CERI Research Report:
Aquifer Underground Pumped Hydro

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Introduction to UPHS

Underground pumped hydroelectric energy storage (UPHS) is an energy storage method that has been the subject of several past studies in the United States and abroad. Most of these studies focus on determining the economic performance of such a system, while others present technical analysis and ideas. Strangely, a surge of interest in this subject happened in the late 1970’s and early 1980’s, but essentially no new literature on this subject has surfaced for over two decades. One exception to this is a 2003 paper treating the design, analysis and construction of a large underground water reservoir for use in a UPHS installation [4]. On the economic side, most of the literature agrees that UPHS may make economic sense for installations sized between 1000 and 3000 MW. It is of note that no large-scale utility sized UPHS plant has ever been built.

In pumped hydroelectric energy storage systems, water is pumped to a higher elevation and then released and gravity-fed through a turbine that generates electricity. Conventional hydroelectric storage systems rely on natural elevation differentials between water bodies on the earth’s surface to store energy. This can be a very limiting characteristic in geographically flat places. Most large hydroelectric installations rely on hydraulic heads of at least 150 feet, with average head of about 400 feet. Since head height is proportional to energy, power, and efficiency, a larger head is desirable (within limits). It is also desirable to minimize the transverse length of the water flow path to reduce friction losses. Many pumped hydroelectric systems can have negative impacts on land and wildlife. Disruption of fish spawning routes or creation of large reservoirs that fill canyons or gorges are common concerns.
Underground pumped hydroelectric energy storage is an adaptation of conventional surface pumped hydroelectric that uses a underground cavern as the lower reservoir. This alleviates many of the problems with surface pumped hydroelectric installations. Dependence on surface topology is eliminated, though suitable underground geology and structures are required. An underground system has a vertical water flow path, which eliminates losses associated with transverse water flow. The environmental impact of an underground installation is less than conventional pumped hydro systems because only one surface reservoir is required, also eliminating potential river dams, large powerhouses on the surface, wildlife habitat disruption, and noise.

In this report, a new adaptation of underground pumped hydroelectric energy storage is analyzed which uses an underground aquifer as the lower reservoir. The usefulness of this concept lies in the utilization of the gravitational potential energy in surface water with respect to an existing aquifer or water table below the earth’s surface. This method eliminates the required surface elevation differential needed for conventional pumped hydro storage systems. The proposed system design, operation of the system, technologies required for implementation, and aquifer characteristics required are described herein. Also in this report are preliminary studies of other options for implementing underground pumped hydro, including the use of abandoned mines, the use of deep oil or natural gas mining caverns, the use of geothermal wells, and the construction of artificial underground caverns.

Figure 3: Conceptual Diagram of UPHS System

2 Aquifer UPHS for Agriculture

Small hydroelectric systems have a long history. For hundreds of years, people have harnessed the energy in flowing water to do useful work such as milling, irrigation pumping, and electricity generation. In the historical “water wheel” system, the problem of energy storage reduces to simply trapping the flow of a river behind a small barrier, then releasing the water when energy is needed. Today, vastly larger amounts of energy are needed, and water flows of sufficient magnitude with sufficient elevation change to produce this energy are rare. The modernization of renewable energy generation using solar and wind power emphasize the need for high capacity, flexible energy storage methods that are useable in various geographical areas.

One major potential application of underground pumped hydroelectric energy storage that motivates this
research is irrigation operations in the agricultural sector. Farmers use large amounts of energy to pump large amounts of irrigation water to their crops. Given the abundance of the solar energy resource in Colorado, utilizing solar energy for power irrigation systems is becoming an attractive economic solution for agriculturalists. Given the use of solar energy, a robust, economic method to store and release this energy as needed is important. Since water is moved in existing irrigation systems, it makes sense to study methods to adapt the irrigation system to accomplish energy storage as well.

