# Pumped Storage Hydropower: A Technical Review

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# Pumped Storage Hydropower: A Technical Review

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## Executive Summary

Pumped storage hydropower is a technology that stores low-cost off-peak, excess, or unusable electrical energy. Historically, it was used in the United States to meet fluctuating power demands in conjunction with nuclear power plants. As renewable energy sources such as wind and solar are increasingly integrated onto the power grid, pumped storage hydropower is again gaining recognition as an effective power storage technology. Due to the age of existing pumped storage projects in the United States, these plants utilize single speed units. Advancements in pump/turbine unit technology have resulted in the development of adjustable speed units, which are used in the majority of newly planned pumped storage hydropower projects.

In this paper, a new model is presented that evaluates the operational characteristics of pumped storage hydropower systems for planning purposes. The model assumes a typical off-stream pumped storage hydropower project, with the overall objective of obtaining an accurate, early prediction of the performance of a pumped storage hydropower project. The model is particularly suited for comparison of single speed units versus adjustable speed units. This tool can be useful during the planning phase to quickly evaluate various technical parameters and select the most appropriate pump/turbine unit type and size.

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## 1. Introduction

As defined by the United States Army Corps of Engineers, pumped storage hydropower is "a special type of hydropower development, in which pumped water rather than natural streamflow provides the source of energy" (USACE, 1985). In general terms, pumped storage hydropower is a technology that stores low-cost off-peak energy or excess or unusable energy (perhaps generated from renewable energy sources) for later use. While pumped storage hydropower projects are a net consumer of electricity, they provide many useful power system operational benefits, including system storage capacity and power grid ancillary services, which allow other types of electrical plants in the system to operate more efficiently.

From the 1960s to the 1980s, pumped storage hydropower projects became popular in the United States and Japan as a way to meet fluctuating power demands in conjunction with nuclear power plants, which are unable to adjust to changing demands in a timely manner. Other countries such as Austria, which have no nuclear power plants, also constructed pumped storage hydropower projects to facilitate better operation of their key conventional hydropower plants (Deane et al, 2010). As renewable energy sources are integrated onto the power grid, pumped storage hydropower projects are again gaining international recognition as an effective power storage technology. With the ever growing appeal of renewable energy sources, wind and solar plants are being developed worldwide. Due to the unpredictable and sometimes intermittent nature of wind and solar power, pumped storage hydropower projects are a reliable fall back to compensate for the variability of wind and solar power, and to store excess or unusable energy from renewable sources, and therefore allow for the better integration of these types of renewable energy into the power grid.

The majority of modern pumped storage hydropower projects use reversible pump/turbine units that act as both a pump and a turbine. Most projects in the United States were built over 30 years ago, before adjustable speed units were available; consequently they have single speed units. Advancements in technology have resulted in the development of adjustable speed units. Consequently, the majority of new pumped storage hydropower projects utilize adjustable speed units. This paper will focus on the use of both single speed and adjustable speed units.

This paper will also include the development of a model to evaluate the operational characteristics of pumped storage hydropower projects using single speed and adjustable speed pump/turbine units. The report is organized as follows: the remained of Section 1 will provide an overview of pumped storage hydropower; Section 2 will present power and energy equations; Section 3 will provide a brief history of pumped storage hydropower projects, Section 4 will provide a technical overview of pumped storage hydropower, Section 5 will discuss pump/turbine technology, Section 6 will provide case studies of proposed adjustable speed pumped storage hydropower projects in the United States, Section 7 will present design considerations, Section 8 will present the methods, results, and discussion of the pumped storage hydropower model, Section 9 will present cost characteristics, and Section 10 will include a summary of the report.

## 1.1. Background and Motivation

Why use pumped storage hydropower? To understand why pumped storage hydropower projects are useful it is first important to develop a general understanding of other types of power plants and how the electrical grid is operated.

### *1.1.1. Types of Power Plants and Power Demand Versus Time*

In the United States, conventional power sources have primarily consisted of coal and nuclear power plants; however there is a growing percentage of natural gas and renewables entering the market over the last ten years. Nearly half of all energy generated in the United States comes from coal plants (USEIA, 2013) due to the abundance of coal domestically and the price stability of coal; unfortunately there are operational limitations and coal plants have increasingly come under fire from environmental activists. Coal plants can take up to 4 days to fully ramp up and go into operation, and up to 4 hours to respond to operational changes; consequently they are normally operated at optimal power generation for a period of months. Coal plants also produce fly ash and emit the greenhouse gas carbon dioxide and other toxic chemicals into the atmosphere. Nuclear power plants have low marginal operating cost; however they also have environmental and fuel storage challenges as well as long ramp up periods and response times. Most nuclear and coal plants use steam to generate power and are designed and optimized for steady-state operation to provide baseload electrical power. Due to thermal stresses induced during the startup and shutdown of both nuclear and coal plants it is preferable to minimize frequent startups and shutdowns.

Power demand is not constant. Power demands vary based on the time of day, day of the week (week-day versus weekend), and seasonally. To maintain stability of the power network different power plants are turned on and off throughout the day to match demand. An example of how power varies throughout a sample day is shown on Figure 1, which illustrates that there is low power demand at night, increasing power demand throughout the day, and a peak demand period during the late afternoon to early evening hours.

The operational characteristics of coal and nuclear plants make them well suited for supplying base load generation requirements, and poorly suited for supplying peak load requirements. Therefore, other types of power plants are needed to supply intermediate and peak power to meet the demands of consumers. To meet the varying demands of consumers, power generation facilities with short response times are needed and are critical to the successful operation of the power grid. The response times for several different types of power plants are shown in Table 1.

Natural gas, fuel oil plants, and hydropower plants are the most ideally suited plants for supplying peaking power. Natural gas plants are an attractive means to supply peaking power due to their shorter startup, shutdown, and downtime requirements as well as their moderate operating costs; however this technology utilizes non-renewable resources and produces carbon dioxide emissions. Fuel oil and diesel plants are popular for supplying peaking power because their fuel source is generally readily available; however they have high operating costs and negative environmental impacts. Hydropower is another attractive means of supplying peaking power. Hydropower projects require a large initial financial investment, but have low operating costs and short startup and shutdown requirements. A summary of the typical operating characteristics for various power plant types is provided in Table 2.

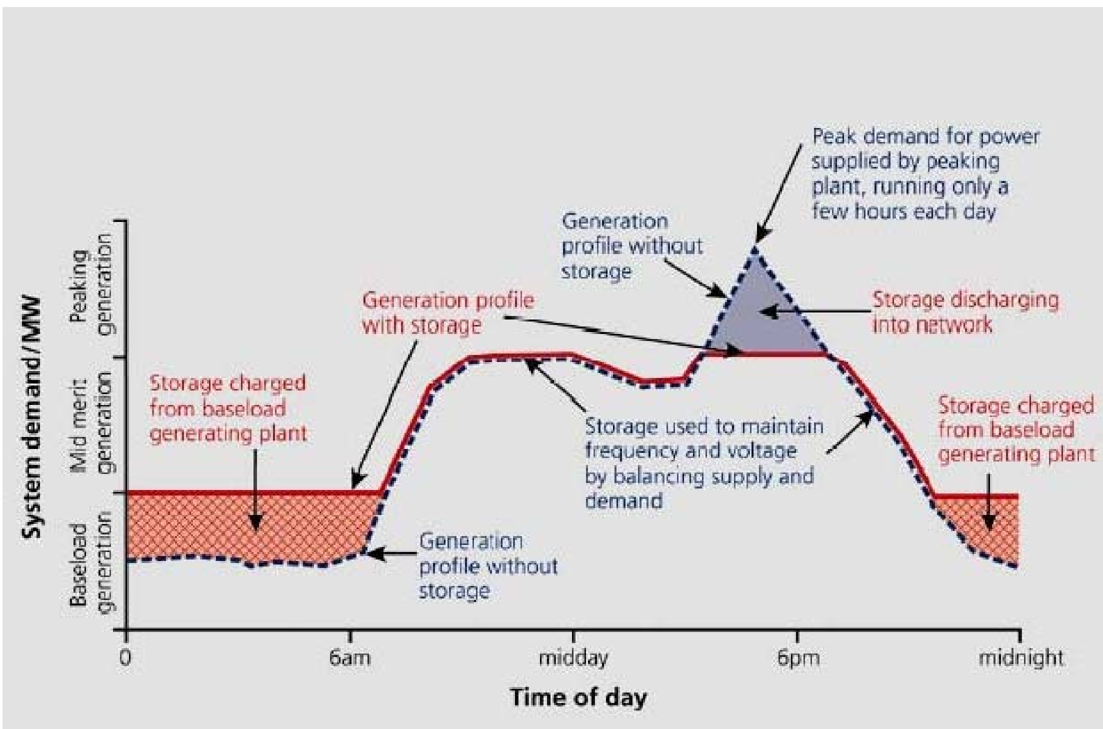


**Figure 1. System Demand Curve – Sample Day (Hultholm, 2014)**

**Table 1. The response of sudden changes for some power plants (Dursun and Alboyaci, 2009)**

| **Type of projects** | **The response time of sudden changes** |
|---|---|
| Classic Hydropower Plants | 3-5 minutes |
| Pumped Storage Hydropower Plants | 3-5 minutes |
| Natural Gas Plants | 1-3 hour |
| Fuel Oil Plants | 3 hours |
| Coal Fired Plants | 4 hours |
| Nuclear Plants | 5 days |

**Table 2. Typical Operating Characteristic of Generating Plant (Deane et al, 2010)**

| | **Pumped Storage Hydropower Plants** | **Natural Gas Plants** | **Fuel Oil Plants** | **Coal Fired Plants** | **Nuclear Power Plants** |
|---|---|---|---|---|---|
| Normal Duty Cycle | Peak-Intermediate | Peak | Peak-Intermediate | Baseload | Baseload |
| Unit Start-Up Daily | Yes | Yes | Yes | No | No |
| Quick Start (<10 minutes) | Yes | Yes | No | No | No |
| Black Start (ability to start without external power source) | Yes | Yes | No | No | No |

### *1.1.2. Renewable Technologies*

With increasing concerns regarding global warming and a push towards energy independence in the United States, renewable technologies are becoming increasing popular. The American Recovery and Reinvestment Tax Act of 2009 (ARRA) has had a large impact on the construction of new renewable power facilities in the United States, because it established funding for renewable energy programs by providing a 30 percent cash grant for renewable facilities (USDOT, 2013). Renewable technologies covered under the grant included wind, solar, biomass, and geothermal, and as of November 1, 2013 a total of 91,871 projects were funded by ARRA resulting in a total installed capacity of 27.9 GW and estimated annual energy generation of 73.3 TWh (USDOT, 2013).

While renewable energy sources have numerous benefits, their ability to penetrate into the power supply mix is limited, particularly wind and solar, due to their variability, which makes it difficult to balance supply and demand on the power grid. Their unpredictability also limits the ability of wind and solar to consistently provide power during peak demand periods when it is most needed and beneficial. To illustrate the inconsistent nature of wind power, the instantaneous power supplied by a sample wind farm is Canada is provided on Figure 2.

As the sample wind farm demonstrates, wind renewable energy generation is intermittent and when compared to the system demand curve provided on Figure 1 power supplied does not consistently match demand. In the example data, for instance, the wind farm generated the least amount of power between 5 pm and 8 pm, when power demand is typically highest. Consequently, to make wind and solar energy systems more effective, other types of electrical power generation or storage facilities are needed, such as pumped storage hydropower, to ensure that power is available during periods of peak demand.


**Figure 2. Instantaneous Power for a Sample Wind Farm in Canada – 76 Turbines (Ibrahim et al, 2007)**

### 1.1.3. Energy Storage

With the increasing integration of renewable energy sources, the need to develop technologies that are able to store power for peak demand periods, and to help maintain supply and demand in the system, is growing greater. Use of stored renewable energy is particularly attractive over expensive peaking plants. Based on modern technology there are a number of energy storage technologies currently available. These technologies include (Ibrahim et al, 2007):

- Pumped storage hydropower: Discussed in this paper.
- Thermal energy storage: There are two types of thermal energy storage. One type uses sensible heat and the other type uses latent heat. Sensible heat thermal storage heats in a bulk material, then energy is recovered via water vapor, which drives a turbo-alternator system. Latent-fusion-heat makes use of the liquid-solid transformation of a material at constant temperature; during storage the material becomes a liquid and during retrieval forms a solid. System efficiencies of about 60%.
- Compressed air energy storage (CAES): There are both large and small CAES applications. Energy is stored by compressing air during times when low-cost energy is available, then a generator is used to retrieve the power during peak demand periods. Efficiencies of about 50% for small scale projects and 70% for large scale projects.
- Flow battery energy storage: A two-electrolyte system in which chemical compounds are in their liquid state in solution with the electrolyte, and have an efficiency of about 75%.
- Flywheel energy storage: There are both low and high speed flywheel energy storage applications. Flywheel energy storage projects consist of a flywheel, motorgenerator, and special brackets housed inside a low pressure environment. This technology has good instantaneous efficiencies of 85%; however long term storage capabilities are poor, diminishing to 48% after 24 hours.

- Superconductor magnetic energy storage (SMES): There are both traditional and micro SMES applications. A direct current (DC) is induced into a coil made of superconducting cables of low resistance, with the current increasing during charging and decreasing during discharge. Good instantaneous efficiency of approximately 95%.
- Supercapacitor energy storage: For this technology there is no chemical reaction. An electrical field between two electrodes is used to storage energy, with short term efficiencies of 95%.
- Electrochemical batteries: These systems are able to transform chemical energy into electrical energy by using electrochemical reactions.

Energy storage systems come in many different sizes with varying power output and energy storage capacity. The quantity of energy stored relative to the power output for the energy storage systems described above are shown on Figure 3. As the figure shows, compressed air energy systems and pumped storage hydropower are the two primary large scale technologies currently available. There are presently only a few compressed air energy system plants that are operational; therefore pumped storage hydropower has the longest history of successful operation for large scale storage systems. While there are numerous benefits and negatives related to each energy storage technology this paper will focus on pumped storage hydropower technologies only.

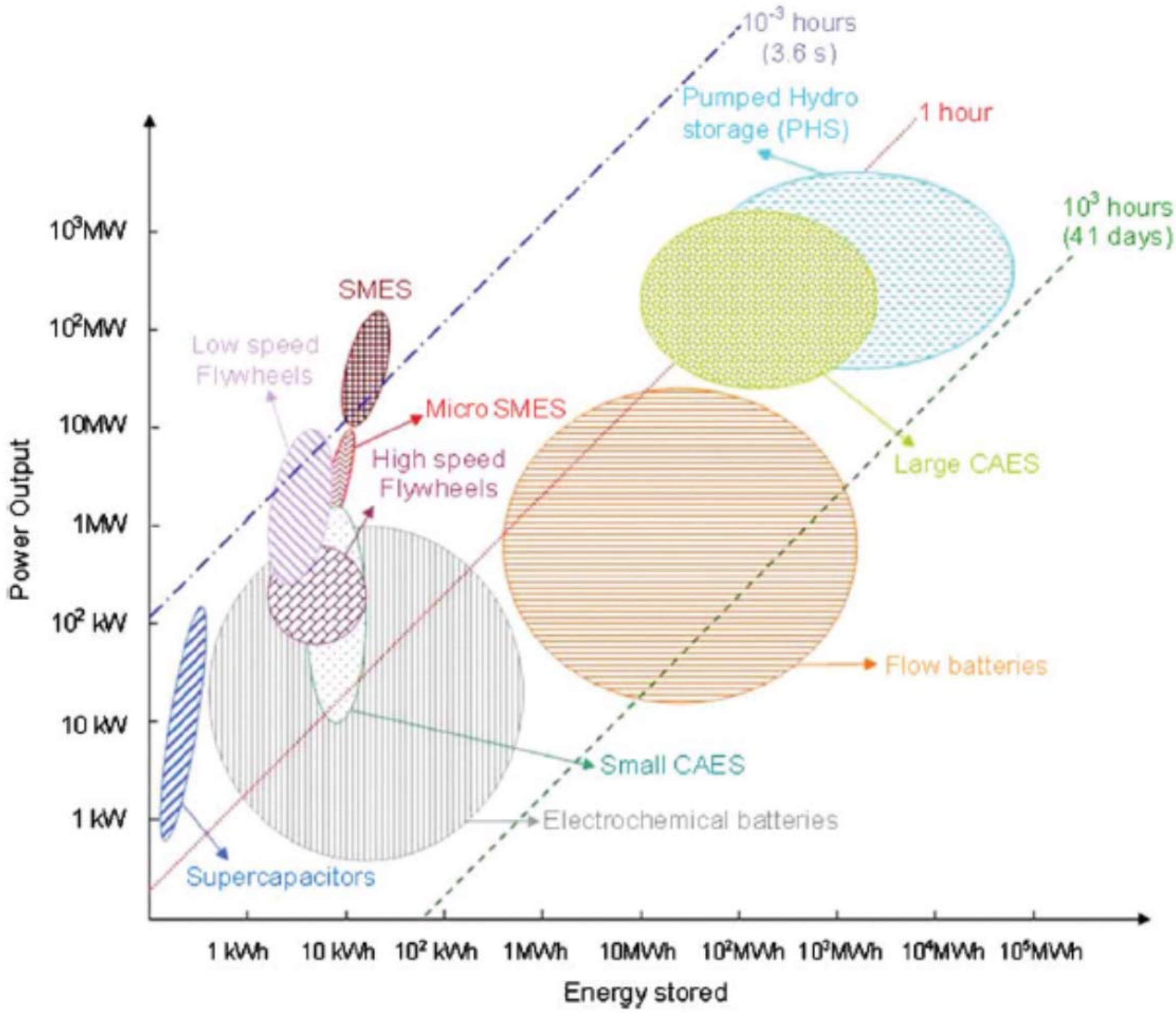


**Figure 3. Different Energy Storage Techniques – Energy Stored and Power Output (Ibrahim et al, 2007)**

## 2. Power and Energy Equations

Hydropower projects, including pumped storage hydropower, use the energy from flowing water to generate electric power. The general power and energy equations that pertain to pumped storage hydropower projects are as follows:

### *2.1.1. Energy*

Energy is the capacity to perform work, and does not consider units of time. It is expressed at the product of the force of water (weight) and distance.

$$E = F * d \qquad (\textit{Equation 2-1})$$

Where,

E = Energy [ft*lb]

F = Force [lb]

d = Distance [ft]

The energy potential of water can consist of potential, pressure, or kinetic energy. Potential energy is related to the elevation potential of water, pressure energy results from pressurization, and kinetic energy is related to the velocity of water in motion. For a system of waterways with varying elevations and pipe diameters, such as a pumped storage hydropower facility, the Bernoulli theorem can be used to evaluate the energy of the system. The Bernoulli equation assumes a constant discharge rate, and states that the energy head at any point in the system is equal to any point downstream in the system plus any losses (pipe friction losses, entrance losses, pump/turbine losses, etc.). The Bernoulli equation is:

$$z_1 + \frac{{v_1}^2}{2g} + \frac{P_1}{\gamma} = z_2 + \frac{{v_2}^2}{2g} + \frac{P_2}{\gamma} + h_L \qquad (\textit{Equation 2-2})$$

Where,

z = elevation head relative to a set datum for the system

v = velocity [ft/s; m/s]

$P$ = pressure [$lb/ft^2$; $N/m^2$]

$h_L$ = total head losses between points 1 and 2 [ft; m]

$\gamma$ = specific weight [$lb/ft^3$; $N/m^3$]

### 2.1.2. Efficiencies

For hydropower projects, particularly pumped storage hydropower projects, the efficiency of the overall project cycle is an important factor in determining whether a project is feasible. The cycle efficiency of a pumped storage hydropower project is the ratio between the energy output and energy input. Pumped storage hydropower projects typically recapture about 70 to 80% of energy inputs (Yang and Jackson, 2011), which means that for every 10 MWh of energy input roughly 7 to 8 MWh are recaptured. Losses in the system are primarily due to losses in the pump/turbine units and waterways.

### 2.1.3. Power

Power is the rate of performing work or utilized energy with respect to time.

$$P = \frac{\Delta E}{\Delta t} \qquad (Equation\ 2\text{-}3)$$

Power is the product of the specific weight of water, the discharge, and the change in hydraulic head ΔH.

$$P = \gamma Q \Delta H \qquad (Equation\ 2\text{-}4)$$

Where,

$\gamma$ = Specific weight of the fluid [$lb/ft^3$;$N/m^3$]

$Q$ = Flow rate [$ft^3/s$; $m^3/s$]

$\Delta H$ = Change in head [ft; m]

Power is generally reported in imperial units as horsepower (HP) and in metric units as kilowatts (kW). To provide units of kilowatt-hours or horsepower-hours the right side of the above equation is multiplied by time.

Using the Bernoulli equation the change in head, ΔH, for the power equation is calculated as follows:

$$\Delta H = H_2 - H_1 = \left[\frac{P_2}{\gamma} + z_2 + \frac{V_2{}^2}{2g}\right] - \left[\frac{P_1}{\gamma} + z_2 + \frac{V_1{}^2}{2g}\right] \qquad \text{(Equation 2-5)}$$

For a pumped storage hydropower project during pumping mode, ΔH is energy/weight applied to the pump water uphill, and during turbine operation ΔH is energy/weight applied by fluid. The power required to pump the water uphill is calculated as:

$$P_{pumping} = \frac{\gamma Q \Delta H}{\eta} \qquad \text{(Equation 2-6)}$$

The power generated during turbine operation is calculated as:

$$P_{generating} = \eta \gamma Q \Delta H \qquad \text{(Equation 2-7)}$$

The product of the total volume of water and the head difference between the reservoirs is proportional to the energy stored. Thus, with an elevation change of 1,000 feet and a reservoir volume of 10,000 acre-feet, approximately 9,000 MWh can be provided to the power grid assuming a generating efficiency of 90%. The energy of a pumped storage hydropower system is illustrated in Figure 4.

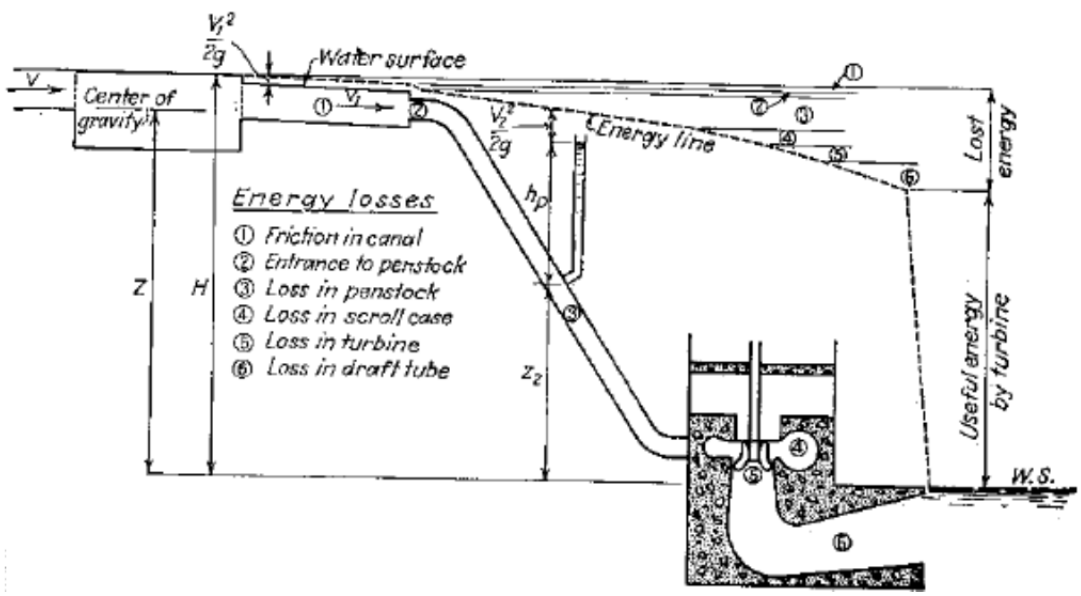


**Figure 4. Hydropower plant system – Illustrates energy in the system (Chen, 1990)**

## 3. History of Pumped Storage Hydropower Projects

In the United States, there are a total of 40 pumped storage hydropower projects currently in operation with a total installed capacity of approximately 22 GW (USEIA, 2013). The technical characteristics for select pumped storage hydropower projects in the United States are summarized in Table 3. The majority of pumped storage hydropower projects both in the United States and Europe were constructed in the 1960s, 1970s and 1980s (Deane et al, 2010), more than 30 years ago. Most of these projects were constructed to help utilize excess energy generated by nuclear power plants. Due to the era in which they were built, existing pumped storage hydropower projects in the United States use single speed pump/turbine units. A map of the existing pumped storage hydropower facilities in the United States is provided on Figure 5.

