provided for pump, it proves that this system is cheapest energy storage system than other technologies.

5.3 Scope of Future Work

The analysis done during the course of this thesis provides important insight on the operation of a water tower energy storage system. However, there is room to improve and build upon the work in this thesis. First of all, this thesis is contained in a virtual environment; real-world testing is necessary to reaffirm the conclusions attained in this document.

Aside from improving the results of the thesis, actual model demonstration is important to test the system which should be analyzed as well. This pilot scale demonstration will be built at the University of Missouri Power Plant and will taste. The power that is derived from the water tower will be integrated into the actual University of Missouri power grid using power electronics. After this experiment, a commercial scale demonstration will be planned for the site of public water utility and will taste.
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