In work leading up to this report, studies looked at the agricultural irrigation situation in the San Luis Valley of Colorado. Irrigation pumping power costs for farmers in the region can be very high, somewhat deep water tables and dry climate. A photovoltaic array was sized to generate electricity for pumping and other on-site electricity demand. Various energy storage options were identified and analyzed for use with the solar array and the utility grid. Because most of the power demand in irrigation applications is used for pumping water, the study showed that using pumped hydroelectric energy storage in some manner was likely the most beneficial and optimized method. This led to the underground aquifer pumped hydroelectric energy storage concept for energy storage addressed in this report.

Figure 4: Aquifer UPHS System Diagram

Figure 4 shows a simplified illustration of the proposed underground pumped hydroelectric storage system using an agricultural well and underground aquifer. The major components of this system include an intermittent renewable energy source, a surface water storage reservoir for irrigation and power generation water, a combined pump-turbine motor-generator unit, and a system control interface. It is assumed that the existing well and existing irrigation boost pumps and distribution system can be utilized. Also important to this system is the existence of or potential to install a surface pond for water storage.

The use of the underground pumped hydro energy storage method contained herein has limitations to achieving widespread use. Across Colorado, a large percentage of irrigation in Colorado is done from surface trenches or irrigation ditches. This energy storage method will not work unless a relatively deep well is used to draw water from for irrigation. Next, the majority of irrigation wells in use today are relatively shallow. This is mainly because agricultural operations tend to occur near rivers where the alluvial aquifer water lever is near the surface. Lastly, a well that has high yield is required for this energy storage system. Many shallow, high permeability aquifer wells have more than sufficient yields for underground pumped hydroelectric systems, however deep wells typically have lower yields. Since high head and high flow are needed for aquifer UPHS, these characteristics represent a challenge in siting this type of system.
Nonetheless, there are promising sites for implementation of the type of system in Colorado. One promising region is the agricultural areas in northeastern Colorado, with irrigation wells drawing from the Ogallala aquifer. Another promising region is the San Luis Valley, its characteristics are discussed in the following section.

3 Irrigation Water Resources in Colorado’s San Luis Valley

3.1 San Luis Valley Water Resource Overview

Previous reports on this research initiative included analysis of irrigation practices, water, and power needs for typical irrigation operations in the San Luis Valley. A brief summary of this information is included here, along with new additional information. The reader may refer to the report titled “Renewable Energy Generation and Storage For Agricultural Use in the San Luis Valley” from June 30, 2006 and the report titled “Renewable Energy Storage Analysis for Irrigation and Residential Applications in Colorado’s San Luis Valley” from August 30, 2006 for additional background information.

Three main aspects of irrigation operations have motivated the proposal to use renewable energy storage in the form of underground pumped hydroelectric in Colorado agriculture. First, many regions of Colorado, especially agricultural regions, enjoy a very favorable solar energy resource. Second, because of semi-arid conditions in Colorado, almost all irrigation water must be pumped from some source, as precipitation cannot be counted on to water crops. Third, the cost to use grid electricity to pump water for irrigation is volatile and generally on the rise. A smart installation of solar energy and energy storage systems could greatly benefit agriculturalists in Colorado.

Prior to installing a new energy system that represents a large investment, operators must strive to decrease energy and water use as much as possible. Agricultural research in Colorado and across the country has identified methods to optimize water and energy use for irrigation. These methods include low energy precision application (LEPA) and optimization of water used versus economic crop yield (this is ongoing research at Colorado State University’s Agricultural Research Station). Conservation of water and energy will help ensure that an agriculturalist makes the best economic decision when considering renewable energy alternatives.

Agriculture in San Luis Valley is unique. The valley receives more sunlight than anywhere else in Colorado, making it a favorable location for solar generation. Furthermore, a relatively large percentage of irrigation water in the valley is pumped from underground sources [1]. Figure 6 shows the irrigation water sources for
Colorado counties.

