June, 2008

To: Colorado Department of Agriculture
Mr. Tom Lipetzky
700 Kipling St., Suite, 4000
Lakewood, CO 80215
Phone: (303) 239-4114
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From: CU-Boulder, Energy Storage Research Group
Dr. Frank S Barnes
ECE-Eng-Elecl/Comp Admin
University of Colorado at Boulder
425 UCB
Boulder, CO 80309-0425

Dear Tom Lipetzky,

The following is a final report for the Surface to Aquifer Energy Storage (STAES) research effort conducted by CU Boulders Energy Storage Research Group. Included in this report is the following set of interim reports:

1. The September 2007, CDA Interim Report: Surface to aquifer pumped hydro energy storage for agriculture as well as the three primary attachments.
2. A copy of MS Thesis: Aquifer Underground Pumped Hydroelectric Energy Storage. By Gregory Martin.
3. A brief memo outlining efforts to obtain well access and data from December 07 through April 2008.

Conclusions and Next Steps:

A new method of storing electrical energy in an agricultural setting for irrigation application has been analyzed. System design analysis, modeling methods, operation reviews, and aquifer hydrogeology research demonstrates that this is a feasible method for storing energy on-site. Various design trade-offs and installation decisions are outlined that must be considered by the system designers and users. These include depth of well and injection flow capacity, aquifer transmissivity, advanced well completions, pump-turbine sizing, and surface reservoir sizing.

The next step in development of this concept is component and field testing. A centrifugal pump should be procured and tested to determine the maximum efficiency head, flow and shaft speed for both pump and turbine operation. Geologic sampling tests of candidate sites should be analyzed for transmissivity and storativity values. Finally, an actual field installation should be tested for performance to fully verify the analysis in this work.

- A significant challenge encountered in this work shows a mismatch of resources needed to implement this system design. Locations that would be most feasible for implementation of this storage technology would need both sufficient depths to water as well as sufficient flow rates. Finding both the depth and the flow in one location is not a common occurrence. One reason for the mismatched situation is in an agricultural setting it is more common to find high flow needs coming from shallower depths due to the prohibitive cost of pumping.
- While not as many locations for implementation exist as originally assumed specific circumstances may enable this technology to function. Both deep geothermal wells that move high volumes of fluids as well as gas and oil wells that inject and produce may prove to be technically viable options. In addition traditional agricultural wells that exhibit both depths to water and high flow while not a common occurrence do exist.
- Given a situation where STAES is technically viable the legal challenges of implementation are significant.

Interim Report:
Surface-To-Aquifer Pumped Hydroelectric Energy Storage for Agriculture

Date:
September 30, 2007

Submitted To:
The Colorado Department of Agriculture (CDA), Markets Division

Submitted By:

Gregory Martin: Project Manager, University of Colorado at Boulder Department of Electrical and Computer Engineering

Dr. Frank Barnes: Project Supervisor, University of Colorado at Boulder Department of Electrical and Computer Engineering

Jonah Levine: Research Associate, University of Colorado at Boulder Department of Electrical and Computer Engineering

Richard Moutoux: Research Associate, University of Colorado at Boulder Department of Electrical and Computer Engineering

Alaine Ginocchio, Esq.: Legal Team Project Leader, University of Colorado at Boulder School of Law EESI Initiative

Margrit Lent-Parker: Research Associate, University of Colorado at Boulder School of Law EESI Initiative

Stephen Sewalk: Research Associate, University of Colorado at Boulder School of Law EESI Initiative

Contents:

1. Work Completed To Date

A body of work has been completed on the specified research topic. This work has occurred between May 31, 2006 and September 30, 2007. This research work has been sponsored by the Colorado Energy Research Institute (CERI), under the direction of Dr. Dag Nummedal and by the University of Colorado at Boulder Department of Electrical and Computer Engineering, under the direction of Dr. Frank Barnes. The areas of research on this topic have included:

- energy storage options and trade study analysis (ATTACHMENT I),
- legal and regulatory analysis (ATTACHMENT II), and
- system description and analysis (ATTACHMENT III).

Full technical reports in these areas of research are included as attachments to this document. The attachments are available on the internet at <http://www.colorado.edu/engineering/energystorage/cda_attachments.html>, and are also accessible by clicking on the hyperlinked text below "ATTACHMENT XX".

ATTACHMENT I: *"Renewable Energy Storage Analysis for Irrigation and Residential Applications in Colorado's San Luis Valley"*

ATTACHMENT II: *"Review of the Legal and Regulatory Requirements Applicable to a Small-Scale Hydro-Energy Storage System in an Agricultural Setting"*

ATTACHMENT III: *"Aquifer Underground Pumped Hydroelectric Energy Storage for Agriculture*"

2. Problems Encountered and/or Mitigating Circumstances

During the research work referenced above, technical and regulatory challenges have been encountered. While none of these challenges compromise the feasibility of employing such a system, they do complicate the development process and design, and may add cost and planning time to implementing such a system. Listed below are the challenges encountered in implementing this system, as well as proposed mitigation options.

2.1. Legal Analysis Executive Summary and Challenges Encountered

The legal analysis was developed with two central caveats. First, the hydro-ES system, which harnesses energy from water moving down through a well and stores water for this purpose, was not a use contemplated during the development of the legal and regulatory framework that applies to water use in Colorado. Thus, the application of existing laws and regulations is not always straightforward. Second, the specific legal and regulatory requirements that apply to this system will be very site dependent. In fact these requirements can vary substantially depending on the site based on the type of underground water implicated (i.e., tributary, designated, Denver Basin or non-tributary), as well as other site specific characteristics. However, given these two caveats, it is possible to generally identify the type of site that would be most advantageous for implementation of the hydro-ES system; this would be a site that draws water from a nontributary source (see sections 3a and b of ATTACHMENT II). For a test site, tributary ground water sources should be considered because a streamlined process for temporary projects called a "substitute supply plan" is available for tributary ground water, (see section 3e of ATTACHMENT II).

Based on the assumption that the project will be implemented on a site with an existing permitted well with water rights sufficient for the current irrigation needs, it is anticipated that the following requirements would need to be pursued to implement the hydro-ES system: (1) application to the water court for a change of use of water rights, (see section 3a of ATTACHMENT II); (2) an augmentation plan approved by the water court, which may include acquiring additional water rights from another source, (see section 3a of ATTACHMENT II); and (3) a new well permit from the state engineer, (see section 3c of ATTACHMENT II). In addition, because water will be drained back into the underground source, or re-injected, water quality becomes an issue and federal regulations regarding Class V injection wells administered by the US EPA Region 8 Director would be implicated. Although a permit is not mandated under these regulations, information must be submitted to the Region 8 Director, and the information requirement can be substantial, (see section 4a of ATTACHMENT II). In addition, the state water courts will consider water quality in assessing permit changes or augmentation plans, (see section 4b of ATTACHMENT II).

An assessment of the viability of this system, in terms of cost, will depend heavily on the site. For example, the cost of compliance with water quality standards will depend largely on the characteristics of the storage impoundment and terms of storage. It is anticipated that additional legal work may be necessary to assess the specific requirements at a site when the engineering team becomes more certain about a specific site for testing and/or implementation of the system.

2.2. Site Selection and Well Capacity Challenges

The first challenge encountered has to do with site selection of the proposed system. To meet the power output performance required, a well having a large depth to water (250 feet or more) and a large flow rate capacity (1000 gpm or more) is required. These extreme well specifications, while they do exist in the state of Colorado, are somewhat rare. Furthermore, the majority of agricultural irrigation happens near river systems, where depth to water is generally small. Additionally, many existing wells exhibit flow rate capacities lower than what is needed for surface-to-aquifer energy storage. To address these challenges, two options are proposed.

The first mitigating step proposed is to widen the search criteria for underground water sources to include deeper confined aquifers, abandoned mines, and depleted oil or natural gas wells. Initial studies focused on using the unconfined aquifer closest to the surface for energy storage. While in some areas this unconfined aquifer is deep enough to implement surface-to-aquifer storage, we propose that deeper, confined aquifer structures below the unconfined aquifer could provide much greater hydraulic head pressures. Use of the confined aquifer could greatly increase the opportunities for installing such a system, as well as enhance the power output performance of such an installation. Studies in the coming months will characterize the opportunities in using confined aquifers for surface-to-aquifer energy storage. Another option to be explored will be the possible use of abandoned mines or depleted oil and gas wells as the lower reservoir for this concept. Studies on these options are ongoing.

The second proposal to mitigate well characteristics challenges is a method of increasing the flow rate capacity of a well. As described in ATTACHMENT III, advanced well completion methods, such as radial or horizontal completions, are a good option for increasing the well flow, and are not site or location specific. Future work on this project will further detail and analyze the utility and costs of advanced well completion techniques.

2.3. Field Testing Site Identification Problem

Because of the above challenges, proposed field testing plans for the surface-to-aquifer system must be re-evaluated. Given the constraints on well depth, flow rate and water quality, implementing a field test of this concept has become more complicated than initially thought. Because advanced well completion techniques may be required, additional cost and time may be required to complete a well for a field test. A test site with a well having depth to water of greater than 250 feet will be required to facilitate a field test with sufficient power output, further complicating the identification of a site. Finally, water quality regulations and permitting needs will also serve to increase the planning phase and cost of a field test. No testing site has been identified as being available to CU-Boulder for the testing of this concept. The researchers request the assistance of the CDA and its resources to help identify test sites that may be available for testing this concept.

3. Work Planned

The planned work to take place on this project between the time of this report and the time of the final report on September 30, 2008 is outlined in this section.

I. Water Pump-Turbine Machinery Specification
    a. Final flow and head design point selection
    b. Pump-turbine technology type selection
    c. Pump-turbine performance analysis
    d. Costing and procurement recommendations
II. Electronics and Electrical System Design
    a. Electrical system function specifications
    b. Motor-generator design
    c. Power electronics design
    d. System controller design
III. Sample Well Data Collection and Analysis
    a. Collect data from Centennial Water Company (John Hendrick) aquifer recharge wells

    b. Analysis of well geology requirements and considerations

IV. Advanced Well Completion Studies
    a. Proposal and description of ideal advanced well completion method
    b. Cost and feasibility of advanced well completion options

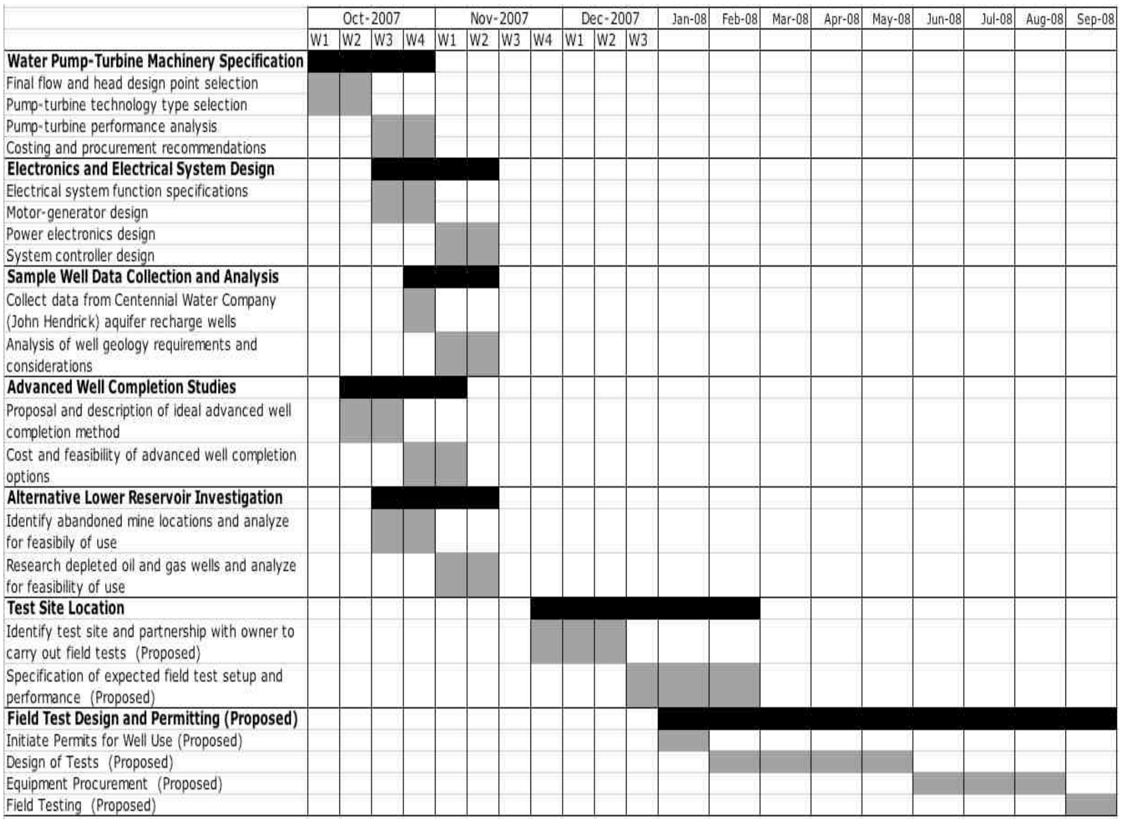
V. Alternative Lower Reservoir Investigation
    a. Identify abandoned mine locations and analyze for feasibility of use
    b. Research depleted oil and gas wells and analyze for feasibility of use

VI. Test Site Location
    a. Identify test site and partnership with owner to carry out field tests (Proposed)
    b. Specification of expected field test setup and performance (Proposed)

VII. Field Test Design and Permitting (Proposed)
    a. Initiate permits for well use (Proposed)
    b. Design of tests (Proposed)
    c. Equipment procurement (Proposed)
    d. Field testing (Proposed)

4. Updated Project Timeline

The updated project timeline for work to be completed on this project between the time of this report and the time of the final report on September 30, 2008 is given in this section. A portion of the planned work will be completed as part of a master's thesis to be completed by Greg Martin during the fall semester of 2007.



	Oct-2007				Nov-2007				Dec-2007			Jan-08	Feb-08	Mar-08	Apr-08	May-08	Jun-08	Jul-08	Aug-08	Sep-08
	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3									
Water Pump-Turbine Machinery Specification	■	■	■	■																
Final flow and head design point selection	▨	▨																		
Pump-turbine technology type selection	▨	▨																		
Pump-turbine performance analysis			▨	▨																
Costing and procurement recommendations			▨	▨																
Electronics and Electrical System Design			■	■	■	■														
Electrical system function specifications			▨	▨																
Motor-generator design			▨	▨																
Power electronics design					▨	▨														
System controller design					▨	▨														
Sample Well Data Collection and Analysis				■	■	■														
Collect data from Centennial Water Company (John Hendrick) aquifer recharge wells				▨																
Analysis of well geology requirements and considerations					▨	▨														
Advanced Well Completion Studies		■	■	■	■															
Proposal and description of ideal advanced well completion method		▨	▨																	
Cost and feasibility of advanced well completion options				▨	▨															
Alternative Lower Reservoir Investigation			■	■	■	■														
Identify abandoned mine locations and analyze for feasibily of use			▨	▨																
Research depleted oil and gas wells and analyze for feasibility of use					▨	▨														
Test Site Location								■	■	■	■	■	■							
Identify test site and partnership with owner to carry out field tests (Proposed)								▨	▨	▨										
Specification of expected field test setup and performance (Proposed)											▨	▨	▨							
Field Test Design and Permitting (Proposed)												■	■	■	■	■	■	■	■	■
Initiate Permits for Well Use (Proposed)												▨								
Design of Tests (Proposed)													▨	▨	▨	▨				
Equipment Procurement (Proposed)																	▨	▨	▨	
Field Testing (Proposed)																				▨

Renewable Energy Storage Analysis for Irrigation and Residential Applications in Colorado's San Luis Valley

Research Progress Update Report
2006-08-30

Greg Martin, Research Assistant, Master's Candidate
Jonah Levine, Master's Candidate
Richard Moutoux, Master's Candidate

Advisement: Dr. Frank Barnes, Dr. Ewald Fuchs

University of Colorado at Boulder

1 Abstract

This report is a progress update on ongoing energy storage research conducted at the University of Colorado at Boulder. A proposal for a comprehensive energy storage research project spanning one year, through June of 2007, was submitted in June of 2006. Information in this report elaborates on and extends the content of the initial proposal. The main purpose of this research is to develop an understanding of the viable energy storage system parameters and trade-offs so that they can be quickly used to analyze the technical and economical aspects of variable user situations.

This paper investigates several energy storage options for use in tandem with renewable energy power generation for agricultural/irrigation use in the San Luis Valley of Colorado. Given the strength of the sun in the San Luis Valley, a photovoltaic (PV) solar generating system is proposed. The system is sized to supply enough energy to meet the electricity needs of four 160-acre center-pivot irrigated plots, as well as shop and residential electrical loads. Because of the intermittent nature of solar power, a method to store energy that provides continually available electricity is needed. In this paper, three energy storage methods are developed and discussed: pumped water, compressed fluid, and batteries. A preliminary estimate of system costs for various options is provided.

2 Introduction

As established in the feasibility report, the insolation in the San Luis Valley is strong enough to merit the use of solar energy. Furthermore, a suitable energy storage system that backs up the solar source is desirable. Irrigation pumping and residential load use during the early morning, night time, or on cloudy days require either the use of utility electricity or the deployment of stored energy from the solar source.

A conventional irrigation system uses an electric well/irrigation pump to draw water from a well and provide pressurized water to a sprinkler. The utility grid supplies the electricity. Recently, large solar arrays have been installed to power the large irrigation loads by day, and utilize utility grid power otherwise. These “hybrid” systems also export any unused solar power back into the utility grid. Depending on the local regulations, this “net-metering” garners payment from the utility or energy credit that can be used later.

The next step may be the rise of on-site energy storage systems that allow independence from the grid. These systems could be net producers of energy, potentially contracting with utility providers as distributed generating sources. Different storage methodologies result in different options for utility grid interaction, as discussed below.

3 Photovoltaic Solar Generating Source

The feasibility report established expected insolation levels in the San Luis Valley. From this information, a suitable PV solar system was sized to support the irrigation load for a single 160-acre center-pivot irrigated potato crop. Since the feasibility study, it has become apparent that a system capable of supporting four of these plots is a more representative sample of the average agriculturalist’s needs. Therefore, the systems developed in this update assume a 270 kW (peak) PV solar array. The parameters and estimated costs of this array are listed in Tables 1 and 2.

Table 1: PV Solar Array Parameters and Costs

Source: <http://solar.sharpusa.com/files/sol_dow_170W_SS.pdf>

Panel Part Make/Model	Sharp / NE-170U1
Panel Height [m]	1.58
Panel Length [m]	0.83
Panel Area [m2]	1.30
Panel Efficiency	13%
Panel Max Rating [kW]	170
l Avg Output [kW @ 80% Insolation]	130
Panel Per Unit Cost [$]	$775.00
Number of Panels Required	1600
Array Cost [$]	$1,240,000.00
Face Area of Panels [m2]	2081.5
Installed Land Area Estimate (acres)	0.6
Panel Mount Cost [$]	$40,000.00
Panel Voltage [V] nom (max)	24 (34.8)
Series Panels	27
Parallel Panels	59
Total Output Power [kW DC]	272.00

Table 2. PV Solar Source Associated Electronics

Component	**Size**	**Cost**
DC Solar Power Transfer Controller	272 kW	$1,000
Grid Tied AC Inverter	272 kW	$4,000
Single Phase Transformer	12 kW	$300
AC Power transfer Controller	272 kW	$1,000
PV Solar Array	272 kW	$1,240,000
Panel Mounting & Wiring	N/A	$40,000
Labor	N/A	$5,000
TOTAL		$1,291,300

The solar panel array cost estimate is higher than the expected actual cost because cost savings due to economies of scale are not accounted for at this time.

Image copied from World Water and Power Corp. Website: http://www.worldwater.com/pages/seley.html

4 "Hybrid" PV Solar and Grid Energy Storage System

The above image is an aerial view of a 267 kW PV solar array installed by World Water and Power Corp. at Seley Ranches in San Diego, California. The array powers a 200 hp irrigation water pump and residential and shop electrical loads. In times of low insolation, power from the utility grid is used. In times of high insolation, this system generates power that is sent back into the utility grid. For more information, visit http://www.worldwater.com/pages/agribusiness.html.

Table 3: Estimated Component Costs For Hybrid Grid Storage System

Part Name	**Part Cost Estimate**	**Comments**
Well Pump VFD	$11,950	220 kW, 380 A, J300-1600HFU (VT)
TOTAL	**$11,950**	

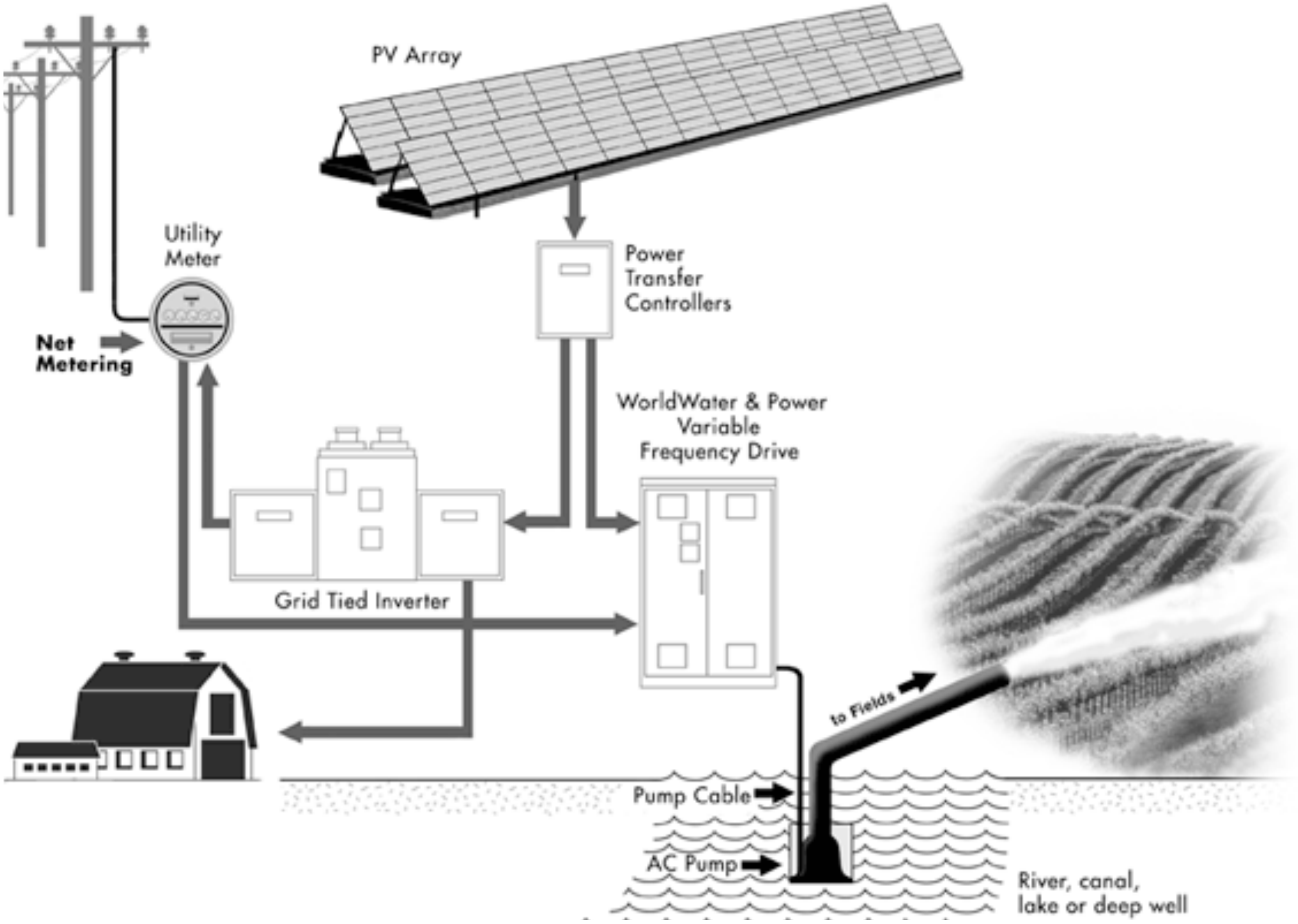


Figure 1: Schematic of World Water and Power AquaMax™ System, taken from http://www.worldwater.com/pages/aquamax.html

5 Pumped Hydroelectric Energy Storage

Pumped hydroelectric energy storage is the most common form of large-scale energy storage. Water is pumped to a higher elevation (normally at least 200 ft) then released and gravity-fed into a turbine that generates electricity. It makes sense to consider the use of pumped hydro energy storage for irrigation applications, because the movement of water from an aquifer to a crop is the ultimate goal. Several methods of employing pumped hydro storage systems merit consideration.