With the increased interest in renewable energy, pumped storage hydropower is again gaining interest from developers. The United States Federal Energy Regulation Commission has reported that preliminary permits have been granted for potential pumped storage hydropower projects in 22 states with a total capacity of 34 GW (EIA, 2013). Nearly all of these potential projects would utilize adjustable speed pump/turbine units. If constructed, these projects would nearly triple the current pumped storage hydropower capacity in the United States. Internationally, more than 20 adjustable speed units have gone into operation since the 1990s.

**Table 3. Existing Pumped Storage Hydropower Projects in the United States (MWH, 2009)**

| Project | Initial Operation | Installed Capacity (MW) | Hours of Storage | Energy Storage (MWh) | Average Gross Head (feet) | Water Conduit Length (feet) | Length to Head Ratio L/H | No. of Existing Res./Lakes |
|---|---|---|---|---|---|---|---|---|
| Taum Sauk | 1963 | 350 | 7.7 | 2,700 | 809 | 7,003 | 8.7 | 0 |
| Yards Creek | 1965 | 330 | 8.7 | 2,894 | 723 | 3,700 | 5.1 | 0 |
| Muddy Run | 1967 | 855 | 14.3 | 12,200 | 386 | 1,290 | 3.3 | 1 |
| Cabin Creek | 1967 | 280 | 5.8 | 1,635 | 1,159 | 4,340 | 3.7 | 0 |
| Seneca | 1969 | 380 | 11.2 | 3,920 | 736 | 2,520 | 3.4 | 1 |
| Northfield | 1972 | 1,000 | 10.1 | 10,100 | 772 | 6,790 | 8.8 | 1 |
| Blenheim Giloboa | 1973 | 1,030 | 11.6 | 12,000 | 1,099 | 4,355 | 4.0 | 0 |
| Ludington | 1973 | 1,888 | 9.0 | 15,000 | 337 | 1,252 | 3.7 | 1 |
| Jocassee | 1973 | 628 | 93.5 | 58,757 | 310 | 1,700 | 5.5 | 1 |
| Bear Swamp | 1974 | 540 | 5.6 | 3,019 | 725 | 2,000 | 2.8 | 0 |
| Raccoon Mountain | 1978 | 1,370 | 24.0 | 33,000 | 968 | 3,650 | 3.8 | 1 |
| Fairfield | 1978 | 512 | 8.1 | 4,096 | 163 | 2,120 | 13.0 | 0 |
| Helms | 1984 | 1,200 | 118.0 | 14,200 | 1,645 | 20,519 | 12.5 | 2 |
| Bath County | 1985 | 2,100 | 11.3 | 23,700 | 1,180 | 9,446 | 8.0 | 0 |


**Figure 5. Existing Pumped Storage Hydropower Projects in the United States (Miller and Winters, 2009)**

## 4. Pumped Storage Hydropower Technical Overview

A pumped storage hydropower project is typically comprised of an upper reservoir and lower reservoir interconnected with a waterway, a powerhouse which contains hydropower electrical-mechanical equipment, and a transmission connection to the power grid. In the traditional (or historical) mode of operation, inexpensive electricity (which is typically available at night or on the weekends, when power demand is low) is used to pump water from the lower reservoir to the upper reservoir (See Figure 6). Water stored in the upper reservoir is then released during peak demand periods, delivering more valuable electricity to the grid. With the introduction of renewable energy technologies the operation of pumped storage hydropower facilities is being expanded to utilize excess energy from renewable energy systems for later use during peak demand periods.

For a particular site to be attractive for a pumped storage hydropower facility, the key technical elements needed are (Deane et al, 2010):

- Topographic conditions that provide adequate head between the upper and lower reservoir.
- Favorable geotechnical conditions.
- Availability of sufficient quantities of water (water quality can also be a concern).
- Access to electrical transmission networks and low cost power.

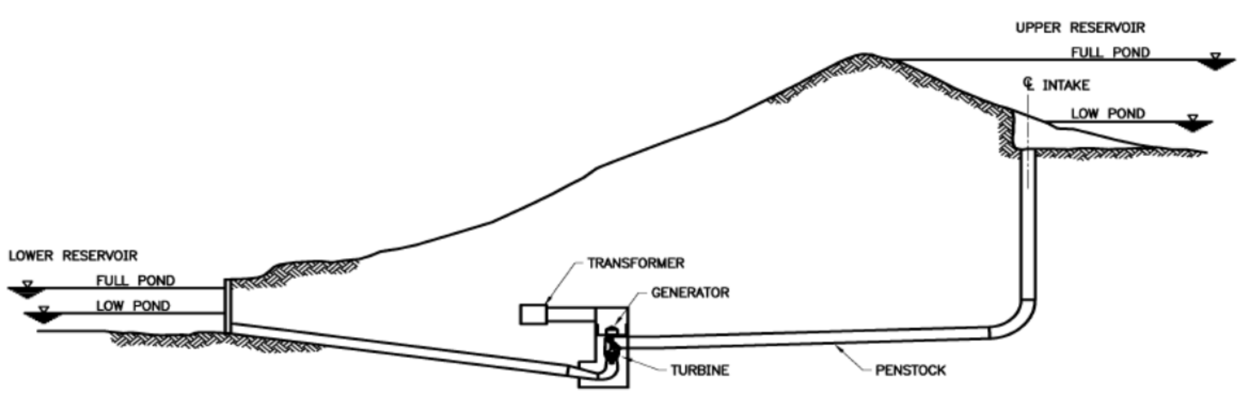


**Figure 6. Typical Pumped Storage Hydropower Project Configuration (Miller and Winters, 2009)**

Additional key technical elements that can potentially make a project more attractive are: (1) use of an existing reservoir for the upper or lower reservoir (which would lower the required initial investment); (2) topographic conditions that provide the shortest possible intake tunnel, penstock and discharge tunnel (which lowers friction losses and lowers the required initial investment), and (3) head conditions that allow the use of smaller pump/turbine units.

There two most common configurations for pumped storage hydropower projects are: (1) Pure/off-stream pumped storage hydropower facilities, and (2) pump-back facilities. In a pure/off-stream pumped storage hydropower facility, the upper reservoir has little or no natural drainage catchment basin. The upper basin is filled only using water pumped from the lower reservoir, hence the term “off-stream”. A typical pure/off-stream pumped storage hydropower facility is illustrated on Figure 7.

Some off-stream pumped storage hydropower projects are constructed with both the upper and lower reservoirs completely independent of a natural lake or stream. The primary advantage of this type of project is that there is little to no interaction with aquatic life, which minimizes the environmental review and permitting process. A water source must still be identified, however, that is able to provide the initial water required as well as replenish any water losses, which can be challenging. Potential off-stream water sources can include groundwater, sea water, and treated wastewater. While off-stream projects have numerous advantages, they may also create other design issues that would need additional consideration such as groundwater testing, water rights investigation, and changes to project components to account for expected water quality.

Pump-back pumped storage hydropower facilities use a combination of both natural streamflow as well as pumped water to generate electricity. Due to the configuration of this type of facility, they are typically larger and better suited for weekly and seasonal variations (Deane et al, 2010). Pump-back pumped storage hydropower facilities are similar to traditional hydropower facilities, except some or all of the turbines are specialty pump/turbine units and there is a reservoir available to form the lower reservoir. Pump-back pumped storage hydropower facilities are attractive in cases where they would like to firm up peaking capacity of the facility during periods of low stream flow, as well as cases where there are traditionally low stream flows but high peaking demands (USACE, 1985). A typical pump-back facility is shown on Figure 8. The analysis of environmental impacts is important during the feasibility stage of a pumped storage hydropower project; however it will not be discussed in this paper.

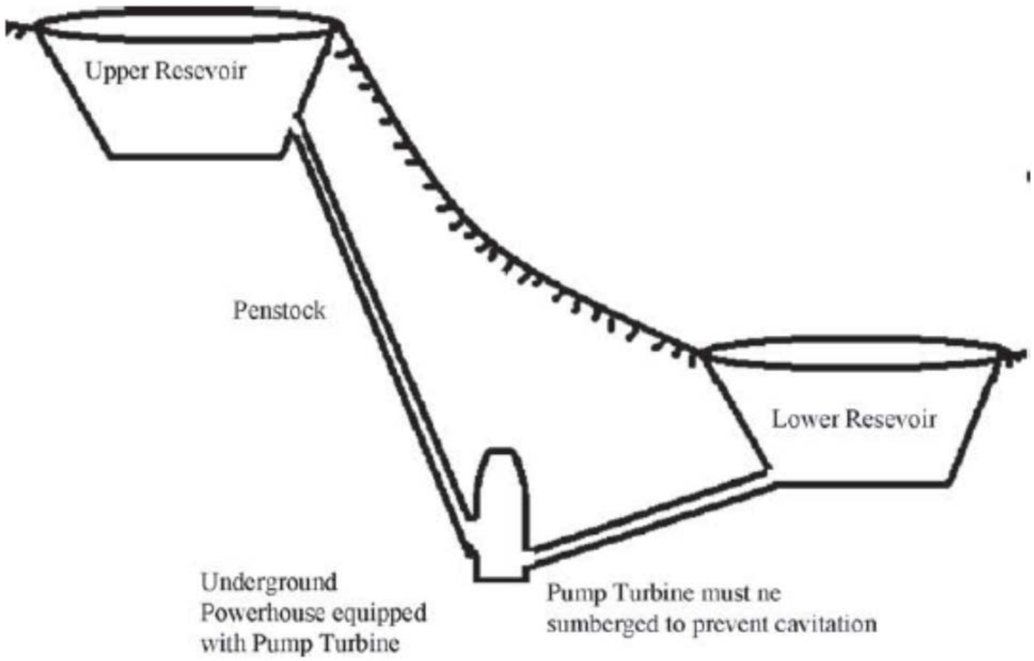


**Figure 7. Pure or Off-Stream Pumped Storage Hydropower (Deane et al, 2010)**

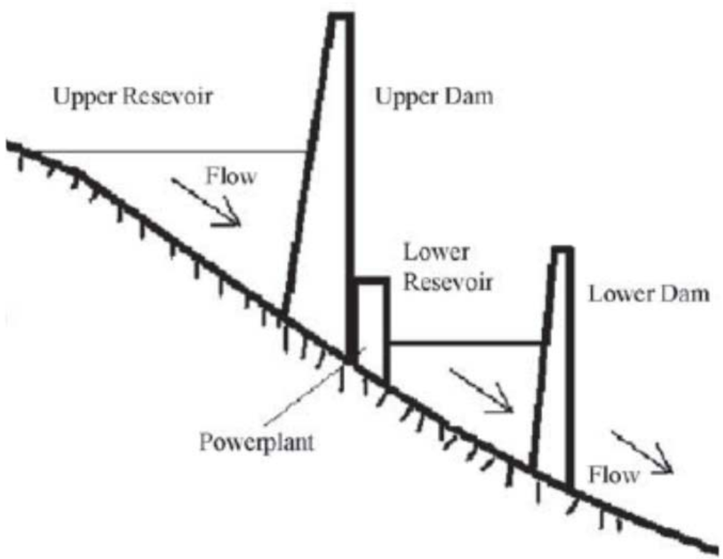


**Figure 8. Pump-Back Pumped Storage Hydropower Configuration (Deane et al, 2010)**

### 4.1. Cycle Efficiencies

Pumped storage hydropower projects are a net consumer of electricity. During periods of low energy demand, typically at night and on the weekends, low cost energy generated from thermal plants is used to pump water from the lower reservoir to the upper reservoir. High value peak power is then generated by moving the water back down to the lower reservoir, via the turbine. Due to system losses (pipe friction losses, turbine and pump efficiencies, etc.) pumped storage hydropower projects are typically able to recover approximately 70 to 80% of power inputs (Yang and Jackson, 2011). The cycle efficiencies for seventeen pumped storage hydropower projects in the United States are shown on Figure 9. The cycle efficiencies reported are between 65 and 80%, consistent with the values reported in Yang and Jackson (2011). The figure additionally shows that cycle efficiencies for new projects have been improving over time consistent with improvements in pump/turbine technology. Therefore, a cycle efficiency of 75% is recommended for use for planning purposes to account for all losses in the system (MWH, 2009).

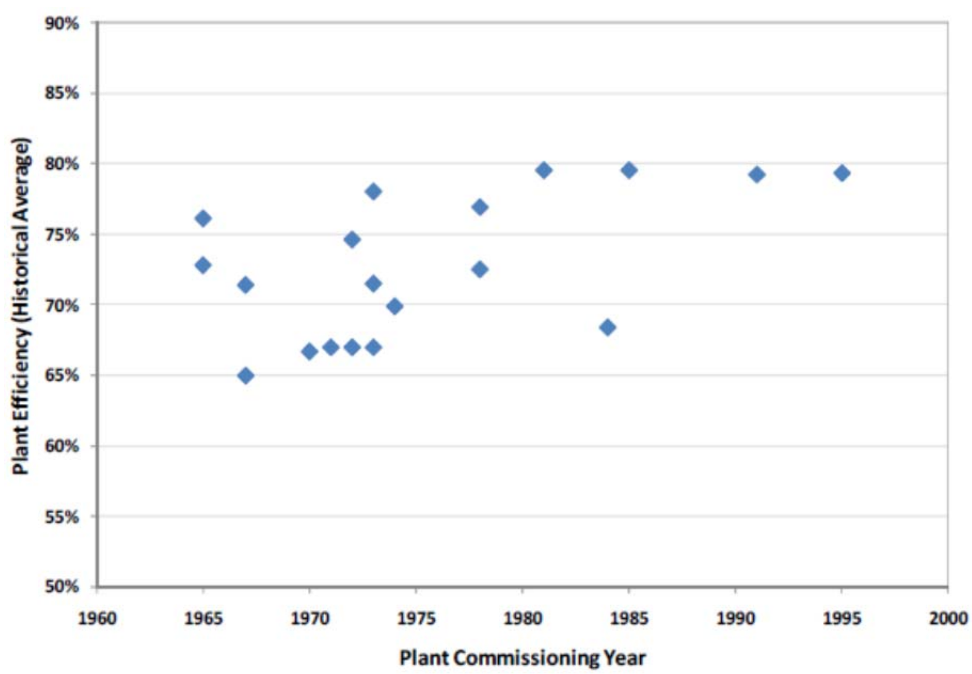


**Figure 9. Cycle Efficiencies for Pumped Storage Hydropower Projects in the United States (MWH, 2009)**

Pumped storage hydropower projects have numerous project components such as waterways and individual electrical-mechanical components, and each of these components affects the overall cycle efficiency for the project. The efficiency values for a typical pumped storage hydropower project with single speed pump/turbine units are provided in Table 4. As the typical efficiency values show, the lowest efficiency and therefore the majority of the losses, are from the pump/turbine units in both pumping and generating mode.

One of the greatest benefits of adjustable speed units is their increased efficiency in generating mode. Turbine efficiency relative to rated power output for adjustable speed versus single speed units is shown graphically on Figure 10. The efficiency of both adjustable speed and single speed units declines rapidly below 70% of the rated power output. Therefore, operators may restrict the range of pump/turbine unit operation to ensure that higher efficiencies are obtained during generating mode and to prevent damage or unnecessary wear and tear on the machines.

**Table 4. Composition of Pumped Storage Hydropower Plant Cycle Efficiency – For Typical Projects with Single Speed Pump/Turbine Units (MWH, 2009)**

| | **Component** | **Indicative Value, %** |
|---|---|---|
| Pump Cycle | Waterways | 98.0-98.6 |
| | Pump | 90.0-92.0 |
| | Motor | 97.8-98.3 |
| | Transformer | 99.0-99.6 |
| | Overall | 85.4-88.8 |
| Generating Cycle | Waterways | 98.6-98.0 |
| | Turbine | 75.0-91.0 |
| | Generator | 97.8-98.3 |
| | Transformer | 99.0-99.6 |
| | Overall | 71.6-86.4 |
| Operational | Losses & Leakage | 98.0-99.8 |

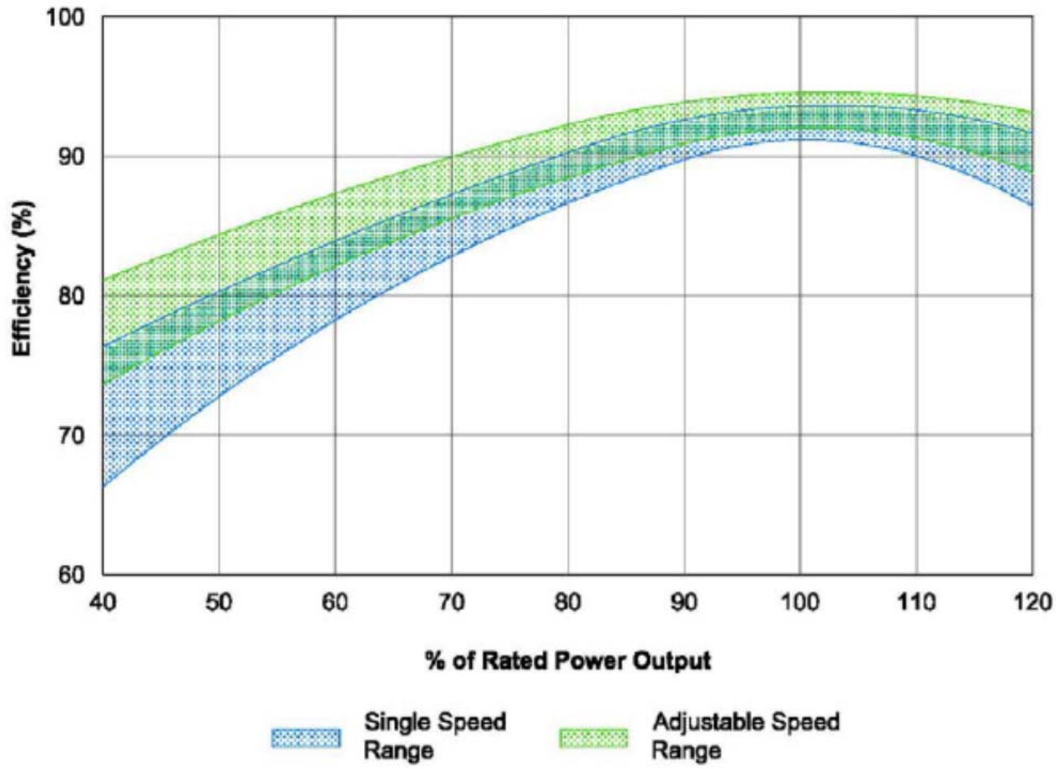


**Figure 10. Turbine Efficiency Versus Rated Power Output (MWH, 2009)**

### 4.2. Disadvantages Associated with Pumped Storage Hydropower Projects

While pumped storage hydropower projects have numerous advantages there are also some disadvantages. First, there are a limited number of sites that have favorable topographic conditions and access to adequate qualities of water. New location concepts, such as using underground caverns, may be a solution to this challenge (Reynolds, 2009). Second, the development of pumped storage hydropower projects can be a lengthy process. The planning, permitting, design and construction of a new project can take up to 10 years (MWH, 2009). Third, the permitting of a new pumped storage hydropower project is expensive. Pumped storage hydropower projects require a large initial financial investment, and other technologies such as gas power plants have lower initial capital costs that may be more attractive to some power suppliers.

### 4.3. Operation of Pumped Storage Hydropower Projects

Pure/off-stream pumped storage hydropower projects are typically been operated on daily or weekly cycles. For projects that are operated on a daily cycle, low-cost power available at night is used to pump water to the upper reservoir. The daily low demand period, when inexpensive energy is available, typically starts between 10pm and midnight and ends in the early morning hours (MWH, 2009). For daily cycle plants, power is then generated the subsequent day during the peak demand period. For projects that are operated on a weekly cycle, water is pumped during the late evening to early morning hours, and additional catchup water is also pumped over the weekend when demand is typically lower. Peaking demand is typically lower on the weekends, so this allows projects that operate on a weekly cycle to begin the work week with a full upper reservoir and end the work week with a nearly empty upper reservoir, with the upper reservoir then refilling over the weekend.

An example of a daily pump cycle is shown on Figure 11, and a weekly pump cycle is shown on Figure 12. These figures illustrate the fluctuations in the upper reservoir volume and the required reservoir storage volumes based on the planned operation cycle of the facility. The figures also illustrate the daily and weekly pumping and generating cycle.