Well and water table depths and yields in the San Luis Valley region vary greatly. Table 1 provides a summary of well characteristics and information about the frequency of occurrence of the high head, high flow outliers. The following passage summarizes the nature of the underground water resource in the San Luis Valley. This passage is taken from the internet and it is a summary of information presented in reference [1], The Ground Water Atlas of Colorado, and is a summary written by the authors of the atlas.

“As of February 2001, water well permit records indicate that nearly 10,000 wells have been completed in the San Luis Valley, 90 percent of which are used for irrigation of commercial crops. Historically, depth to water in the unconfined aquifer has been generally less than 12 feet below ground surface. Extensive irrigation in the valley using ground water wells has resulted in depletion of the aquifer. In the period 1969 to 1980 water level declines of up to 40 ft. were documented in the unconfined aquifer. Since 1976, the Water Division engineer estimates that the unconfined aquifer has lost 1 million ac-ft of storage…”

Figure 6: Irrigation Water Sources in Colorado [1]

Based on well permit records, 90 percent of the wells have reported completion depths of less than 400 feet. The mean well depth is 172 feet, and the median well depth is 100 feet. These statistics include wells in both the unconfined and confined aquifers. Many of the wells completed in the confined aquifer in the central part of the basin are flowing artesian wells. In general, the shape and configuration of the water level surfaces of the unconfined and the confined aquifers are similar, indicating some degree of hydraulic connectivity. Water level
elevations for the unconfined aquifer in the northern part of the valley range from approximately 7,700 feet on the edges of the valley to approximately 7,500 feet in the valley center near the San Luis Hills…”

“Yields of the nearly 10,000 wells of record completed in the San Luis Valley range from less than 5 to a maximum of 8,000 gallons per minute (gpm). Over 50 percent of the wells have reported yields less than 100 gpm, and 90 percent of the wells have reported yields less than 1,600 gpm. The mean yield of these data is 532 gpm, but the median is only 50 gpm, indicating large-capacity irrigation wells significantly influence the statistics…”

“Transmissivity in the confined aquifer is generally much greater than in the unconfined aquifer, ranging from less than 100,000 to greater than 1,200,000 gal/day/ft…”

The San Luis Valley is estimated to contain over 2 billion acre-feet of ground water in storage, with over 140 million acre-feet estimated to be recoverable. The principal use of ground water is agricultural. Estimated average withdrawals for irrigation are 2 million acre-feet annually, of which an estimated 800,000 acre-feet is from ground-water sources. An estimated 85 to 90 percent of the irrigation water in the central portion of the valley is from managed recharge and pumping of the unconfined aquifer.”

Potentiometric surfaces of the confined aquifer are higher than the unconfined water table in the San Luis Valley Water Basin [1]. This means that while one may have to drill a 2000 feet deep well to tap into the confined aquifer, the water level will rise to a point higher than the unconfined water level, which could be accessed with a much shallower well. For the purposes of pumped hydroelectric uses, the deeper the water level, the better, irregardless of well depth.
The water table elevations across the San Luis Valley Basin are shown in Figure 7. The interesting feature shown on this map is change in water table elevation of about 400 feet over only a few miles. This indicates the possible presence of high hydraulic head to the unconfined aquifer.

The take away from this discussion is the fact that a number of wells having characteristics favorable to the implementation of aquifer UPHS likely exist in the San Luis Valley. A reasonable expectation for the range of depth to water values for aquifer UPHS sites in the unconfined aquifer is 100 to 250 feet. A reasonable expectation for yields is 200 to 2000 gpm. Given these ranges, the most powerful installation could possibly yield about 65 kW (2000 gpm at 250 feet, see Figure 10), while the least favorable site may only yield about 10 kW (200 gpm at 100 feet, see Figure 10). The technical considerations of these well characteristics are covered in section 4.4.
3.2 Well Modification