5.1 Elevated Reservoir Storage

The first system that comes to mind involves constructing an elevated water holding tank as an intermediate irrigation water source between the aquifer and the crop. The well pump fills the elevated tank when electricity is available from the solar source. Water is gravity fed, requiring no additional energy input, to the irrigator head. A small amount of electricity is still required to power the drive motors to move the irrigator, which could easily be provided by the solar array with a small battery bank, or by the utility power grid. The holding tank sizing assumptions, per 160-acre plot, are as follows:

i) Sufficient water volume must be stored at elevation to provide 2 days (16 hours) of irrigation, at 850 gallons per minute flow per plot, when solar power is not available.

ii) The irrigated crop is assumed to be potatoes in San Luis Valley. This crop requires about 16 inches of water per season.[1]

iii) The tank must be high enough to provide 50 psi at the irrigator head for low-pressure drop nozzle systems. High pressure systems can require up to 90 psi operating pressure.[2] LEPA (Low Energy Precision Application) irrigation systems can significantly reduce this pressure requirement to about 20 psi.[3] 50 psi is chosen as a "middle-ground" design pressure for this study.

To minimize the tank size reasonable and to minimize losses, each center-pivot irrigated plot will require a dedicated elevated storage tank. The size of such a tank is calculated here:

Water volume required:
850 [gpm] x 60 [min] x 16 [hours] = **816,000 [gal]** = 3088 [m^3]
Tank dimensions:
Diameter = 16 [m] = **52 [ft]**
Height = 15 [m] = **49 [ft]**
Tank elevation:
50 [psi] = **115 [ft of head]** = 35 [meter of head]
Full tank water weight:
8.345 [lb/gal] x 816,000 [gal] = 6,809,520 [lb] = **3,404 [ton]** = 3,088,000 [kg]

The pumped hydro elevated water storage system requires a water tank 50 feet high by 50 ft across capable of holding 3,404 tons of water at an elevation of 115 feet. This installation is obviously cost prohibitive. For comparison, a utility scale water tower to be constructed in Janesville, Wisconsin stores 500,000 gallons (2086 tons) of water at 110 feet and is expected to cost 2.7 million for the entire project.[4] Based on prohibitive costs, this option is discarded from further analysis.

5.2 Surface Water Reservoir Storage

A surface reservoir is a possibility for storing water and energy for irrigation. Water is drawn from the aquifer (100 ft to 300+ ft below the surface) and held in a surface reservoir. Water in a surface level reservoir, if pumped from a lower elevation (aquifer) represents stored energy, with respect to the aquifer elevation. Once the water is at surface level, there are two options. The first is to

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[1] I. Broner, J. Schneekloth; *Seasonal Water Needs and Opportunities for Limited Irrigation for Colorado Crops*; http://www.ext.colostate.edu/Pubs/crops/04718.html.

[2] R. Barta, I. Broner, J. Schneekloth, R. Waskom; *Colorado High Plains Irrigation Practices Guide: Water Saving Operations for Irrigators in Eastern Colorado*; Colorado Water resources Research Institute; Spring 2004, Special report No. 14, Page 15.

[3] http://www.unesco.org.uy/phi/libros/efficient_water/wfipps.html

[4] http://www.gazetteextra.com/jvlwatertower081006.asp

directly pump the surface water to the irrigator heads and the crops. This requires additional energy (electricity) input to power a “boost” pump. This electric power would have to come from either the solar array when the sun is shining, or from the utility grid. The major benefit of this method is that the majority of the energy required for moving irrigation water is extracted from the solar array, offsetting utility grid electricity costs. Since the reservoir can be filled when sun is available and need not continue to be filled at night, the problem of intermittence of the solar source is solved. However, irrigation cannot be powered solely from the energy storage system.

Table 4: Estimated Component Costs For Simple Surface Reservoir Water Storage System

Part Name	**Part Cost Estimate**	**Comments**
Surface Reservoir	$32,310	16,155 cubic yard (10 acre-ft) @ $2.00 per cubic yard
Boost Pump Motor VFD (qty. 4)	$6,700	30 kW each (total cost shown, $1675 each)
Boost Pump (qty. 4)	$1,000	30 kW each (total cost shown, $ each
Well Pump VFD	$11,950	220 kW, 380 A, J300-1600HFU (VT)
TOTAL	**$51,960**	

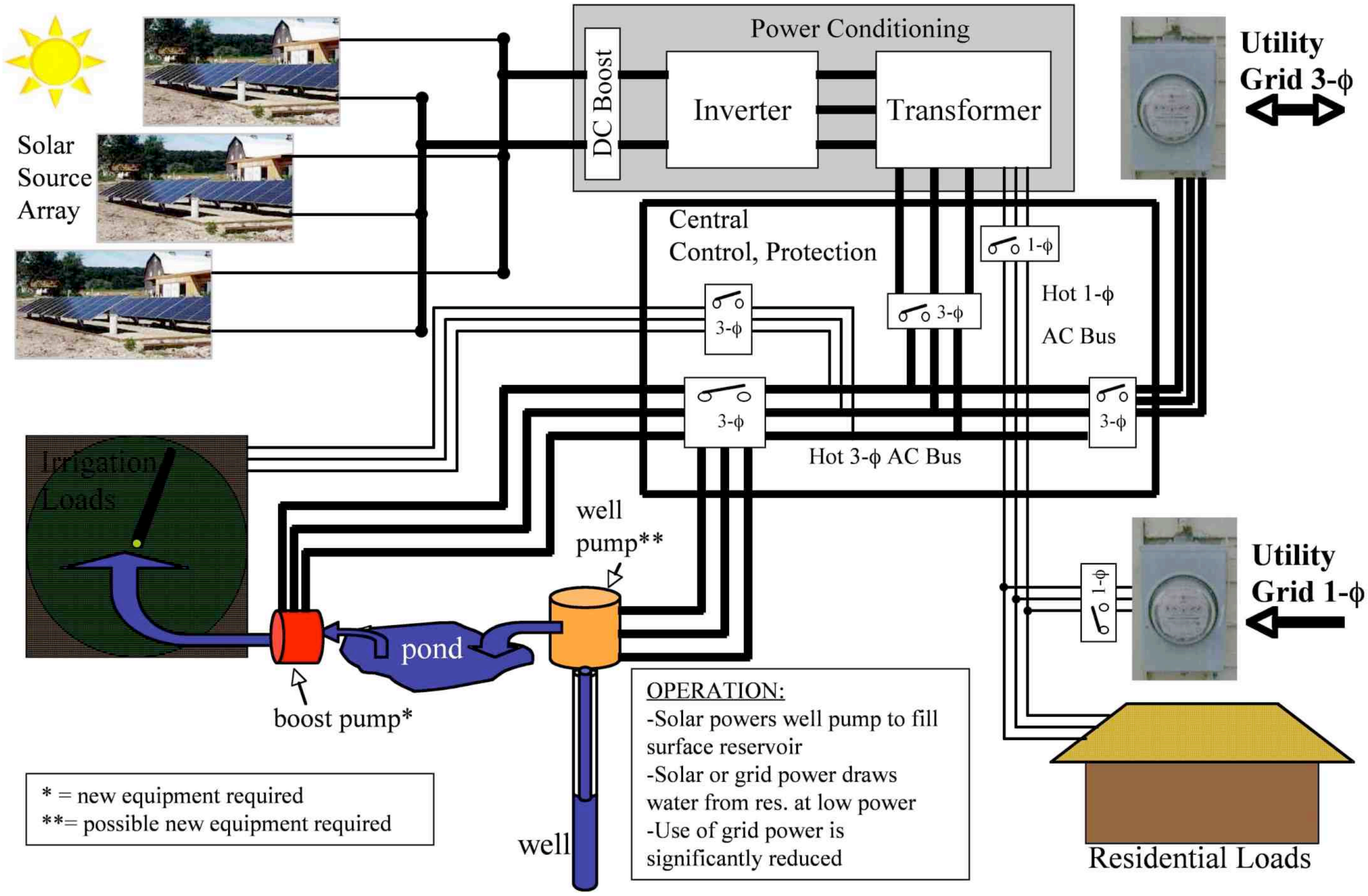


Figure 2: Simple Surface Water reservoir Energy Storage Diagram

The second option using a surface reservoir is to generate electricity from the water held at the surface. This is accomplished by releasing surface water back down into the aquifer. The potential energy of the surface water with respect the aquifer below it can be harnessed to generate electricity. Figure 4 shows a schematic of such a system. A turbine generator located near the aquifer surface is driven by the gravitational potential energy of the released water, which generates electricity to drive irrigation pumps. A well pump that runs as a turbine in reverse direction is installed in place of the standard well pump. Available solar energy pumps water to the surface. When solar power is not available, the water flow is reversed, and electricity is generated from the turbine. A propeller type pump-turbine, or a modified Francis style pump-turbine power a shaft connected to an electric generator. The turbine requires sufficient pressure head to operate effectively. Thus, shallow aquifers may not provide sufficient head for decent turbine operation. It is recommended that the pump-turbine be installed at least about 150 feet below the surface reservoir. Due to contamination concerns, care must be taken in properly filtering any water returned to the aquifer

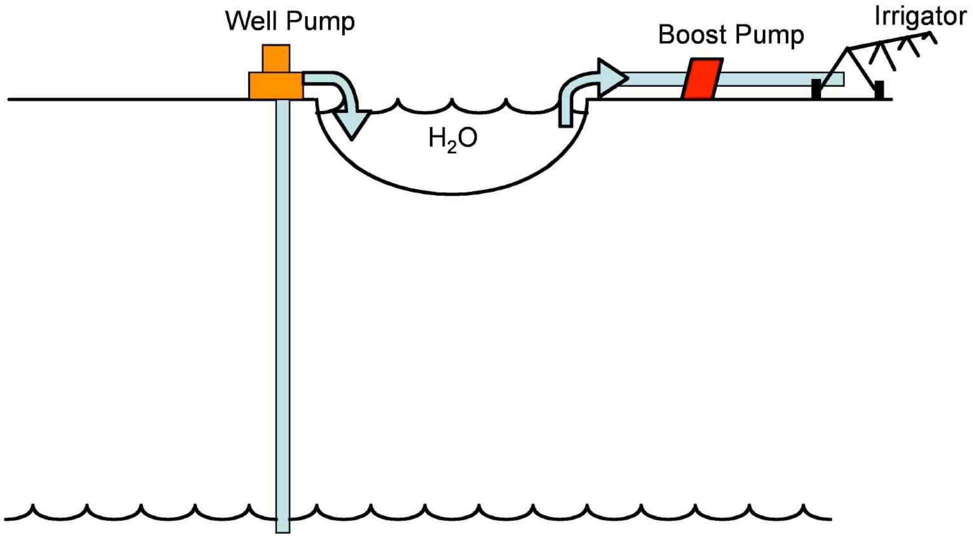


Figure 3: Electrical Diagram of Surface Reservoir Energy Storage System

Table 5: Estimated Component Costs For Regenerating Surface Reservoir Storage Installation

Part Name	**Part Cost Estimate**	**Comments**
Surface Reservoir	$32,310	16,155 cubic yard (10 acre-ft) @ $2.00 per cubic yard
Boost Pump Motor VFD (qty. 4)	$6,700	30 kW each (total cost shown, $1675 each)
Boost Pump (qty. 4)	$1,000	30 kW each (total cost shown, $ each
Motor/Generator	$5,000	260 kW
Well Pump VFD / Turbine GCU	$8,000	260 kW, custom part
Well Pump/Turbine	$10,000	260 kW, custom part
TOTAL	**$63,010**	

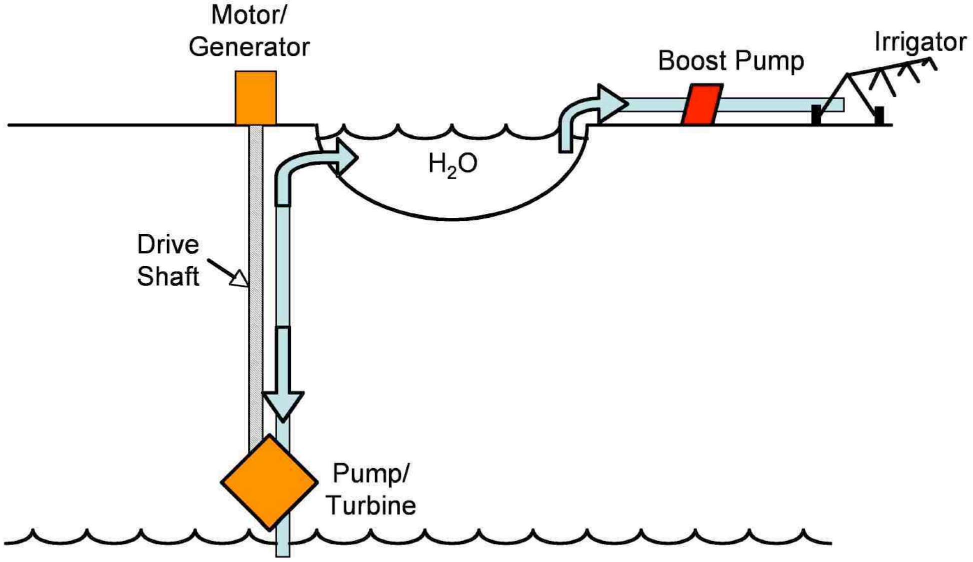


Figure 4: Regenerating Surface Water Reservoir Storage Installation

The idea of using a surface reservoir for water storage can be extended further to optimize the system for year-round operation. Given that the irrigation season lasts five months, the system is under-utilized during the remaining seven months. If sufficient irrigation water can be stored in a surface reservoir to meet the total crop water needs for the entire season, the PV solar array can be sized down.

The total seasonal crop water needs for 4 plots of 130 acre potato crops is:

16 [in H_2O] x 520 [acres] = 8320 [acre-in] = **693 [acre-ft]** = 854,802 [m^3]

The dimensions of a surface reservoir to hold this volume of water are:

693 [acre-ft] ÷ **20 [acres]** = **34 [ft]**

A minimum 20 acre surface reservoir that is 34 feet deep is required. To account for evaporation and runoff losses, and to add extra capacity to generate electricity using the well turbine concept, the size could be increased. There is about 34 acres of "dead space" between the center pivot irrigated crops, as shown in Figure 5.

With all the water needed for the entire season stored on the surface, the energy required to provide pressure and flow to the irrigator heads is significantly reduced. Thus, the power required from the PV solar array is reduced, and the system size is smaller. Since there are seven months between irrigation seasons to fill up this reservoir, the energy demand of the well pump is also reduced. This method is estimated to reduce the PV array to 2/3 the original size. However, the cost to build such a large reservoir is great. Using the rule of thumb that excavation costs are about $1.50 per cubic yard, the 693 acre-foot reservoir would cost close to $1.1 million.

Table 6: Estimated Component Costs For Regenerating Surface Reservoir Storage Installation

Part Name	Part Cost Estimate	Comments
Surface Reservoir	$1,118,000	693 acre-ft (1,118,000 cubic feet) @ $1.00 per cubic foot
Boost Pump Motor VFD (qty. 4)	$6,700	30 kW each (total cost shown, $1675 each)
Boost Pump (qty. 4)	$4,000	30 kW each (total cost shown, $1000 each
Motor/Generator	$5,000	260 kW
Well Pump VFD / Turbine GCU	$6,000	260 kW, custom part
Well Pump/Turbine	$8,000	260 kW, custom part
TOTAL	**$1,147,700**	

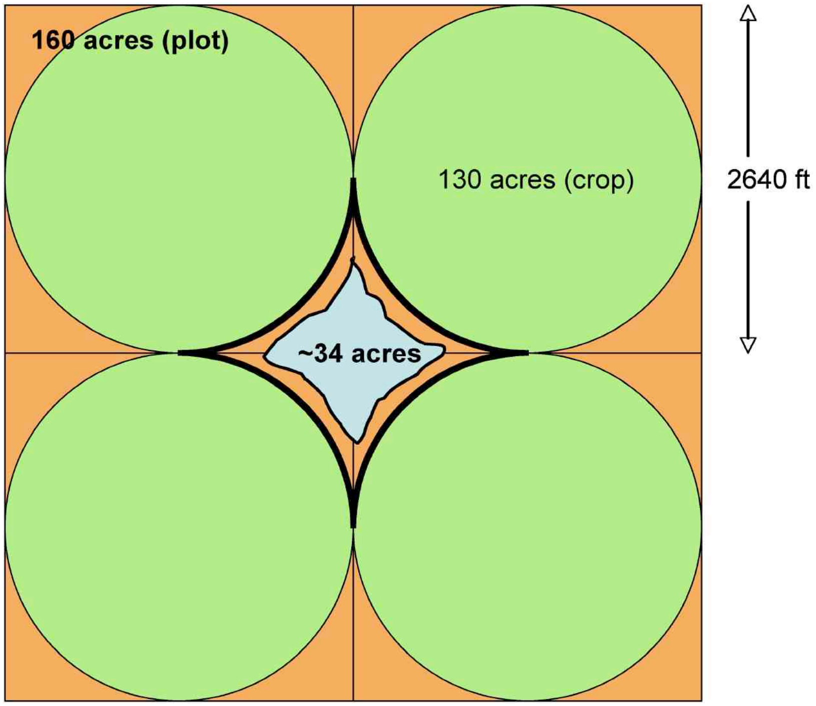


Figure 5: Reservoir space available with center-pivot irrigated crops.

5.3 Optimized Water Storage System With DC Loads

Either of the above systems could be optimized to operate from solar power more efficiently by employing any or all of several methods. If the standard AC motor pumps are replaced by DC motor loads, the voltage and current output of the solar array can be controlled to increase the motor efficiency. Further details of this method are included in Appendix I. Maximum Power Point Tracking (MPPT) can also be used to optimize interaction between solar source and load.

6 Compressed Fluid Energy Storage Systems

Compressed Air Energy Storage (CAES) is an emerging energy storage method. It has been successfully applied on two large scale projects, the 110 MW McIntosh plant in Alabama, USA, and the 290 MW Huntorf plant in Germany. It is planned for several other installations around the world. CAES plants store compressed air to drive a gas turbine more efficiently, thus they still require fossil fuel for operation. Use of compressed air storage increases the efficiency of the gas turbine from about 50% to nearly 85%. However, the round trip efficiency of compressed air energy storage is lower, due mostly to the combination air compression efficiency loss, cooling loss, and turbine generation efficiency loss. Because of the loss of energy in the form of heat, CAES plants normally incorporate additional provisions to capture and use the lost heat, driving the system cost up.

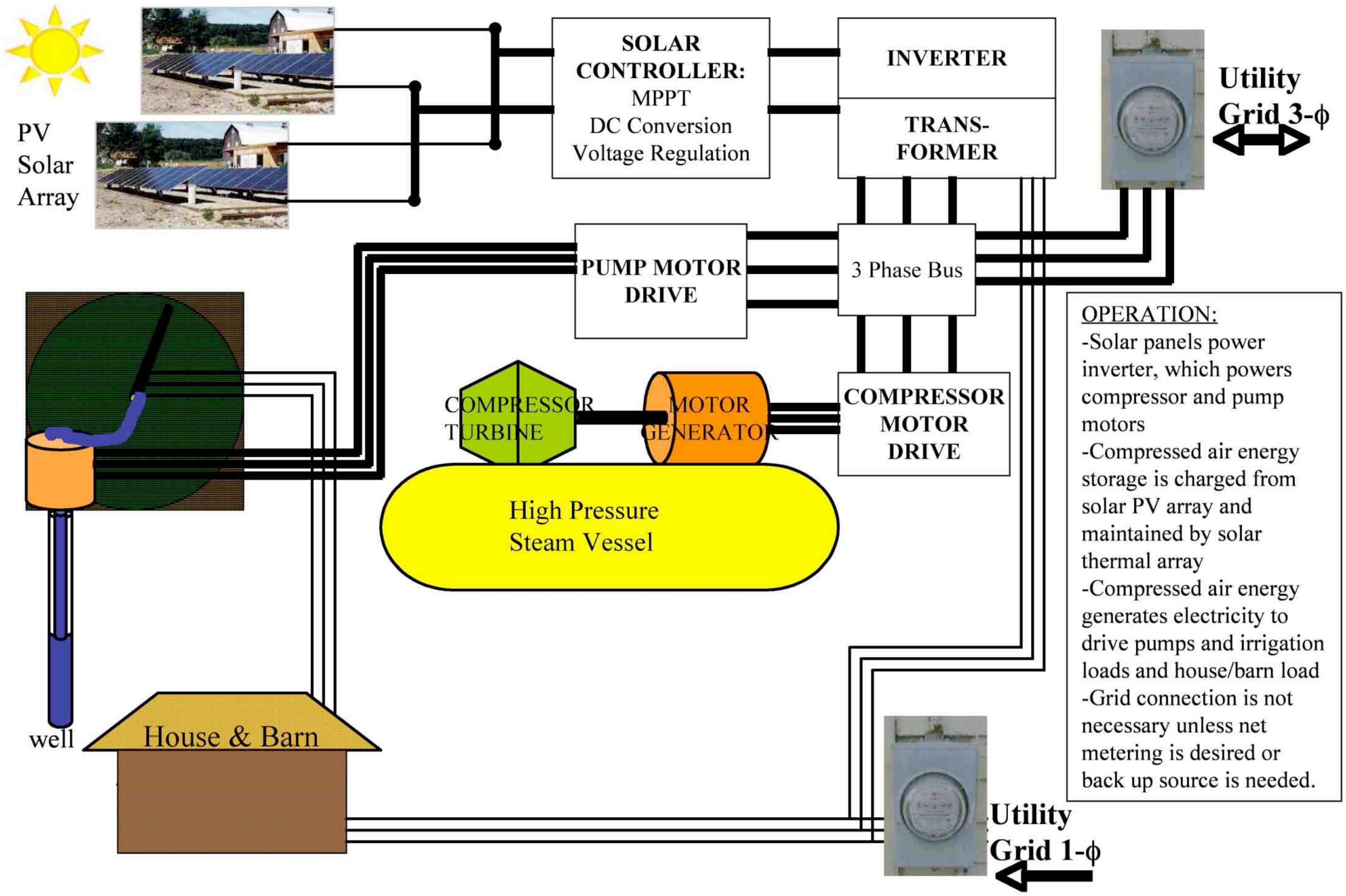
In this study, concepts for using compressed air to store energy on a small scale have been explored. The use of a gas-fired turbine has been excluded.