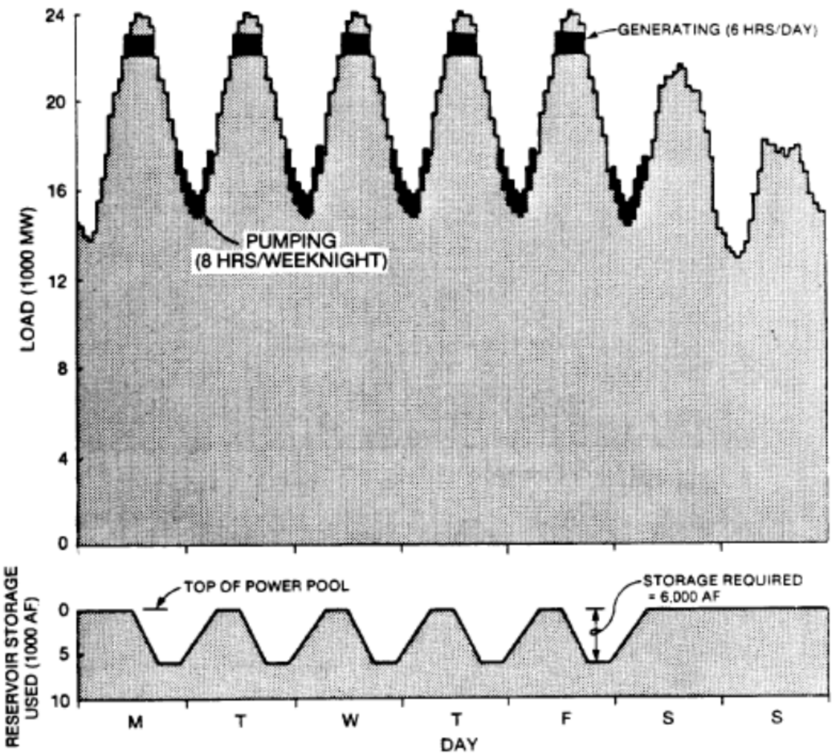


**Figure 11. Operation of Daily Cycle Pumped Storage Hydropower Project (USACE, 1985)**

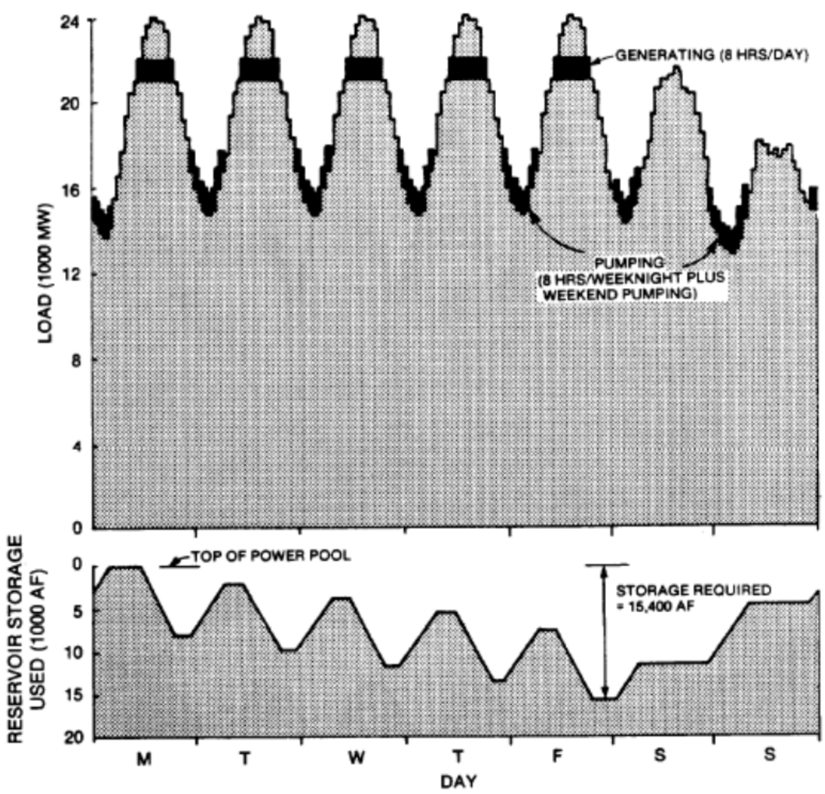


**Figure 12. Operation of Weekly Cycle Pumped Storage Hydropower Project (USACE, 1985)**

## 5. Pump/Turbine Technology

The majority of pumped storage hydropower projects use reversible pump/turbine and motor/generator assemblies that act as both a pump and a turbine. Due to the age of most pumped storage projects in the United States they typically have single speed units. Many of the new pumped storage hydropower projects being constructed internationally use adjustable speed units. Adjustable speed units have been installed at several power plants in Japan (Deane et al, 2010) and are proposed for several new pumped storage hydropower projects in the United States. Due to the high cost of new pump/turbine units and the increased powerhouse size requirements for adjustable speed units, it is generally not current practice to replace existing single speed units with adjustable speed units (Personal Communication, 2014). Pumped storage hydropower projects typically have two or more pump/turbine units to allow for operational flexibility. Pump turbine technology is discussed in more detail in the following section.

### 5.1. Pump/Turbine Configuration

Pumped storage hydropower projects can be developed with two primary configurations: 1) with a separate pump and turbine and 2) with a combined pump/turbine. Having a separate pump and turbine allows for a shorter transition time between pumping and generation modes; however it requires a larger more complex powerhouse structure and additional electrical-mechanical equipment, which increases costs for plants with this configuration. Combined pump/turbines have smaller, less expensive configurations and more affordable electrical-mechanical equipment; however the tradeoff is that the transition between the pumping and generating modes is longer because the blade must completely stop and reverse direction to switch modes. Most modern pumped storage hydropower projects utilize combined pump/turbine units, while separate pump and turbine configurations are generally associated with early pumped storage hydropower projects constructed prior to advances in combined unit technologies.

### 5.2. Single Speed Units (Conventional Pumped Storage Hydropower)

Single speed units utilize a synchronous electric machine. A synchronous machine allows the unit to operate in both pumping and generating machine by changing the rotational direction of the motor. With a conventional single speed unit, pumping occurs at a fixed synchronous speed and a nearly fixed wicket gate opening. In pumping mode, power input is nearly constant (for cases where pumping head is nearly constant) and discharge varies based on the pumping head; generally speaking power input during pumping mode varies inversely with head. Single speed units are unable to provide frequency regulation during pumping mode because traditional synchronous speed units are directly connected to the power grid and operate at a constant speed and input pumping power.

In the generating mode, the reversible pump/turbine is used to drive the single-speed synchronous generator and deliver electric energy and regulation to the system. During the generating mode the operator is able to adjustable the position of the wicket gates to vary the discharge. To maintain optimal efficiencies, operators typically operate single speed units within 70 to 100% of the pump/turbine unit maximum capacity (MWH, 2009). For instance, a 250 MW unit would be operated within a range of 200 to 250 MW. The ability of the unit to ramp up and down in generation mode allows the operator to follow the load demands of the power grid.

### 5.3. Adjustable Speed Units

The primary advantage of adjustable speed units is that they are able to vary the pump and turbine rotation speed for more efficient overall operation and better integration with the power grid. The operation of adjustable speed units varies based on the size of the unit. For units less than 50 MW a conventional synchronous generator is linked to the power grid by a static frequency converter (Schwery and Kunz, 2009). For larger units, over 50 MW, operation of the unit in adjustable mode is possible due to the application of a doubly fed induction machine (DFIM), with a three phase sinusoidal rotor voltage and current that is provided by an

AC/DC/AC solid state converter. The frequency of the rotor voltage and current are adjusted to control the speed of the rotor. To maintain optimal efficiencies operators typically operate adjustable speeds units within 70 to 100% of the pump/turbine unit maximum capacity (MWH, 2009). A side-by-side comparison between a conventional single speed pumped storage hydropower unit with a synchronous motor/generator and an adjustable speed unit with a doubly-fed would rotor induction motor/generator is shown on Figure 13.

The main components of a motor/generator for an adjustable speed unit are a three-phase stator, three-phase cylindrical rotor, and three-phase collector assembly. The rotor consists of a laminated steel cylinder with slots for three-phase windings, and the windings are connected to an external exciter by slip rings mounted to the top of the shaft. The stator winding is energized by the constant frequency of the bulk power system to establish a synchronous alternating magnetic field. For single speed units the rotor is excited by a DC source; however for an adjustable speed unit the rotor is excited from an adjustable frequency voltage source. When the frequency and phase angle of the rotor excitation is adjusted above or below direct current, the rotor speed can be adjusted.

The operation of a single speed pump/turbine unit is along a single pump curve (discharge vs. head). During generation mode, the wicket gates are positioned to minimize the throttling effect, which reduces losses in the system. The wicket gates are not throttling during pumping mode because it creates additional losses, causes excessive vibrations, and reduces the life of the mechanical equipment. The operation of an adjustable speed unit is greatly improved over single speed units. The increased operational range allows adjustment of input power, helps to avoid reverse flow when operating at high heads, controls electrical power frequency on the power grid during pumping mode, and helps to avoid cavitation when operating at low heads.

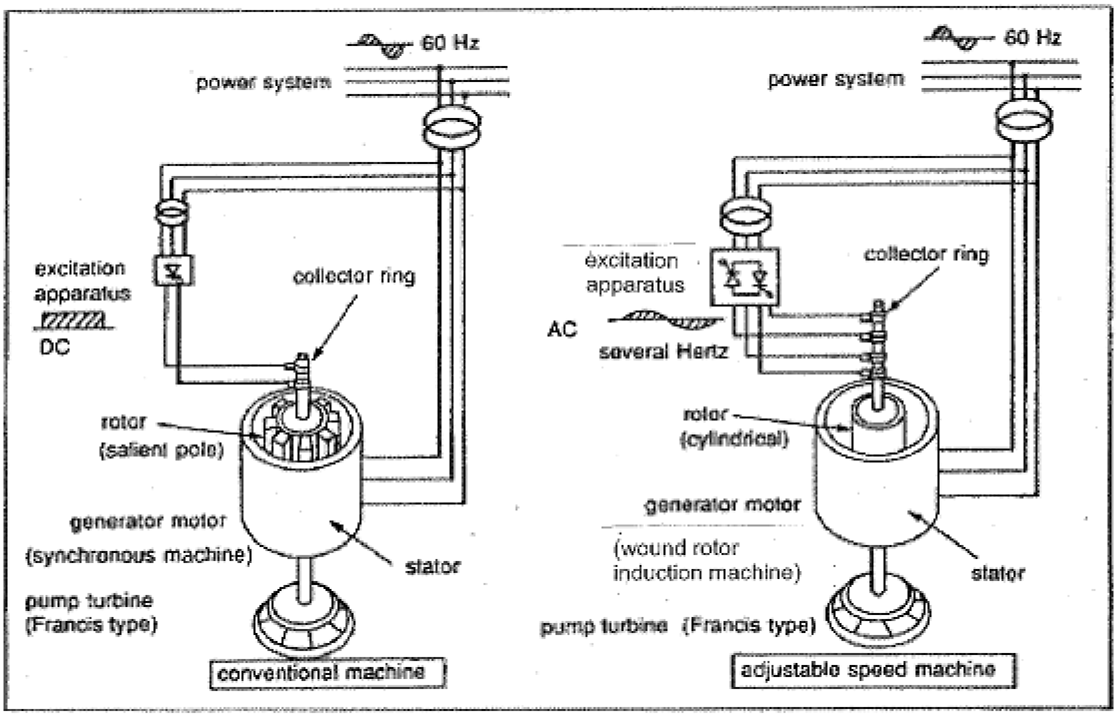


**Figure 13. Comparison of Single Speed and Adjustable Speed Electrical Connections (Kuwabara et al, 1996)**

The operating range of single speed and adjustable speed pumps, in pumping mode, is illustrated on Figure 14. The pumping curve for a single speed synchronous unit is defined by a single curve. This means that single speed unit is restricted to operating at only points along the curve. An adjustable speed unit is able to operate within a range defined by the minimum speed, maximum speed of the pump, maximum power (limited by the amount of power available to drive the pump), the turbulent operation limit (limited by pump discharge), and the cavitation limit (the minimum suction conditions required to prevent pump cavitation – depends on the pressure at the inlet to the pump impeller and the fluid vapor pressure). This range is showed in grey on the figure below. The ability to operate over a range, at different speeds, in pumping mode allows operation at the best efficiency as the elevation of the upper reservoir changes affecting the operating head.

Single speed and adjustable speed pump/turbine units operate in a similar manner during generation mode. In generation mode, single speed units are able to operate down to 50% of the rated capacity and adjustable speed units are able to operate down to 30% of the rated capacity

(MWH, 2009). Since net head available will reduce as the units are operated in generation mode, the flow required will increase in order to provide an equivalent power output.

There are numerous benefits of adjustable speed units versus single speed units. First, adjustable speed pump/turbine units have greater efficiency during generating mode because they are able to modify the turbine rotational speed to target higher efficiencies. This concept is illustrated on Figure 15 and Figure 16.

Second, during pumping mode, adjustable speed units are able to operate at partial load by adjusting the rotational speed to capture low excess power levels. This operation limits the number of starts and stops during the pumping mode, which is important, because it reduces the number of disturbances on the power grid and provides for better overall grid operation. This aspect of adjustable speed units makes them attractive when used in conjunction with renewable energy sources. As Figure 17 shows, the ability to adjust the rotational speed during pump mode results in improved power network balancing and storage of additional power.

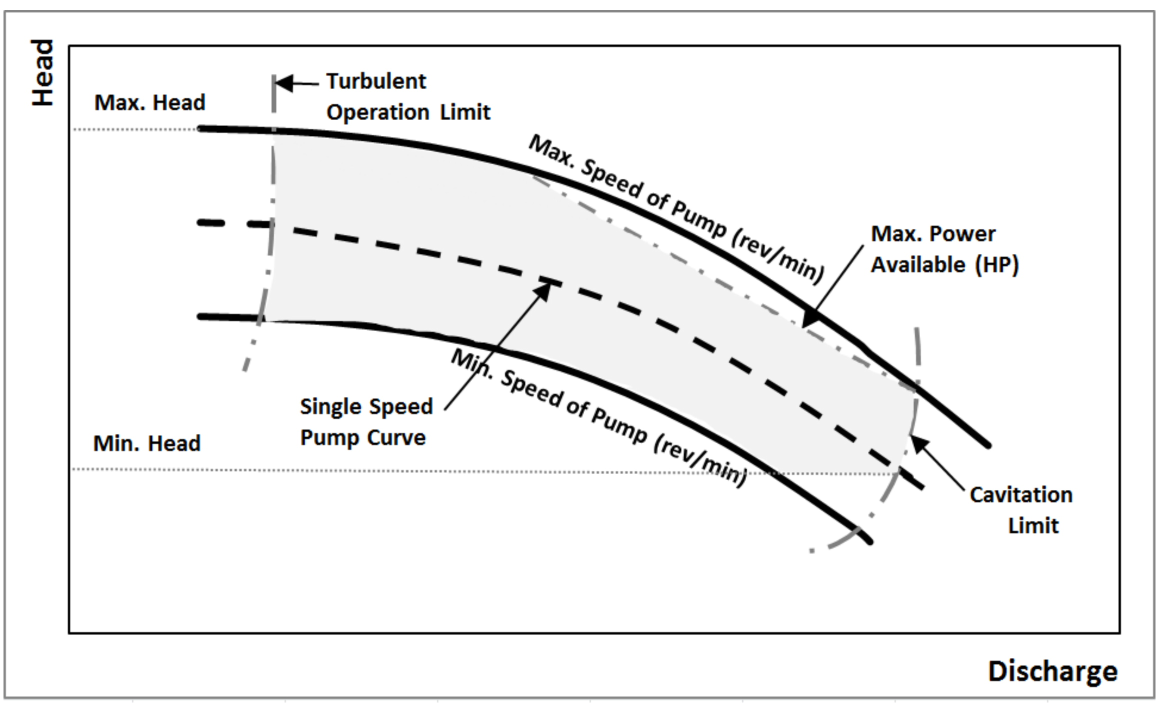


**Figure 14. Operating Range of Pumps – Single Speed Versus Adjustable Speed**

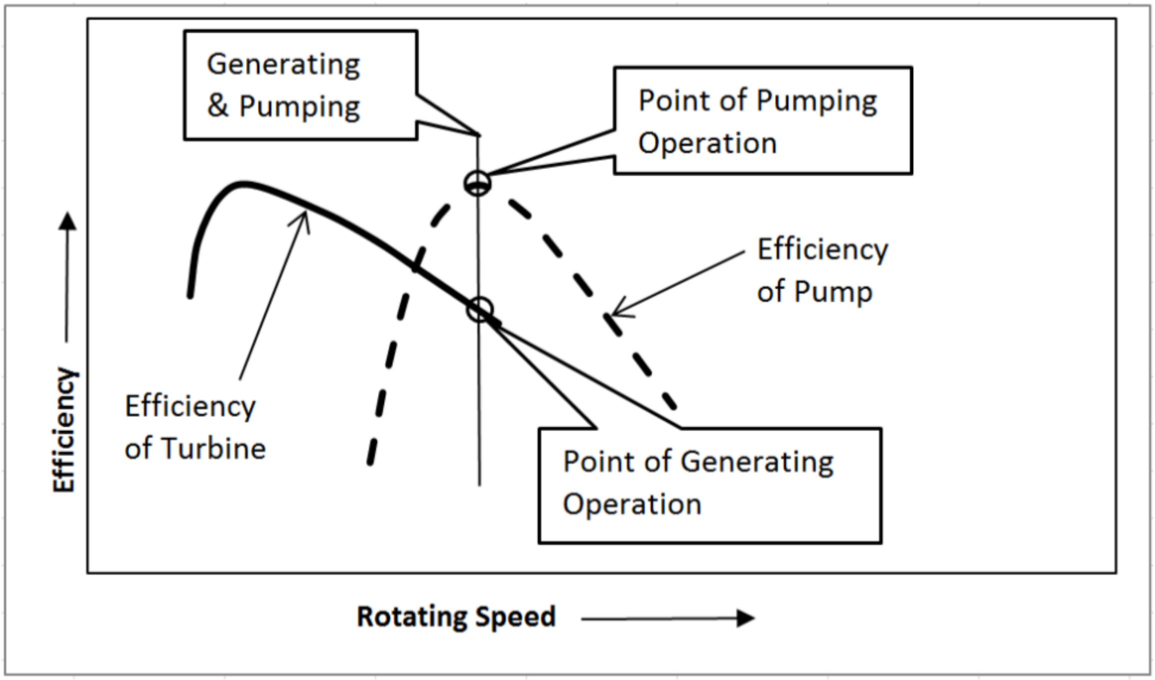


**Figure 15. Comparison of Pump/Turbine Efficiencies - Single Speed Pump/Turbine (MWH, 2009)**

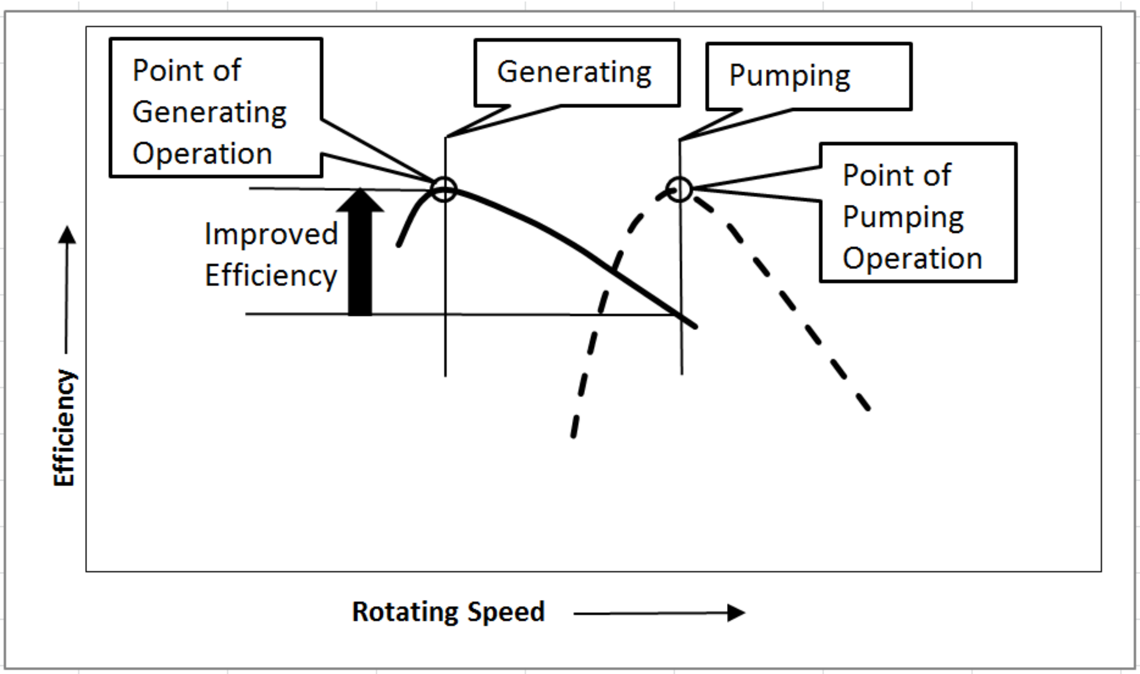


**Figure 16. Comparison of Pump/Turbine Efficiencies – Adjustable Speed Pump/Turbine (MWH, 2009)**

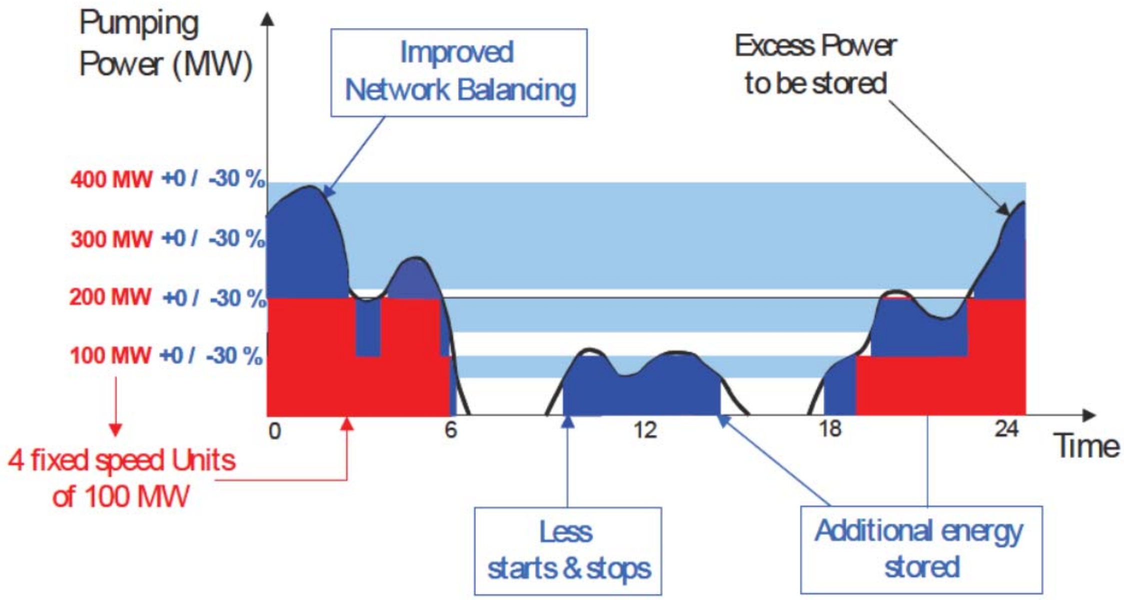


Fig. 3. Operation of fix speed – red and variable speed – blue power plant

**Figure 17. Operation of Single Speed and Adjustable Speed Pump/Turbine Units in Pumping Mode (Kunz et al, 2012)**

## 6. Case Studies of Adjustable Speed Pumped Storage Hydropower

To develop an understanding of proposed modern pumped storage hydropower technologies and project layouts several projects in the United States were reviewed. These projects include the 1000 MW Lorella Pumped Storage Hydropower Project in Klamath County, Oregon, the 400 MW Iowa Hill Pumped Storage Hydropower Project located in El Dorago County, California, and the 1300 MW Eagle Mountain Pumped Storage Hydropower Project in Riverside County, California. The case studies help to provide a range of project values. The case studies considered are summarized in Table 5. Project drawings for the case studies considered are provided in Appendix A through Appendix C.