Given certain limits on the typical flow capability of existing irrigation wells, it follows that one would consider ways to increase the recharge flow capability of a well in order to extract the maximum possible power. Aquifer recharge (AR) and Aquifer Storage and Recharge (ASR) wells exist in Colorado. These wells are designed to replace water in an aquifer by flowing water backwards into a water well, thereby “recharging” the aquifer. Modified AR wells designed for direct injection operations have been proposed by R. Topper et. al. in the report titled “Artifical Recharge of Groundwater in Colorado – A Statewide Assessment” in 2004 [3]. Figures 8 and 9 are taken from this report, and they shows some options for modified wells to increase the recharge flow capacity.

Figure 8: Direct Injection Radial Unconfined Aquifer Well Concept

Figure IV-5. Direct injection in an unconfined aquifer. Water for recharge is injected through a well directly into the saturated aquifer raising the water table in a conical mound around the well. The well can also be used for recovery of the injected water as an ASR well. Injection can use a dedicated injection pipe or the pump column equipped with a down-hole flow control valve. A radial well increases the radius of influence of the well through a series of horizontal feeder screened pipes arranged in a radial pattern around the well.
Well modifications of this type are proposed for use in implementing aquifer UPHS. The best method of increasing well flow rates will depend on site specific geology and aquifer characteristics.

4 System Analysis

Energy is stored in the form of gravitation potential energy of the weight of the water in the surface reservoir with respect to the subterranean water table. Simply put, after water has been pumped out of the well to the surface, the water can then be released from the surface back to the aquifer, reversing the operation of the motor and pump to generate electricity (as a turbine and generator). To determine the amount of power that can be produced by releasing water back down to the aquifer, the following equation applies (neglecting dynamic head effects):

\[ P = Q \cdot H \cdot \rho \cdot g \cdot \eta \]

- \( P \) = generated output power in Watts [W]
- \( Q \) = fluid flow in cubic meters per second [m\(^3\)/s]
- \( \rho \) = fluid density in kilograms per cubic meter [kg/m\(^3\)] = 1000 [kg/m\(^3\)] for water
- \( H \) = hydraulic head height in meters [m]
- \( g \) = acceleration due to gravity [m/s\(^2\)] = 9.81 [m/s\(^2\)] on earth
- \( \eta \) = efficiency
To implement this system, a pump-turbine coupled with an electrical motor-generator is installed as a single unit at the bottom of the well. The assembly may be completely submerged or partially submerged in water, though at least the pump intake must be submerged so that the pump stays primed. Since turbine efficiency is low with low head, the system needs to have a reasonable height between the bottom of surface reservoir and the top of the water table. It is recommended to have at least 100 feet of head, and ideal installations will have 200–400 feet of head. See Figure 8 for the relationship between power, head, and flow of such a system.

From previous analysis, the desired range of output power for an irrigation system is about 40 kW to 150 kW, depending on site specifics. This range is shown as a green shaded region on Figure 10. From the well characteristics analysis in the previous section, a maximum flow of 2000 gpm can reasonably be expected. The minimum flow for a feasible system is assumed here to be 500 gpm. The range of flow rates is shown as a blue shaded region on Figure 10. Also from the previous well characteristics analysis, 500 feet is chosen as an upper bound for hydraulic head. The family of lines on Figure 10 represent power curves at different hydraulic heads, as labeled. Next, we outline the intersection of these three regions with a bold red triangle. This triangle gives the range of hydraulic heads and flow rates needed to give the desired power output range.

An electric control and conversion center interfaces the energy source, the hydro motor-generator, and the user connection to the system. This controller can optimize the system performance by matching the pump load to the energy source to extract maximum power from the sun or wind. The controller would also decide when to supply user demand directly from the energy source or from stored energy, as well as when to pump water using excess generated energy from the wind or solar source.