6.1 Compressed Air Energy Storage With Air Turbine

One possible storage system option mimics the design of the large CAES plant. The main differences are that the system is much smaller, the air is stored in an above ground vessel, and the gas-fired turbine is replaced by an air turbine. A simplified diagram of this system is shown in Figure 6. This system operates by compressing air into a high-pressure storage vessel from available solar energy. The air remains in the tank until stored energy is demanded. Then, pressurized air is released back into the air turbine, which spins the generator and generates power. The thermodynamics of this system become important to efficient operation. The air is heated as it is compressed into the vessel, to temperatures of nearly 800 K (980 ºF). As the compressed air sits idle, this heat is dissipated to the environment, and the pressure in the vessel drops. The system could lose significant amounts to this effect, perhaps up to 50%. Given that the compressor and turbine efficiencies are about 40%, this storage method has relatively low overall efficiency.

Table 7: Estimated Component Costs For Simple Compressed Air Storage System

Part Name	**Part Cost Estimate**	**Comments**
Motor/Generator	$5,000	260 kW
Compressor/Turbine	$10,000	May have multiple stages, custom part
High Pressure Vessel	$3,000	1000 psi, 900 ºF
VF Motor Drive/GCU	$1,000	260 kW, custom part
TOTAL	**$19,000**	



OPERATION:

-Solar panels power inverter, which powers compressor and pump motors

-Compressed air energy storage is charged from solar PV array and maintained by solar thermal array

-Compressed air energy generates electricity to drive pumps and irrigation loads and house/barn load

-Grid connection is not necessary unless net metering is desired or back up source is needed.

Figure 6: Diagram of Small CAES System With Air Turbine

6.2 Compressed Water/Steam Storage With Solar Heater

Because of the challenges of the simple compressed air storage system, provisions to improve this system should be considered. One method is to address the issue of heat loss from the compressed air. A concentrating solar thermal system can continually heat the air vessel when the sun is shining. Also, the use of steam as a storage and turbine drive fluid is desirable because of the ability to use the phase changing properties of water to optimize the system. Thus, a closed steam and water loop, heated by a solar thermal concentrator is proposed. The compressor can compress the steam, and the pressurized water is heated by the solar thermal input. Superheated water and steam are stored in the main storage tank, ready to be discharged into the turbine for electricity generation. As steam is released into the turbine, the pressure decreases, and the temperature drops. The pressure drop causes more water to convert to steam to feed the turbine. As more steam is deployed, the pressure and temperature drop will eventually take the turbine offline, when the stored energy is depleted. The pressurized storage tanks are well insulated to maintain their thermal energy at night. Thus, more energy is available from this storage system at dusk rather than at dawn, because the system has been heated to its maximum level only at the end of the day. This system can discharge electrical power in the absence of any of external energy input.

Table 8: Estimated Component Costs For Regenerating Surface Reservoir Storage Installation

Part Name	Part Cost Estimate	Comments
Motor/Generator	$5,000	260 kW
Compressor/Turbine	$10,000	May have multiple stages
High Pressure Vessel	$3,000	1000 psi, 900 ºF
VF Motor Drive/GCU	$8,000	260 kW
Solar Concentrating Panels	$20,000	Custom part
Low Pressure Holding Tank	$1,000	
TOTAL	**$47,000**	

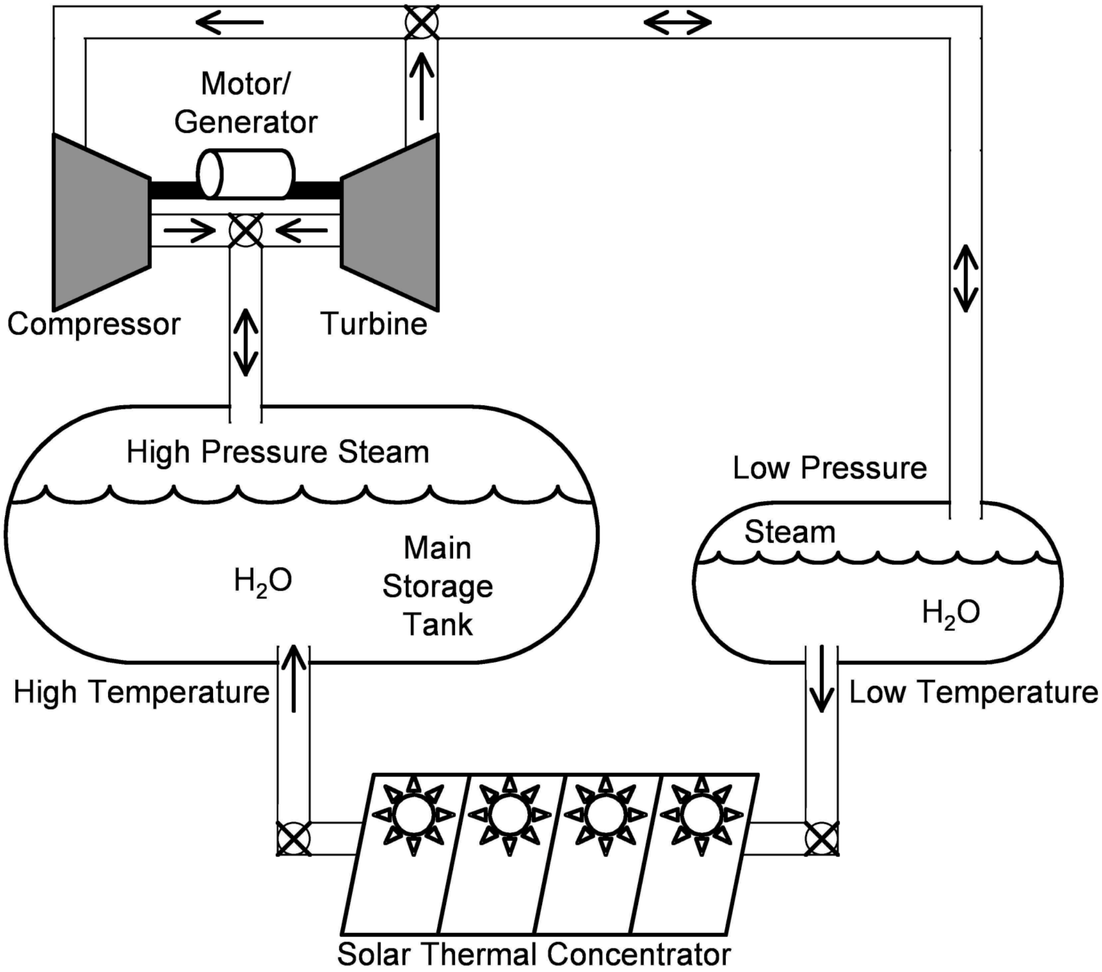


Figure 7. Closed Loop Compressed Steam Energy Storage System Diagram

7 Battery Energy Storage

Chemical energy storage, or batteries, is possibly the most common form of electrical energy storage. Its use has been prominent for small energy and power applications, however recent interest in electric vehicles and utility energy storage methods has widened its scope. The technologies available for chemical energy storage include:

- Lithium Ion (Li+)

- Nickel Metal Hydride (NiMH)
- Nickel Cadmium (NiCd)
- Lead Acid
- Zinc Bromide
- Vanadium Redox Flow
- Soduim Sulfur (NaS)

Each technology has specific merits and disadvantages. The issue of short life cycle is important, and batteries generatlly suffer from lifetimes of less than ten years.

7.1 Battery Storage With AC Load System

The design of the PV solar with battery storage plant is relatively common, especially on smaller scale systems, for example residential sized systems. The DC power matches well with the DC output of the solar array. Essentially, the battery system works in tandem with the solar array to act as a joint source. It is technically easier to recharge the batteries from the PV solar source than it is with other storage methods mentioned in this paper.

The major challenges with using batteries are their short lifetimes and somewhat high costs. Lifetimes generally range from 2 to 10 years. Costs are more difficult to estimate. Some technologies, such as lead acid, are mature technologies and it is a matter of scaling up the size from known installations. Some of the more promising technologies, such as Sodium Sulfur are still in the development phase and have not experienced the economies of scale that could bring costs down. A very rudimentary cost estimate of the best apparent candidate technologies is included here. The data is taken from the EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, pertinent tables are included in Appendix II.

Table 9: Estimated Component Costs For NaS Battery Bank Energy Storage System

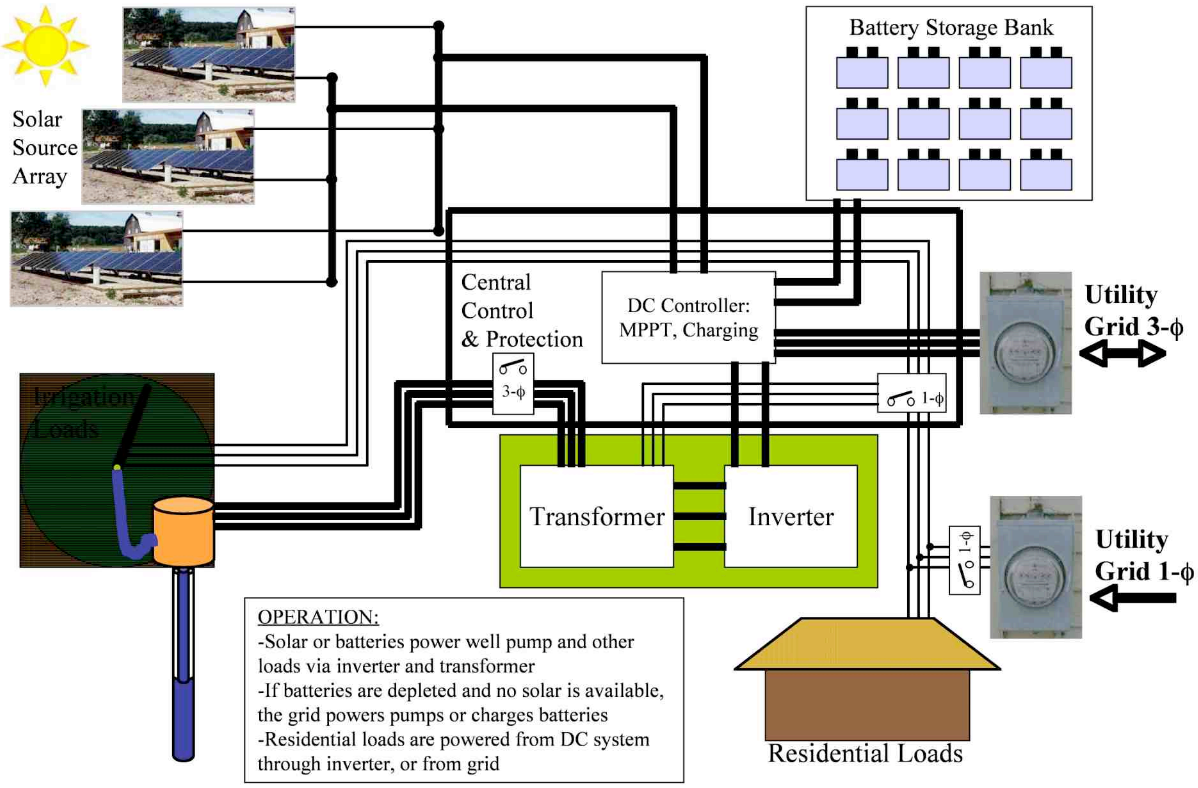
Estimated Component Costs For NaS Battery Bank Energy Storage System		
Part Name	**Part Cost Estimate**	**Comments**
Battery Controller	$3,000	
NaS Battery Bank	$132,080	260 kW, 4000 kWh @ $508/kW

Table 10: Estimated Component Costs For Lead Acid Battery Bank Energy Storage System

Estimated Component Costs For Lead Acid Battery Bank Energy Storage System		
Part Name	**Part Cost Estimate**	**Comments**
Battery Controller	$3,000	
Lead Acid Battery Bank	$84,500	260 kW, 4000 kWh @ $325/kW

Table 11: Estimated Component Costs For Vanadium Redox Battery Bank Energy Storage System

Part Name	**Part Cost Estimate**	**Comments**
Battery Controller	$3,000	
Vanadium Battery Bank	$368,420	260 kW, 4000 kWh @ $1,417/kW



OPERATION:
-Solar or batteries power well pump and other loads via inverter and transformer
-If batteries are depleted and no solar is available, the grid powers pumps or charges batteries
-Residential loads are powered from DC system through inverter, or from grid

Figure 8: Battery Energy Storage System Diagram

8 System Comparisons And Recommendations

Table 12: Estimated Cost Summary For Storage Options

The numbers entered in this table are part quantities, except for the "Part Cost" column.

Part Name	Part Cost [$]	Conventional	Grid Store	Water Store	Battery Store	Steam Store	DC Grid Store
LOADS		$0	$0	$0	$0	$0	$0
AC Well Pump	0	4	4	4	4	4	4
AC Wheel Drive	0	28	28	28	28	28	28
AC Residential & Shop	0	1	1	1	1	1	1
SOLAR SOURCE		$0	$1,593,000	$1,598,000	$1,598,000	$1,598,000	$1,598,000
PV Solar Panels	775	0	2000	2000	2000	2000	2000
Panel Mounting	20	0	2000	2000	2000	2000	2000
Solar Power Controller	3000	0	1	1	1	1	1
Grid Tied Solar Inverter/Xfmr	5000	0	0	1	1	1	1
POWER ELECTRONICS		$3,000	$19,780	$9,390	$15,780	$15,780	$32,340
Grid Tied AC Inverter/Xfmr	4000	0	1	0	0	0	0
Distribution & Control	3000	1	1	1	1	1	1
AC Well Pump VFD	3195	0	4	2	4	4	4
DC Well Pump Drive	3890	0	0	0	0	0	4
Rectifier	1000	0	0	0	0	0	1
STORAGE COMPONENTS		$720,000	$108,000	$162,700	$135,080	$49,000	$108,000
Grid Power Bill	36,000	20	3	3	0	0	3
Surface Water Reservoir	44,000	0	0	1	0	0	0
AC Boost Pump	1000	0	0	4	0	0	0
AC Boost Pump VFD	1675	0	0	4	0	0	0
AC Compressor/Turbine	10000	0	0	0	0	1	0
Motor/Generator Drive & GCU	8000	0	0	0	0	1	0
Steam High Pressure Vessel	3000	0	0	0	0	1	0
Motor /Generator	5000	0	0	0	0	1	0
Liquid Thermal Loop	3000	0	0	0	0	1	0
Thermal Solar Collector	20000	0	0	0	0	1	0
260 kW Battery Bank (NaS)	132080	0	0	0	1	0	0
Battery Bank Controller	3000	0	0	0	1	0	0
TOTALS							
Total System Cost	-	**$723,000**	**$1,720,780**	**$1,770,090**	**$1,748,860**	**$1,662,780**	**$1,738,340**
Estimated Pay Back Period	-						

The estimated total system costs for several storage options are compiled in Table 12. The dominant cost of each system is the photovoltaic solar system. This suggests that the next step is to investigate ways to reduce the cost of the PV array. First, economies of scale need to be taken into account for the large solar system needed. Next, the storage options might be redesigned in ways that minimize the instantaneous power requirement. The very large water reservoir storage concept is an example of opportunities to do this.

Additional future work must include design of DC load systems for use with each of the storage options. The concept of the compressed steam and water system must be developed further including thermodynamic analysis and refined component cost research.

There are promising options for on-site energy storage systems. These systems can potentially provide users with a very reliable, economically beneficial, and environmentally sound energy source. The installation and testing of these energy storage systems will solidify our understanding of their economic and technical performance, leading to successful commercial energy storage system installations.

APPENDIX I - Matching Solar Array Output To A DC Motor Pump Load

Objective

It is desirable to employ control methods that allow maximum power to be supplied from a solar panel array to a motor load for any given insolation. This proposal outlines a method to switch the number of series and parallel connected solar panels to arrange the photovoltaic source voltage and current output such that maximum power is delivered to the load.

Background

Three familiar control techniques exist for maximizing solar array output power:

- Sun tracking employs two-axis (tilt and azimuth) positioning of each solar panel so it directly faces the sun and captures the maximum possible direct sunlight.
- Tailoring the motor and pump load characteristic to align it with the solar output in such a way that maximum power is delivered at most insolation levels.[5]
- Current or voltage maximum power point voltage tracking (CMPPT, VMPPT) is a more complex technique that involves adjusting a buck-boost DC converter to maximize power flow to the load.[6]

All of these methods are compatible, that is, any of them can be used together to further optimize the system.

Proposal

The new proposed method switches the connection topology of the solar array to adjust the current and voltage output so that maximum power is delivered to the load. This technique will change the number of panels connected in series and parallel to control voltage and current output. The array connections are controlled based on the level of solar insolation at each panel and on the load operation point. Power electronic switches (MOSFETs) are connected in a matrix that allows various combinations of series and parallel solar panel connections. The control scheme would use a look up table to determine the necessary array connection topology based on insolation and load operating point. For example, when insolation is low (at dusk or dawn) the control method will connect the solar array with the optimal number of parallel and series panels, increasing the power transmitted to the pump load. Array connections are also updated based on the speed and torque operating point of the motor load. The case analyzed assumes a motor driven water pump load. Figure 1 illustrates the conceptual operation of such a scheme. The normal I-V characteristics are shown with solid lines, and the proposed method's effect is shown with dotted lines. An approximate water pump characteristic is included. It can be seen from the figure that the new solar characteristic more closely matches the pump characteristic.

Testing this scheme at a suitable facility is proposed. Actual voltage current characteristics of the optimized scheme operating at different insolation levels and load operating points would be experimentally determined. For reference, the characteristic of the fixed connection array would also be determined. Insolation would be measured using a reference solar panel, and the look up table information would be determined experimentally. The actual pump current-voltage and speed-torque characteristics would be determined. The proposed test setup calls for a minimum solar array power rating of 10 kW DC, with which a 13 horsepower water pump would be tested. Access to the solar array interconnections would be required so that the switching matrix can be

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[5] *Starting and Steady-State Characteristics of DC Motors Powered by Solar Cell Generators;* J. Appelbaum; IEEE Transactions on Energy Conversion, Vol EC-1, No. 1, March 1986.

[6] *Theoretical and Experimental Analyses of Photovoltaic Systems With Voltage- and Current-Based Maximum Power-Point; Tracking;* Mohammad A. S. Masoum, Hooman Dehbonei, Ewald F. Fuchs; IEEE Transactions on Energy Conversion, Vol. 17, No. 4, December 2002.

inserted. Standard test equipment is required to measure output voltage and current of the solar array, and speed and torque of the motor drive.

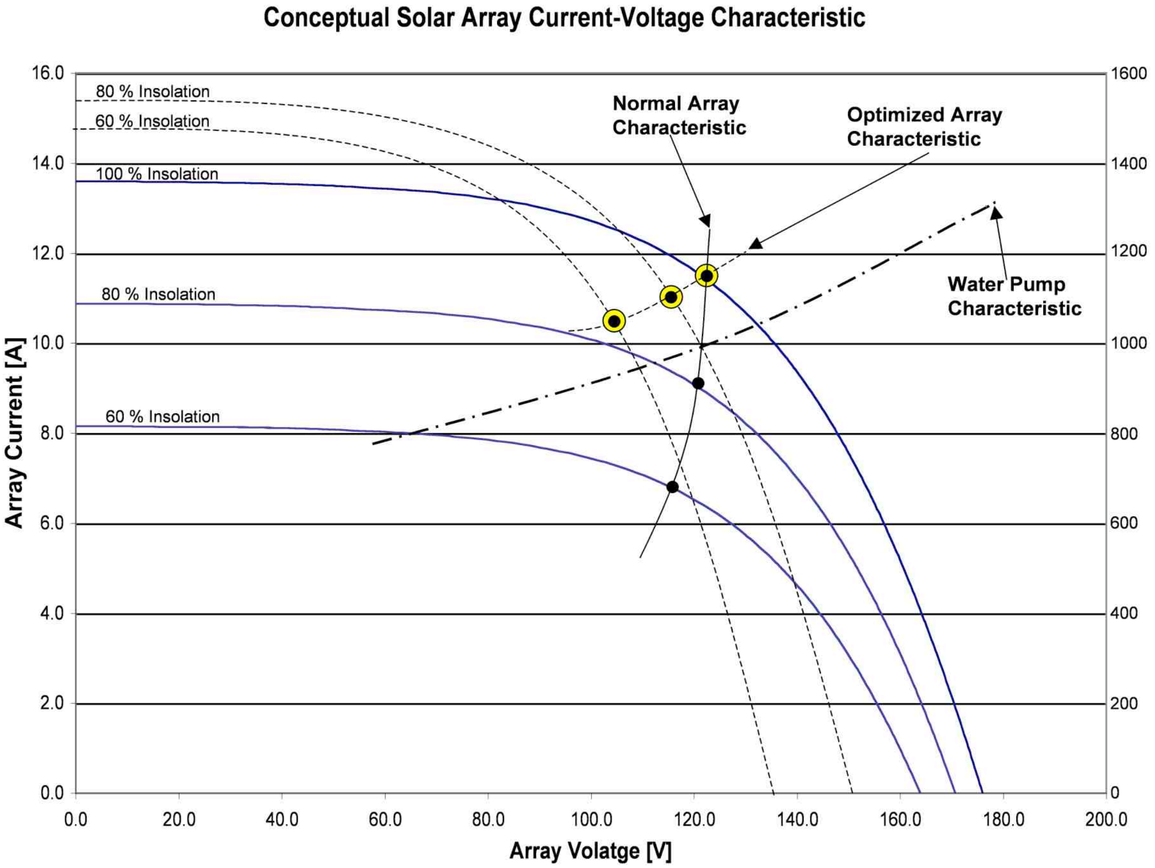

Figure A 1.

Conceptual Current-Voltage Characteristics of Solar Array and Load.

APPENDIX II – Battery System Costs

The following tables are taken from the EPRI – DOE Handbook of Energy Storage for Transmission and Distribution Applications:

EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington, DC: 2003. 1001834.