**Table 5. Case Studies of Proposed Adjustable Speed Pumped Storage Hydropower Projects**

| **Project Name** | **Lorella (FFP, 2012)** | **Iowa Hill (SMUD, 2013)** | **Eagle Mountain (ECEC, 2009)** |
|---|---|---|---|
| **State** | Oregon | California | California |
| **County** | Klamath | El Dorago | Riverside |
| **Existing Facilities** | No existing dam | uses existing transmission line and lower reservoir (Slab Creek Reservoir) | project reservoirs will be formed by filling existing mines |
| **Type of Project** | closed-system | off-stream | closed-system |
| **Water source** | Groundwater | Existing lower reservoir | Groundwater |
| **Pump/Turbine Units** | pump/turbine units | adjustable speed pump/turbine units | pump/turbine units - one of more will be adjustable speed |
| *Total Capacity* | 1000 MW | 400 MW | 1300 MW |
| *No. of Units* | 4 | 3 | 4 |
| *Unit Capacity* | 250 MW | 133 MW | 325 MW |
| **Average Annual Energy Output** | 1,600 GWh/year | 2,779 GWh/yr | 4,308 GWh/year |
| **Average Annual Energy Consumption** | | | 5,744 GWh/year |
| **Design Head** | 1,190 to 1,300 feet | 1,200 feet | Avg net head 1410 feet |
| **Design Flow** | | | (Max Plant) 11,600 cfs (Max Unit) 2,900 cfs |
| **Hours of Equivalent full-load generation** | | | 10 hours |
| **Overall Efficiency** | | | 86.6% |

| Project Name | Lorella (FFP, 2012) | Iowa Hill (SMUD, 2013) | Eagle Mountain (ECEC, 2009) |
| --- | --- | --- | --- |
| **Waterways** | | | |
| *Upper Pressure Tunnel* | - | - | 4,000-foot-long, 29 foot diameter (low pressure) |
| *Vertical Shaft* | 1,350-foot-deep, 24-foot diameter | 1,120-foot-deep, 19.02-foot diameter | 1,348-foot-long, 33 foot diameter |
| *Power Tunnel* | 3,200-foot-long, 24-foot diameter | D shaped, 1,110-foot-long, 19.02-foot diameter (high pressure);<br>D shaped, 250-foot-long, 15.74 foot diameter (steel lined high pressure) | 1,560-foot-long, 29 foot diameter (high pressure) |
| *Penstock* | four 355-foot-long, 12-foot diameter, steel lined | Maniford - D shaped, 150-foot-long; 12.45 foot diameter<br>D shaped, three, 180-foot-long, 7.87-foot diameter penstocks | |
| *Draft Tube* | four 16-foot diameter, 100-foot-long draft tube tunnels | D shaped, three, 12.46 diameter, 450-foot-long | |
| *Low Pressure Tunnel* | | Maniford - D shaped, 150-foot-long, 17.22 foot diameter<br>Low Pressure Tunnel - D shaped, 1,230-foot-long, 20.93-foot diameter | 6,835-foot-long, 33 foot diameter (tailrace tunnel) |
| **Powerhouse** | 380 by 80 foot powerhouse | underground, Height = 121 foot, Length = 277 foot, Width = 60 foot | underground, Height = 130 foot, Length = 360 foot, Width = 72 foot |
| **Upper Reservoir** | | | |
| *Surface Area (at normal maximum surface elevation)* | 200 acres | 109 acres | 191 acres |
| *Surface Elevation* | 5,400 to 5,523 feet msl | 3,073 to 2,945 feet msl | 2343 tp 2485 feet msl |
| *Storage Capacity* | 14,300 acre-feet | 6,400 acre-feet | 17,700 acre-feet (active storage) |
| **Lower Reservoir** | | *Uses existing reservoir* | |
| *Surface Area (at normal maximum surface elevation)* | 400 acres | | 163 acres |
| *Surface Elevation* | 4,147 to 4,191 feet msl | | 925 to 1092 feet msl |

| Project Name | Lorella (FFP, 2012) | Iowa Hill (SMUD, 2013) | Eagle Mountain (ECEC, 2009) |
| --- | --- | --- | --- |
| *Storage Capacity* | 16,900 acre-feet | | 17,700 acre-feet (active storage) |
| **Project Status** | Preliminary Permit Approved | Contract recently awarded for Owner's Engineer services contract for preliminary design and construction services | Final license application submitted June 22, 2009 |
| **Costs and Financing** | $1,174M (February 1995) | Estimated $690M plus contingency, network upgrades, and CM costs (January 2013) - Electromechanical equipment $242M | Total Project Cost = $1,410M; Waterwheels, Turbines & Generators = $263M; Accessory Electrical Equipment = $209M; Miscellaneous Power plant Equipment = $47M |

## 7. Design Considerations

During the design of a pumped storage hydropower project, there are numerous project components that need to be considered. The primary considerations include head, flow rates, waterways, upper and lower reservoirs, pump/turbine selection, and other design issues.

### 7.1. Head

The operating head of pumped storage hydropower projects in the United States typically range between 300 and 2,100 feet. Low head projects generally require larger conduits, which are cost prohibitive. High head projects (typically over 2,500 feet) require more complex multi-stage pump/turbine units, and eliminate the ability to regulate the units in generating mode. High head projects are typically more cost effective, because based on the power equation, the product of the total volume of water stored by the total head is proportional to the total energy stored; therefore a project with a higher head would require smaller reservoirs and have smaller electrical-mechanical provide an equivalent amount of energy. The case studies considered have design heads ranging between 1,190 feet and 1,410 feet, consistent with other domestic projects.

### 7.2. Flow Rates

The basic criterion used during planning is the desired generating capacity, and based on this and available head, flow rates are calculated. For a given head, projects with higher design flow rates require larger waterway conduits and pump/turbine units. As part of the project planning process, it is important to perform a cost-benefit analysis to look at different flow rates/plant sizing capacity that will provide the greatest overall benefit. Another important consideration regarding design flow rates are the desire to minimize the head losses in the waterways. Smaller flow rates, and associated smaller conduit diameters, typically have higher head losses versus larger conduits; however larger conduits are typically more expensive to construct because they require more civil works. Design flow rates were not available for the case studies considered, except Eagle Mountain, which has a design plant flow rate of 11,600 cfs.

### 7.3. Waterway

The design of the waterways for a pumped storage hydropower project is an important part of the overall project design as it has the potential to greatly impact the overall efficiency of the facility and the performance of the pump/turbine units. For pumped storage hydropower projects the waterways are the system of conduits that connect the upper reservoir, powerhouse, and lower reservoir. Based on the hydraulics of the system, some projects may also require a surge tank to protect the waterway and pump/turbine units from water hammer. Pumped storage hydropower projects typically have two sections of waterways. The first section is the high head portion between the upper reservoir and the pump/turbine unit(s) and the second section is the low head portion between the pump/turbine unit(s) and the lower reservoir.

A waterway that travels the shortest distance possible between the upper reservoir, powerhouse, and lower reservoir is optimal. A shorter waterway is preferred to minimize both construction costs and friction losses in the system. The water conduit system should further be designed to minimize friction losses in both pumping and generating modes. The site specific geology and topography have a significant influence on potential waterway configurations. Waterways can either be located on the surface of the slope or buried underground. The Iowa Hill and Eagle Mountain case studies both consider buried underground waterways (See Appendix B and Appendix C). Tunnel materials include steel and concrete water pipe, and underground waterways may additionally be constructed at tunnels in hard rock.

### 7.4. Upper and Lower Reservoirs

The design of the upper and reservoirs is dependent on a number of factors. First, it depends on whether an existing reservoir is available. Often an existing reservoir or reservoirs may be used. This is attractive because it reduces construction costs and may provide a reliable water source (assuming water rights are available). Second, the layout of reservoirs depends on the topography of the project site and the presence of streams and rivers (and possibly access to groundwater). Assuming favorable geologic conditions are present a ring-like dam can be constructed on a mountain plateau or a dam can be constructed across a valley (with or without a stream or other water feature). Third, the geologic conditions present have a big impact on selecting the location of potential reservoirs and the design of a reservoir lining system (if needed). Due to the rapid change in water levels in both the upper and lower reservoirs during reservoir filling and emptying (during pumping and turbine operation) the stability of the reservoir slopes can be greatly impacted; consequently lining of the reservoir may be required. Seepage losses in the reservoir foundations are also a concern, which may require a grout curtain or lining of the reservoir. This is of particular concern for a closed-system pumped storage hydropower project where conservation of water is important.

The sizing of the upper and lower reservoirs depends on the size of the installed units, the operating head, the site characteristics, and the number of hours that operation of the turbines is required. A typical plant is sized to operate between 4 and 20 hours depending on local energy needs. Operational models are used to evaluate the cost-benefit of different reservoir sizing options to refine the design.

A simplified equation for determining the storage required in the system, can be estimated using the following equation (USACE, 1985):

$$S = \frac{976\,(C)t_s}{He_g} \qquad (\textit{Equation 7-1})$$

Where,

S = Storage (acre-feet)

C = Plant capacity (MW)

$t_s$ = Storage requirement in hours of equivalent full-load generation (hours)

H = Average gross head (feet)

$e_g$ = generation efficiency, including head losses (%)

The simplified equation for determining the storage required in the system was applied to each of the proposed pumped storage hydropower projects, and the results are summarized in Table 6. The hours of equivalent full-load generation were not available for the Lorella and Iowa Hill projects so a typical value of 10 hours was assumed. The generation efficiency for both projects was also not available, therefore an efficiency of 85% typical for a modern pumped storage hydropower project was assumed. In general, the calculated storages are 40% lower than the planned design upper reservoir storage volumes. This would suggest that the USACE equation consistently underestimates the required storage volume, so additional design considerations such as seepage losses, evaporation, dead storage, and operational cycle anticipated may need to be considered separately.

**Table 6. Simplified Storage Equation – Case Studies**

| | **Lorella** | **Iowa Hill** | **Eagle Mountain** |
|---|---|---|---|
| Plant Capacity (MW) | 1000 | 400 | 1300 |
| $T_s$ (hours) | Not Available (assume 10 hours) | Not Available (assume 10 hours) | 10 |
| H (feet) | 1,190 to 1,300 feet | 1,200 feet | 1410 feet |
| $e_s$ | Not Available (assume 85%) | Not Available (assume 85%) | 86.6% |
| Storage (actual planned) – Upper Reservoir (acre-feet) | 14,300 acre-feet | 6,400 acre-feet | 17,700 acre-feet |
| Calculated Storage (acre-feet) | 9,220 acre-feet | 3,830 acre-feet | 10,30 acre-feet |

### 7.5. Pump/Turbine Selection

The sizing of pump/turbine units primarily depends on the project economics, site characteristics, and requirements of the power system. Most constructed pumped storage hydropower projects provide between 300 to 2,500 MW, which would suggest that larger scale projects are generally more economically viable. For larger scale projects, and therefore the selection of larger pump/turbine units, sufficient water available, sufficient operating head, and adequately sized upper and lower reservoirs are needed. For projects with low head or limited water available, a smaller scale project is more appropriate.

The type of pump/turbine units, single speed versus adjustable speed or a combination of both, should also be evaluated as part of the design process. While some early pumped storage hydropower projects used separate pumps and turbines, most modern project used combined pump/turbine units. The selection of pump/unit size and type also affects the size and configuration of the powerhouse. For instance, adjustable speed units require additional components, which result in larger overall powerhouse dimensions and higher construction costs.

The case studies identified use combined pump/turbine units. The system capacities range between 400 and 1,300 MW, with individual pump/turbine unit capacities of 133 to 325 MW. All three projects include adjustable speed units, with the Eagle Mountain project using a combination of both single speed and adjustable speed units.

# 8. Technical Analysis

## 8.1. Objective

For project planning purposes, the development of a simple tool that can quickly evaluate numerous technical parameters and operational characteristics is important. For pumped storage hydropower projects, the performance of single speed versus adjustable speed pump/turbine units is of particular interest. As a result, a new model was developed to consider the key design elements for pumped storage hydropower systems using fixed or adjustable speed pump/turbine units, for a typical “off-stream” pumped storage hydropower system. The model can further be used to help size the upper and lower reservoirs based on different operational scenarios, unit selection, and other technical parameters. This is accomplished by forming an understanding of the methodologies and procedures used to develop the model, the inputs, outputs and assumptions used by the model, and how changes to pump/turbine unit operation impacts power generation. The demand scenario considered by the model considers simulated typical excess values for the power available (available for pumping mode) and peak power required (target during generating mode).

## 8.2. Methods

The model was developed for a simplified typical “off-stream” pumped storage hydropower project. The system comprises of a lower reservoir, powerhouse, electrical-mechanical equipment, upper reservoir, and a connecting waterway. During pumping mode water travels from the lower reservoir to the upper reservoir. Then, during generating mode water travels from the upper reservoir back to the lower reservoir. A simplified layout for a typical “off-stream” pumped storage hydropower project is illustrated on Figure 18.

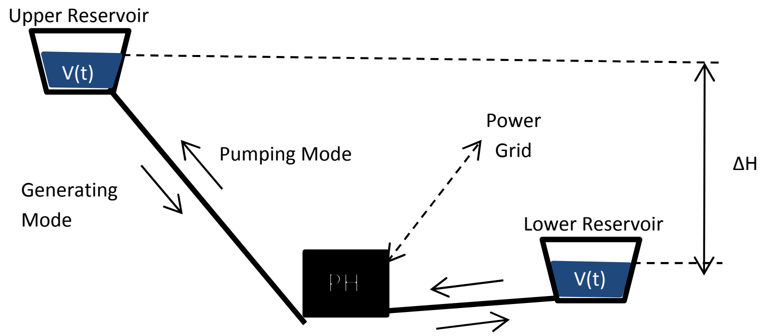


**Figure 18. Simplified Pumped Storage Hydropower Project Configuration**

The model was prepared using a time step of 1 hour, and a total duration of 7 days or 1 week. The power used or generated at each time step depends on a number of factors. These factors include:

- Excess energy available on the power grid.
- Peak energy required by the power grid.
- Volume of water available in the upper reservoir.
- Space available in the upper reservoir.
- Volume of water available in the lower reservoir.
- Space available in the lower reservoir.
- Efficiency of pump/turbine units during both pumping and generating mode.
- Capacity of pump/turbine units
- Type of pump/turbine units (e.g., single speed versus adjustable speed)
- Head loss in waterway.
- Total head available.

To simplify the modeling exercise several assumptions were made:

- Constant Head. Assumes the total head during both pumping and generating mode is constant. This is generally only a reasonable assumption if there isn’t a lot of variation in head during the pumping cycle. If there is a significant variation in head with respect to time, during pumping and turbine mode, then this assumption would not be reasonable.

- Evaporation and Seepage is negligible. Assumes that there will be minimal losses in upper and lower reservoirs due to reservoir lining systems and small reservoir surface areas.
- The waterway conduits are adequately sized to prevent the waterway from creating a discharge capability constraint.
- Waterway losses during pumping and generating mode are equal to 3% of the total head. This includes all pipe friction losses and minor system losses.
- To achieve better turbine efficiencies the pump/turbine units are assumed to operate between 70 to 100 percent of their rated capacity during generation mode.
- Typical “off-stream” pumped storage hydropower configuration. A pumped-back configuration would require additional inputs such as stream inflows, required minimum environmental (stream) flows, etc.

### *8.2.1. Power Supply and Demand*

For the purposes of this paper, supply of energy available for the pumped storage hydropower system is called excess energy on power grid and demand for energy to be met by the pumped storage hydropower system is called peak energy required. A simulated scenario was developed based on Figure 1, and is presented on Figure 19. The demand scenario was simulated to develop an understanding of the range of pumped storage hydropower facility operation.

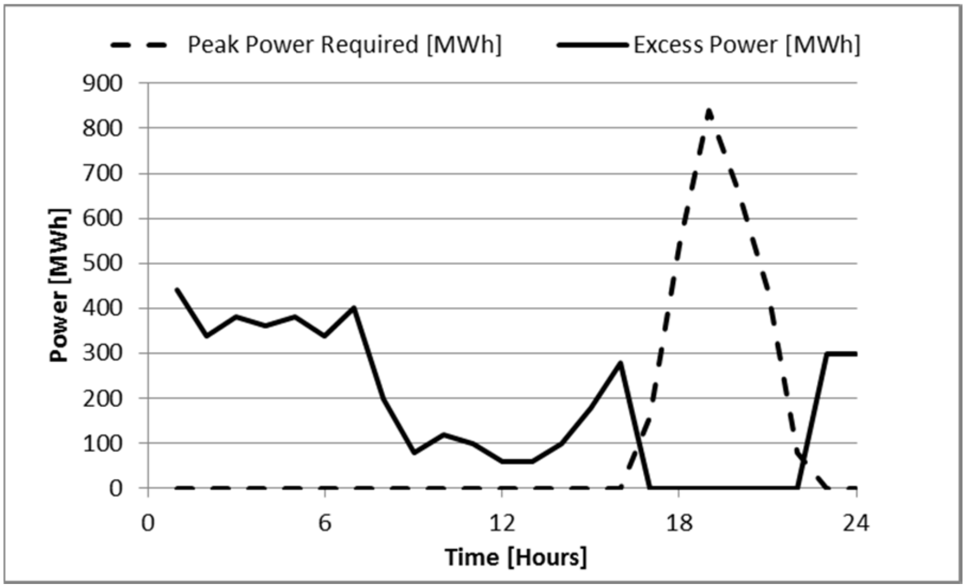


**Figure 19. Energy Supply and Demand - Case 3**

### *8.2.2. Efficiency of Project Components*

The model considers the efficiency of three main project components: the waterways, the pump/turbine units in pumping mode, and the pump/turbine units in generating mode. For the purposes of this model, other minor losses (typically 1-2% each) such as motor, generator, and transformer losses are not considered. The efficiency values used are discussed as follows:

- **Waterways:** Each project has a unique configuration therefore head losses vary from project to project. A head loss of 3% of the total head was considered in the model.
- **Pump/Turbine Units**: As discussed previously, the majority of the efficiency losses for a pumped storage hydropower projects are due to the pump/turbine units in pumping and generating mode.
  - **Pumping Mode**: Based on Table 4, an efficiency value of 91 percent was assumed for both single and adjustable speed units in pumping mode.
  - **Generating Mode**: Figure 10 was used to select efficiency values for both single speed and adjustable speed pump/turbine units in generating mode. The pump/turbine units were assumed to operate between 70 to 100 percent of the

rated power output, so average efficiency values were assumed based on the figure. For adjustable speed units an efficiency value of 92 percent was assumed and for single speed units an efficiency value of 89 percent was assumed.

### *8.2.3. Pumping and Generating Mode*

At each time step, the model first considers whether excess energy is available on the power grid or whether peaking power is needed on the power grid. When excess energy is available on the power grid and the system is able to pump water to the upper reservoir, this is referred to as **Pumping Mode** (assuming other criteria are satisfied). Conversely, when peaking power is required and the system is able to generate power, this is referred to as **Generating Mode** (assuming other criteria are satisfied). A detailed account of the logic followed in the model is described below.

**Pumping Mode**

In pumping mode the model considers a number of factors to establish whether water will be pumped to the upper reservoir at each time step. There are four main limiting factors that dictate whether energy is available, and if so, what quantity of energy is available for pumping. The limiting factors include:

1) ***Available Excess Energy*** - Is excess energy available on the power grid? If so, how much excess energy on the power grid is available for pumping?

2) ***Unit Capability*** - What is the capacity of the pump/turbine units (e.g., 200 MW)? The model considers single speed and adjustable speed pumps separately.

3) ***Water Available in Lower Reservoir*** - What is the quantity of water available in the lower reservoir?

4) ***Volume Available in Upper Reservoir*** - What is the volume available in the upper reservoir? At each time step water can only be pumped if there is space available in the upper reservoir.

For each time step, of one hour, the pumping mode limiting factors were converted to units of cfs, to allow for better comparison at each time step. The model evaluates each limiting factor and selects the minimum value for further analysis. For energy, E is used and for power, P is used. The ***Available Excess Energy*** was calculated using the following power equations:

$$\boldsymbol{E_{pump} = P_{pump} * t} \qquad \text{(Equation 8-1)}$$

$$\boldsymbol{P_{pump} = \frac{\gamma\, Q\, \Delta H}{\eta}} \qquad \text{(Equation 8-2)}$$

Solving for Q,

$$\boldsymbol{Q = \frac{P_{pump}\eta}{\gamma \Delta H}} \qquad \text{(Equation 8-3)}$$

Now, for example, consider a situation where power available for pumping is 1,000 MW, pumping efficiency is 98%, and net head is 1,452.3 feet. Using Equation 8-3, the available excess energy limiting factor is 7,973 cfs:

$$\boldsymbol{\frac{1000\ MW * 0.98}{62.4 \frac{lb}{ft^3} * 1452.3\ ft} * \frac{550 \frac{ft*lb}{s}}{746\ W} * \frac{1{,}000{,}000\ W}{1\ MW} = 7{,}973\ cfs} \qquad \text{(Equation 8-4)}$$

The ***Unit Capability*** was calculated using separate equations for single speed units and adjustable speed units. Separate equations are needed because the two types of units operate differently. A pull down menu is included in the Microsoft Excel model to allow the model to switch between the two sets of equations. The methodology and equations used for each type of unit are as follows:

Single Speed Units: In pumping mode, the power input for single speed units is nearly constant. While discharge typically varies based on pumping head the model assumes constant head therefore discharge is also considered to be constant for single speed units.

The model considers each single speed unit separately. Since power input is nearly constant for each unit, the model assumes that Unit 1 turns on once available excess energy available exceeds unit capacity. Each subsequent unit is then programmed to turn on once each subsequent interval of energy available is achieved. A series of “if” statements in used in Microsoft Excel to turn each unit on and off. For each unit the model uses Equation 8-3 to calculate the flow, Q.

Now, for example, consider a situation where power available for pumping is 700 MW, there are 4 pump/turbine units, a pump/turbine unit capacity of 325 MW each, pumping efficiency of 98%, and a net head of 1,452.3 feet. The model first evaluates Unit 1, and whether power available power available is greater than the rated unit capacity of 325 MW. Then using Equation 8-3, the equivalent flow for Unit 1 is 2,591 cfs:

$$\frac{325\ MW * 0.98}{62.4\,\frac{lb}{ft^3} * 1452.3\ ft} * \frac{550\,\frac{ft*lb}{s}}{746\ W} * \frac{1{,}000{,}000\ W}{1\ MW} = \mathbf{2,591\ cfs} \qquad (\textit{Equation 8-5})$$

The model next evaluates Unit 2, and whether power available is greater than 650 MW (2*325MW = 650 MW), which is the combined rated capacity for two units. Then using Equation 8-3, the equivalent flow for Unit 2 is 2,591 cfs:

$$\frac{325\ MW * 0.98}{62.4\,\frac{lb}{ft^3} * 1452.3\ ft} * \frac{550\,\frac{ft*lb}{s}}{746\ W} * \frac{1{,}000{,}000\ W}{1\ MW} = \mathbf{2,591\ cfs} \qquad (\textit{Equation 8-6})$$

Since excess power on the power grid is less than 975 MW (325 MW*3 = 975MW), which is the rated capacity for three units, then Unit 3 and any other subsequent units will not turn on. Since the units are considered separately the flows are added from each of the units resulting in a cumulative flow of 5,182 cfs:

$$2,591 + 2,591 = 5,182\ cfs \qquad \text{(Equation 8-7)}$$

<u>Adjustable Speed Unit</u>: In pumping mode, adjustable speed pumps are capable of operating at a broader range of power inputs. Since adjustable speed pumps are capable of operating at a range of power inputs a single equation, Equation 8-3, is used by the model to calculate the flow, Q.

Next a sample calculation for adjustable speed units is performed. A situation is considered where the power available for pumping is 500 MW, the pumping efficiency of 98%, and net head is 1,452.3 feet. Equation 8-3 is used resulting in a limiting factor flow of 3,986 cfs:

$$\frac{500\ MW * 0.98}{62.4\frac{lb}{ft^3} * 1452.3\ ft} * \frac{550\frac{ft*lb}{s}}{746\ W} * \frac{1,000,000\ W}{1\ MW} = 3,986\ cfs \qquad \text{(Equation 8-8)}$$

The ***Water Available in Lower Reservoir*** at each time step is calculated based on the elevation of the lower reservoir at the end of the prior time step. For each 1 hour time step, the volume of water available (V) in the lower reservoir is converted into units of cfs (for comparison purposes) using the following equation where t is time:

$$V = Qt \qquad \text{(Equation 8-9)}$$

Solving for Q provides the following,

$$Q = \frac{V}{t} \qquad \text{(Equation 8-10)}$$

Now, for example, consider a situation where the water available is 1,000 acre-feet and the time period is 1 hour (1 time step). Using Equation 8-10, the equivalent flow is 12,100 cfs:

$$\frac{1,000\ ac-ft}{1\ hr} * \frac{1\ hour}{3,600\ sec} * \frac{43,560\ ft^2}{1\ ac} = 12,100\ cfs \qquad \text{(Equation 8-11)}$$

The ***Volume Available in Upper Reservoir*** at each time step is calculated based on the elevation of the upper reservoir at the end of the prior time step. The volume available in the upper reservoir is converted to cfs using Equation 8-9 and Equation 8-10. A sample situation would use a similar calculation method to that used in Equation 8-11.