One of the requirements of this system is a surface water reservoir that can supply direct water uses as well as be “drained” back into the aquifer to generate electricity. The volume of this reservoir will be dictated by the amount of energy storage and water use needs required by the application. In the example of an irrigation
system, the surface water may be used to both irrigate crops and generate electricity simultaneously. In all cases, proper filtering and sediment management techniques are needed to maintain water quality at acceptable levels.

A deep well to the ground water is required. The diameter of the well may impact the size of the pump-turbine assembly that can be installed, and thus may affect the maximum power that the system can be sized for. In addition, the well accommodates a water tube of sufficient diameter to meet flow demands, and a conduit carrying electrical feeders.

This system may be powered by a standard utility power meter, however it is intended for use with accompanying renewable energy sources such as wind or solar. Even with the standard utility power, the user can derive economic benefits from the system by storing energy during “off-peak” demand hours and releasing the energy on demand, avoiding the cost of expensive “on-peak” electricity charges. The renewable energy source is sized to supply the average direct load demand of the user system. Then, when the source is not directly supplying the user loads, it will store any excess energy by pumping water up to the surface reservoir.

![Diagram of the system schematic for Aquifer UPHS]

**Figure 11: Example System Schematic for Aquifer UPHS**

## 5 Proof of Concept Testing

To prove the validity and expected performance of this concept, an experimental test is proposed. The test will use an existing deep well and be flexible to use different options for surface water holding. To adequately prove the concept, a system generating capacity of 37.3 kW (50 hp) and 74.6 kWh is targeted, with a minimum acceptable standard of 10 kW and 10 kWh. The power capacity and water flow rate may be adjusted to accommodate limitations in available well characteristics, surface water storage availability, and
The first step for the testing initiative is to select a test well that is expected to have sufficient flow capacity, head depth, and bore construction to facilitate all planned testing. The best available data, as well as permitting situation, well ownership, location, and owner interest are evaluated when selecting the test site. At the time of this report, the most promising site is an aquifer recharge well in Highlands Ranch (Denver), Colorado. The site is owned by Centennial Water and Sanitation District. The operations manager, John Hendrick, has expressed willingness to review the test plan and potentially partner with this research project for well testing.

Two testing phases are envisioned. The first exploratory test phase will serve to provide flow data, aquifer characteristics, and construction information of the selected test site. Simple flow and water depth measurements are taken, as well as aquifer core samples. Data collected in the first testing phase are then used to design hardware for the second phase.

The second phase of testing will involve installing experimental pump-turbine hardware in the well, and executing a full set of performance tests. The expected operation, including power output, flow, dynamics, and system control, will be fully tested. Any deviation from expected operation will be analyzed.

A possible, optional third test phase could involve modification of the well to increase the flow capacity.

5.1 Draft Test Procedure for Phase One Testing (Phase 1)

1) Artificial Recharge Flow Test.
   a) Water is released into the well from the surface. A flow meter or simple method of flow measurement will measure the rate of flow into the well. The flow into the well must be controllable by the experimenters.
   b) The depth of water in the well will be monitored using standard water depth monitoring equipment.
   c) The flow of water from the surface source will be slowly increased until the point at which water level in the well begins rising. This is the static recharge flow capacity of the well. Recharge flow and water depth are recorded.
   d) As the flow of recharge water is slowly increased, the water depth in the well rises. As the water depth rises, head pressure is applied (by gravity) that pushes water into the aquifer. Thus the steady state recharge flow will increase as water level increases.
   e) Water depth and recharge flow will be recorded for several steady-state operating conditions above the static recharge flow and water depth level.

2) Aquifer Geology Soil Sample Test
   a) If not already available, up to four soil core samples will be taken at strategic depths and proximities to the well.
   b) Standard core sample collection processes are used to collect the core samples.
   c) Soil composition, permeability, and saturation percentage will be analyzed.