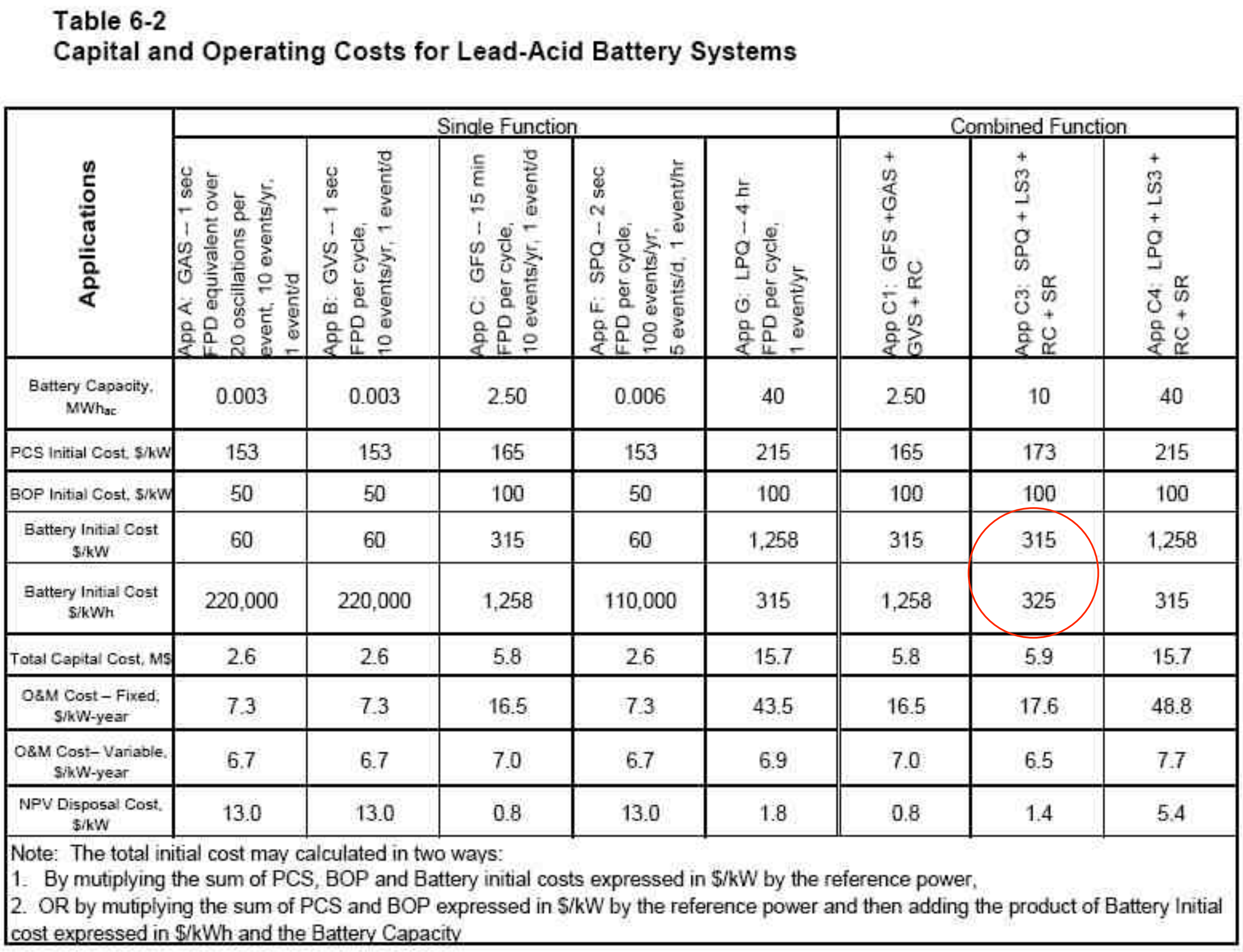

Table 6-2
Capital and Operating Costs for Lead-Acid Battery Systems

Applications	Single Function					Combined Function		
	App A: GAS – 1 sec FPD equivalent over 20 oscillations per event, 10 events/yr, 1 event/d	App B: GVS – 1 sec FPD per cycle, 10 events/yr, 1 event/d	App C: GFS – 15 min FPD per cycle, 10 events/yr, 1 event/d	App F: SPQ – 2 sec FPD per cycle, 100 events/yr, 5 events/d, 1 event/hr	App G: LPQ – 4 hr FPD per cycle, 1 event/yr	App C1: GFS +GAS + GVS + RC	App C3: SPQ + LS3 + RC + SR	App C4: LPQ + LS3 + RC + SR
Battery Capacity, MWh_{ac}	0.003	0.003	2.50	0.006	40	2.50	10	40
PCS Initial Cost, $/kW	153	153	165	153	215	165	173	215
BOP Initial Cost, $/kW	50	50	100	50	100	100	100	100
Battery Initial Cost $/kW	60	60	315	60	1,258	315	315	1,258
Battery Initial Cost $/kWh	220,000	220,000	1,258	110,000	315	1,258	325	315
Total Capital Cost, M$	2.6	2.6	5.8	2.6	15.7	5.8	5.9	15.7
O&M Cost – Fixed, $/kW-year	7.3	7.3	16.5	7.3	43.5	16.5	17.6	48.8
O&M Cost– Variable, $/kW-year	6.7	6.7	7.0	6.7	6.9	7.0	6.5	7.7
NPV Disposal Cost, $/kW	13.0	13.0	0.8	13.0	1.8	0.8	1.4	5.4

Note: The total initial cost may calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Table 8-6
Capital and Operating Costs for NAS Battery Systems

Applications	Single Function		Combined Function				
	App F: SPQ – 2 sec FPD per cycle, 100 events/yr, 5 events/d, 1 event/hr	App I: LS10 – 10 hr FPD per cycle, 250d/yr	App C1: GFS +GAS + GVS + RC	App C2: SPQ + LS10 + RC + SR	App C3: SPQ + LS3 + RC + SR	App C4: LPQ + LS3 + RC + SR	App C5: LS10 + RC + SR
NAS Battery Capacity, MWh$_{ac}$	0.006	100	2.50	22	10	40	100
PCS Initial Cost, $/kW	153	204	449	202	202	289	204
BOP Initial Cost, $/kW	100	100	100	100	100	100	100
NAS Battery Initial Cost, $/kW	305	1,964	461	508	508	1,523	1,964
NAS Battery Initial Cost, $/kWh	550,000	196	1,845	235	508	381	196
Total Capital Cost, M$	5.6	22.7	10.1	8.1	8.1	19.1	22.7
O&M Cost – Fixed, $/kW-year	13.8	51.2	23.1	19.2	19.2	43.2	51.2
O&M Cost– Variable, $/kW-year	9.6	13.4	2.6	2.6	3.9	8.1	9.1
NPV NAS Disposal Cost, $/kW	6.7	43.2	10.1	11.2	11.2	33.5	43.2

Note: The total initial cost may be calculated in two ways:

1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Table 10-4
Capital and Operating Costs for VRB Battery Systems

Applications	Single Function	Combined Function			
	App I: LS10 – 10 hr FPD per cycle, 250d/yr	App C2: SPQ + LS10 + RC + SR	App C3: SPQ + LS3 + RC + SR	App C4: LPQ + LS3 + RC + SR	App C5: LS10 + RC + SR
VRB Battery Capacity, MWhac	100	67	20	40	100
PCS Initial Cost, $/kW	397	311	311	516	397
BOP Initial Cost, $/kW	100	100	100	100	100
VRB Battery Initial Cost, $/kW	2,125	1,417	883	1,825	2,125
VRB Battery Initial Cost, $/kWh	213	213	442	456	213
Total Capital Cost, M$	26.2	18.3	12.9	24.4	26.2
O&M Cost – Fixed, $/kW-year	54.8	38.8	28.1	51.2	54.8
O&M Cost– Variable, $/kW-year	7.0	1.9	4.1	5.2	2.4

Note: The total initial cost may be calculated in two ways:

1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Review of the Legal and Regulatory Requirements Applicable to a Small-Scale Hydro-Energy Storage System in an Agricultural Setting

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September 30, 2007

1. Introduction

The legal team was asked to review the legal and regulatory requirements applicable to implementation, in Colorado, of a small-scale hydro-energy storage system that would be used in an agricultural setting, primarily to provide energy for irrigation. To compile the information in this chapter, we reviewed both state (Colorado) and federal statutes and regulations, legal texts and other legal documents, and conducted interviews with staff and officials whose regulatory responsibilities are relevant to this system.[1] The following reflects the results of our research.

Section two explains the scope of our work, assumptions made, and general remarks about limitations. Sections three and four address the bulk of the regulatory and legal analysis. In Colorado, water law is fairly complex and specialized. The Hydro-Energy Storage (hydro-ES) system involves water rights, water use, well permitting, reinjection and water quality issues. Therefore, hydro-ES would fall under the purview of several state entities and the Federal Environmental Protection Agency (US EPA). Based on the legal issues involved, the analysis is divided into two sections. Section three addresses the bulk of the state laws and regulations applicable to implementation of the system and also includes information regarding enforcement, provisions relevant to well permits and special provisions for temporary use. Section four addresses water quality issues associated with the drainage of water back into the underground source and implicates federal laws and regulations. Section five concludes the chapter with a summary of the most significant factors relevant to siting of the hydro-ES system. Our research addresses the regulatory framework applicable for implementation of a permanent system in order to assess the viability of addressing agricultural energy needs with a renewable resource. Our research also addresses any provisions for temporary or short-term permitting that might be relevant for the testing phase of this project.

2. Scope of Work

This analysis is based on a hydro-ES system with the following parameters:

- The lower water body will be an underground water source.
- The upper water body, or impoundment, will be on the surface (e.g., a pond or reservoir).
- Water will move between the two bodies through a well and the pump-turbine apparatus will be installed at the lower end of the well.[2]

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[1] Interviews were followed up with legal research and, in most cases, the information in this chapter is based on the legal research.

[2] This apparatus is a pump-turbine coupled with an electrical motor-generator installed as a single unit as described in an earlier chapter of the Interim Report.

- The upper water body/impoundment must be large enough to hold water for two purposes: 1) to meet irrigation needs during a period when wind/sun is not available; and 2) the additional water to flow down through the turbine to produce the energy necessary to pump the irrigation water from the impoundment onto the fields.[3]

- The system will be implemented on an existing agricultural concern that has an existing well and water rights to support irrigation.

- The hydro-power portion of the system is designed to work in conjunction with an energy system that uses a renewable source (e.g., solar or wind).[4] That is, the hydro-power is not the primary source of power for energy generation in this system. It addresses the intermittence problem associated with solar and wind generation systems so that they are more viable alternatives to utility supplied energy.

It is important to recognize that the applicable legal/regulatory requirements will be site specific and can vary substantially depending on the location of the well. For example, the type of underground water source will determine which regulatory entity or entities have jurisdiction and the particular regulations that will apply. Also, the existing water right associated with the specific implementation/testing site as well as the other water rights and uses attached to that particular underground source will impact the analysis. The research was approached in a general manner, making note of differences relevant to different site characteristics. To the extent we could, we addressed differences applicable to different siting scenarios and noted the type of sites with the least prohibitive regulations. However, it was not within our resources to address every potential siting possibility. As the engineering team narrows its focus on a particular site, for testing and/or implementation, it is anticipated that additional legal research will be required to analyze the specific regulatory framework applicable.

It is also important to note that the use of water for hydro-ES using an underground to surface water design is a novel approach for meeting the energy requirements of agricultural concerns. This approach was not contemplated when the legal and regulatory framework to address and protect water quality and usage in Colorado was developed. Therefore, the application of current statutes and regulations can be awkward at best and in some cases there is no definitive answer for issues regarding implementation. In terms of permitting the application, Colorado water law has been adaptive over the years and is founded on the common goal of extending water's

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[3] Evaporation during impoundment would also have to be considered.

[4] The analysis here is limited to the legal and regulatory framework associated with the pumped hydro portion of the system. Issues associated with implementing the solar or wind generation associated with this system are not addressed here. This system may also be powered by standard utility power; the user can derive economic benefits from this system by storing energy during "off peak" demand hours and releasing energy on demand, thus avoiding the cost of expensive "on peak" electricity charges.

benefit to as many useful purposes as our customs and values as a people grow to recognize. *Colorado Water Law Benchbook*, at vii First Ed. (Carrie L. Ciliberto ed., CLE in Colo., Inc. Supp. 2007) [hereinafter *Benchbook*]. However, one must also consider water availability in a state with a dry climate that suffers drought conditions regularly and water sources that are in many cases over-subscribed,[5] and how water limitations and regulatory requirements on a case by case basis will impact cost effectiveness.

The Statutory and Regulatory Framework

There are a number of state entities, offices and officials involved with the regulation of water rights to underground sources and the wells used to extract water from underground sources. In Colorado there are specific regulations addressing wells in addition to those that address water rights and uses, and water rights are regulated based on the designation of the ground water at issue. Further, both water extraction and water return (reinjection in this case) have distinct requirements, and the U.S. EPA is implicated when water return is implemented through a well. In addition, in some cases, temporary permitting requirements exist which are relevant in regard to planning a test phase for this system.

In conducting this research, the legal team pursued the following objectives:

- Provide a basic understanding of the relevant water law in Colorado;
- Provide some insight as to the regulatory framework applicable to the implementation of this novel system with an eye towards the viability of such a system within that framework;
- Provide guidance in the choice of a site for a hydro-ES system; and
- Identify any potential temporary permitting process that could be applicable to the testing phase of this project.

3. The State Statutory and Regulatory Requirements

The key issues in regard to using water from an underground source for hydro-ES can be summarized with three questions: 1) will any part of the system be considered a "new use" of an existing water right and, if so, what are the implications of a change of use; 2) will additional water rights, in terms of amount of water, be necessary; and 3) will a commitment to return water to the underground source be required, (in addition to that

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[5] The majority of stream systems in Colorado's eastern slope qualified as overappropriated in the 1890's. *Benchbook* at 2-6.

returned as part of the system to produce power).[6] There are four primary legal classifications of ground water[7] in Colorado: 1) tributary; 2) nontributary; 3) designated; and 4) Denver Basin. The answers to the three key questions will depend on the classification of the water at issue because the relevant regulatory scheme and agencies with oversight authority will depend on this classification. Further, the "answers" are not always clear. It becomes obvious when trying to apply the laws and regulations to this system that harnessing the energy from water moving down through a well is not a use contemplated in the development of the regulatory schemes, nor was storage of water for this purpose.

a. The Basics of the Relevant Colorado Water Law: The Four Types of Ground Water

The primary principle of Colorado water law is the doctrine of prior appropriation which is often summarized by the phrase "first in time, first in right." Colo. Const. Art. XVI, §§ 5 and 6; Colo. Rev. Stat. ("C.R.S.") § 37-92-102(1); *see* Michael F. Browning, *A Summary of Colorado Water Law*, 21 Colo. Law. 63 (1992); *Benchbook* at 1-2. In its most basic sense, an appropriation is water put to a beneficial use. C.R.S. § 37-92-103(3). Beneficial use is "the use of that amount of water that is reasonable and appropriate under reasonably efficient practices to accomplish without waste the purpose for which the appropriation is lawfully made." C.R.S. § 37-92-103(4). The earlier appropriator, or user of the water, has a better right against all subsequent users. *Benchbook* at 1-2. In times of short supply water is allocated pursuant to this priority. Under the Colorado Water Resources and Power Development Authority Act, Colorado recognizes power generation as a beneficial use. C.R.S. § 37-95-103(2); *Bd. of Cty Comm'rs v. Crystal Creek Homeowners' Assoc.*, 14 P.3d 325, 337 (Colo. 2000).

However, ground water, which is the type of water implicated in hydro-ES, may or may not be subject to appropriation as set forth in the Colorado Constitution. The governing law depends upon the legal classification of the ground water, (i.e., tributary, nontributary, designated basin, or Denver Basin

i) Tributary v. Nontributary. Generally, the two types of ground water are 'tributary' and 'nontributary.' These terms are both legal classifications and physical descriptors, (i.e., they describe physical attributes of ground water). All ground water has the physical attributes of one or the other, however, only water that is not classified as a designated

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[6] The water quality of water returned or drained back into the underground source is also a key issue and is addressed separately in section 4.

[7] "Underground water" and "ground water" are used interchangeably in this chapter and mean any water not visible on the surface of the ground under natural conditions. *See*, C.R.S. §37-90-103(19).

basin (discussed below) is legally classified as 'tributary' or 'nontributary.' In this chapter, these terms are used as legal classifications unless otherwise noted.

Tributary ground water is considered "water of every natural stream" as the phrase is used in the Colorado Constitution and is thus subject to appropriation. *See* C.R.S. § 37-82-101. The basis for this classification is the hydrological connection of this ground water to surface water. Legally, it is generally treated the same as surface water (e.g., rivers and streams). The provisions of the Water Right Determination and Administration Act of 1969, as modified since original enactment, govern the use of natural stream water within the state, including tributary ground water. Thus, tributary ground water is subject to the prior appropriation scheme.

There is a presumption that all ground water is tributary. *Stonewall Estates v. CF & I Steel Corp.*, 592 P.2d 1318, 1320 (Colo. 1979). Thus, one must prove to the court that ground water is nontributary in order to receive that designation. If so designated, nontributary ground water is subject to a different set of rules. However, it is difficult to prove that ground water is not tributary to a stream.

While tributary water is annually replenished, nontributary water is "subject to eventual depletion." Brett Heckman, *Principles & Law of Colorado's Nontributary Ground Water*, 62 D.U. L. REV. 809, 814 (1985). This distinction, in large part, leads to the different schemes that address withdrawal of water. Use of water that is not tributary to a natural surface stream is not subject to prior appropriation. C.R.S. § 37-90-102(2). "Nontributary ground water" is defined as water located outside of a designated ground water basin (discussed below) that, upon withdrawal, will not in 100 years cause a depletion of the flow of a natural stream at a rate more than one-tenth of one percent of the annual rate at which the water was withdrawn. C.R.S. § 37-90-103(10.5). The determination of whether ground water is nontributary is made at the time of permit application. *Id.* Essentially, the idea is that nontributary ground water is not hydrologically connected to any water considered tributary. Browning, *supra* at 65. Further, nontributary ground water legally exists only outside the boundaries of a designated ground water basin. Allocations of nontributary ground water are made pursuant to statute and are based upon ownership of the overlying land. *Id.*[8]

Because tributary aquifer ground water is water contained in an aquifer that is directly connected to the local stream system, generally, the water table in such an aquifer is relatively shallow. On the other hand, deep aquifer ground water is not so directly connected to the surface stream system (i.e., nontributary ground water is more likely to be deep aquifer ground water). Thus, typically, a site using nontributary ground water will better meet the needs (i.e., head requirement) for the Hydro-ES system. Further, there are other advantages associated with the nontributary regulatory scheme, such as the

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[8] A variation on nontributary ground water regulation comes into play when discussing Denver Basin aquifers. *See* C.R.S. § 37-90-103(10.5); *Benchbook*, at § 3.2.3.

manner in which water rights are allocated and the accounting mechanism for water use. This is addressed below.

ii) Designated Basins and the Denver Basin. The location of the well is important because the Colorado Ground Water Commission ("CGWC") designates certain areas of the state as Designated Ground Water Basins ("Designated Basins") pursuant to C.R.S. Section 37-90-106. *See* Colo. Dept. of Natural Resources, Div. of Water Resources, Guide to Colo. Well Permits, Water Rights, and Water Admin. 5 (Mar. 2006). Attached as Attachment A is a map of designated ground water basins. [9] The vast majority of designated basins are located in the eastern half of Colorado. The classifications as "designated basin" or "Denver aquifer" are purely legal constructs. There is a presumption that designated basins are hydrologically not connected with any surface water source, that physically they are nontributary. However, notwithstanding the physical attributes of the underground water source, designated water is not legally classified as nontributary or tributary. For purposes of regulation and administration it is in a separate classification.[10]

Designated ground water is governed by the Colorado Ground Water Management Act ("GWMA"), C.R.S. §§ 37-90-101 to -143. It is managed under a modified system of appropriation. C.R.S. § 37-90-102(1). Designated ground water is defined as ground water that is located within the boundaries of a Designated Basin and "which in its natural course would not be available to and required for the fulfillment of decreed surface rights," or which is not adjacent to a continuously flowing natural stream and withdrawals of which have "constituted the principal water usage for at least fifteen years preceding the date of the first hearing on the proposed designation of the basin." C.R.S. § 37-90-103(6)(a). The CGWC determines the boundaries of Designated Basins and has the sole jurisdiction to appropriate designated ground water. C.R.S. § 37-90-106 (enabling statute); *State ex rel. Danielson v. Vickroy*, 627 P.2d 752 (Colo. 1981) (exclusive jurisdiction); see also, State of Colo., Dept. of Natural Resources, Div. of Water Resources, Guide to Colo. Well Permits, Water Rights, and Water Admin., Mar. 2006; C.R.S. § 37-90-107(8) (well permitting). The CGWC can define how each specific source within designated borders should be allocated and administered.

Denver Basin ground water is ground water within specific aquifers contained in a large part of the state called the Denver Basin. *Benchbook* at 3-4. Some of the aquifers in the Denver Basin are designated ground water. Designated Denver Basin ground water is

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[9] This map is produced by the Office of the State Engineer and is available at http://www.water.state.co.us/images/DesBasins.pdf. For additional information regarding the locations of the Designated Basins, see http://water.state.co.us/groundwater/basins.asp and http://water.state.co.us/cgwc/DB-GWMgmtDist.htm.

[10] If it is proven that part of a designated basin is hydrologically connected to surface water, that water will be removed from the scheme regulating designated ground water and be subject to the scheme pertaining to tributary water.

bedrock aquifer and allocated based on overlying land ownership. Other designated ground water, alluvial, is allocated based on availability. *Benchbook* at 3-4, 4-3.

The permitting process in designated basins is significantly more involved. In addition, water on the eastern slope, where designated basins are primarily located, is considered largely over-appropriated. *See* footnote 5, *supra*. Further, the irrigation techniques used in eastern Colorado are largely surface or ditch and the types of wells used, when they are used, are estimated to be in the range of only 50 feet deep.[11] For these reasons, we narrowed our analysis in the remaining sections to ground water that is not designated.

b. The Three Primary Issues: Change is Use, Additional Water Rights and Replacement Water

Because hydro-ES will be putting water to a different use, a change of water right (a.k.a. "change of use") must be undertaken for both tributary and nontributary ground water. A change of water right is "a change in the type, place, or time of use, a change in the point of diversion," as well as variations on the point of diversion, means of diversion, and variations of direct application and storage. C.R.S. § 37-92-103(5). An application for a change of water right must be pursued through the water court. The details to be included in such an application are listed in C.R.S. §37-92-302(2).

Changes of water rights, whose purpose is to continue an appropriation in effect under its priority date for another type of use, place of use, or through a different point of diversion, are limited to their historic beneficial consumptive use measured over a representative period of time and cannot be decreed if they will cause injury to other water rights. This is considered a fundamental principle of Colorado water law. *Benchbook* at ix.

A change of use does not affect the priority of a water right. However, in times of shortage, the State Constitution designates the priority of water usage for tributary water; Section 6 of Article XVI sets forth the right to appropriate and preferences of uses:

> …Priority of appropriation shall give the better right as between those using the water for the same purpose; but when the waters of any natural stream are not sufficient for the service of all those desiring the use of the same, those using the water or domestic purposes shall have the preference over those claiming for any other purpose, and those using the water for agricultural purposes shall have preference over those using the same for manufacturing purposes.

No other purpose is mentioned or given special priority in the Constitution. In times of short supply, the water officials must administer water rights in the order of their decreed and Constitutional priority. Therefore, if some of the water used for hydro-ES is not designated

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[11] This is addressed in the engineering section of the Interim Report.

as agricultural (which may include the water necessary to impound for drainage/energy production and any associated evaporation), this water will not enjoy Article XVI protection in times of shortage.

Direct flow rights are typically quantified in terms of flow. When application for change of use is made a historical flow right will typically be turned into a volumetric water right. Volumetric quantifications are based on analysis of historical use and other factors. *See Benchbook* at 2-17.

Although the right to effectuate a change may not be denied by statue and the law expressly favors changes, the change will be approved only if it "will not injuriously affect the owner of or persons entitled to use water under a vested water right or a decreed constitutional water right." C.R.S. § 37-92-305(3). A change to a water right also cannot cause injury to a vested instream flow right or adversely affect the decreed minimum flow for the right. *Benchbook* at 2-16. In this regard return flows would be considered. That is, water from irrigation that seeps back into a water source used by others or even runoff may be considered another party's water right. *Benchbook* at 2-6. So for example, if the agricultural concern fallows a portion of the property for a change of use that will cover evaporation or storage for non-irrigation water requirements of the hydro-ES system, return flow of the prior use would be a consideration in whether to approve the change of use or permit conditions that may be required. Examples of terms and conditions to prevent injuries to other water rights from change proceedings include: 1) relinquishment of part of the decreed amount if necessary to prevent enlargement of historical consumptive use or diminishment of return flows; 2) a season of diversion if necessary to track historical patterns; and 3) any other condition necessary to protect vested rights of other users. C.R.S. § 37-92-305(4); *Benchbook* at 2-16.