Now that Q values are available for each of the limiting criteria - ***Available Excess Energy***, ***Unit Capability***, ***Water Available in Lower Reservoir*** - the model selects the minimum flow value available for pumping at each time step, then evaluates whether there is ***Volume Available in Upper Reservoir*** to received pumped water. The minimum Q value is used in the power equation, Equation 8-1, to calculate the energy used to pump water to the upper reservoir. For example, consider a situation where the flow available is 3,986 cfs, the pumping efficiency is 98%, the net head is 1,452.3 feet, and the time period is 1 hour. Using Equation 8-1, the power is 500 MWh:

$$\boldsymbol{E_{pump} = \frac{62.4\frac{lb}{ft^3} * 3{,}986\ cfs * 1{,}452.3\ ft}{0.98} * \frac{746\ W}{550\frac{ft\,lb}{s}} * \frac{1\ MW}{1{,}000{,}000\ W} * 1\ hr = 500\ MWh} \qquad \text{(\textit{Equation 8-12})}$$

Now that the energy used to pump water to the upper reservoir is known, Equation 8-9 is used to calculate the volume of water pumped to the upper reservoir. For example, consider a situation where flow available is 3,986 cfs and the time period is 1 hour. Using Equation 8-9, the volume of water pumped to the upper reservoir is 329 acre-feet:

$$\boldsymbol{V = 3{,}986\ \frac{ft^3}{sec} * \frac{3{,}600\ sec}{1\ hr} * \frac{1\ ac}{43{,}560\ ft^3} * 1\ hr = 329\ ac - ft} \qquad \text{(\textit{Equation 8-13})}$$

At the end of the pumping cycle the volume of water in the upper and lower reservoirs is calculated for use during the next time step.

**Generating Mode**

In generating mode the model considers a number of factors to establish whether peaking power is required, and if so, what quantity of energy is available and/or provided at each time step. There are four main limiting factors during generating mode, which include:

1) ***Peaking Power Required*** - Is peaking power required on the power grid? If so, what quantity of energy is required?

2) ***Unit Capability*** - What is the capacity of the pump/turbine units (e.g., 200 MW)? The model considers single speed and adjustable speed pumps separately.

*3)* ***Water Available in Upper Reservoir*** - What is the quantity of water available in the upper reservoir for turbine operation?

*4)* ***Volume Available in Lower Reservoir*** – What is the volume available in the lower reservoir? At each time step power can only be generated if there is space available in the lower reservoir to received water. At the first time step the reservoir is assumed to be empty.

The generating mode limiting factors were all converted to units of cfs, to again allow for better comparison at each time step. The model evaluates each limiting factor and selects the minimum value for further analysis. The ***Peaking Power Required*** was calculated using the following power equation:

$$\boldsymbol{E_{turbine} = P_{turbine} * t} \qquad (\textit{Equation 8-14})$$

$$\boldsymbol{P_{turbine} = \gamma Q \Delta H \eta} \qquad (\textit{Equation 8-15})$$

Solving for Q,

$$\boldsymbol{Q = \frac{P_{turbine}}{\gamma\, \Delta H\, \eta}} \qquad (\textit{Equation 8-16})$$

Now, for example, consider a situation where the power required is 1,000 MW, the turbine efficiency is 98%, and net head is 1,452.3 feet. Using Equation 8-16, the peaking power limiting factor is 8,302 cfs:

$$\frac{1000\ MW}{62.4\,\frac{lb}{ft^3} * 1452.3\ ft * 0.98} * \frac{550\,\frac{ft*lb}{s}}{746\ W} * \frac{1{,}000{,}000\ W}{1\ MW} = \boldsymbol{8,302\ cfs} \qquad (\textit{Equation 8-17})$$

The ***Unit Capability*** was again calculated using separate equations for single speed units and adjustable speed units. Separate equations are needed because the two types of units operate at different efficiencies and potentially operate differently. For the purposes of this model both types of units are assumed to operate similarly. The pull down menu is included in the Microsoft Excel model also switches the model between the two sets of equations in generating mode.

To maintain favorable efficiency values single speed and adjustable speed units are assumed to operate between 70 to 100 percent of the rated unit capacity. Based on the operational characteristics of the units the model considers each pump/turbine unit separately. For each pump/turbine unit, the model assumes that Unit 1 operates when peaking power required is between 70 to 100 percent of the unit capacity. Each subsequent unit is then programmed to turn on once each subsequent interval of peaking power required is achieved. A series of "if" statements in used in Microsoft Excel to account for turn each unit on and off.

The methodology and equations used for each type of unit are as follows:

Single Speed Unit: In generating mode, the single speed units can operate over a range of flows down to 50 percent of the rated discharge (MWH, 2009); however the range of operation is limited down to 70% to maintain unit efficiency. For each unit the model uses Equation 8-16 to calculate the flow, Q.

Now, for example, consider a situation where peaking power required is 700 MW, 4 pump/turbine units, a pump/turbine unit capacity of 325 MW each, turbine efficiency is 89%, and net head is 1,452.3 feet. The model assumes that each unit operates when power required is between 70 to 100% of the rated unit capacity, which results in a pump turbine range of 228 to 325 MW:

$$\text{Minimum Range} \qquad 325\ \text{MW} * .7 = 228\ \text{MW} \tag{Equation 8-18}$$

The model first evaluates Unit 1, and whether peaking power required is greater than 325 MW. Since 700 MW > 325 MW, Equation 8-16 is used to calculate an equivalent flow for Unit 1 of 2,971 cfs:

$$\frac{325\ MW}{62.4\frac{lb}{ft^3}*1452.3\ ft*0.89}*\frac{550\frac{ft*lb}{s}}{746\ W}*\frac{1{,}000{,}000\ W}{1\ MW}=\mathbf{2{,}971\ cfs} \quad \text{(Equation 8-19)}$$

The model next evaluates Unit 2, and whether the peaking power required is greater than 650 MW (2*325MW = 650 MW), which is that rated capacity of two pump/turbine units. Since 700 MW > 650 MW, Equation 8-16 is used to calculate an equivalent flow for Unit 2 of 2,971 cfs:

$$\frac{325\ MW}{62.4\frac{lb}{ft^3}*1452.3\ ft*0.89}*\frac{550\frac{ft*lb}{s}}{746\ W}*\frac{1{,}000{,}000\ W}{1\ MW}=\mathbf{2{,}971\ cfs} \quad \text{(Equation 8-20)}$$

The model next considers Unit 3. Since the peaking power required is less than 975 MW (3*325 MW = 975MW), equivalent to operating three units at full capacity, and less than 878 MW (325 MW*2 + 325MW*.7 = 878MW), equivalent to two units operating at full capacity and the third unit operating at 70%, then Unit 3 and any other subsequent units will not turn on. The units are considered separately, so the flows are added from each of the operating units resulting in a cumulative flow of 5,942 cfs:

$$\mathbf{2{,}971+2{,}971=5{,}942\ cfs} \quad \text{(Equation 8-21)}$$

<u>Adjustable Speed Unit</u>: In generating mode, adjustable speed pumps are capable of operating at a broader range of power outputs, down to 30 percent of the rated discharge (MWH, 2009). However, to maintain optimum efficiencies they are typically operated within 70% of the rated pump/turbine unit capacity. Since adjustable speed pumps are operated in a similar manner as single speed pumps the methodology used for single speed pump/turbine units in generating mode also applies. The model assumes Unit 1 operates when peaking power required is between 70 to 100 percent of the unit capacity. Each subsequent unit is then programmed to turn on once each subsequent interval of

peaking power required is achieved. For each unit the model uses Equation 8-16 to calculate the flow, Q.

Now, for example, consider a situation where peaking power required is 675 MW, 4 pump/turbine units, a pump/turbine unit capacity of 325 MW each, turbine efficiency is 92%, and net head is 1,452.3 feet. The model assumes that each unit operates when power required is between 70 to 100% of the rated unit capacity, which results in a pump turbine range of 228 to 325 MW:

Minimum Range 325 MW * .7 = 228 MW (*Equation 8-22*)

The model first evaluates Unit 1, and whether peaking power required is greater than 325 MW, which is the rated capacity of one pump/turbine unit. Using Equation 8-16, the equivalent flow for Unit 1 is 2,874 cfs:

$$\frac{\mathbf{325}\ \boldsymbol{MW}}{\mathbf{62.4}\,\frac{\boldsymbol{lb}}{\boldsymbol{ft}^{\mathbf{3}}}*\mathbf{1452.3}\ \boldsymbol{ft}*\mathbf{0.92}}*\frac{\mathbf{550}\,\frac{\boldsymbol{ft*lb}}{\boldsymbol{s}}}{\mathbf{746}\ \boldsymbol{W}}*\frac{\mathbf{1{,}000{,}000}\ \boldsymbol{W}}{\mathbf{1}\ \boldsymbol{MW}}=\mathbf{2,874}\ \boldsymbol{cfs} \quad \textbf{(\textit{Equation 8-23})}$$

The model next evaluates Unit 2, and whether peaking power required is greater than 650 MW (2*325MW = 650 MW), which is the combined capacity for two units. Using Equation 8-16, an equivalent flow for Unit 2 of 2,874 cfs is obtained:

$$\frac{\mathbf{325}\ \boldsymbol{MW}}{\mathbf{62.4}\,\frac{\boldsymbol{lb}}{\boldsymbol{ft}^{\mathbf{3}}}*\mathbf{1452.3}\ \boldsymbol{ft}*\mathbf{0.92}}*\frac{\mathbf{550}\,\frac{\boldsymbol{ft*lb}}{\boldsymbol{s}}}{\mathbf{746}\ \boldsymbol{W}}*\frac{\mathbf{1{,}000{,}000}\ \boldsymbol{W}}{\mathbf{1}\ \boldsymbol{MW}}=\mathbf{2,874}\ \boldsymbol{cfs} \quad \textbf{(\textit{Equation 8-24})}$$

Again, the peaking power required is 675 MW. Since the peaking power required is less than 975 MW (3*325 MW = 975MW), equivalent to each unit operating at 100%, and also less than 878 MW (325 MW*2 + 325MW*.7 = 878MW), equivalent to two units operating at 100% and the third unit operating at 70%, then Unit 3 and any other subsequent units will not turn on. Since the units are considered separately the flows are added from each of the units resulting in a cumulative flow of 5,748 cfs:

$$\mathbf{2,874 + 2,874 = 5,748\ \mathit{cfs}} \quad (\textit{Equation 8-25})$$

The ***Water Available in Upper Reservoir*** is the next limiting factor considered. The model converts the volume of water available into units of cfs using Equation 8-9 and Equation 8-10. The volume of water available in the upper reservoir increases during **Pumping Mode** time steps and decreases during **Generating Mode** time steps. An example situation similar to that provided for pumping mode also applies for generating mode (Equation 8-11).

The ***Volume Available in Lower Reservoir*** at each time step is calculated based on the elevation of the lower reservoir at the end of the prior time step. The volume available in the lower reservoir is converted to cfs using Equation 8-9 and Equation 8-10. A sample situation would use a similar calculation method as Equation 8-11.

Now that Q values are available for each of the limiting criteria – ***Peaking Power Required***, ***Unit Capability***, and ***Water Available in Upper Reservoir*** - the model selects the minimum flow value available for generating at each time step, then evaluates whether there is ***Volume Available in Lower Reservoir***. The minimum Q value is used in the power equation, Equation 8-15, to calculate the energy generated.

For example, consider a situation where flow available is 5,748 cfs, net head is 1,452.3 feet, turbine efficiency is 92%, and the time step is 1 hour. The resulting energy provided in generation mode is 629 MWh:

$$\boldsymbol{E_{turbine} = 62.4\frac{lb}{ft^3} * 5,748\ cfs * 1,452.3\ ft * 0.92 * \frac{746\ W}{550\frac{ft\ lb}{s}} * \frac{1\ MW}{1,000,000\ W} * 1\ hr = 629\ MWh} \quad (\textit{Equation 8-26})$$

Now that the energy generated is known, the volume of water used to generate power is calculated using Equation 8-9, and results in a volume of 475 acre-feet:

$$\boldsymbol{V = 5,748\ \frac{ft^3}{sec} * \frac{3,600\ sec}{1\ hr} * \frac{1\ ac}{43,560\ ft^3} * 1\ hr = 475\ ac - ft} \qquad \textit{(Equation 8-27)}$$

At the end of the generating pumping cycle the volume of water in the upper and lower reservoirs is calculated for use during the next time step.

## 8.3. Results and Discussion

The model was used to evaluate the performance of the case study projects based on published technical parameters, and a simulated typical electricity demand-supply scenario. In particular, the model evaluated the performance of single speed versus adjustable speed pump/turbine units. To exaggerate the differences between single speed and adjustable speed units during pumping mode it was assumed that the upper reservoir was empty and the lower reservoir was full at the beginning of the 7 day long simulation.

### Pumping Mode

As previously discussed, one of the main advantages of adjustable speed pump/turbine units over single speed units is their ability to operate at partial load during pumping mode. For the case studies considered, adjustable speed units in pumping mode were capable of storing between 6% to 95% additional energy over single speed units. The pumping mode model results are summarized in Table 7. To further illustrate the difference between single speed and adjustable speed units during pumping mode, the following figures use the format of Figure 17 to present results for the Lorella (Figure 20), Iowa Hill (Figure 21), and Eagle Mountain Pumped Storage Hydropower projects (Figure 22).

The Lorella and Eagle Mountain Pumped Storage Hydropower Projects showed substantial increases in energy storage capability when using adjustable speed over single speed units, while the Iowa Hill Pumped Storage Project only showed a 6% increase in energy storage. For the demand scenario considered, this would suggest that from a purely pumping perspective that the Lorella and Eagle Mountain Pumped Storage Projects would benefit from using adjustable speed units, while single speed units may be more appropriate for the Iowa Hill Pumped Storage Project. The Iowa Hill Pumped Storage Hydropower Project has a plant capacity of 400 MW, which is 60 to 70 percent smaller than the Lorella and Eagle Mountain Pumped Storage Hydropower Projects, therefore the demand scenario considered may not be appropriate for the Iowa Hill Pumped Storage Hydropower Project. Additional analysis of the Iowa Hill Pumped Storage Hydropower Project is recommended prior to selecting the pump/turbine units.

**Table 7. Pumping Mode Model Results – Energy Stored by Single Speed Versus Adjustable Speed Pump/Turbine Units**

| | Lorella (1000 MW) | Iowa Hill (400 MW) | Eagle Mountain (1300 MW) |
|---|---|---|---|
| Single speed units – energy stored | 17,750 MWh | 18,886 MWh | 15,925 MWh |
| Adjustable speed units – energy stored | 31,240 MWh | 20,025 MWh | 30,940 MWh |
| Additional energy stored by adjustable speed units | 13,490 MWh | 1,139 MWh | 15,015 MWh |
| (Additional energy stored) / (Single speed units energy stored) | 75% | 6% | 95% |

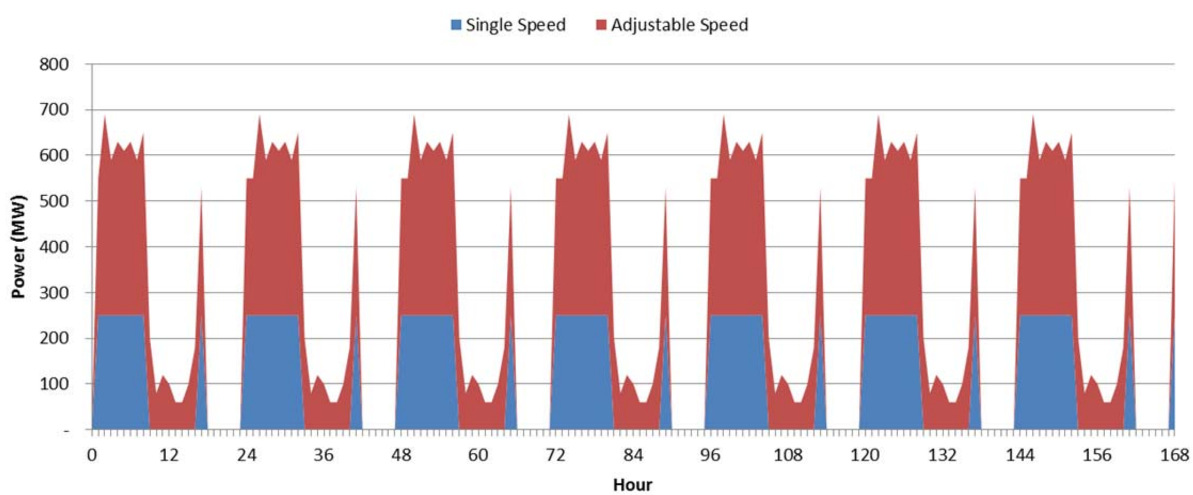


**Figure 20. Operation During Pumping Mode – Lorella Pumped Storage Hydropower Project**

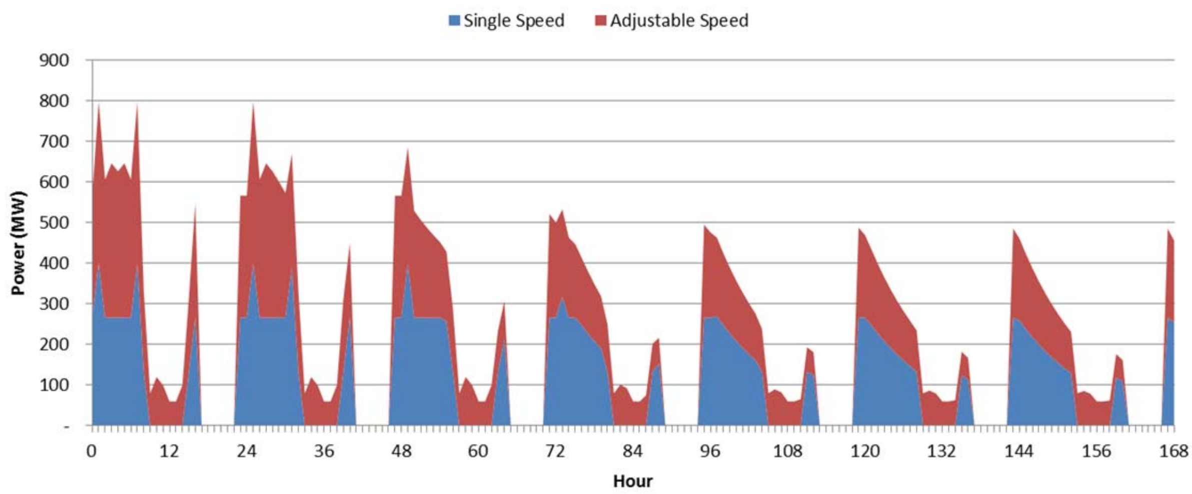


**Figure 21. Operation During Pumping Mode - Iowa Hill Pumped Storage Hydropower Project**

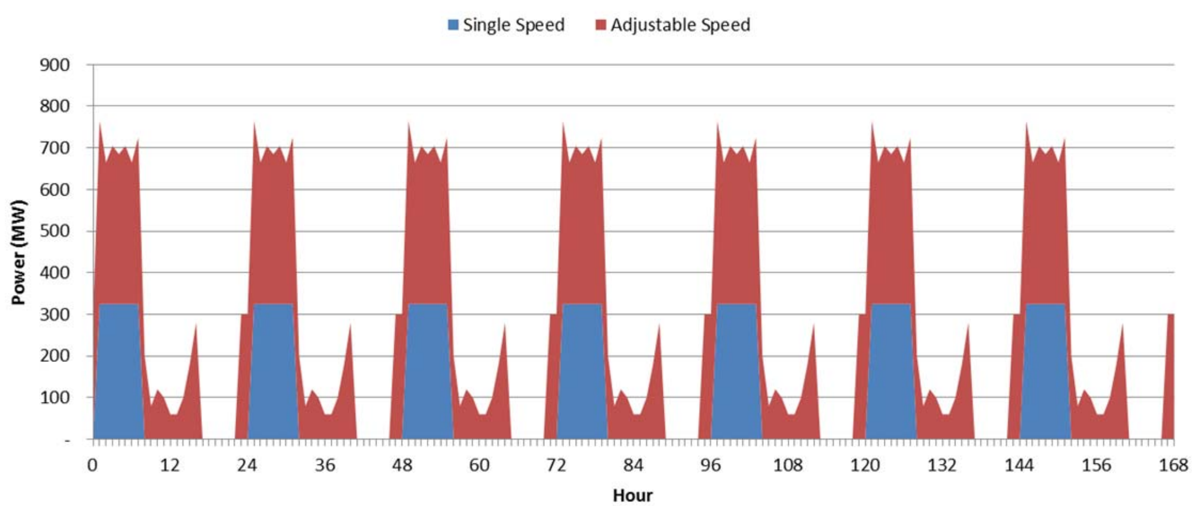


**Figure 22. Operation During Pumping Mode - Eagle Mountain Pumped Storage Hydropower Project**

### Generating Mode

During generating mode both single speed and adjustable speed pumped are operated in a similar manner. For the case studies considered, adjustable speed units in generating mode were capable of generating between 4% to 40% additional energy over single speed units. The generating mode model results are summarized in Table 8. To further illustrate the difference between single speed and adjustable speed units during generating mode, the following figures present the results for the Lorella (Figure 23), Iowa Hill (Figure 24), and Eagle Mountain Pumped Storage projects (Figure 25). The figures show that power generated increases during the week, which is due to the initial conditions considered, which assumed that the upper reservoir was empty at the beginning of the simulation. Water levels in the upper reservoir increase throughout the week which allows for additional power to be generated.

The Lorella and Eagle Mountain Pumped Storage Hydropower Projects showed increases of 40% in energy generation capability when using adjustable speed over single speed units, while the Iowa Hill Pumped Storage Project only showed a 5% increase in energy generation. For the demand scenario considered, this would suggest that from a generation perspective that the Lorella and Eagle Mountain Pumped Storage Projects would benefit from using adjustable speed units, while single speed units may be more appropriate for the Iowa Hill Pumped Storage Project. Again, the Iowa Hill Pumped Storage Hydropower Project is approximately 60 to 70 percent smaller; consequently the demand scenario considered may not be appropriate for the Iowa Hill project relative to the other case studies considered. Additional analysis is recommended prior to selecting appropriate units for the Iowa Hill Pumped Storage Hydropower project.