5.2 Well Requirements (Phase 1 and 2)

The well required for this test is an irrigation, residential, or aquifer recharge well with 6 inch to 18 inch bore diameter. The well must have been constructed following Colorado well construction guidelines. Well construction specifications must be available that detail the type and depth of solid casing, screen casing, pump assembly, well bore, and water table depth, at a minimum. Water rights for the well must be in place, and the well must be permitted under an appropriate permit with the State of Colorado.

5.3 Surface Water Reservoir Requirements (Phase 1 and 2)
A source of water from the surface must be available. The volume for the surface level water reservoir is proportional to the energy capacity of the system. To accommodate the energy target for this test, a surface reservoir that can supply a maximum flow of 1500 gpm for 1 hour is targeted. These parameters lead to a surface reservoir volume of about 12,000 gallons or 0.035 acre-feet. However, if surface reservoir limitations arise, this test will still be valid with a slightly smaller surface reservoir. Alternately, a flowing water source such as a river diversion or pumped water from other wells would suffice to supply the required flow. The water source must be able to deliver drinking water quality water, or whatever minimum water quality standards are required. There are several options for this source, including:

1. River flow diversion
2. Rental of a commercial drinking water tanker that can be driven to the well site.
3. A large holding tank that can hold water pumped up from the well and maintain drinking water quality.
4. Utilization of any water pipeline that may supply the required flow into the top of the well.
5. A dug-out reservoir, pond, or swimming pool equipped with a filtration system that yields drinking quality water.

### 5.4 Primary Power Source (Phase 2)

The primary power source for pumping water to the surface from the well is standard utility power. The system will need either a 240 Vac or 480 Vac, 60 Hz, 3-phase utility power meter connection. Renewable generating sources may be added at a later phase in the testing, depending on availability, cost, schedule, and site owner discretion.

### 5.5 Electrical System (Phase 2)

A power control center will be assembled that has the following functions:

1. Provide power to the pump from the primary power source (utility power)
2. Condition output power from the generator during turbine operation
3. Provide a resistive or motor user load to use the generated power
4. Provide a user interface and safety functions
5. Monitor all necessary system operational parameters

### 5.6 Well Pump-Turbine Assembly (Phase 2)

A modified submersible well pump assembly will be installed in the well, half submerged in aquifer water. This unit will be suspended from a cable fixed at the surface. The unit will be a modified standard high capacity well pump that can be operated in reverse as a turbine that generates electricity. The estimated turbine efficiency is maximum 70%. There are two main modifications that must be done to a standard well pump to allow turbine operation. The first is to assemble the unit using keyed shaft connections rather than threaded shafts to allow reverse direction operation. Secondly, excitation capacitors will be added to the motor leads to allow it to operate as a generator in reverse direction. Other modifications may be identified as the unit is specified and selected. Most standard submersible pumps are axial flow or Francis impeller designs. They are commonly 8 inches in diameter. For this test, it is expected that a Francis impeller type pump that does not have double curvature internal foils will be used. A sealed electric motor at the bottom of the assembly accomplishes the electro-mechanical energy conversion. The estimated cost for such an assembly is $18,000 to $25,000.

The electric motor will require attachment to 3-phase power feeders routed in a conduit to the surface. The pump-turbine will interface to a valved 4 to 6 inch diameter water pipe that is connected to the surface reservoir at the bottom of the reservoir.
6 Economic Analysis

In this section, an attempt to estimate the cost of an aquifer UPHS as described in this report is made. The major cost of the system is the construction of a surface reservoir if one does not already exist. Sites with existing surface ponds or access to easily constructing a surface reservoir will experience the most economic benefit. Also, the motor-pump/turbine-generator unit needed is a new device for which cost estimates are not easily verifiable. The technology for such a unit has precedence in large pumped hydroelectric plants, however the aquifer UPHS system proposed would need a much smaller unit. Electronic control units, wiring, and water piping are the next major system costs. If a well is to be modified as described in section 4.3.2, significant additional costs could be incurred. No estimates for this additional cost were made in this analysis.

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7 UPHS References