Where tributary ground water is being used and the well does not have an associated right sufficient for the desired use, the well will be taking water out-of-priority (because it is too junior in the system). Here, a plan for augmentation must by applied for through the water court. C.R.S. § 37-92-301; *see Empire Lodge Homeowner's Assoc. v. Moyer*, 39 P.3d 1139, 1153 (Colo. 2001). A plan for augmentation prevents injury to senior water rights holders by replacing the water withdrawn in time, place, amount and quality. *Benchbook*, §§ 2.3.2, 3.2.1, 14.6.3. The augmentation plan is designed to protect existing uses of water by replacing the water permitted for a new use. *See Benchbook*, § 14.1.6.

As defined by statute:

> "Plan for augmentation" means a detailed program, which may be either temporary or perpetual in duration, to increase the supply of water available for beneficial use in a division or portion thereof by the development of new or alternate means or points of diversion, by a pooling of water resources, by water exchange projects, by providing substitute supplies of water, by the development of new sources of water, or by any other appropriate means. "Plan for augmentation" does not include the

> salvage of tributary waters by the eradication of phreatophytes, nor does it include the use of tributary water collected from land surfaces that have been made impermeable, thereby increasing the runoff but not adding to the existing supply of tributary water.

§ 37-92-103(9), C.R.S. *See also*, *Benchbook* § 2.3.2.

Nontributary ground water is treated somewhat differently in that the amount of water that can be withdrawn under the permit is the amount determined by the court decree of rights. C.R.S. § 37-90-137(4)(d). This is further discussed below.

Determinations of water rights, changes to water rights, and plans for augmentation of tributary ground water are subject to the WRDA, C.R.S. §§ 37-92-101 to -602, and are thus within the authority of the water referee within a water division. C.R.S. § 37-92-301. Applications for any of these things must be made to the water court. C.R.S. § 37-92-302. Determination of rights for nontributary ground water is also under the jurisdiction of the water judge for the particular district in which the well is located. C.R.S. § 37-92-203(1); *see State Engr. v. Smith Cattle, Inc.*, 780 P.2d 546, 550 n.4 (Colo. 1989). However, while nontributary ground water rights are determined pursuant to the WRDA in C.R.S. Sections 37-92-302 to -305, determinations of such rights must be in accordance with the permit requirements and limitations of C.R.S. section 37-90-107(4) and (5) of the Colorado Ground Water Management Act ("GWMA"). C.R.S. § 37-90-137(6). Essentially, these rights are determined through the same court process as for tributary waters but are subject to specific requirements that relate to underground waters.

It is assumed in this analysis that a permitted well already exists. As a result, the well may already have an augmentation plan associated with it if it does not have rights sufficiently senior so as to not be out-of-priority. An augmentation plan decree includes an identification of the beneficial uses that the plan is augmenting. *Empire Lodge*, 39 P.3d at 1150–51. It likely follows then that where the augmented beneficial uses change, some sort of notification, application, or amendment needs to be made to the water court. It is possible to have more than one plan for augmentation on a well at one time. *Id.* Having a separate plan preserves the original use in case the new use ceases sometime in the future. *Id.* Therefore, the water right holder may opt not to change an existing augmentation plan and to instead develop a new and separate plan. Email from Dick Wolfe, Assistant State Eng'r, July 1, 2007 (on file with authors).

Nontributary water does not have the same difficulties of replacing out-of-priority depletions because it is not governed by prior appropriation. As a result, it is considered "developed water" (the phrase normally refers to water imported from another basin) and can be used and reused by the appropriator. *Benchbook*, *supra* at § 3.2.3. Instead of by prior appropriation, it is allotted based on overlying land ownership. *Id.* Permitted withdrawal is based on an arbitrary determination that the aquifer life is 100 years and one percent of the total amount in the aquifer under the owner's property is allowed to be withdrawn each year. *Id.* Another benefit to having and using nontributary ground water is that the landowner can "bank" his supply of ground water, saving any unused allotment for use in future years. *Id.*

Another question that arises is whether a storage right must be obtained for the surface impoundment. Because hydro-ES will be utilizing the water by storing in the surface impoundment for later use rather than putting it directly to use (such as for irrigation), it may be that a storage right is necessary. *City & County of Denver v. N. Colo. Water Conservancy Dist.*, 27 P.2d 992, 999 (1954). However, if the plan for augmentation or the change of water right, or both, clearly describe the process to be used and clearly accounts for all losses (like evaporation and seepage), one likely does not need to file for a storage right. Email, Wolfe, *supra*.

When returning water to the underground source, the quality of the water being "reinjected" must also meet some legal requirements, addressed in section 4 below. These requirements are not insignificant and the outcome will be largely impacted by the type of impoundment.

c. Well Permitting

We presume in this analysis that the agricultural concern implementing this system already has a permitted well that includes the right to pump water from the underground source for the necessary irrigation. Well permits are required for the construction of a new well. *See* C.R.S. § 37-90-137 (referring to well permits in the context of construction of new wells). Changes of use, then, would refer only to the water right, and remain the province of the water courts in an adjudication for the change of a water right. However, if the equipment in a well is changed, such as that required for the hydro-ES system, it appears that, a new well permit must be obtained.

The Water Well Construction Rules provide:

> 6.2 Permit Requirement - A permit issued by the State Engineer is required prior to constructing a new well and prior to the repair, replacement, or modification of an existing well. See Sections 37-90-105(3)(a)(I), 37-90-108(1)(a), 37-90-137(1), 37-90-138(3), and 37-92-602(3)(a) C.R.S.).
>
> 6.2.1 The State Engineer requires that a new well permit be obtained prior to:
>
> a. changing the producing interval of an existing well,
>
> b. installing certain dewatering systems as specified by the State Engineer,
>
> c. installing pumping equipment that will withdraw ground water for beneficial use, or
>
> d. installing pumping equipment having a sustained production rate in excess of the permitted production rate.

> The extraction of casing or pumping equipment for the purpose of repair or replacement does not require a new permit if the interval of perforated casing is not altered and the production rate does not exceed the rate specified on the existing valid well permit.

C.C.R. 402-2-6.2 and 6.2.1.[12] It is likely that more than one of the four different contexts in which a new well permit is required will exist for the hydro-ES equipment.

Further, there may be well construction requirements, pursuant to federal laws and regulations applicable to reinjection of water into underground sources. Again, the hydro-ES system is not specifically contemplated by the Safe Drinking Water Act (SDWA). However, when aquifer recharge and ASR wells inject water into an aquifer, it is important that they be constructed of materials that cannot rust, so that rust materials are not injected into the aquifer. Power, 1992 and Pyne, 1995. The relevant SDWA provisions and associated regulations are addressed below.

d. Enforcement

The available enforcement measures may introduce additional costs to the system. With respect to wells and ground water, the State Engineer has enforcement authority (along with the CGWC) of the regulations under the GWMA. C.R.S. § 37-90-110; *Jackson v. Colorado*, 294 F.Supp. 1065 (D. Colo. 1968). For the administration and enforcement of the GWMA, the State Engineer can impose certain physical construction requirements for wells, such as valves for flow control; go upon public or private land for inspection of wells, related components, and measuring devices; order cessation of the use of a well while a defect is fixed; commence actions to enjoin illegal activities or join proceedings that implicate the depletion of ground water resources. *Id.* More broadly, the State Engineer is empowered to "take such action as may be required to enforce compliance with any regulation, control, or order promulgated pursuant to the provisions of this article." C.R.S. § 37-90-110(f); *see also* C.R.S. § 37-90-138(2).

Under the WRDA for waters governed by prior appropriation, the State Engineer and division engineers have near exclusive jurisdiction over the administration, distribution, and regulation of the waters of the state. C.R.S. § 37-92-501(1). To this end, they may issue orders to water rights owners and users to curtail non-beneficial use, to release illegally or improperly stored water, to install and maintain metering devices, and to report readings of metering devices, among other things. C.R.S. § 37-92-502(2)-(5)(a). They may also order those supplying energy to pump ground water to provide records of the energy used. C.R.S. § 37-92-502(5)(b). In addition, they have the authority and the duty to go upon private lands for related inspections. C.R.S. § 37-92-502(6).

When there is noncompliance with any orders by the State Engineer or division engineer, they may, through the attorney general, seek an injunction against the person violating

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[12] *Available at* http://www.sos.state.co.us/CCR/Welcome.do.

the order. C.R.S. § 37-92-503(1)(a). There are also fines involved for improper diversion of ground water, failure to report or falsification of required data, and for willful interference or destruction of measuring devices. C.R.S. § 37-92-503(6).

e. Test Site: Special Provisions for Temporary Use or Change of Use

For tributary waters which are subject to prior appropriation and thus are governed by the Water Rights and Determination Act of 1969 (WRDA), C.R.S. sections 37-92-101 to -602, obtaining approval to perform a one-time pumped hydro test is governed by C.R.S. section 37-92-308(5).[13] This provision allows for a new out-of-priority diversion and a change of water right to be approved by the state engineer if the depletions associated with the change are temporary and will not exceed five years. *Id.* These plans (for a water use involving a new out-of-priority diversion or change of water right) are called "substitute supply plans." *See id.* It is possible that both a plan for augmentation (for the out-of-priority diversion) and a change of water right will need to occur for this to go forward. Phone conversation, Wolfe, *supra*. However, there are conditions for the applicant to meet.

(1) An application must be filed: Form GWS-45, *available at* http://water.state.co.us/pubs/forms/gws-45.pdf.
(2) The applicant must notify the parties listed on the relevant notification list.
(3) The notified parties are given thirty days to comment on the plan, including claims of injury.
(4) The state engineer considers all comments, determines sufficient time, place, and amount replacements will take place and will prevent injury to other rights, including water quality.
(5) A plan under this rule cannot be approved for longer than one year, but may be renewed yearly for up to five years.

C.R.S. § 27-92-308(5)(a)(I)–(IV); *see* Policy 2003-2 Implementation of Section 37-92-308, C.R.S. (2003) Regarding Substitute Water Supply Plans, ¶ 15 and Attachment, *available at* http://water.state.co.us/pubs/policies/policy2003-2.pdf (contains detailed descriptions of permit requirements). On average, applications of this nature can take 60 to 90 days from the filing of the application to the issuance of the temporary permit. Phone conversation, Dick Wolfe, Assistant State Eng'r, May 17, 2007. This process can be shortened slightly by proactively contacting each of the potentially affected parties that are notified in the process. One can seek to speed up their response process by asking them to comment sooner or make a statement that they do not plan to comment. Engineers or lawyers experienced with the process generally complete such applications and assist with the process, although a lawyer is likely not necessary for this unless a party submits a comment objecting to the proposal or raises other concerns.

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[13] *Available at* http://198.187.128.12/colorado/lpext.dll?f=templates&fn=fs-main.htm&2.0.

4. Water Quality: Draining Water Back into the Underground Source

The drainage of water from the surface impoundment down to the underground source, or aquifer, implicates laws and regulations regarding water quality. There are both federal and state laws and regulations that apply. Class V injection well requirements under the federal Safe Drinking Water Act (SDWA) will apply. The Underground Injection Control (UIC) program is implemented directly by Regions 8 of the U.S. Environmental Protection Agency (US EPA) in Colorado. Although a permit is not required, there are informational requirements, and these requirements are not necessarily negligible. In addition, the state water courts, in adjudicating augmentation plans, have adopted a standard that protects water rights of other users that includes both quality and quantity of water, (i.e., "shall be of a quality and quantity so as to meet the requirements for which the water of the senior appropriator has normally been used."). Finally, the WQCC has adopted basic standards for ground water. For those waters not currently covered by a site-specific standard, the rule is to protect the existing quality of ground water. *Benchbook* at 8-5. The Water Quality Control Division (WQCD), is the division of the Colorado Department of Public Health and Environment (CDPHE) that carries out discharge permitting and enforcement, however, EPA Class V injection wells are exempt from Division permitting. 5 CCR 1002-61.141(1)(b)(iiv). A full discussion of these water quality standards follows.

a. US EPA and Class V Injection Well Requirements.

Underground injection is the technology of placing fluids underground through wells.[14] Because of ground water contamination occurrences in the 1960-1970s as a result of underground injection, Congress passed the Safe Drinking Water Act (SDWA) in 1974 which required the US EPA to establish a system of regulations for injection activities. 42 U.S.C. §§ 300h to 300h-8 (Part C of the SDWA). The regulations are designed to establish minimum requirements for controlling all injection activities and provide mechanisms for implementation and authorization of enforcement authority and also provide protection for underground sources of drinking water. *Id.*

Historically, the SDWA has applied to water returned to an underground source through aquifer recharge or aquifer storage recovery (ASR) wells. However, based on the definition of "well" and the lack of any applicable exclusion, it appears that this Act would apply to the hydro-ES system contemplated here as a Class V well. The Underground Injection Control (UIC) program defines a well as any bored, drilled or

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[14] While underground rock formations may appear to be solid, most formations contain voids or pores that allow fluids to fill or move through the pores. Man-made or produced fluids can move into the pores of rocks through the use pumps and existing gravity.

driven shaft or a dug hole, where the depth is greater than the largest surface dimension that is used to discharge fluids underground. See 40 C.F.R. §144.1(g)(1)(ii).

The general provisions of Part 144 of the UIC regulations state that the "SDWA provides that all underground injections ...are unlawful and subject to penalties unless authorized by a permit or a rule." 40 C.F.R. §144.1(e). The regulations apply to "any dug hole or well that is deeper than its largest surface dimension, where the principal function of the hole is emplacement of fluids." 40 C.F.R. §144.1(g)(1)(ii) (defining regulated wells). This definition covers a variety of injection practices from sophisticated wells that inject more than two miles underground to many types of on-site drainage systems, such as septic systems, cesspools and storm water wells that discharge to a few feet underground. *See* 42 U.S.C. §300h. The regulations could have, but did not, state that for the regulations to be applicable, an underground source of drinking water (USDW) had to be present. Under the section that lists wells specifically excluded from regulation, there is no exclusion for wells located in an area where no USDW exists. *See* 40 C.F.R. Section 144(g)(2). The decision to deliberately subject all underground injection wells to regulation is repeated in Subpart B, General Program Requirements of Part 144: "Any underground injection, except into a well authorized by rule or except as authorized by permit ... is prohibited." 50 C.F.R. §144.11.

Wells are classified into five categories in Part 146 of the regulations, which contains the criteria and standards for the injection control program. 40 C.F.R. § 146.5. Drainage from the hydro-ES system falls under Class V:[15]

> **Class V:** This category includes any well that is not included in the above categories. Including, but not limited to: air conditioning return flow wells, cesspools, drainage wells, recharge wells, salt water intrusion barrier wells, septic system for a multiple dwelling, subsidence control wells, and spent brine disposal wells among others. There is no need to have proximity to USDW, as it is not specified. 40 C.F.R. § 146.5(b)(5).

In Colorado, USEPA Region 8 directly implements the UIC program for Class V injection wells. However, Colorado also has additional jurisdiction over aquifer recharge and ASR wells through permitting of extraction and use of waters artificially recharged. Ground water Law Sourcebook of the Western United States, available at http://www.colorado.edu/Law/centers/nrlc/publications/.

Injections of fluids without regulation could potentially contaminate ground water and drinking water sources. Because the contamination of ground water would be very difficult to remediate, it is important to ensure that contaminants do not enter the ground water in the first place. Under 40 CFR §144.12(a), owners or operators of all injection wells, including aquifer recharge and ASR wells, are prohibited from engaging in any injection

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[15] A description of the other classes, Class I-IV can be found at 40 C.F.R. §146.5(b)(1)-(4).

activity that allows the movement of fluids containing any contaminant into USDW's, "if the presence of that contaminant may cause a violation of any primary drinking water regulation…or may otherwise adversely affect the health of persons." 40 CFR § 144.12(a).

To comply the owner or operator of a Class V well is required to submit basic inventory information and is required to operate the well such that a USDW is not endangered. 40 CFR § 144.12(a). In addition, the US EPA under section 144.27 may require the owner or operator to submit additional information deemed necessary to protect USDW's. If an owner or operator fails to submit the information required under sections 144.26 and 144.27, they would be prohibited from using their wells. Depending on the type of well and the additional data that the Region 8 Director requests using his/her discretionary authority, the information required to legally reinject water will not necessarily be negligible. Copies of Regulation 144.26 and 144.27 are attached, as well as, the information required by the Region 8 Director for Class V injection wells used for aquifer recharge or ASR[16]. See Attachment B.

For wells not in compliance with Section 144.12(a), Sections 144.12(c) and (d) provide mandatory and discretionary actions to be taken by the UIC Program Director. The Director must choose between requiring an individual permit, ordering well closure or taking an enforcement action. Of great interest to this project is that because ASR and aquifer recharge wells are authorized by rule, they do not have to obtain a permit unless required to do so by the UIC Program Director under 40 CFR §144.25. Authorization by rule is terminated on the date of a permit issued or upon closure of the well. 40 CFR §144.25.

b. State Water Quality Standards

On the state level, water quality in Colorado is regulated through a 'dual system.' *City of Thornton v. Bijou Irr. Co.*, 926 P.2d 1, 92 (1996). The water courts and the Water Quality Control Commission (WQCC) created by the Water Quality Control Act (WQCA) both have authority with respect to water quality, but their authorities do not overlap. Additionally, the State Engineer is the relevant agency in the hydro-ES setting which both implements the WQCC's regulations and also has some of its own authority with respect to water quality. This dual system limits both water courts and the WQCC in their authorities with respect to water quality issues. This result unfortunately leaves some gap where issues may not be addressable by either the court or the agency. *See Concerning the Application for Plan for Augmentation of the City and County of Denver*, 44 P.3d 1019 (Colo. 2002) [hereinafter *Denver Application*].

The WQCA was enacted in response to the federal Clean Water Act. The WQCA created the WQCC, which has general authority to regulate Colorado water quality issues. §§ 25-

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[16] The *Site Information Request Fact Sheet Class V Underground Injection Control: Aquifer Recharge and Aquifer Storage and Recovery Wells* included in this attachment is available at the US EPA Region 8 website, www.epa.gov/region8/water/uic/FSASR.pdf.

8-201, -202, C.R.S.; *see Denver Application*, 44 P.3d at 1029. Water quality regulations by the WQCC that affect water rights are not prohibited as long as they do not cause material injury or impairment to the rights. *City of Thornton*, 926 P.2d at 92. Thus, the regulations cannot compromise appropriative rights. The Water Quality Control Division, (WQCD), a division of the Colorado Department of Public Health and Environment (CDPHE), carries out the WQCC's regulations. However, in the context of reinjection, or drainage, of water in the hydro-ES system, the WQCD's role is likely limited to an advisory capacity, as discussed below.

The WQCA designates the State Engineer as an implementing agency with responsibility for implementing the WQCC's standards and regulations. C.R.S. § 25-8-202(7) ("SB 89-181"). Where activities under the jurisdiction of the State Engineer result in discharges subject to the Act, the WQCC develops the water quality standards and classifications, but the State Engineer implements them in their own programs after consulting with the WQCC and the WQCD. C.R.S. § 25-8-202(7).[17] Although the WQCD has the sole responsibility for issuing and enforcing permits for point source discharges, EPA Class V injection wells are exempt from WQCD permitting. 5 CFR 1002-61.14(1)(b)(iiv).

The WQCC has adopted the Basic Standards for Ground Water to establish statewide water quality standards for radioactive materials and organic chemicals in ground water. This regulation also establishes site-specific ground water quality classifications and standards for particular areas, primarily to protect water quality in municipal well fields. Finally, this regulation creates an interim narrative standard to protect the existing quality of ground water until site-specific classifications and standards can be established. *Benchbook* at 8-5. Water sources under consideration for hydro-ES will likely be under the standard to protect existing quality.

The WQCC is limited to addressing water quality impacts that result from discharge of pollutants as opposed to diversion (withdrawals). *Colorado Wild, Inc. v. U.S. Forest Serv.*, 122 F.Supp.2d 1190, 1192 (D. Colo. 2000). As a result, the WQCA is specifically focused upon regulating the discharge of pollution, and the conclusion has been drawn that water quality standards apply only to discharges of pollution, not withdrawals or

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[17] In order to further the working relationship between the three entities, the WQCC, the WQCD, the State Engineer, and the Department of Natural Resources, entered into a Memorandum of Agreement ("MOA") to formalize the previous informal cooperative working relationships between the agencies and to provide procedures for communication, exchange of information, and resolution of problems. Memorandum of Agreement for the Implementation of SB 181 Amendments to the Colo. Water Quality Control Act (25-8-101, *et seq*), Aug. 30, 1990, *available at* http://www.cdphe.state.co.us/op/wqcc/SB181/moaseo.pdf. As a result the State Engineer and the WQCD work closely together on issues, especially those that do not clearly fall under a particular law or regulation. *See also*, SB 89-181 (requiring same).

appropriations of water. *Id.* at 1193. Therefore, it is not clear how the Basic Standards would be applied, or how compliance would be enforced in the hydro-ES setting.

The second 'system' in Colorado's dual system governing water quality is the court system. While the majority of water quality issues are delegated to the WQCC, *Denver Application*, 44 P.3d 1019, water courts still retain exclusive authority with respect to the determination and administration of water rights, C.R.S. § 25-8-104(1). Thus, water courts still have the control to assess injury to water rights in augmentation plan proceedings. *Denver Application*, 44 P.3d at 1029. Typically, the water courts' primary area of focus with respect to injury is generally water quantity as it affects other appropriations. *Bijou*, 926 P.2d at 92. However, water quality has been protected "to the extent necessary to preserve the water's sustainability for the uses of appropriators." *Denver Application*, 44 P.3d at 1028. Thus, if the change in quality of the water does not affect the use that the downstream appropriators are entitled to, then there is no pollution and no injury with respect to the augmentation plan or reinjection of water. *Id.*

In its decrees, the water court can delegate authority to the State Engineer to make quality determinations of the substituted water that are consistent with the statutes and regulations governing water quality. *City of Thornton v. Bijou Irr. Co.*, 926 P.2d 1, 97 (1996). Thus, by statute, the State Engineer must assure that "[a]ny substituted water shall be of a quality and continuity to meet the requirements of use to which the senior appropriation has normally been put." C.R.S. § 37-80-120(3).

Again, Hydro-ES is not a use contemplated by the regulatory scheme. However, water return is contemplated through augmentation plans and the standards applied in those adjudications are instructive. Augmentation plans are approved by the water court "if such change, contract, or plan will not injuriously affect the owner of or persons entitled to use water." C.R.S. § 37-92-305(3). "Any substituted water shall be of a quality and quantity so as to meet the requirements for which the water of the senior appropriator has normally been used." C.R.S. § 37-92-305(5). Thus, "when no unappropriated water is available, augmentation plans permit junior water right holders to divert water out-of-priority while ensuring the protection of senior water right holders." *Denver Application*.

This leaves the question of how a water court would determine whether the quality of the planned augmentation will be sufficient so as not to harm potentially affected senior appropriators. Water court findings appear to be based heavily upon the factual determinations of each case. This would include assessing the downstream uses and the quality necessary to maintain those uses. And there could potentially be significant research and engineering reports about the movement of the water underground in the specific situation.