**Table 8. Generating Mode Model Results – Energy Generated by Single Speed Versus Adjustable Speed Pump/Turbine Units**

| | Lorella (1000 MW) | Iowa Hill (400 MW) | Eagle Mountain (1300 MW) |
|---|---|---|---|
| Single speed units – energy generated | 9,498 MWh | 10,591 MWh | 8,441 MWh |
| Adjustable speed units – energy generated | 13,174 MWh | 11,056 MWh | 11,881 MWh |
| Additional energy generated by adjustable speed units | 3,676 MWh | 465 MWh | 3,440 MWh |
| (Additional energy generated) / (Single speed units energy generated) | 40% | 4% | 40% |

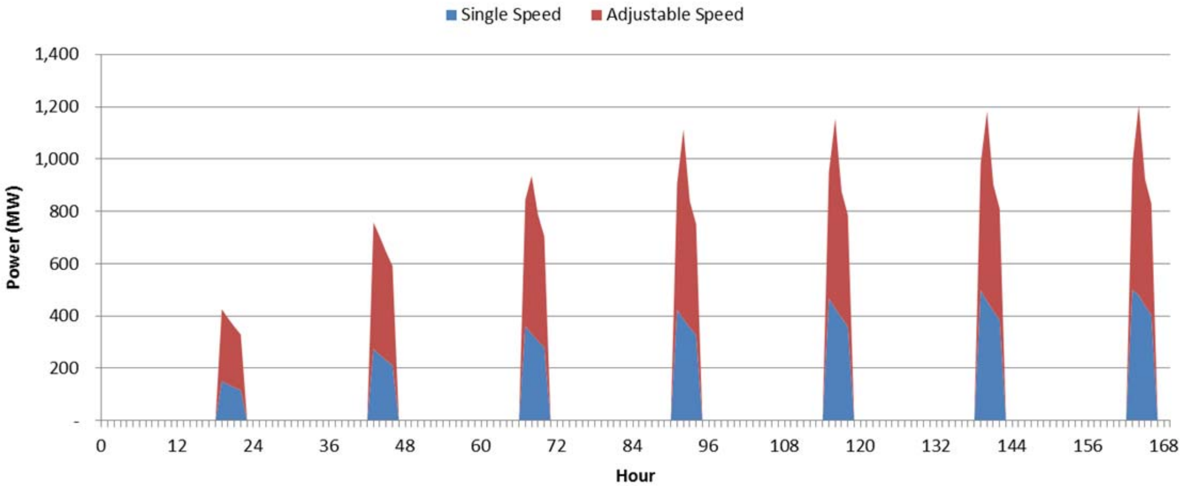


**Figure 23. Operation During Generating Mode – Lorella Pumped Storage Hydropower Project**

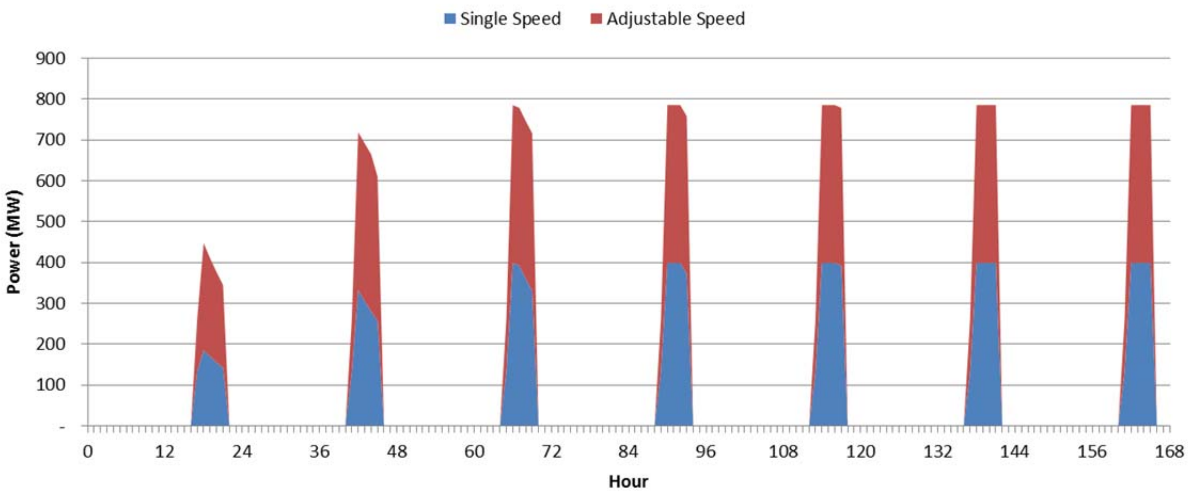


**Figure 24. Operation During Generating Mode - Iowa Hill Pumped Storage Hydropower Project**

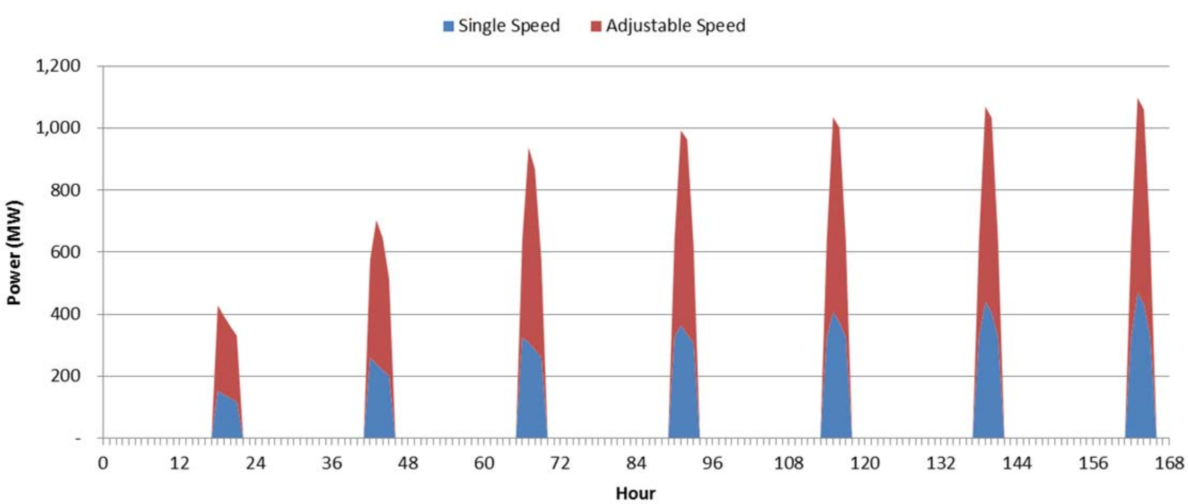


**Figure 25. Operation During Generating Mode - Eagle Mountain Pumped Storage Hydropower Project**

# 9. Costs of Pumped Storage Hydropower

## 9.1. Cost Characteristics

During operation of a pumped storage hydropower project, inexpensive off-peak power is used to pump water from the lower reservoir to the upper reservoir, then power is generated during peak demand periods when power is more valuable; therefore the cost differential between the pumping and generating power becomes an import metric for project evaluation. For a pumped storage hydropower project to be viable, the cost differential needs to be sufficiently large to recover energy lost in the pumping/generating cycle, initial capital costs, as well as operation and maintenance costs.

There is limited publicly available cost data for pumped storage hydropower projects; therefore analysis of cost characteristics can be challenging. The costs for a proposed pumped storage hydropower project are separated into two categories: 1) initial capital costs and 2) operation and maintenance costs. Each of these categories is discussed as follows:

### *9.1.1. Initial Capital Costs*

The initial capital costs for a proposed pumped storage hydropower project include:

- Permitting
- Planning phase costs
- Design phase costs
- Other project costs
- Construction costs
    - Electrical-Mechanical Equipment
    - Civil Earthwork Costs

In the United States, the Federal Energy Regulatory Commission (FERC) controls the permitting of all new pumped storage hydropower projects. The permitting process can be lengthy and expensive (MWH, 2009). During the planning phase, various project layouts and configurations are evaluated to develop recommended parameters. The design phase includes costs related to environmental investigations and development of detailed design drawings and specifications. Other project costs can include public relations, land acquisition costs, purchase of water rights, financing and interest costs, and legal costs. The construction costs include materials such as the electrical-mechanical equipment, construction management, and plant startup costs.

Typical initial capital costs are difficult to quantify due to the potentially large range of site specific project layouts, geologic formations, and environmental considerations. Initial capital costs are additionally hard to quantify because nearly all pumped storage hydropower projects in the United States were constructed several decades ago so modern statistical data is not available. Initial capital costs are large due to the lengthy permitting process, engineering design costs, and large scale heavy construction required for a new pumped storage hydropower project, and can range up to $1-2 billion dollars (MWH, 2009). A study conducted by the Electrical Power Research Institute, evaluated 14 installed pumped storage hydropower projects in the United States, and found that capital costs varied between $300/kW to $600/kW with an average of $434/kW (in 1988 dollars) and are summarized on Figure 26. Using a simplified inflation calculator this roughly equates to $600/kW to $1200/kW in 2014 dollars (using http://data.bls.gov/cgi-bin/cpicalc.pl) These costs exclude transmission and interest during construction costs (Deane et al, 2009). In addition to being costly, pumped storage hydropower projects also have a lengthy development timeline of 10 years or more (MWH, 2009). The large initial investment and long project development timeline required can make it difficult to construct new pumped storage hydropower projects.

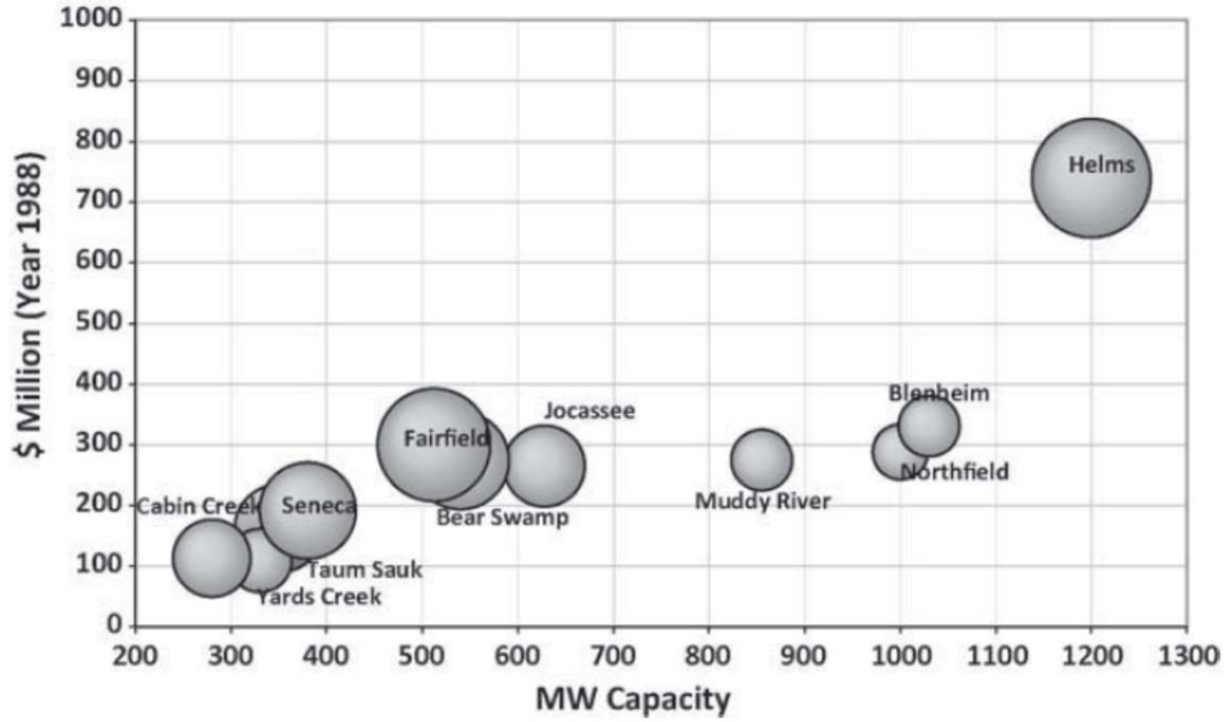


**Figure 26. Capital Costs for Sample Projects in the United States (Deane et al, 2009)**

### *9.1.2. Operation and Maintenance Costs*

While initial capital costs are high for pumped storage hydropower projects, they typically have long project lives of up to 100 years (Deane et al, 2009) and low operation and maintenance costs. Similar to initial capital costs, operation and maintenance costs can be highly site specific, and depend on a number of factors. First, operational costs depend on the owners' operational philosophy. Some owners prefer to perform routine maintenance in the efforts to extend the life of project components while other owners have a more hands-off approach and prefer to replace components as they break. Second, the age of the project will affect operation and maintenance costs with costs generally increasing with the life of the plant. Third, the number, type, and size of the pump/turbine units will effect operation and maintenance costs. Fourth, operation and maintenance costs it will depend on how and where the project is operated. For instance, does staff need to be stationed at the project site or can be it operated remotely at a central control center? Finally, operation and maintenance costs will depend on the size, type of and configuration of the project reservoirs. For instance, some projects require reservoir lining systems that may require routine maintenance.

## 10.Summary

With increasing concerns regarding global warming and a push towards energy independence, renewable technologies are becoming increasing popular. However, their variable nature limits the ability of renewable technologies to provide a larger portion of the power supply. Pumped storage hydropower is a proven large scale energy storage technology that allows for better integration of renewable energy into the power gird by allowing storage of excess energy for later use. Pumped storage hydropower has a long history in the United States and internationally, and is currently gaining interest from developers in the United States as a means to better integrate renewable energy sources.

A model was developed to evaluate the operation of three proposed pumped storage hydropower projects in the United States using both single speed and adjustable speed pump/turbine units. For two of the three case studies considered, the model showed increases in both energy storage capability and energy generation capability, when using adjustable speed units over single speed units; however, the third project showed only minimal improvements.

While there are limited favorable pumped storage hydropower sites available, long project timelines, and large initial investment costs; pumped storage hydropower provides valuable energy storage when used in conjunction with renewable energy technologies, peaking power during period of high demand, and allows other types of power plants to operate more efficiently. In recent years the Federal Energy Regulatory Commission has granted numerous preliminary permits in over 22 states for new pumped storage hydropower facilities in the United States, which would suggest that pumped storage hydropower technology will continue to become an increasingly valuable part of the power grid in the United States and increase our ability to utilize renewable energy sources.

## 11. References


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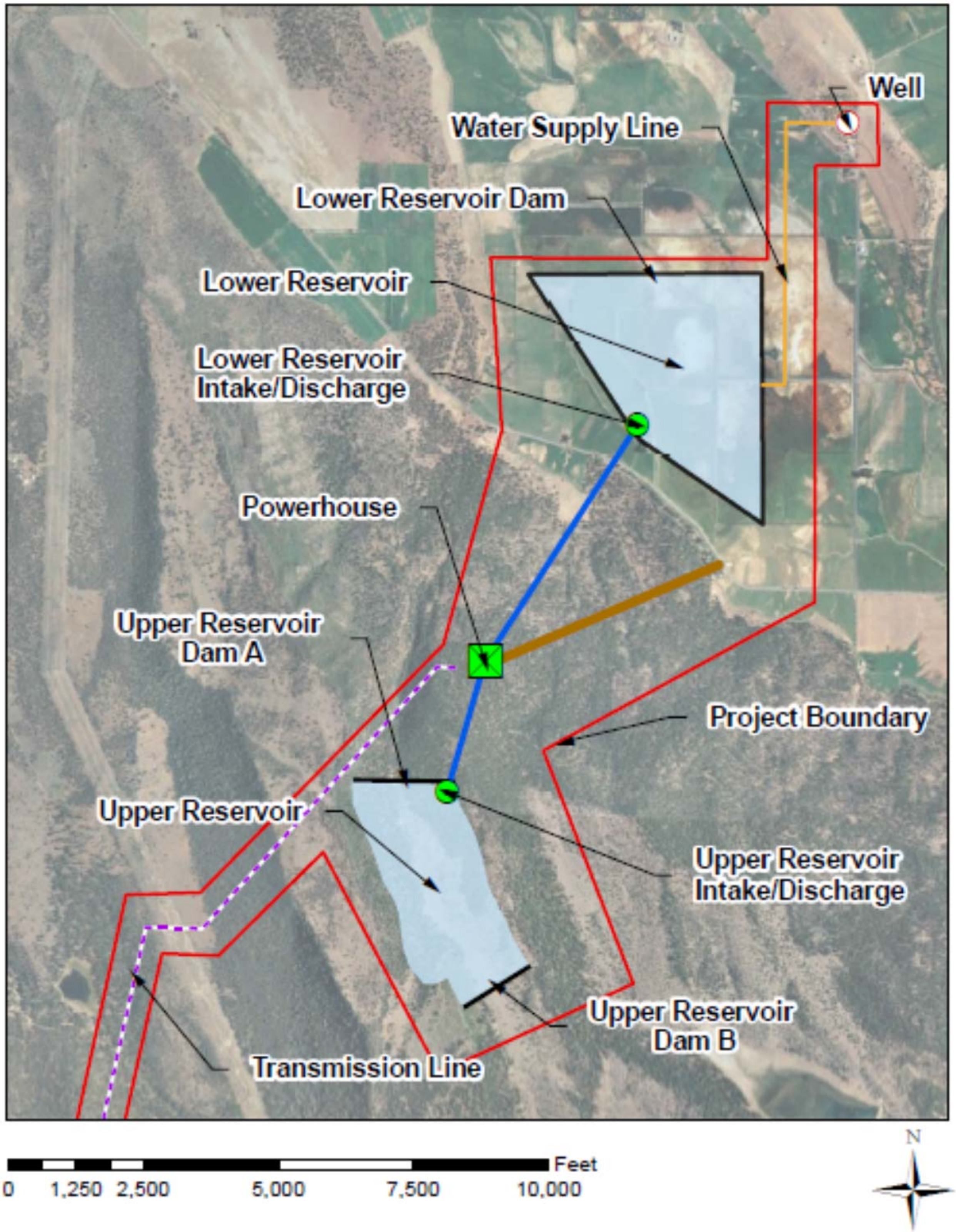
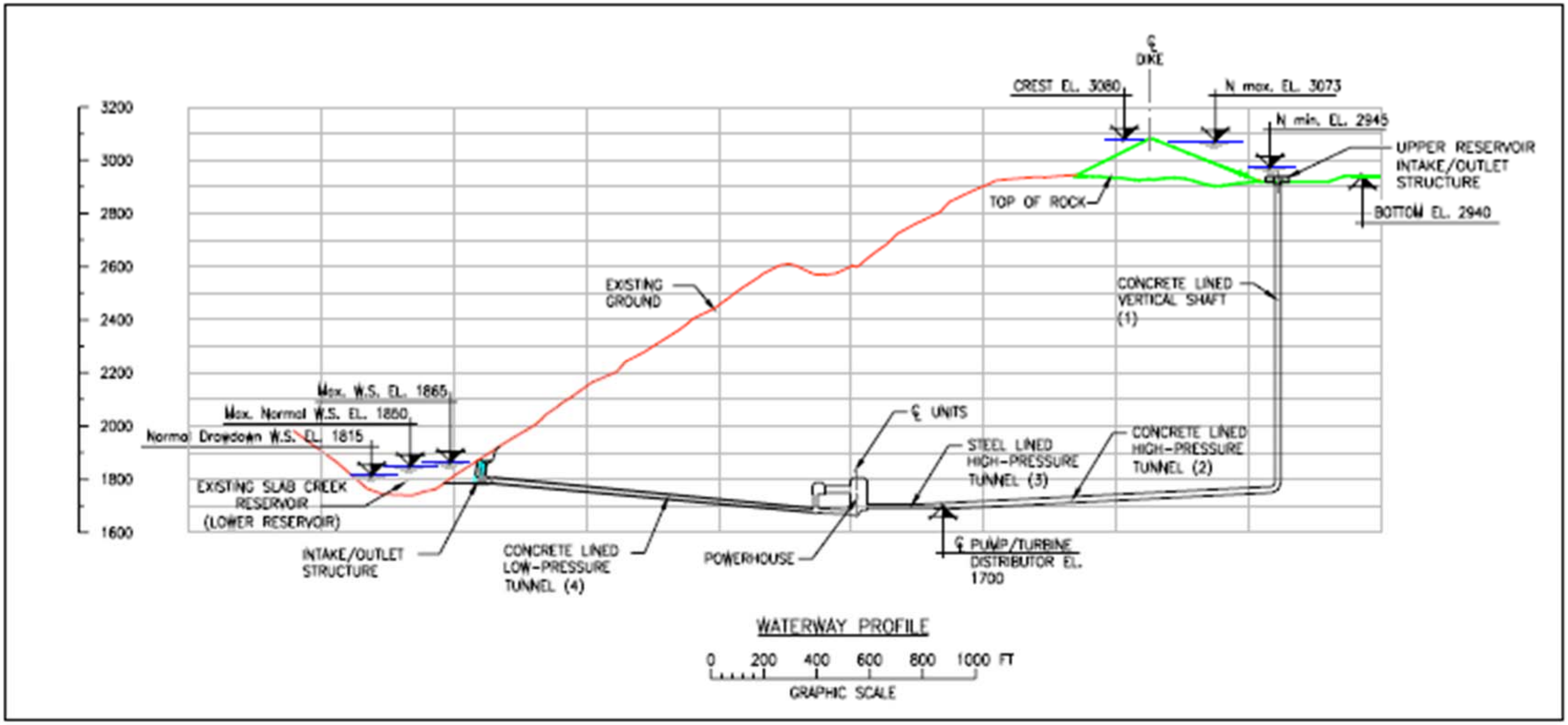
## Appendices

## Appendix A. Lorella Pumped Storage Project Layout (FFP, 2012)

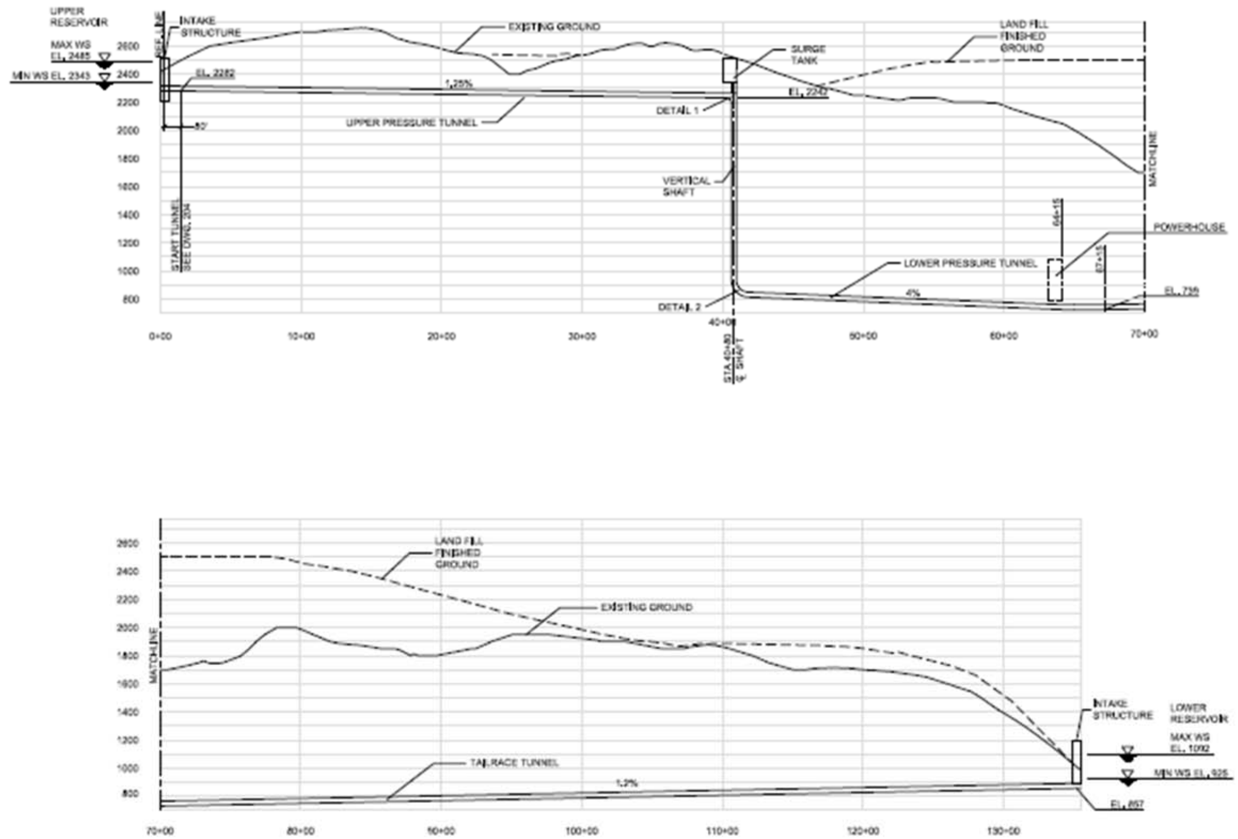

Well
Water Supply Line
Lower Reservoir Dam
Lower Reservoir
Lower Reservoir Intake/Discharge
Powerhouse
Upper Reservoir Dam A
Project Boundary
Upper Reservoir
Upper Reservoir Intake/Discharge
Upper Reservoir Dam B
Transmission Line
Feet
0 1,250 2,500 5,000 7,500 10,000
N

**Appendix B. Iowa Hill Pumped Storage Project – Cross-Section (SMUD, 2013)**



℄ DIKE
CREST EL. 3080
N max. EL. 3073
N min. EL. 2945
UPPER RESERVOIR INTAKE/OUTLET STRUCTURE
TOP OF ROCK
BOTTOM EL. 2940
CONCRETE LINED VERTICAL SHAFT (1)
EXISTING GROUND
Max. W.S. EL. 1865
Max. Normal W.S. EL. 1850
Normal Drawdown W.S. EL. 1815
EXISTING SLAB CREEK RESERVOIR (LOWER RESERVOIR)
INTAKE/OUTLET STRUCTURE
CONCRETE LINED LOW-PRESSURE TUNNEL (4)
POWERHOUSE
℄ UNITS
STEEL LINED HIGH-PRESSURE TUNNEL (3)
CONCRETE LINED HIGH-PRESSURE TUNNEL (2)
℄ PUMP/TURBINE DISTRIBUTOR EL. 1700
3200
3000
2800
2600
2400
2200
2000
1800
1600
WATERWAY PROFILE
0 200 400 600 800 1000 FT
GRAPHIC SCALE

**Appendix C. Eagle Mountain Pumped Storage Project – Cross-Section (ECEC, 2009)**




NOTES:

1. UNDEFINED LANDFILL CONTOURS WERE ASSUMED TO FOLLOW DEFINED CONTOURS AND TO COME INTO ALIGNMENT WITH THE EXISTING GROUND SURFACE.