The Colorado Supreme Court recently addressed water quality in the similar situation of recharging water for the purposes of storage. *Bd. of County Comm'rs v. Park County Sportsmen's Ranch, LLP*, 45 P.3d 693, 717 (Colo. 2002). Injected water is considered augmentation water when it is used to replace out-of-priority depletions, but it is stored water when impounded and reserved solely for the party that placed the water there. *Id.* (Kourlis, J., specially concurring and dissenting in part). Despite this difference, both uses involve "basic tenets of Colorado water law." *Id.* at 704. Based upon these tenets, the Court in *Board of County Commissioners* determined that an applicant to store water through artificial recharge would have to meet certain specified conditions. *Id.* at 705. One of the criteria the court specified is that the applicant "must not injure water use rights, either surface or underground, as a result of recharging the aquifer and storing water in it." Quality, as discussed above, is contemplated in the court's injury determination. It would seem to follow that in the case of recharge for augmentation, or drainage, the same quality assessment would need to be performed.[18]

c. Meeting the Standards

The key issue will be what changes occur to the water while it is impounded and whether it will introduce "pollutants" into the underground source when it is drained, or reinjected, back down. This in turn will depend on a number of factors, for example: the length of time the water remains stagnant in the impoundment; composition of material the impoundment is made of; the height of the barrier and whether it permits runoff to enter; whether the surface of the impoundment is closed or open; what kind of airborne pollutants are in the area; and if the water is filtered before reinjection. The type of impoundment will also affect the amount of water necessary to implement the hydro-ES system, (i.e., the evaporation rate). Unlined surface ponds inevitably lose water to under ground seepage and exposed surface area evaporation. The amount of seepage is a function of the soil type and can be relatively high in coarse or sandy soils found on the eastern plains. *Benchbook* at 6-7. Therefore, the cost of compliance with water quality standards would need to be assessed on a case by case basis.

5. Conclusions

Some generalities can be made about site preferences for the hydro-ES system. Designated basins, for a number of reasons, will probably not be advantageous sites for implementation of the system. These reasons include: the depth of wells associated with designated basins are typically too shallow for the necessary head; these are typically over-appropriated water sources; and there is a more involved permitting process. Between tributary and nontributary sources, nontributary sources appear to be more advantageous because of the manner in which water rights are allocated and the

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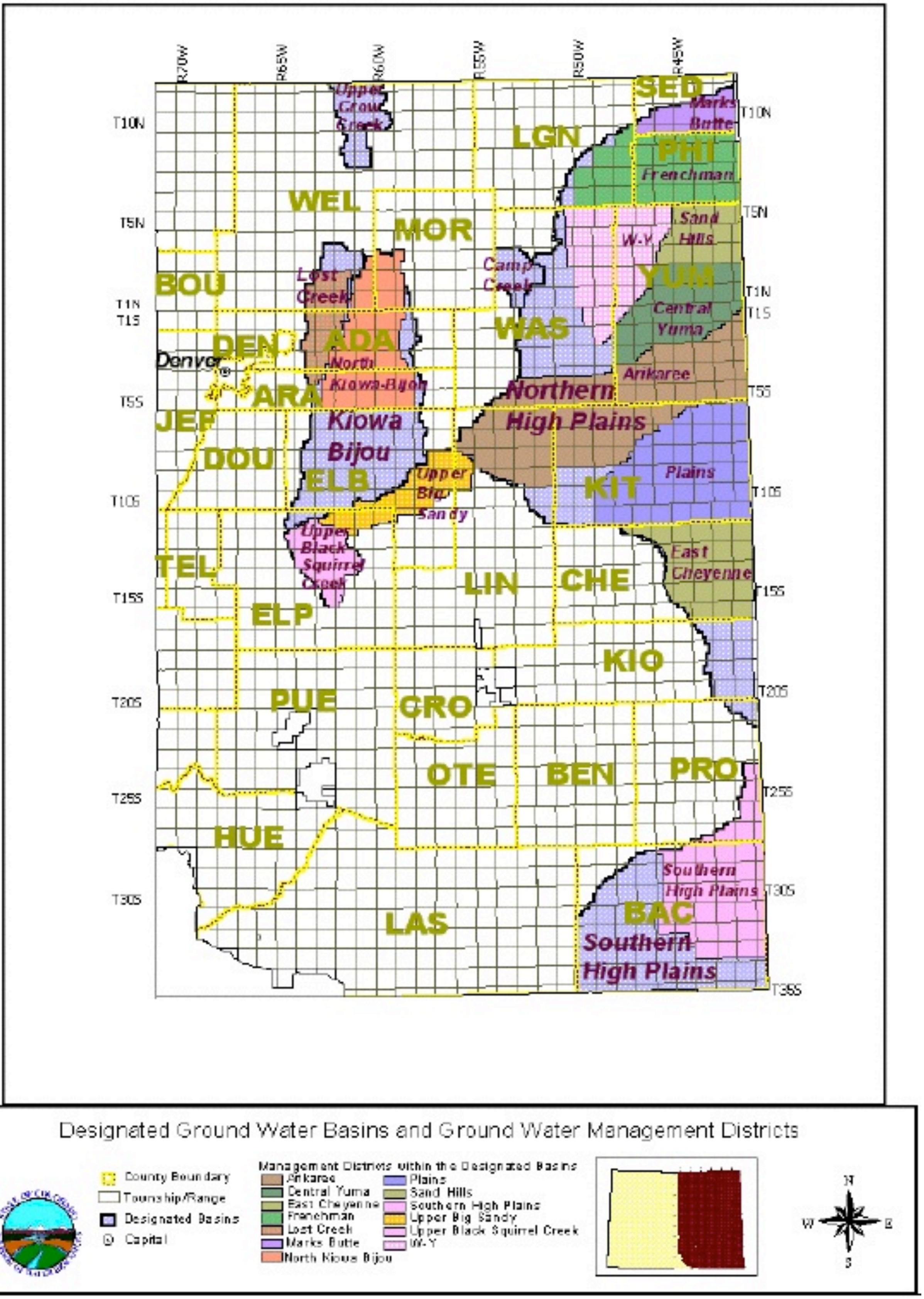
[18] While case law primarily deals with augmentation water returned to the stream, *see Denver Application*, 44 P.3d 1019, C.R.S. section 37-92-305(5) does not appear to contemplate different treatment for tributary ground water and tributary surface water. Furthermore, a purpose of the WRDA was to treat all tributary waters, both surface and ground water, under the same prior appropriation system. *See C.R.S.* § 37-92-102(1)(a).

accounting mechanism for water uses. In addition, wells for nontributary water sources will usually be deeper. However, for testing purposes, substitute supply plans (SSP) are an option for tributary water sources. The SSP provides an expedited permitting process for temporary projects that meet certain criteria.

However, as pointed out in this chapter, these conclusions are generalities and much of the final assessment will depend on the specific characteristics of a particular site, especially in regard to water quality issues. As the engineering team becomes more certain about a specific site for testing and/or implementation of the system, additional legal research will, in all likelihood, be necessary.

Finally, throughout the chapter an attempt was made to include the policies and rationales behind various regulations, laws and standards. This information is intended to provide a framework for the consideration of potential changes to the current regulations and laws to accommodate this novel approach to energy generation.

Attachment A



Designated Ground Water Basins and Ground Water Management Districts

Attachment B1

C

➡§ 144.26 Inventory requirements.

The owner or operator of an injection well which is authorized by rule under this subpart shall submit inventory information to the Director. Such an owner or operator is prohibited from injecting into the well upon failure to submit inventory information for the well within the time frame specified in paragraph (d) of this section.

(a) Contents. As part of the inventory, the Director shall require and the owner/operator shall provide at least the following information:

(1) Facility name and location;

(2) Name and address of legal contact;

(3) Ownership of facility;

(4) Nature and type of injection wells; and

(5) Operating status of injection wells.

Note: This information is requested on national form "Inventory of Injection Wells," OMB No. 158-R0170.

(b) Additional contents. For EPA administered programs only, the owner or operator of a well listed in paragraph (b)(1) of this section shall provide the information listed in paragraph (b)(2) of this section.

(1) This section applies to the following wells:

(i) Class II enhanced recovery wells;

(ii) Class IV wells;

(iii) The following Class V wells:

(A) Sand or other backfill wells [§ 146.5(e)(8)];

(B) Radioactive waste disposal wells that are not Class I wells (40 CFR 146.5 (e)(11))

(C) Geothermal energy recovery wells [§ 146.5(e)(12)];

(D) Brine return flow wells [§ 146.5(e)(14)];

(E) Wells used in experimental technologies [§ 146.5(e)(15)];

(F) Municipal and industrial disposal wells other than Class I; and

(G) Any other Class V wells at the discretion of the Regional Administrator.

(2) The owner or operator of a well listed in paragraph (b)(1) shall provide a listing of all wells owned or operated setting forth the following information for each well. (A single description of wells at a single facility with substantially the same characteristics is acceptable).

(i) For Class II only, the field name(s);

(ii) Location of each well or project given by Township, Range, Section, and Quarter-Section, or by latitude and longitude to the nearest second, according to the conventional practice in the State;

(iii) Date of completion of each well;

(iv) Identification and depth of the formation(s) into which each well is injecting;

(v) Total depth of each well;

(vi) Casing and cementing record, tubing size, and depth of packer;

(vii) Nature of the injected fluids;

(viii) Average and maximum injection pressure at the wellhead;

(ix) Average and maximum injection rate; and

(x) Date of the last mechanical integrity test, if any.

(c) Notice. Upon approval of the UIC Program in a State, the Director shall notify owners or operators of injection wells of their duty to submit inventory information. The method of notification selected by the Director must assure that the owners or operators will be made aware of the inventory requirement.

(d) Deadlines.

(1) The owner or operator of an injection well shall submit inventory information no later than one year after the date of approval or effective date of the UIC program for the State. The Director need not require inventory information from any facility with interim status under RCRA.

(2) For EPA administered programs the information need not be submitted if a complete permit application is submitted within one year of the effective data of the UIC program. The owner or operator of Class IV well shall submit inventory information no later than 60 days after the effective date of the program.

Attachment B2

➡§ 144.27 Requiring other information.

(a) For EPA administered programs only, in addition to the inventory requirements of § 144.26, the Regional Administrator may require the owner or operator of any well authorized by rule under this subpart to submit information as deemed necessary by the Regional Administrator to determine whether a well may be endangering an underground source of drinking water in violation of § 144.12 of this Part.

(b) Such information requirements may include, but are not limited to:

(1) Performance of ground-water monitoring and the periodic submission of reports of such monitoring;

(2) An analysis of injected fluids, including periodic submission of such analyses; and

(3) A description of the geologic strata through and into which injection is taking place.

(c) Any request for information under this section shall be made in writing, and include a brief statement of the reasons for requiring the information. An owner or operator shall submit the information within the time period(s) provided in the notice.

(d) An owner or operator of an injection well authorized by rule under this subpart is prohibited from injecting into the well upon failure of the owner or operator to comply with a request for information within the time period(s) specified by the Director pursuant to paragraph (c) of this section. An owner or operator of a well prohibited from injection under this section shall not resume injection except under a permit issued pursuant to §§ 144.25, 144.31, 144.33 or 144.34.

Attachment B3

EPA

Site Information Request Fact Sheet
Class V Underground Injection Control

Aquifer Recharge and Aquifer Storage and Recovery Wells

The Underground Injection Control (UIC) Program, created under the authority of the Safe Drinking Water Act (SDWA), is a preventative program aimed at protecting existing and future underground sources of drinking water (USDWs). Shallow wells or disposal systems that discharge fluids into the subsurface are known as Class V wells and can be authorized to inject by rule or permit. Class V wells that have the potential for ground water contamination or degradation are usually permitted. Those that do not have a potential to contribute to contamination or degradation of ground water are usually rule authorized, once inventory information has been submitted according to the requirements of 40 CFR 144.26. In addition to the inventory requirements, EPA may, under the authority of 144.27, require the owner or operator of any well authorized by rule to submit additional information to determine if injection activity could endanger a USDW.

Aquifer recharge and Aquifer Storage and Recovery (ASR) wells are Class V wells used to inject water into an aquifer for subsequent use. An aquifer recharge well is used only for injection to replenish the water in an aquifer; an ASR well is used for injection to store water in the aquifer, then to recover the stored water from the same well for a beneficial use.

The following information is needed to evaluate the impact a Class V injection well used for aquifer recharge or ASR will have on the local hydrogeologic system, potential for USDW contamination, and whether a **permit** for this operation, rather than a **rule authorization**, should be required.

Please provide the following information to EPA:

- ☐ Property owner of facility including a physical and mailing address; phone and fax numbers.
- ☐ Operator of facility including a physical an mailing address; phone and fax numbers.
- ☐ Responsible party for the operation, maintenance, and closure of the injection system including a physical and mailing address; phone and fax numbers.
- ☐ Contact persons representing any other regulatory agencies that have an interest in the site; include a physical and mailing address and phone number.
- ☐ Describe the project plan, including
  - ☐ source of injectate,
  - ☐ injection procedures, injection rate, volume and pressure
  - ☐ intended receiving formation,
  - ☐ hydrologeology of the area.
  - ☐ overlying and underlying aquifers that could be impacted,
  - ☐ the effect of injection activities on these aquifers,
  - ☐ public and private wells within 1 mile of the project area,
  - ☐ whether wells are completed in the intended receiving formation, and
  - ☐ the effect of injection activities on these wells.

Aquifer Underground Pumped Hydroelectric Energy Storage for Agriculture

September 30, 2007

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Table Of Contents

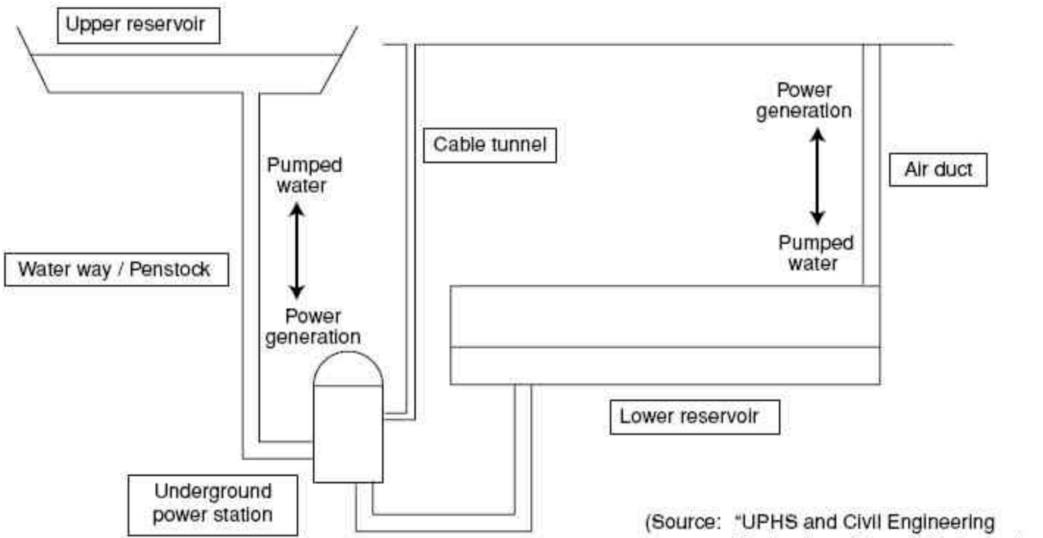
1 Introduction to UPHS

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.



(Source: "UPHS and Civil Engineering Technology: Current Status and Technical Challenges" by the Japan Society of Civil Engineers)

Figure 1: Conceptual Diagram of UPHS System

2 Overview of 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.

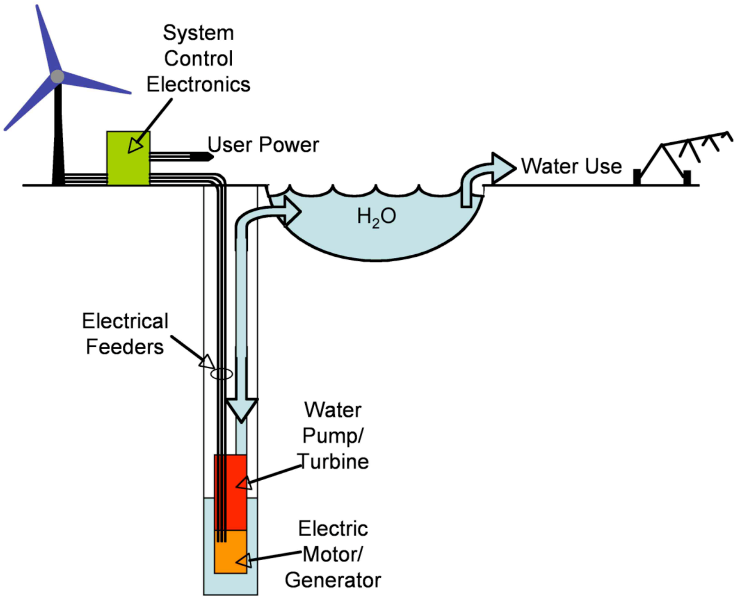


Figure 2: Aquifer UPHS System Diagram

Figure 2 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. This section provides information on the overall irrigation resource in Colorado. It also provides some concepts for advanced well completion techniques proposed to enhance the performance of this system. Figure 3 shows a satellite image depicting the prevalence of center-pivot irrigation activity in Colorado's San Luis Valley.

This modified Landsat photo illustrates the magnitude of center-pivot irrigation in the central portion of the valley.

Figure 3: Satellite Photo Highlighting Crop Irrigation Circles in the San Luis Valley [1]

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 4 shows the irrigation water sources for Colorado counties.

Well and water table depths and yields in the San Luis Valley region vary greatly. 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…"*

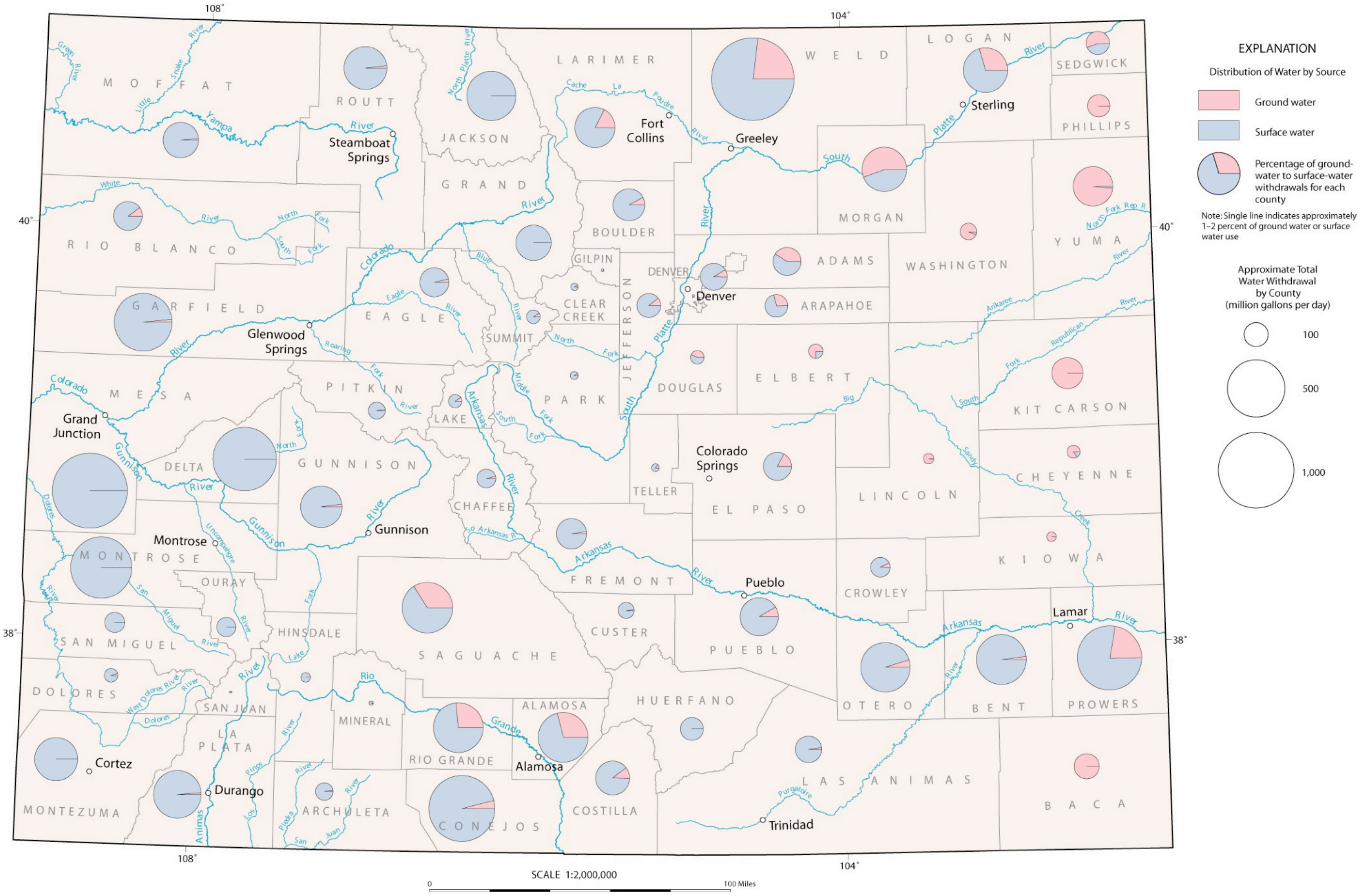


Figure 4: Irrigation Water Sources in Colorado [1]

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.