## CROSS SECTION ALONG WATER CONDUITS

PLAN

SCALE, FEET

NOTES:

1. PLAN BASED ON MAP PREPARED BY C.M. ENGINEERING ASSOCIATES, SAN BERNARDINO, CA.



| NO. | DATE | ISSUE/REVISION | DES | DRN | CHK | APP |
|---|---|---|---|---|---|---|

EAGLE CREST ENERGY COMPANY

GEI PROJECT 080473

EAGLE MOUNTAIN PUMPED STORAGE PROJECT

LANDFILL COMPATIBILITY FLA LAYOUT - CROSS SECTION

FIGURE NO. 3

SHEET NO. 3 of 3

## Appendix D. Pumped Storage Hydropower Model Layout

Pumped Storage Analysis

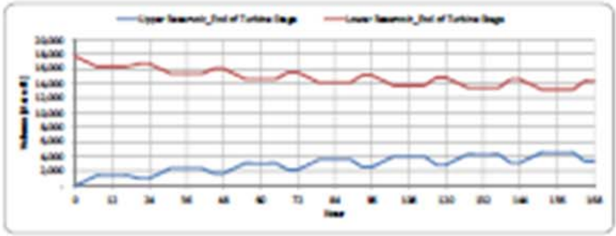
**Assumptions:**

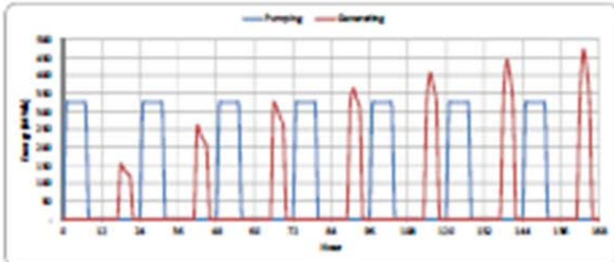
1. Head Constant
2. Evaporation and Seepage Negligible
3. Waterway losses during pumping and turbine mode equal to 3% of total head.
4. Waterways are adequately sized to prevent a discharge capability constraint.
5. Minimum range in turbine mode for both single speed and adjustable speed units is 70% to maintain efficiency of units.
6. Model assumes maximum of 4 pump/turbine units
7. Model assumes "off stream" Pumped Storage Project.

Hydropower Station — Type of Unit: Single Speed — SELECT UNIT TYPE

ENTER PROJECT VARIABLES IN "YELLOW" CELLS

| | | | |
|---|---|---|---|
| Pumped Storage Plant Capacity | 1300 MW | **Upper Reservoir** | |
| **Unit Characteristics** | | Full Reservoir Level (FRL) | 2485 ft |
| Number of Units | 4 | Lower Reservoir Level (LRL) | 2343 ft |
| Unit Per Unit | 325 MW | Drawdown | 142 ft |
| ΔH | 1413 ft | Volume FRL (Active) | 17,700 acre-ft |
| Flow (Unit) | 2,900 cfs | Volume LRL | 0 acre-ft |
| Flow (Plant) | 11,600 cfs | Volume at Time Step 0 | - acre-ft |
| **Pumping Mode** | | **Lower Reservoir** | |
| Efficiency (MWh, 2008) | 81% | Full Reservoir Level (FRL) | 1082 ft |
| Assume Σ $h_L$ are 3% of ΔH | 42.3 ft | Lower Reservoir Level (LRL) | 925 ft |
| ΔH + $h_L$ | 1452.3 | Drawdown | 157 ft |
| **Turbine Mode** | | Volume FRL (Active) | 17,700 acre-ft |
| Efficiency - Single Speed (MWh, 2008) | 88% | Volume LRL | 0 acre-ft |
| Efficiency - Adjustable Speed (MWh, 2008) | 92% | Volume at Time Step 0 | 17,700 acre-ft |
| Assume Σ hl are 3% of ΔH | 42.3 ft | | |
| ΔH + $h_L$ | 1452.3 | | |
| Minimum range in turbine mode | 70% | Specific Weight of Water | 62.4 lb/ft3 |
| Minimum capacity in turbine mode | 228 MW | | |
| | | Total Energy used in Pumping Mode | 15,825 |
| | | Total Energy produced in Generating Mode | 8,441 |




**Pumping Mode**

| Time Step, Hour | Hour | Weekday = 0 Weekend = 1 | Excess Energy on Power Grid [MWh] | Peak Energy Required [MWh] | Available Excess Energy [cfs] | Unit Capability (Unit 1) [cfs] | Unit Capability (Unit 2) [cfs] | Single Speed Unit Capability (Unit 3) [cfs] | Unit Capability (Unit 4) [cfs] | Total Unit Capability [cfs] | Variable Speed Variable Speed Unit Capacity [cfs] | Water Available In Lower Reservoir [cfs] | Volume Available In Upper Reservoir [cfs] | Limiting Discharge [cfs] | Volume In Lower Reservoir_Begin of Pump Mode [acre-feet] | Energy_Pumping Mode [MWh] | Volume of Water Pumped [acre-feet/hr] | Volume In Lower Reservoir_End of Pump Mode [acre-feet] | Volume of Water In Upper Reservoir_End of Pump Mode [acre-feet] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Discharge, Q | | | | | | | | | | | | | | |
| 0 | 24 | 0 | 500 | 0 | 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 214,170 | 17,700 | - | 17,700 | - | 0 | 17,700 | - |
| 1 | 1 | 0 | 640 | 0 | 3257 | 2404 | 0 | 0 | 0 | 2404 | 0 | 214,170 | 17,700 | 2,404 | 17,700 | 325 | 199 | 17,501 | 199 |
| 2 | 2 | 0 | 940 | 0 | 2917 | 2404 | 0 | 0 | 0 | 2404 | 0 | 211,764 | 17,501 | 2,404 | 17,501 | 325 | 199 | 17,302 | 398 |
| 3 | 3 | 0 | 580 | 0 | 2613 | 2404 | 0 | 0 | 0 | 2404 | 0 | 208,958 | 17,302 | 2,404 | 17,302 | 325 | 199 | 17,103 | 597 |
| 4 | 4 | 0 | 940 | 0 | 2665 | 2404 | 0 | 0 | 0 | 2404 | 0 | 206,952 | 17,103 | 2,404 | 17,103 | 325 | 199 | 16,905 | 795 |
| 5 | 5 | 0 | 580 | 0 | 2613 | 2404 | 0 | 0 | 0 | 2404 | 0 | 204,548 | 16,905 | 2,404 | 16,905 | 325 | 199 | 16,706 | 994 |
| 6 | 6 | 0 | 940 | 0 | 2917 | 2404 | 0 | 0 | 0 | 2404 | 0 | 202,140 | 16,706 | 2,404 | 16,706 | 325 | 199 | 16,507 | 1,193 |
| 7 | 7 | 0 | 600 | 0 | 2061 | 2404 | 0 | 0 | 0 | 2404 | 0 | 199,756 | 16,507 | 2,404 | 16,507 | 325 | 199 | 16,308 | 1,392 |
| 8 | 8 | 0 | 200 | 0 | 1481 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 9 | 9 | 0 | 80 | 0 | 583 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 10 | 10 | 0 | 120 | 0 | 688 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 11 | 11 | 0 | 100 | 0 | 760 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 12 | 12 | 0 | 60 | 0 | 464 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 13 | 13 | 0 | 60 | 0 | 464 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 14 | 14 | 0 | 100 | 0 | 760 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 15 | 15 | 0 | 180 | 0 | 1359 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 16 | 16 | 0 | 280 | 0 | 2079 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 17 | 17 | 0 | 0 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 18 | 18 | 0 | 0 | 540 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 197,328 | 16,308 | - | 16,308 | - | 0 | 16,308 | 1,392 |
| 19 | 19 | 0 | 0 | 840 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 198,710 | 16,429 | - | 16,429 | - | 0 | 16,429 | 1,277 |
| 20 | 20 | 0 | 0 | 640 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 199,996 | 16,526 | - | 16,526 | - | 0 | 16,526 | 1,171 |
| 21 | 21 | 0 | 0 | 440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 201,168 | 16,625 | - | 16,625 | - | 0 | 16,625 | 1,075 |
| 22 | 22 | 0 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 202,242 | 16,714 | - | 16,714 | - | 0 | 16,714 | 986 |
| 23 | 23 | 0 | 500 | 0 | 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 202,242 | 16,714 | - | 16,714 | - | 0 | 16,714 | 986 |
| 24 | 24 | 0 | 500 | 0 | 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 202,242 | 16,714 | - | 16,714 | - | 0 | 16,714 | 986 |
| 25 | 1 | 0 | 640 | 0 | 3257 | 2404 | 0 | 0 | 0 | 2404 | 0 | 202,242 | 16,714 | 2,404 | 16,714 | 325 | 199 | 16,515 | 1,185 |
| 26 | 2 | 0 | 940 | 0 | 2917 | 2404 | 0 | 0 | 0 | 2404 | 0 | 199,836 | 16,515 | 2,404 | 16,515 | 325 | 199 | 16,317 | 1,385 |
| 27 | 3 | 0 | 580 | 0 | 2613 | 2404 | 0 | 0 | 0 | 2404 | 0 | 197,430 | 16,317 | 2,404 | 16,317 | 325 | 199 | 16,118 | 1,582 |
| 28 | 4 | 0 | 940 | 0 | 2665 | 2404 | 0 | 0 | 0 | 2404 | 0 | 195,024 | 16,118 | 2,404 | 16,118 | 325 | 199 | 15,919 | 1,781 |
| 29 | 5 | 0 | 580 | 0 | 2613 | 2404 | 0 | 0 | 0 | 2404 | 0 | 192,618 | 15,919 | 2,404 | 15,919 | 325 | 199 | 15,720 | 1,980 |
| 30 | 6 | 0 | 940 | 0 | 2917 | 2404 | 0 | 0 | 0 | 2404 | 0 | 190,212 | 15,720 | 2,404 | 15,720 | 325 | 199 | 15,521 | 2,179 |
| 31 | 7 | 0 | 600 | 0 | 2061 | 2404 | 0 | 0 | 0 | 2404 | 0 | 187,806 | 15,521 | 2,404 | 15,521 | 325 | 199 | 15,322 | 2,378 |
| 32 | 8 | 0 | 200 | 0 | 1481 | 0 | 0 | 0 | 0 | 0 | 0 | 185,400 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,378 |
| 33 | 9 | 0 | 80 | 0 | 583 | 0 | 0 | 0 | 0 | 0 | 0 | 185,400 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,378 |
| 34 | 10 | 0 | 120 | 0 | 688 | 0 | 0 | 0 | 0 | 0 | 0 | 185,400 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,378 |

| | | | | | Pumping Mode | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Discharge, Q | | | | | | | | | | | | | | |
| Time Step, Hour | Hour | Weekday = 0 Weekend = 1 | Excess Energy on Power Grid [MWh] | Peak Energy Required [MWh] | Available Excess Energy [cfs] | Unit Capability (Unit 1) [cfs] | Unit Capability (Unit 2) [cfs] | Single Speed Unit Capability (Unit 3) [cfs] | Unit Capability (Unit 4) [cfs] | Total Unit Capability [cfs] | Variable Speed Variable Speed Unit Capacity [cfs] | Water Available In Lower Reservoir [cfs] | Volume Available In Upper Reservoir [cfs] | Limiting Discharge [cfs] | Volume In Lower Reservoir_Begin of Pump Mode [acre-feet] | Energy_Pumping Mode [MWh] | Volume of Water Pumped [acre-feet/hr] | Volume In Lower Reservoir_End of Pump Mode [acre-feet] | Volume of Water In Upper Reservoir_End of Pump Mode [acre-feet] |
| 35 | 11 | 0 | 100 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 188,430 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,376 |
| 36 | 12 | 0 | 60 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 188,430 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,376 |
| 37 | 13 | 0 | 60 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 188,430 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,376 |
| 38 | 14 | 0 | 100 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 188,430 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,376 |
| 39 | 15 | 0 | 180 | 0 | 1333 | 0 | 0 | 0 | 0 | 0 | 0 | 188,430 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,376 |
| 40 | 16 | 0 | 280 | 0 | 2073 | 0 | 0 | 0 | 0 | 0 | 0 | 188,430 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,376 |
| 41 | 17 | 0 | 0 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 188,430 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,376 |
| 42 | 18 | 0 | 0 | 540 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 188,430 | 15,322 | - | 15,322 | - | 0 | 15,322 | 2,376 |
| 43 | 19 | 0 | 0 | 840 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 187,776 | 15,538 | - | 15,538 | - | 0 | 15,538 | 2,161 |
| 44 | 20 | 0 | 0 | 490 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 190,850 | 15,698 | - | 15,698 | - | 0 | 15,698 | 2,001 |
| 45 | 21 | 0 | 0 | 440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 191,960 | 15,844 | - | 15,844 | - | 0 | 15,844 | 1,856 |
| 46 | 22 | 0 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 193,795 | 16,016 | - | 16,016 | - | 0 | 16,016 | 1,684 |
| 47 | 23 | 0 | 300 | 0 | 2221 | 0 | 0 | 0 | 0 | 0 | 0 | 193,795 | 16,016 | - | 16,016 | - | 0 | 16,016 | 1,684 |
| 48 | 24 | 0 | 300 | 0 | 2221 | 0 | 0 | 0 | 0 | 0 | 0 | 193,795 | 16,016 | - | 16,016 | - | 0 | 16,016 | 1,684 |
| 49 | 1 | 0 | 440 | 0 | 3257 | 2406 | 0 | 0 | 0 | 2406 | 0 | 193,795 | 16,016 | 2,404 | 16,016 | 528 | 199 | 15,817 | 1,883 |
| 50 | 2 | 0 | 340 | 0 | 2517 | 2406 | 0 | 0 | 0 | 2406 | 0 | 191,389 | 15,817 | 2,404 | 15,817 | 528 | 199 | 15,618 | 2,082 |
| 51 | 3 | 0 | 380 | 0 | 2813 | 2406 | 0 | 0 | 0 | 2406 | 0 | 188,983 | 15,618 | 2,404 | 15,618 | 528 | 199 | 15,420 | 2,280 |
| 52 | 4 | 0 | 360 | 0 | 2665 | 2406 | 0 | 0 | 0 | 2406 | 0 | 186,577 | 15,420 | 2,404 | 15,420 | 528 | 199 | 15,221 | 2,479 |
| 53 | 5 | 0 | 380 | 0 | 2813 | 2406 | 0 | 0 | 0 | 2406 | 0 | 184,171 | 15,221 | 2,404 | 15,221 | 528 | 199 | 15,022 | 2,678 |
| 54 | 6 | 0 | 340 | 0 | 2517 | 2406 | 0 | 0 | 0 | 2406 | 0 | 181,765 | 15,022 | 2,404 | 15,022 | 528 | 199 | 14,823 | 2,877 |
| 55 | 7 | 0 | 400 | 0 | 2961 | 2406 | 0 | 0 | 0 | 2406 | 0 | 179,359 | 14,823 | 2,404 | 14,823 | 528 | 199 | 14,624 | 3,076 |
| 56 | 8 | 0 | 200 | 0 | 1481 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 57 | 9 | 0 | 80 | 0 | 592 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 58 | 10 | 0 | 120 | 0 | 888 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 59 | 11 | 0 | 100 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 60 | 12 | 0 | 60 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 61 | 13 | 0 | 60 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 62 | 14 | 0 | 100 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 63 | 15 | 0 | 180 | 0 | 1333 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 64 | 16 | 0 | 280 | 0 | 2073 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 65 | 17 | 0 | 0 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 66 | 18 | 0 | 0 | 540 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 176,953 | 14,624 | - | 14,624 | - | 0 | 14,624 | 3,076 |
| 67 | 19 | 0 | 0 | 840 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 179,024 | 14,870 | - | 14,870 | - | 0 | 14,870 | 2,830 |
| 68 | 20 | 0 | 0 | 490 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 182,794 | 15,104 | - | 15,104 | - | 0 | 15,104 | 2,596 |
| 69 | 21 | 0 | 0 | 440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 186,382 | 15,318 | - | 15,318 | - | 0 | 15,318 | 2,382 |
| 70 | 22 | 0 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 187,752 | 15,515 | - | 15,515 | - | 0 | 15,515 | 2,186 |
| 71 | 23 | 0 | 300 | 0 | 2221 | 0 | 0 | 0 | 0 | 0 | 0 | 187,752 | 15,515 | - | 15,515 | - | 0 | 15,515 | 2,186 |
| 72 | 24 | 0 | 300 | 0 | 2221 | 0 | 0 | 0 | 0 | 0 | 0 | 187,752 | 15,515 | - | 15,515 | - | 0 | 15,515 | 2,186 |
| 73 | 1 | 0 | 440 | 0 | 3257 | 2406 | 0 | 0 | 0 | 2406 | 0 | 187,752 | 15,515 | 2,404 | 15,515 | 528 | 199 | 15,316 | 2,384 |
| 74 | 2 | 0 | 340 | 0 | 2517 | 2406 | 0 | 0 | 0 | 2406 | 0 | 185,326 | 15,316 | 2,404 | 15,316 | 528 | 199 | 15,117 | 2,583 |
| 75 | 3 | 0 | 380 | 0 | 2813 | 2406 | 0 | 0 | 0 | 2406 | 0 | 182,920 | 15,117 | 2,404 | 15,117 | 528 | 199 | 14,918 | 2,782 |
| 76 | 4 | 0 | 360 | 0 | 2665 | 2406 | 0 | 0 | 0 | 2406 | 0 | 180,514 | 14,918 | 2,404 | 14,918 | 528 | 199 | 14,720 | 2,980 |
| 77 | 5 | 0 | 380 | 0 | 2813 | 2406 | 0 | 0 | 0 | 2406 | 0 | 178,108 | 14,720 | 2,404 | 14,720 | 528 | 199 | 14,521 | 3,179 |
| 78 | 6 | 0 | 340 | 0 | 2517 | 2406 | 0 | 0 | 0 | 2406 | 0 | 175,702 | 14,521 | 2,404 | 14,521 | 528 | 199 | 14,322 | 3,378 |
| 79 | 7 | 0 | 400 | 0 | 2961 | 2406 | 0 | 0 | 0 | 2406 | 0 | 173,296 | 14,322 | 2,404 | 14,322 | 528 | 199 | 14,123 | 3,577 |
| 80 | 8 | 0 | 200 | 0 | 1481 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 81 | 9 | 0 | 80 | 0 | 592 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 82 | 10 | 0 | 120 | 0 | 888 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 83 | 11 | 0 | 100 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 84 | 12 | 0 | 60 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 85 | 13 | 0 | 60 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 86 | 14 | 0 | 100 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 87 | 15 | 0 | 180 | 0 | 1333 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 88 | 16 | 0 | 280 | 0 | 2073 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 89 | 17 | 0 | 0 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 90 | 18 | 0 | 0 | 540 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 170,890 | 14,123 | - | 14,123 | - | 0 | 14,123 | 3,577 |
| 91 | 19 | 0 | 0 | 840 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 173,860 | 14,369 | - | 14,369 | - | 0 | 14,369 | 3,331 |
| 92 | 20 | 0 | 0 | 490 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 177,102 | 14,644 | - | 14,644 | - | 0 | 14,644 | 3,056 |
| 93 | 21 | 0 | 0 | 440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 180,248 | 14,880 | - | 14,880 | - | 0 | 14,880 | 2,820 |
| 94 | 22 | 0 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 183,051 | 15,128 | - | 15,128 | - | 0 | 15,128 | 2,572 |
| 95 | 23 | 0 | 300 | 0 | 2221 | 0 | 0 | 0 | 0 | 0 | 0 | 183,051 | 15,128 | - | 15,128 | - | 0 | 15,128 | 2,572 |
| 96 | 24 | 0 | 300 | 0 | 2221 | 0 | 0 | 0 | 0 | 0 | 0 | 183,051 | 15,128 | - | 15,128 | - | 0 | 15,128 | 2,572 |
| 97 | 1 | 0 | 440 | 0 | 3257 | 2406 | 0 | 0 | 0 | 2406 | 0 | 183,051 | 15,128 | 2,404 | 15,128 | 528 | 199 | 14,929 | 2,771 |
| 98 | 2 | 0 | 340 | 0 | 2517 | 2406 | 0 | 0 | 0 | 2406 | 0 | 180,645 | 14,929 | 2,404 | 14,929 | 528 | 199 | 14,731 | 2,969 |
| 99 | 3 | 0 | 380 | 0 | 2813 | 2406 | 0 | 0 | 0 | 2406 | 0 | 178,239 | 14,731 | 2,404 | 14,731 | 528 | 199 | 14,532 | 3,168 |
| 100 | 4 | 0 | 360 | 0 | 2665 | 2406 | 0 | 0 | 0 | 2406 | 0 | 175,833 | 14,532 | 2,404 | 14,532 | 528 | 199 | 14,333 | 3,367 |
| 101 | 5 | 0 | 380 | 0 | 2813 | 2406 | 0 | 0 | 0 | 2406 | 0 | 173,427 | 14,333 | 2,404 | 14,333 | 528 | 199 | 14,134 | 3,566 |
| 102 | 6 | 0 | 340 | 0 | 2517 | 2406 | 0 | 0 | 0 | 2406 | 0 | 171,021 | 14,134 | 2,404 | 14,134 | 528 | 199 | 13,935 | 3,765 |
| 103 | 7 | 0 | 400 | 0 | 2961 | 2406 | 0 | 0 | 0 | 2406 | 0 | 168,615 | 13,935 | 2,404 | 13,935 | 528 | 199 | 13,736 | 3,964 |
| 104 | 8 | 0 | 200 | 0 | 1481 | 0 | 0 | 0 | 0 | 0 | 0 | 166,209 | 13,736 | - | 13,736 | - | 0 | 13,736 | 3,964 |
| 105 | 9 | 0 | 80 | 0 | 592 | 0 | 0 | 0 | 0 | 0 | 0 | 166,209 | 13,736 | - | 13,736 | - | 0 | 13,736 | 3,964 |
| 106 | 10 | 0 | 120 | 0 | 888 | 0 | 0 | 0 | 0 | 0 | 0 | 166,209 | 13,736 | - | 13,736 | - | 0 | 13,736 | 3,964 |
| 107 | 11 | 0 | 100 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 166,209 | 13,736 | - | 13,736 | - | 0 | 13,736 | 3,964 |
| 108 | 12 | 0 | 60 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 166,209 | 13,736 | - | 13,736 | - | 0 | 13,736 | 3,964 |
| 109 | 13 | 0 | 60 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 166,209 | 13,736 | - | 13,736 | - | 0 | 13,736 | 3,964 |
| 110 | 14 | 0 | 100 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 166,209 | 13,736 | - | 13,736 | - | 0 | 13,736 | 3,964 |
| 111 | 15 | 0 | 180 | 0 | 1333 | 0 | 0 | 0 | 0 | 0 | 0 | 166,209 | 13,736 | - | 13,736 | - | 0 | 13,736 | 3,964 |