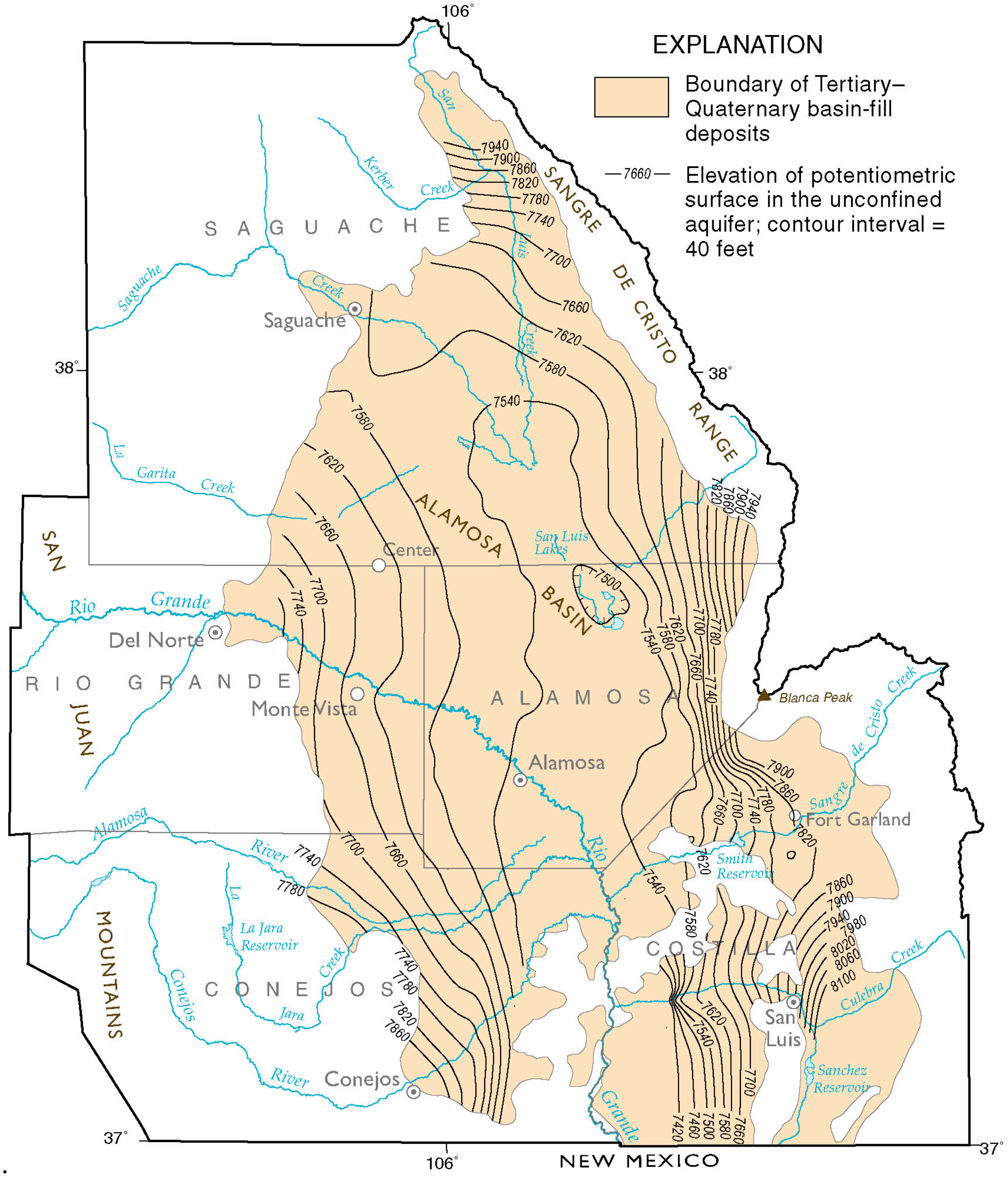


Figure 5: Water Table Elevation of Unconfined Aquifer of the San Luis Valley [1]

The water table elevations across the San Luis Valley Basin are shown in Figure 5. 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 8), while the least favorable site may only yield about 10 kW (200 gpm at 100 feet, see Figure 8). The technical considerations of these well characteristics are covered in section 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 6 and 7 are taken from this report, and they show some options for modified wells to increase the recharge flow capacity.

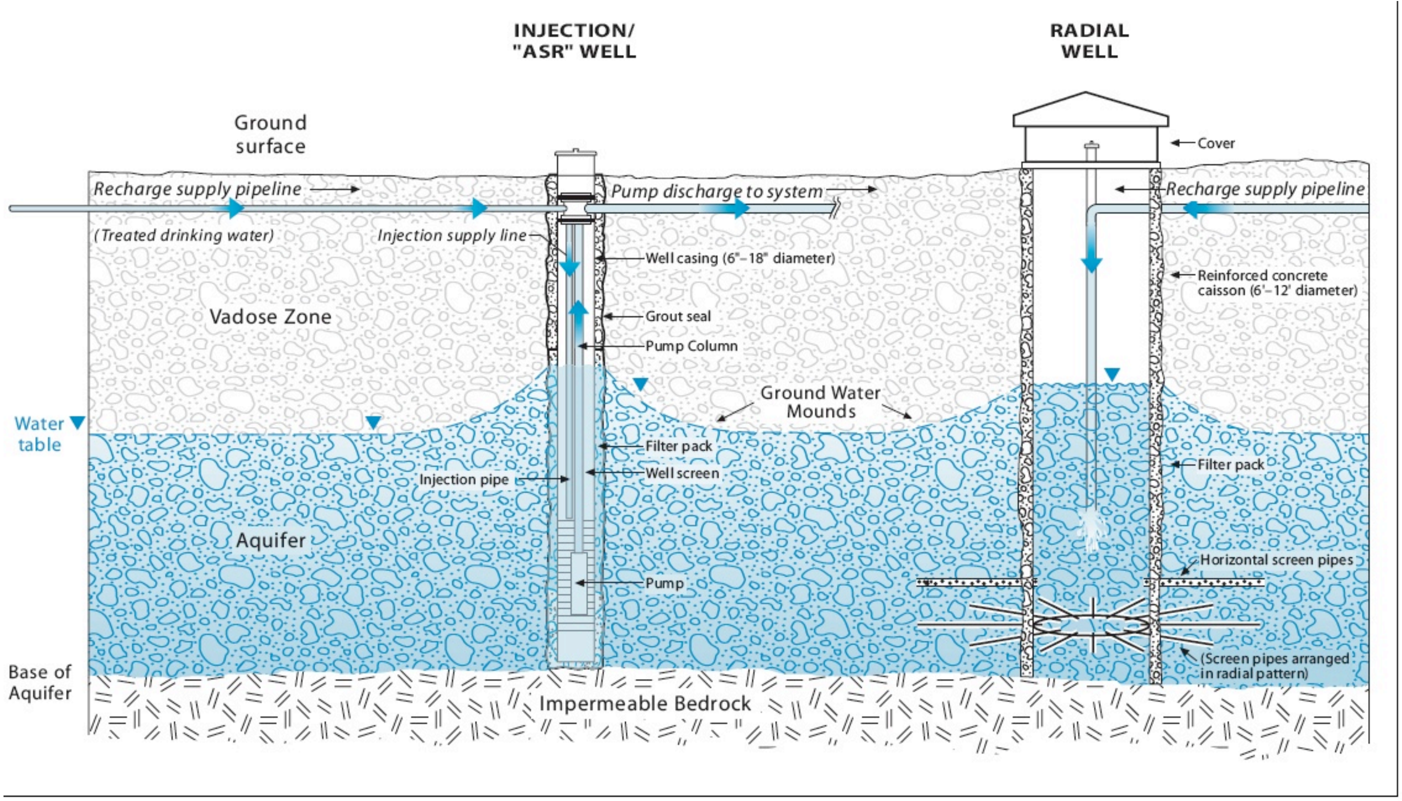
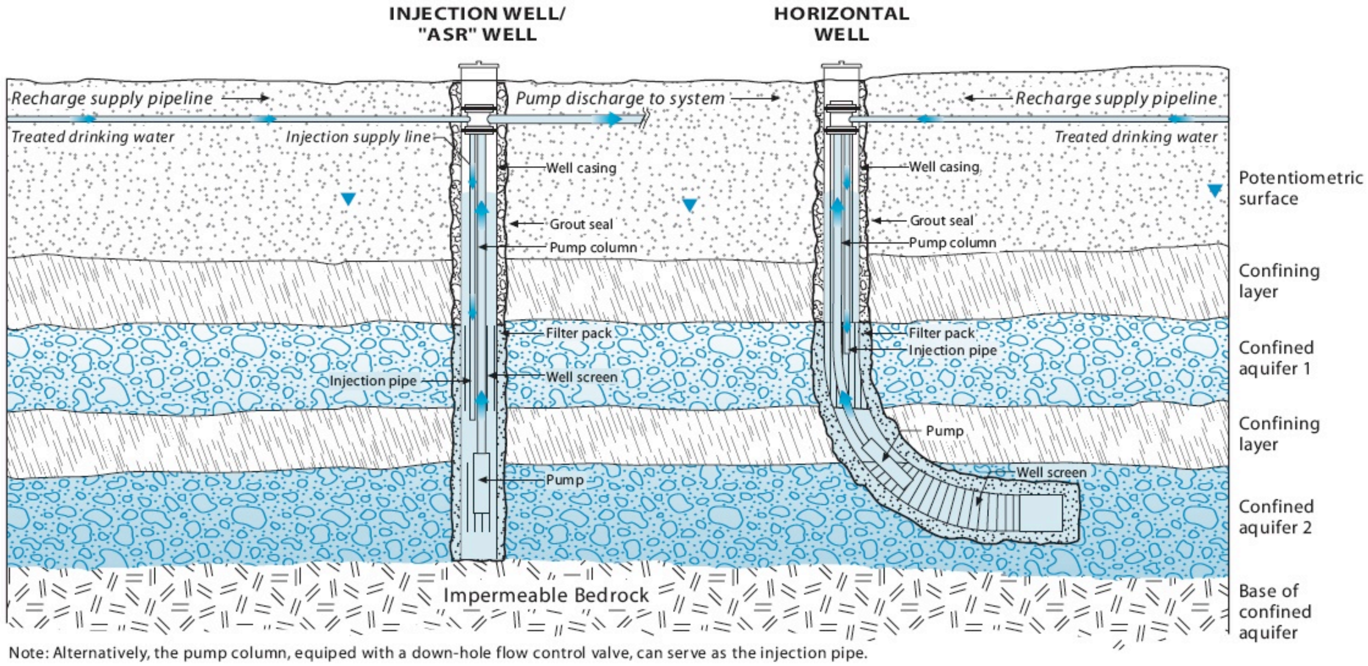


Figure IV-3. **Direct injection in an unconfined aquifer. Water for recharge is injected through a well directly into the saturated aquifer raising the water table in a conical mound around the well. The well can also be used for recovery of the injected water as an ASR well. Injection can use a dedicated 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.**

Figure 6: Direct Injection Radial Unconfined Aquifer Well Concept



Note: Alternatively, the pump column, equiped with a down-hole flow control valve, can serve as the injection pipe.

Figure IV-4. **Direct injection in a confined aquifer. Water for recharge is injected through a well directly into a confined aquifer raising the potentiometric surface 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 horizontal well increases the area of the well open to the aquifer and can potentially increase well yields and/or injection rates.**

Figure 7: Direct Injection Horizontal Confined Aquifer Well Concept

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

4.1 Design and Operation

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]
ρ = 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
η = efficiency

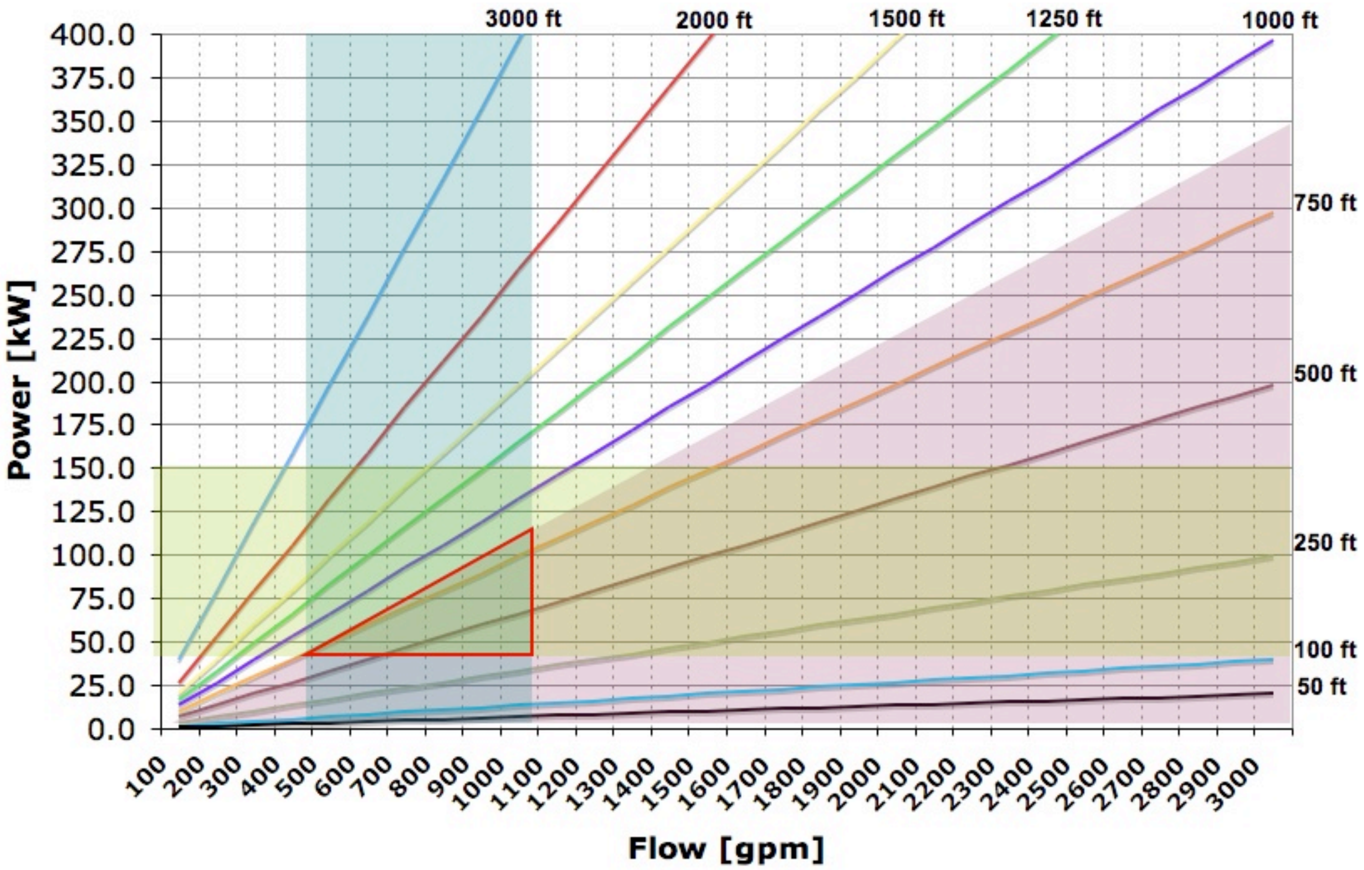


Figure 8: Relationship of Flow and Head to Power Output and Expected Ranges

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.

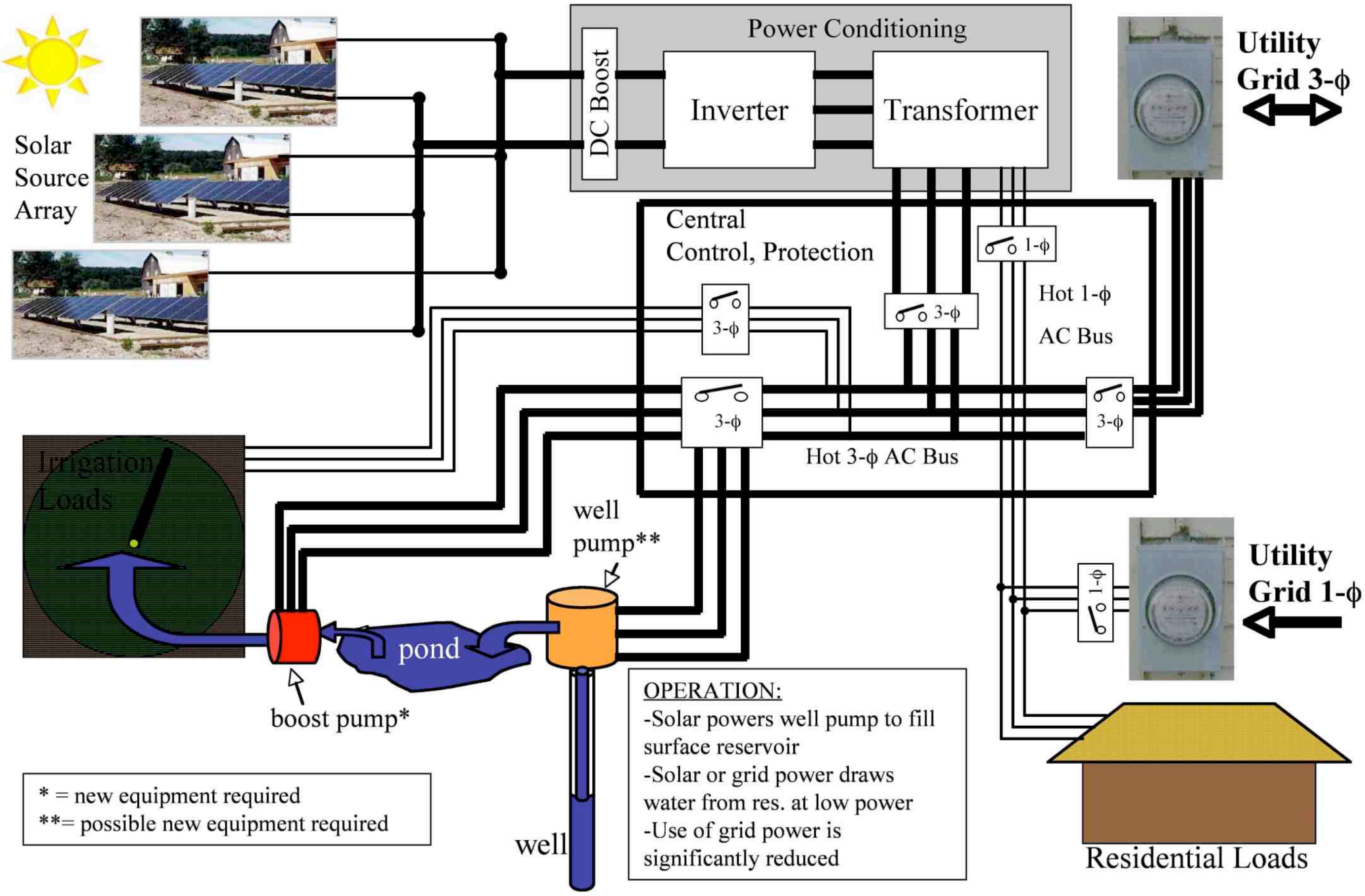
From previous analysis, the desired range of output power for an irrigation system is about 40 kW to 150 kW, depending on site specifics. This range is shown as a green shaded region on Figure 8. From the well characteristics analysis in the previous section, a maximum flow of 2000 gpm can reasonably 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 8. Also from the previous well characteristics analysis, 500 feet is chosen as an upper bound for hydraulic head. The family of lines on Figure 8 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.



* = new equipment required
**= possible new equipment required

OPERATION:
-Solar powers well pump to fill surface reservoir
-Solar or grid power draws water from res. at low power
-Use of grid power is significantly reduced

Figure 9: Example System Schematic for Aquifer UPHS

4.2 System Efficiency

The efficiency of such a system is largely driven by the pump and turbine efficiencies. A dual use pump-turbine unit is required for this application. Studies indicate that a Kaplan style pump-turbine is a good fit for this application. In the design of these components, one can generally optimize the efficiency of either the pumping action or of the turbine action. To maximize the economic performance of this system, the machinery should be designed to optimize efficiency during turbine generating operation. Table 1 lists estimated efficiencies of the major components of the system, and shows a total round-trip efficiency of this storage system to be about 40%.

Table 1: Component and System Efficiency Estimations

MOTORING (PUMP)	
DC-AC Inversion	95%
Cable	99%
Motor	95%
Pump	70%
Penstock Friction	97%
Total	**61%**
GENERATING (TURBINE)	
Penstock Friction	97%
Turbine	75%
Generator	96%
Cable	99%
AC-AC Conversion	95%
Total	**66%**
ROUND-TRIP EFFICIENCY	
	40%

4.3 Economic Analysis

In this section, an attempt to estimate the cost of an aquifer UPHS system 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. Finally, if a well is to be modified as described in section 3.2, additional costs could be incurred.

Table 2: Estimated Costs For Aquifer UPHS System

Description	**Estimated Cost**	**Comments**
Motor-Generator	$8,000	~50 kW
Pump-Turbine	$20,000	~50 kW
Motor VFD/GCU	$9,000	~50 kW
Boost Pumps (qty. 4)	$2,000	10 kW each
Boost Pump VFD (qty. 4)	$6,700	10 kW each
System Control Panel	$7,500	
Water Tubing	$4,000	
Labor/Engineering	$40,000	
Minimum Cost Total	**$97,200**	
Surface Reservoir	$32,310	32,000 cu. yd. (20 acre-ft) @ $2.00/cu. yd.
Special Well Completion	$50,000	Depends on type of well completion
Maximum Cost Total	**$179,510**	

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 pump-turbine hardware.

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 UPHS References

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Aquifer Underground Pumped Hydroelectric Energy Storage

by

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A thesis submitted to the
Faculty of the Graduate School of the
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This thesis entitled:
Aquifer Underground Pumped Hydroelectric Energy Storage
Written by Gregory D. Martin
Has been approved for the Department Electrical and Computer Engineering

Dr. Frank S. Barnes (Chair)

Dr. Frank Kreith

Dr. Roseanna Neupauer

Date_____________________

The final copy of this thesis has been examined by the signatories, And we find that both the content and the form meet acceptable Presentation standards of scholarly work in the above mentioned Discipline.

Abstract

This paper presents an electrical energy storage method designed to capture and store excess energy from renewable generating sources in an agricultural setting. The concept, called “aquifer underground pumped hydroelectric energy storage”, stores electricity in the form of gravitational potential energy between a surface reservoir and an underlying subterranean aquifer water table. An integrated pump-turbine unit installed in an irrigation water well serves to pump water to the surface (storage cycle) and generate electricity from water injected into the aquifer from the surface (generating cycle). The major application of this concept is to agricultural irrigation water pumping when a local renewable energy source is available. An aquifer UPHS system is designed to store excess energy from the generating source, and make that energy deployable for on-demand use in irrigation pumps. The concept utilizes much of the existing agricultural infrastructure, including wells, surface reservoirs and irrigation pumps. This makes it a viable, cost effective, reliable, and environmentally benign method of storing electricity. The associated electrical system, hydrogeologic conditions, legal considerations, and irrigation practices pertinent to such a system are reviewed. Finally, a case study analysis, including example system design specifications and an economic analysis, are presented.

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1 Introduction

1.1 Motivation

Our continued dependence on fossil fuels causes pollution, health problems, climate change, and political unrest. The issue of providing clean, reliable, locally produced energy for our civilization far exceeds the challenge of simply integrating renewable energy sources into the existing utility system. The challenges ahead include reducing greenhouse gas emissions and pollution and providing reliable, domestically produced energy. As the end of the bountiful supply of fossil fuel energy we now enjoy draws closer, decisive, calculated action to shift how energy is currently harvested and used must be taken to secure mankind’s energy future. Renewable energy technologies such as wind and solar generation are near-term options for producing large amounts of inexhaustible, non-polluting energy. At the other end of the spectrum, demand-side management must be comprehensively adopted to limit the amount of energy we use. In the middle of the spectrum, energy efficiency measures, transmission and distribution system updates, distributed energy generation, and energy storage provisions can be used to improve our energy infrastructure.

The enormous effort required to revitalize the energy industry for the future brings with it a valuable opportunity for states and countries to develop useful technologies, build jobs, grow economies, and provide a more stable and secure energy resource to their people. Political unrest, trade deficits, and negative effects of climate change punctuate the need for this evolution of the energy industry. States or countries that take the initiative to invest in non-fossil fuel energy technology and development will not only set an example for others to follow, but will be positioned to benefit the most economically from continued renewable energy growth. In addition, the level of reliability and security of energy can be enhanced greatly by implementing diversified and distributed generation and energy storage methods.

In the near future, the solution to the energy crisis will involve using all available technologies together in the most beneficial manner. Conventional energy sources using fossil fuels must become more efficient and cleaner. Hybrid systems that use both renewable fuels and fossil fuels will emerge. Optimized transmission and distribution systems will evolve from the existing infrastructure to support the diversified generation methods. Solar and wind energy generation will continue to grow. System-wide energy efficiency will be scrutinized and improved. Energy use and demand will be optimized through time-of-use management and efficient technologies. Energy storage systems must emerge and evolve which enable renewable energy source deployment, and greatly reduce wasted energy inherent in the current system.

Technical, economic, and political evolution is currently leading state and national electric utilities down a new path. Renewable Portfolio Standards (RPS) are examples of real political measures motivated by voter demand and economic foresight. A recent legislative effort in the state of Colorado has succeeded in increasing the amount of renewable energy planned by raising its RPS from 10% to 20% renewable generation.