Pumping Mode

Discharge, Q

| Time Step, Hour | Hour | Weekday = 0 Weekend = 1 | Excess Energy on Power Grid [MWh] | Peak Energy Required [MWh] | Available Excess Energy [MW] | Unit Capability (Unit 1) [MW] | Unit Capability (Unit 2) [MW] | Single Speed Unit Capability (Unit 3) [MW] | Unit Capability (Unit 4) [MW] | Total Unit Capability [MW] | Variable Speed Variable Speed Unit Capacity [MW] | Water Available In Lower Reservoir [AF] | Volume Available In Upper Reservoir [AF] | Limiting Discharge [AF] | Volume In Lower Reservoir_Begin of Pump Mode [acre-feet] | Energy_Pumping Mode [MWh] | Volume of Water Pumped [acre-feet/hr] | Volume In Lower Reservoir_End of Pump Mode [acre-feet] | Volume of Water In Upper Reservoir_End of Pump Mode [acre-feet] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 112 | 16 | 0 | 420 | 0 | 2079 | 0 | 0 | 0 | 0 | 0 | 0 | 146,208 | 13,756 | - | 13,756 | - | 0 | 13,756 | 4,044 |
| 113 | 17 | 0 | 0 | 180 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 146,208 | 13,756 | - | 13,756 | - | 0 | 13,756 | 4,044 |
| 114 | 18 | 0 | 0 | 540 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 146,208 | 13,756 | - | 13,756 | - | 0 | 13,756 | 4,044 |
| 115 | 19 | 0 | 0 | 840 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 149,180 | 13,882 | - | 13,882 | - | 0 | 13,882 | 3,718 |
| 116 | 20 | 0 | 0 | 480 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 172,468 | 14,388 | - | 14,388 | - | 0 | 14,388 | 3,411 |
| 117 | 21 | 0 | 0 | 440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 176,508 | 14,571 | - | 14,571 | - | 0 | 14,571 | 3,128 |
| 118 | 22 | 0 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 179,280 | 14,816 | - | 14,816 | - | 0 | 14,816 | 2,884 |
| 119 | 23 | 0 | 405 | 0 | 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 179,280 | 14,816 | - | 14,816 | - | 0 | 14,816 | 2,884 |
| 120 | 24 | 0 | 405 | 0 | 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 179,280 | 14,816 | - | 14,816 | - | 0 | 14,816 | 2,884 |
| 121 | 1 | 0 | 660 | 0 | 3257 | 2404 | 0 | 0 | 0 | 2404 | 0 | 179,280 | 14,816 | 2,404 | 14,816 | 525 | 199 | 14,618 | 3,082 |
| 122 | 2 | 0 | 590 | 0 | 2917 | 2404 | 0 | 0 | 0 | 2404 | 0 | 178,874 | 14,618 | 2,404 | 14,618 | 525 | 199 | 14,419 | 3,281 |
| 123 | 3 | 0 | 570 | 0 | 2819 | 2404 | 0 | 0 | 0 | 2404 | 0 | 174,487 | 14,419 | 2,404 | 14,419 | 525 | 199 | 14,220 | 3,480 |
| 124 | 4 | 0 | 540 | 0 | 2665 | 2404 | 0 | 0 | 0 | 2404 | 0 | 172,961 | 14,220 | 2,404 | 14,220 | 525 | 199 | 14,021 | 3,679 |
| 125 | 5 | 0 | 570 | 0 | 2819 | 2404 | 0 | 0 | 0 | 2404 | 0 | 168,655 | 14,021 | 2,404 | 14,021 | 525 | 199 | 13,822 | 3,878 |
| 126 | 6 | 0 | 590 | 0 | 2917 | 2404 | 0 | 0 | 0 | 2404 | 0 | 167,240 | 13,822 | 2,404 | 13,822 | 525 | 199 | 13,623 | 4,077 |
| 127 | 7 | 0 | 600 | 0 | 2961 | 2404 | 0 | 0 | 0 | 2404 | 0 | 164,865 | 13,623 | 2,404 | 13,623 | 525 | 199 | 13,424 | 4,276 |
| 128 | 8 | 0 | 300 | 0 | 1481 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 129 | 9 | 0 | 120 | 0 | 592 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 130 | 10 | 0 | 180 | 0 | 888 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 131 | 11 | 0 | 150 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 132 | 12 | 0 | 90 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 133 | 13 | 0 | 90 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 134 | 14 | 0 | 150 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 135 | 15 | 0 | 270 | 0 | 1333 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 136 | 16 | 0 | 420 | 0 | 2079 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 137 | 17 | 0 | 0 | 180 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 138 | 18 | 0 | 0 | 540 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 142,657 | 13,424 | - | 13,424 | - | 0 | 13,424 | 4,276 |
| 139 | 19 | 0 | 0 | 840 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 149,408 | 13,470 | - | 13,470 | - | 0 | 13,470 | 4,050 |
| 140 | 20 | 0 | 0 | 480 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 160,456 | 14,008 | - | 14,008 | - | 0 | 14,008 | 3,687 |
| 141 | 21 | 0 | 0 | 440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 179,138 | 14,306 | - | 14,306 | - | 0 | 14,306 | 3,381 |
| 142 | 22 | 0 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 176,106 | 14,554 | - | 14,554 | - | 0 | 14,554 | 3,146 |
| 143 | 23 | 0 | 405 | 0 | 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 176,106 | 14,554 | - | 14,554 | - | 0 | 14,554 | 3,146 |
| 144 | 24 | 0 | 405 | 0 | 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 176,106 | 14,554 | - | 14,554 | - | 0 | 14,554 | 3,146 |
| 145 | 1 | 0 | 660 | 0 | 3257 | 2404 | 0 | 0 | 0 | 2404 | 0 | 176,106 | 14,554 | 2,404 | 14,554 | 525 | 199 | 14,355 | 3,345 |
| 146 | 2 | 0 | 590 | 0 | 2917 | 2404 | 0 | 0 | 0 | 2404 | 0 | 173,750 | 14,355 | 2,404 | 14,355 | 525 | 199 | 14,156 | 3,544 |
| 147 | 3 | 0 | 570 | 0 | 2819 | 2404 | 0 | 0 | 0 | 2404 | 0 | 171,285 | 14,156 | 2,404 | 14,156 | 525 | 199 | 13,958 | 3,742 |
| 148 | 4 | 0 | 540 | 0 | 2665 | 2404 | 0 | 0 | 0 | 2404 | 0 | 168,687 | 13,958 | 2,404 | 13,958 | 525 | 199 | 13,759 | 3,941 |
| 149 | 5 | 0 | 570 | 0 | 2819 | 2404 | 0 | 0 | 0 | 2404 | 0 | 166,481 | 13,759 | 2,404 | 13,759 | 525 | 199 | 13,560 | 4,140 |
| 150 | 6 | 0 | 590 | 0 | 2917 | 2404 | 0 | 0 | 0 | 2404 | 0 | 164,075 | 13,560 | 2,404 | 13,560 | 525 | 199 | 13,361 | 4,339 |
| 151 | 7 | 0 | 600 | 0 | 2961 | 2404 | 0 | 0 | 0 | 2404 | 0 | 161,480 | 13,361 | 2,404 | 13,361 | 525 | 199 | 13,162 | 4,538 |
| 152 | 8 | 0 | 300 | 0 | 1481 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 153 | 9 | 0 | 120 | 0 | 592 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 154 | 10 | 0 | 180 | 0 | 888 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 155 | 11 | 0 | 150 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 156 | 12 | 0 | 90 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 157 | 13 | 0 | 90 | 0 | 444 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 158 | 14 | 0 | 150 | 0 | 740 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 159 | 15 | 0 | 270 | 0 | 1333 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 160 | 16 | 0 | 420 | 0 | 2079 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 161 | 17 | 0 | 0 | 180 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 162 | 18 | 0 | 0 | 540 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 158,265 | 13,162 | - | 13,162 | - | 0 | 13,162 | 4,538 |
| 163 | 19 | 0 | 0 | 840 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 162,256 | 13,408 | - | 13,408 | - | 0 | 13,408 | 4,282 |
| 164 | 20 | 0 | 0 | 480 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 166,526 | 13,762 | - | 13,762 | - | 0 | 13,762 | 3,958 |
| 165 | 21 | 0 | 0 | 440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 170,466 | 14,088 | - | 14,088 | - | 0 | 14,088 | 3,612 |
| 166 | 22 | 0 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 179,456 | 14,333 | - | 14,333 | - | 0 | 14,333 | 3,347 |
| 167 | 23 | 0 | 405 | 0 | 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 179,456 | 14,333 | - | 14,333 | - | 0 | 14,333 | 3,347 |
| 168 | 24 | 0 | 405 | 0 | 2001 | 0 | 0 | 0 | 0 | 0 | 0 | 179,456 | 14,333 | - | 14,333 | - | 0 | 14,333 | 3,347 |
| | | | | | | | | | | | | | | | | 15,408 | | | |

| Turbine Mode | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Discharge, Q | | | | | | | | | | | | | | | | | | | |
| | Single Speed | | | | | Adjustable Speed | | | | | | | | | | | | | |
| Peaking Power Required [kW] | Unit Capability (Unit 1) [cfs] | Unit Capability (Unit 2) [cfs] | Unit Capability (Unit 3) [cfs] | Unit Capability (Unit 4) [cfs] | Total Unit Capability [cfs] | Unit Capability (Unit 1) [cfs] | Unit Capability (Unit 2) [cfs] | Unit Capability (Unit 3) [cfs] | Unit Capability (Unit 4) [cfs] | Total Unit Capability [cfs] | Water Available In Upper Reservoir [cfs] | Volume Available In Lower Reservoir [cfs] | Limiting Discharge [cfs] | Volume of Water In Upper Reservoir_Start of Turbine Mode [acre-feet] | Energy Generated In Turbine Mode [MWh] | Volume of Water Used During Turbine Mode [acre-feet] | Volume of Water In Upper Reservoir_End of Turbine Mode [acre-feet] | Volume of Water In Lower Reservoir_End of Turbine [acre-feet] | Equivalent Q Available (Lower Reservoir) [cfs] |
| | | | | | | | | | | | | | | | | 0 | | | 314270 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | - | - | 0 | - | 17,700 | 314270 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2404 | 100 | 0 | 100 | - | 0 | 100 | 17,501 | 311964 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4813 | 908 | 0 | 908 | - | 0 | 908 | 17,502 | 309858 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7218 | 907 | 0 | 907 | - | 0 | 907 | 17,109 | 304852 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9624 | 705 | 0 | 705 | - | 0 | 705 | 16,605 | 304566 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12030 | 904 | 0 | 904 | - | 0 | 904 | 16,704 | 302140 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14436 | 1,109 | 0 | 1,109 | - | 0 | 1,109 | 16,507 | 300754 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 1465 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 0 | 1,902 | - | 0 | 1,903 | 16,508 | 187528 |
| 4596 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | 14863 | 1,902 | 1902 | 1,902 | 152 | 115 | 1,277 | 14,625 | 188719 |
| 7476 | 2871 | 2871 | 0 | 0 | 5742 | 0 | 0 | 0 | 0 | 0 | 15651 | 1,277 | 1277 | 1,277 | 140 | 104 | 1,171 | 14,528 | 189864 |
| 6285 | 2871 | 2871 | 0 | 0 | 5742 | 0 | 0 | 0 | 0 | 0 | 14174 | 1,171 | 1171 | 1,171 | 128 | 97 | 1,075 | 14,625 | 301168 |
| 4022 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | 15003 | 1,075 | 1075 | 1,075 | 118 | 86 | 896 | 14,714 | 302242 |
| 751 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11028 | 896 | 0 | 896 | - | 0 | 896 | 14,714 | 302242 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11028 | 896 | 0 | 896 | - | 0 | 896 | 14,714 | 302242 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11028 | 896 | 0 | 896 | - | 0 | 896 | 14,714 | 302242 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14554 | 1,189 | 0 | 1,189 | - | 0 | 1,189 | 14,525 | 189856 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16740 | 1,588 | 0 | 1,588 | - | 0 | 1,589 | 14,517 | 187493 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 18166 | 1,582 | 0 | 1,582 | - | 0 | 1,583 | 14,118 | 189224 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21863 | 1,781 | 0 | 1,781 | - | 0 | 1,781 | 15,018 | 183618 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 23858 | 1,880 | 0 | 1,880 | - | 0 | 1,880 | 15,730 | 182212 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24964 | 2,179 | 0 | 2,179 | - | 0 | 2,179 | 15,821 | 187804 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26770 | 2,378 | 0 | 2,378 | - | 0 | 2,378 | 15,822 | 189400 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26770 | 2,378 | 0 | 2,378 | - | 0 | 2,378 | 15,822 | 189400 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26770 | 2,378 | 0 | 2,378 | - | 0 | 2,378 | 15,822 | 189400 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26770 | 2,378 | 0 | 2,378 | - | 0 | 2,378 | 15,822 | 189400 |

| Turbine Mode | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Discharge, Q | | | | | | | | | | | | | | | | | | |
| | Single Speed | | | | | Adjustable Speed | | | | | | | | | | | | | |
| Peaking Power Required [kW] | Unit Capability (Unit 1) [cfs] | Unit Capability (Unit 2) [cfs] | Unit Capability (Unit 3) [cfs] | Unit Capability (Unit 4) [cfs] | Total Unit Capability [cfs] | Unit Capability (Unit 1) [cfs] | Unit Capability (Unit 2) [cfs] | Unit Capability (Unit 3) [cfs] | Unit Capability (Unit 4) [cfs] | Total Unit Capability [cfs] | Water Available in Upper Reservoir [cfs] | Volume Available in Lower Reservoir [cfs] | Limiting Discharge [cfs] | Volume of Water in Upper Reservoir_Start of Turbine Mode [acre-feet] | Energy Generated in Turbine Mode [MWh] | Volume of Water Used During Turbine Mode [acre-feet] | Volume of Water in Upper Reservoir_End of Turbine Mode [acre-feet] | Volume of Water in Lower Reservoir_End of Turbine [acre-feet] | Equivalent Q Available (Lower Reservoir) [cfs] |
| | | | | | | | | | | | | | | | | 0 | | | 214170 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24770 | 3,378 | 0 | 3,378 | - | 0 | 3,378 | 19,522 | 185400 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24770 | 3,378 | 0 | 3,378 | - | 0 | 3,378 | 19,522 | 185400 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24770 | 3,378 | 0 | 3,378 | - | 0 | 3,378 | 19,522 | 185400 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24770 | 3,378 | 0 | 3,378 | - | 0 | 3,378 | 19,522 | 185400 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24770 | 3,378 | 0 | 3,378 | - | 0 | 3,378 | 19,522 | 185400 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24770 | 3,378 | 0 | 3,378 | - | 0 | 3,378 | 19,522 | 185400 |
| 1465 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24770 | 3,378 | 0 | 3,378 | - | 0 | 3,378 | 19,522 | 185400 |
| 4596 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | 24770 | 3,378 | 2878 | 3,378 | 240 | 187 | 3,181 | 19,518 | 187776 |
| 7476 | 2871 | 2871 | 0 | 0 | 5742 | 0 | 0 | 0 | 0 | 0 | 24083 | 3,181 | 2161 | 3,181 | 298 | 180 | 3,001 | 19,698 | 189959 |
| 6285 | 2871 | 2871 | 0 | 0 | 5742 | 0 | 0 | 0 | 0 | 0 | 24211 | 3,001 | 2001 | 3,001 | 218 | 165 | 1,836 | 19,864 | 183363 |
| 4322 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | 22016 | 1,836 | 1856 | 1,836 | 201 | 152 | 1,684 | 16,016 | 183795 |
| 731 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20878 | 1,684 | 0 | 1,684 | - | 0 | 1,684 | 16,016 | 183795 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20878 | 1,684 | 0 | 1,684 | - | 0 | 1,684 | 16,016 | 183795 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20878 | 1,684 | 0 | 1,684 | - | 0 | 1,684 | 16,016 | 183795 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 22761 | 1,689 | 0 | 1,689 | - | 0 | 1,689 | 15,617 | 181580 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25187 | 2,082 | 0 | 2,082 | - | 0 | 2,082 | 15,628 | 180885 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 27989 | 2,380 | 0 | 2,380 | - | 0 | 2,380 | 15,420 | 184877 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 28866 | 2,476 | 0 | 2,476 | - | 0 | 2,476 | 19,221 | 186171 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 32405 | 2,478 | 0 | 2,478 | - | 0 | 2,478 | 19,222 | 181795 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 34811 | 2,877 | 0 | 2,877 | - | 0 | 2,877 | 14,829 | 179888 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 1465 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 0 | 3,276 | - | 0 | 3,276 | 14,424 | 176855 |
| 4596 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | 37217 | 3,276 | 2871 | 3,276 | 528 | 246 | 3,030 | 14,670 | 179824 |
| 7476 | 2871 | 2871 | 0 | 0 | 5742 | 0 | 0 | 0 | 0 | 0 | 34246 | 3,030 | 2850 | 3,030 | 510 | 234 | 2,796 | 15,104 | 182794 |
| 6285 | 2871 | 2871 | 0 | 0 | 5742 | 0 | 0 | 0 | 0 | 0 | 31614 | 2,796 | 2584 | 2,796 | 284 | 215 | 2,582 | 15,518 | 185950 |
| 4322 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | 28820 | 2,582 | 2583 | 2,582 | 241 | 187 | 2,188 | 15,525 | 187792 |
| 731 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24658 | 2,188 | 0 | 2,188 | - | 0 | 2,188 | 15,525 | 187792 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24658 | 2,188 | 0 | 2,188 | - | 0 | 2,188 | 15,525 | 187792 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24658 | 2,188 | 0 | 2,188 | - | 0 | 2,188 | 15,525 | 187792 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 28664 | 2,386 | 0 | 2,386 | - | 0 | 2,386 | 15,316 | 185326 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 31292 | 2,588 | 0 | 2,588 | - | 0 | 2,588 | 15,117 | 182833 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 33856 | 2,782 | 0 | 2,782 | - | 0 | 2,782 | 14,918 | 180814 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 36063 | 2,980 | 0 | 2,980 | - | 0 | 2,980 | 14,730 | 178108 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 38668 | 3,176 | 0 | 3,176 | - | 0 | 3,176 | 14,521 | 175702 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 40874 | 3,378 | 0 | 3,378 | - | 0 | 3,378 | 14,322 | 173268 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 1465 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 0 | 3,577 | - | 0 | 3,577 | 14,128 | 173860 |
| 4596 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | 43260 | 3,577 | 2871 | 3,577 | 528 | 246 | 3,331 | 14,568 | 173863 |
| 7476 | 2871 | 2871 | 0 | 0 | 5742 | 0 | 0 | 0 | 0 | 0 | 42610 | 3,331 | 5551 | 3,331 | 564 | 275 | 3,056 | 14,644 | 177102 |
| 6285 | 2871 | 2871 | 0 | 0 | 5742 | 0 | 0 | 0 | 0 | 0 | 34079 | 3,056 | 5056 | 3,056 | 534 | 255 | 2,828 | 14,887 | 180248 |
| 4322 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | 33023 | 2,828 | 2809 | 2,828 | 507 | 252 | 2,572 | 15,128 | 183051 |
| 731 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 31118 | 2,572 | 0 | 2,572 | - | 0 | 2,572 | 15,128 | 183051 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 31118 | 2,572 | 0 | 2,572 | - | 0 | 2,572 | 15,128 | 183051 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 31118 | 2,572 | 0 | 2,572 | - | 0 | 2,572 | 15,128 | 183051 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 33529 | 2,771 | 0 | 2,771 | - | 0 | 2,771 | 14,928 | 180665 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 35851 | 2,960 | 0 | 2,960 | - | 0 | 2,960 | 14,751 | 178298 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 38057 | 3,148 | 0 | 3,148 | - | 0 | 3,148 | 14,552 | 175888 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 40768 | 3,347 | 0 | 3,347 | - | 0 | 3,347 | 14,355 | 173427 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 43148 | 3,546 | 0 | 3,546 | - | 0 | 3,546 | 14,154 | 171021 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 45555 | 3,745 | 0 | 3,745 | - | 0 | 3,745 | 13,995 | 168615 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 47961 | 3,944 | 0 | 3,944 | - | 0 | 3,944 | 13,756 | 166208 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 47961 | 3,944 | 0 | 3,944 | - | 0 | 3,944 | 13,756 | 166208 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 47961 | 3,944 | 0 | 3,944 | - | 0 | 3,944 | 13,756 | 166208 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 47961 | 3,944 | 0 | 3,944 | - | 0 | 3,944 | 13,756 | 166208 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 47961 | 3,944 | 0 | 3,944 | - | 0 | 3,944 | 13,756 | 166208 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 47961 | 3,944 | 0 | 3,944 | - | 0 | 3,944 | 13,756 | 166208 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 47961 | 3,944 | 0 | 3,944 | - | 0 | 3,944 | 13,756 | 166208 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 47961 | 3,944 | 0 | 3,944 | - | 0 | 3,944 | 13,756 | 166208 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 47961 | 3,944 | 0 | 3,944 | - | 0 | 3,944 | 13,756 | 166208 |

| Turbine Mode | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Discharge, Q | | | | | | | | | | | | | | | | | | | |
| | Single Speed | | | | | Adjustable Speed | | | | | | | | | | | | | |
| Peaking Power Required [MW] | Unit Capability (Unit 1) [MW] | Unit Capability (Unit 2) [MW] | Unit Capability (Unit 3) [MW] | Unit Capability (Unit 4) [MW] | Total Unit Capability [MW] | Unit Capability (Unit 1) [MW] | Unit Capability (Unit 2) [MW] | Unit Capability (Unit 3) [MW] | Unit Capability (Unit 4) [MW] | Total Unit Capability [MW] | Water Available In Upper Reservoir [MW] | Volume Available In Lower Reservoir [MW] | Limiting Discharge [MW] | Volume of Water In Upper Reservoir_Start of Turbine Mode [acre-feet] | Energy Generated In Turbine Mode [MWh] | Volume of Water Used During Turbine Mode [acre-feet] | Volume of Water In Upper Reservoir_End of Turbine Mode [acre-feet] | Volume of Water In Lower Reservoir_End of Turbine [acre-feet] | Equivalent Q Available (Lower Reservoir) [MW] |
| | | | | | | | | | | | | | | | | 0 | | | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 1465 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 4596 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 2871 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 7476 | 2871 | 2871 | 0 | 0 | [illegible] | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 6255 | 2871 | 2871 | 0 | 0 | [illegible] | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4322 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 2871 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 731 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 1465 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 4596 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 2871 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 7476 | 2871 | 2871 | 0 | 0 | [illegible] | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 6255 | 2871 | 2871 | 0 | 0 | [illegible] | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4322 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 2871 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 731 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 1465 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 4596 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 2871 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 7476 | 2871 | 2871 | 0 | 0 | [illegible] | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 6255 | 2871 | 2871 | 0 | 0 | [illegible] | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 4322 | 2871 | 0 | 0 | 0 | 2871 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 2871 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 731 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | - | 0 | [illegible] | [illegible] | [illegible] |
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