It is becoming increasingly clear that simply installing additional wind or solar generation and connecting it to the grid is not the whole answer. Integration and dispatch challenges become more important as the ratio of renewable generation increases.

Making renewable energy sources as effective as possible will require planning to address their intermittent energy generation profile. Even with increased renewable energy generation, no conventional power generation infrastructure will be displaced without proper planning, and the only savings would be in the form of fossil fuel use reduction, not the desired reduction in the number of coal or gas plants needed. A method to smooth, firm, and control the usability of wind and solar sources, such as energy storage, is desirable. The risks of neglecting these issues may include unnecessary increase in the cost of electric power, or unacceptable loss of reliability if these issues are not addressed.

This vision of the future and the problem statement associated with it necessarily call for new ideas and concepts in the renewable energy arena. For this reason, this thesis paper proposes a method of energy storage to be used locally with distributed renewable energy sources such as solar or wind. This energy storage concept is herein called "Aquifer Underground Pumped Hydroelectric Energy Storage (UPHS)." The goal of this system is to provide a cost effective method of capturing and storing excess energy by using, to the extent possible, existing infrastructure. The major target application is irrigation in an agricultural setting.

1.2 Energy Storage Background

As growing electricity demand and volatile fossil fuel prices increase the value and cost of energy, means of storing excess and waste energy becomes increasingly important. Conventional coal or nuclear plants that cannot quickly change their power output end up wasting energy when the demand drops off quickly. Significant investment in fast-response gas turbine generating is the dominant method used to address this problem. Transmission and distribution lines are oversized to account for short-term peak demand cycles. Excess energy produced by wind and solar generators is not useable without a means to store it.

Over the years, energy production has developed that strives to match the user demand in the most economical way possible. This has manifested itself in the construction of large coal, nuclear, and hydroelectric base generating plants coupled with fast-response, expensive, peaking gas turbine plants, and in some cases, energy storage plants. Where energy storage plants have been used (mainly pumped hydroelectric), the operators enjoy a flexible energy source that yields considerable revenue. Energy storage serves as a bridge between the limited generation capability and response time of energy sources and the highly variable, cyclical grid demand. Grid demand not only varies substantially minute-to-minute, but also hourly and seasonally. Energy storage can be implemented as a buffer to match the available generation to the variable user demand.

The recognized need for electrical energy storage is not new. People have devised many methods of storing energy over the years, however, the problem of storing large amounts of electrical energy in a cost effective and efficient manner has remained one of the most difficult science and engineering problems the world has known. Today, the advent of modern renewable energy sources greatly improves our ability to harvest energy, but not to store what we gather. Modern, efficient, and cost effective renewable energy sources intensify the search for robust, cost effective means to store energy. Intermittent renewable energy sources require energy storage capacity if they are to provide consistent, on-demand power to the user, and be able to replace traditional fossil fueled sources. In U.S. patent #1,247,520 titled “System of Storing Power” filed on June 7, 1907 by R. A. Fessenden and patented on Nov 20, 1917, Fessenden writes:

> *"The invention herein described relates to the utilization of intermittent sources of power and more particularly to natural intermittent sources, such as solar radiation and wind power, and has for its object the efficient and practical storage of power so derived…*
>
> *It has long been recognized that mankind must, in the near future, be faced by a shortage of power unless some means were devised for storing power derived from the intermittent sources of nature…*
>
> *…These sources are, however, intermittent and the problem of storing them in a practicable way, i.e. at a cost which should be less than that of direct generation from coal, has for many years engaged the attention of the most eminent engineers, among whom may be mentioned Edison, Lord Kelvin, Ayrton, Perry, and Brush."*

Nearly one hundred years have passed and arguably little progress has been made toward achieving the goals set forth by Fessenden and others. The need to store the available energy from nature still exists, and is even more critical in today's world. While significant energy storage technology advances have been made in many areas, none have been successfully engineered to meet this storage challenge. No single method of long term, high power, high energy storage has been shown to be cost-effective, efficient and flexible enough to inspire widespread use.

Many advances in electrical energy storage technology and methods have been made in recent times. These advances have come in the areas of batteries, large scale pumped hydroelectric storage plants, compressed air energy storage, flywheels, superconducting magnetic energy storage, and super-capacitors. Chemical energy storage, most commonly applied in batteries, is the world's most prolific form of energy storage. However, there are several drawbacks to using batteries in very high energy applications, including cost, short lifetime, and disposal concerns. The next most common form of energy storage is pumped hydroelectric (PHES). This method has been successfully applied to large utility scale projects in the 50 MW to 2 GW power range, though it is severely limited by geography. Compressed air energy storage (CAES) is an emerging option for storage, also finding its best application in large utility scale projects. Flywheels, superconducting magnetics, and super-capacitors are suitable for lower energy, higher power applications. These devices are generally quite expensive, especially in high-energy applications. No cost-effective and efficient energy storage method for large-scale needs has yet emerged from these advances in technology.

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 [16]. On the economic side, most of the literature agrees that UPHS may make economic sense for installations sized between 1000 MW and 3000 MW [17]. 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 (45 meters), with average head of about 400 feet (120 meters). 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 greatly reduces loss 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. This eliminates possible river dams and large powerhouses on the surface, minimizes wildlife habitat disruption, and reduces noise.

The dominant electrical energy storage technology for use on a small scale (1 kW to 100 kW) is batteries. Lifetime, cost and materials concerns make this a less than ideal solution, though efficiencies are relatively high. The proposed aquifer UPHS concept can have very long lifetimes, can be less expensive than comparable

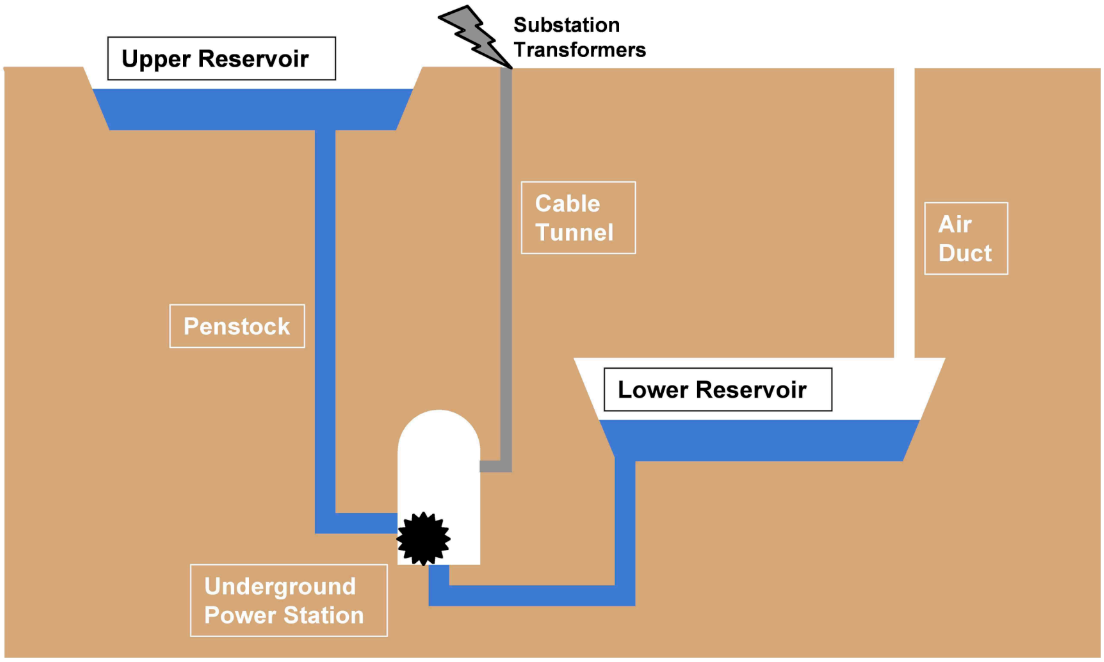


Figure 1-1: Diagram of UPHS

battery solutions, utilizes existing infrastructure, and is environmentally benign. In the agricultural sector, irrigation water pumping can be expensive. Aquifer UPHS is a distributed energy storage method that maximizes utilization of local renewable energy generation.

1.3 Purpose and Scope of Research

The research and analysis presented herein present a new adaptation of the pumped hydroelectric method of storing energy. The purpose of this research is to propose and analyze a cost effective and environmentally benign method of storing energy produced by solar panels or wind turbines for use in agricultural irrigation. The power ratings for the proposed storage method range from 10 kW to 200 kW, depending on site characteristics. This thesis paper provides a comprehensive review of the considerations in implementing such a system. These include hydrogeology, irrigation practices, electrical and mechanical technologies, legal considerations, system design, system operation, and economics.

As an example, the heavily farmed San Luis Valley in south-central Colorado enjoys a high level of impingent solar energy. Center pivot irrigation systems abound in the valley, leaving much of the land area in the corners of the square crop plots vacant. Grid electricity, the most common source of power for irrigation pumping, experiences volatile and variable costs depending on time of day, season, and other factors. For these reasons, agriculturalists in the valley are interested in using photovoltaic solar energy generation, to replace conventional grid electricity for irrigation pumping. Unfortunately, solar power is not always available when it is time to irrigate. This fact leads to a search for the most sensible method of storing the abundant solar energy, and has led to this proposal of using aquifer UPHS.

This paper is divided into three major chapters. Chapter 2 introduces the aquifer UPHS system, provides design and performance models, and describes major components of the system. In Chapter 3, a review of Colorado hydrogeology, irrigation practices, and legal and regulatory considerations is presented. Chapter 4 ties the information in Chapters 2 and 3 together by developing and analyzing a case study describing practical aspects of an aquifer UPHS system.

It is the hope of the author that this paper will provide guidance for assessing the use of aquifer UPHS to store electricity used for irrigation in an agricultural setting. Where there are unknown details in pump-turbine technologies and hydrogeologic characteristics, this paper strives to give guidance and estimations pertinent to making an informed decision on whether or not to pursue use of this concept at a particular site.

2 Aquifer UPHS System

This section introduces, describes and analyzes the aquifer underground pumped hydroelectric energy storage (UPHS) system. Aquifer UPHS is a new adaptation of underground pumped hydroelectric energy storage that uses an underground aquifer as the lower reservoir. The basis of this concept is the utilization of gravitational potential energy in surface water with respect to an aquifer or water table below the earth’s surface. The proposed system design, operation of the system, necessary technologies and components, and aquifer characteristics are described here.

2.1 System Description and Operation

The aquifer underground pumped hydroelectric storage system is designed to store energy in the form of gravitational potential energy in water separated between a surface reservoir and a subterranean aquifer. Energy is stored by pumping water from the underground source into a surface reservoir for storage (the “up-cycle”). This energy is later recovered by releasing surface-stored water back to the source through a turbine which generates electricity (the “down-cycle”). Figure 2-1 is an illustration of the overall aquifer UPHS system. The main elements of the aquifer UPHS system include:

- A source of electricity (solar panels, wind turbine, grid)
- A surface reservoir or pond
- A deep, high flow capacity water well
- An integrated motor-pump turbine-generator unit
- Electrical wiring and water piping
- Electrical center (power electronics, controls, protection)

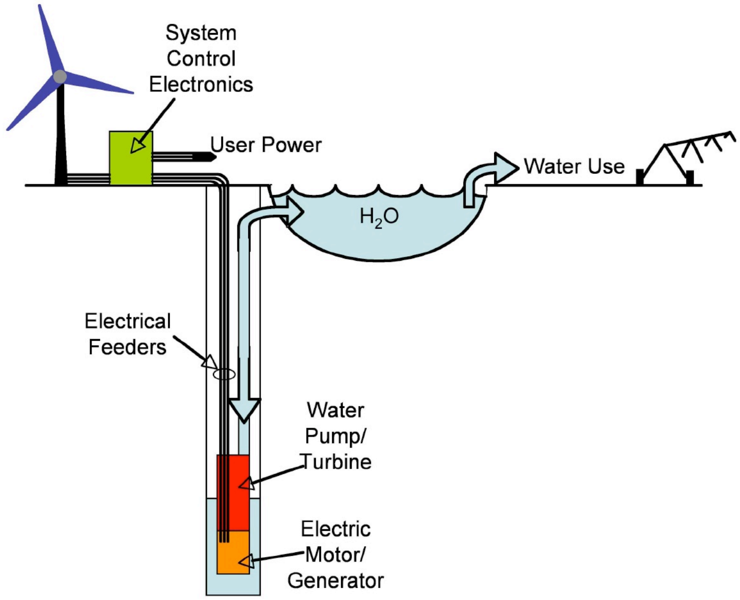


Figure 2-1: Illustration of the Aquifer UPHS System

The system is designed in a fashion that maximizes the power output capability for a given installation. To this end, the efficiency of the turbine, the available hydraulic head, and the flow capability of the well are maximized. To calculate the power output during the generation cycle, the basic fluid power equation applies (neglecting dynamic head effects):

$$P = Q \cdot H \cdot \rho \cdot g \cdot \eta$$

where,

P = power generated in watts [W] (horsepower [hp]; 1000 W = 1.341 hp)

Q = fluid flow in cubic meters per second [m^3/s] (gallons per minute [gal/min])

ρ = water density in kilograms per cubic meter [kg/m^3] (pounds per cubic foot [lb/ft^3]) = 1000 [kg/m^3]

H = hydraulic head height in meters [m] (feet [ft])

g = acceleration due to gravity [m/s^2] (feet per second squared [ft/s^2]) = 9.81 [m/s^2]

η = efficiency

Figure 2-2 shows a plot of various hydraulic head values on the power versus flow plane, assuming a turbine efficiency of 70%. The calculation was performed using Metric units and the results converted to English units. It can be seen from this plot that power output is maximized when hydraulic head and flow are also maximized. While the head is generally dictated by the characteristics of the installation site, the flow parameter can potentially be increased for a given well, as is discussed in following sections.

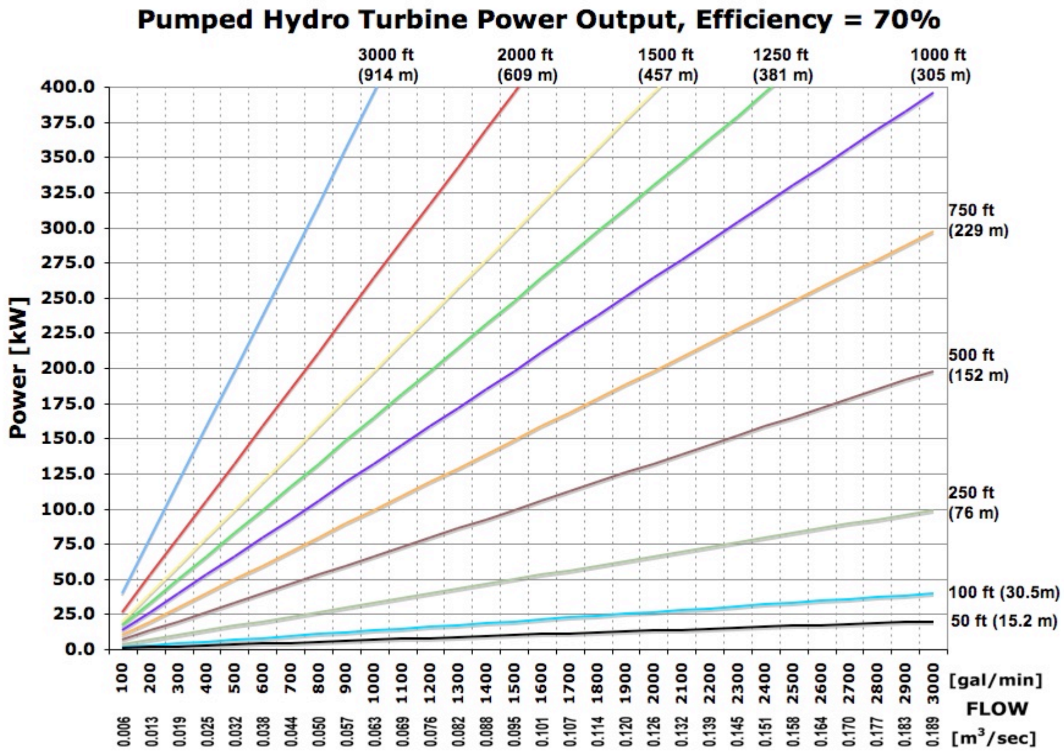


Figure 2-2: Relationship of Power to Flow and Hydraulic Head

In addition to power output, it is desirable to maximize the energy output delivered by the system. Energy storage capacity is determined by the volume of stored water and the rated power (head, flow, and efficiency) of the system. It is desirable to maximize hydraulic head to get the maximum possible energy output. Flow and reservoir volume are closely coupled parameters that affect the energy capacity, and are constrained by the required duration of power generation. These parameters will be determined by the site characteristics as well as the end use requirements. A case study and application sizing exercise is addressed in Chapter 4, which reviews the specifications of the various components of the system.

2.2 Performance Modeling

The most important parameters for optimization of the design of this system are the well hydraulic head, flow capacity, and electrical system efficiency. Contrary to common well flow yield measurements, the parameter of interest here is the measured flow that can be re-injected into the aquifer, not the flow that can be pumped out or “yielded”. While aquifer re-injection is accomplished in various projects across the country, methods to accurately determine re-injection flow capacity are more complicated than the common pumping calculations. This section will provide simplified models to predict the re-injection flow of a well with given hydraulic head. It will also analyze the allocation of hydraulic head between the head that powers the turbine and the head that re-injects water into the aquifer. Also addressed are the electrical system performance and efficiency during electricity generation.

The initial thought of a designer of this type of system is to approximate the re-injection flow capacity as roughly the same as the yield capacity of the well. Let us test this assumption for steady state flow conditions. When drawing water from a well, a cone of depression is created around the well because of the finite transmissivity of the aquifer material. This cone can depress down to the point at which the pump is located, and no farther. Thus, the well yield is limited by the hydraulic conductivity of the material and the location of the pump in the well. The right portion of

Figure 2-3 depicts two-dimensional effect of the cone of depression that occurs when water is drawn from a well.

When water is injected into a well, the opposite phenomenon, herein called a "mound of injection" occurs, also as a result of the finite hydraulic conductivity of the aquifer material. The left portion of Figure 2-3 illustrates the mound of injection. The injection flow rate depends on hydraulic head and transmissivities of the aquifer. The turbine/pump location affects the injection flow rate insofar as it drops some of the hydraulic head that could function to "push" more water into the aquifer at a higher rate. That is, there is a trade-off between the amount of head allocated to the turbine for electricity generation and the amount of head pressure functioning to inject water flow back into the aquifer.

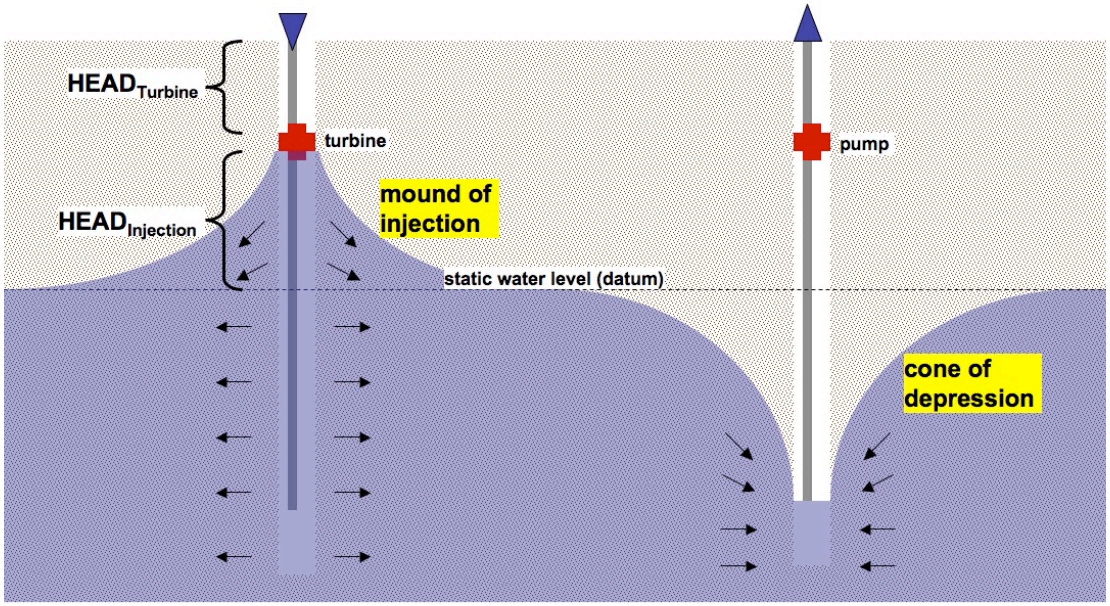


Figure 2-3: Mound of Injection and Cone of Depression

The governing equation describing hydraulic and water flow parameter interactions is the corollary in groundwater hydraulics to the thermal conduction problem. The general form of the groundwater equation for water flow in an aquifer is:

$$\frac{S}{T}\cdot\frac{\partial h}{\partial t}=\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\cdot\frac{\partial h}{\partial r}\right)$$

This equation applies to confined aquifers. However, the drawdown, or head, calculated for a confined aquifer using this equation can be correlated to the height of an injection mound if operating in an unconfined aquifer. If the assumption that the pumping occurs over a long time is adopted, the Cooper-Jacob approximation to the Theis equation, expressed in terms of drawdown over time, can be used:

$$\text{drawdown}=\frac{2.3\cdot Q}{4\cdot\pi\cdot T}\cdot\log\left(\frac{2.25\cdot T\cdot t}{r^2\cdot S}\right)$$

where;

Q = water flow [ft^3/min] ([gal/min] and [m^3/s])

S = storage coefficient

T = transmissivity [ft^2/min] (1 [cm^2/s] = 0.06456 [ft^2/min])

h = hydraulic head [ft] ([m])

drawdown = $h_{initial}$ - h [ft] ([m])

r = radius from well [ft] ([m])

With the goal of estimating the height of the mound of injection (negative drawdown) the following assumptions are made:

Q = -133.7 ft^3/min (-1000 gal/min, or -0.0631 m^3/s)

S = 0.1 (unconfined aquifer) or 0.0001 (confined aquifer)

T = 2 ft^2/min (30.9 cm^2/s)

r = 1 ft (0.305 m)

t = 6 hours = 360 min

k_T = T ÷ aquifer thickness [ft/min] or [cm/s]

Solving for well drawdown at r = 1 ft (0.305 m);

$$\text{drawdown} = \frac{2.3\cdot(-133.7\,\frac{\text{ft}^3}{\text{min}})}{4\cdot\pi\cdot 2\,\frac{\text{ft}^2}{\text{min}}}\cdot\log\left(\frac{2.25\cdot 2\,\frac{\text{ft}^2}{\text{min}}\cdot 360\,\text{min}}{1\text{ft}^2\cdot 0.1}\right)$$

$$\text{drawdown} = -51.5\text{ft} = -15.7\text{m}$$

This result, that the mound of injection rises 63.7 feet (19.4 meters) above the water table, presents a difficulty. The well is only 200 feet (61 meters) deep, so the water rises 25% of the way up the well when water is injected in this fashion. The coefficient of storage has a much smaller effect on the mound height, though an aquifer having a high S experiences a decrease in drawdown or a decrease in mound height. On the other hand, if the transmissivity is raised to 10 ft^2/min (154.8 cm^2/s), the mound height decreases to 12 feet (3.7 meters). Therefore, transmissivity plays an important role in the height of the injection mound, and therefore in the design of the system.

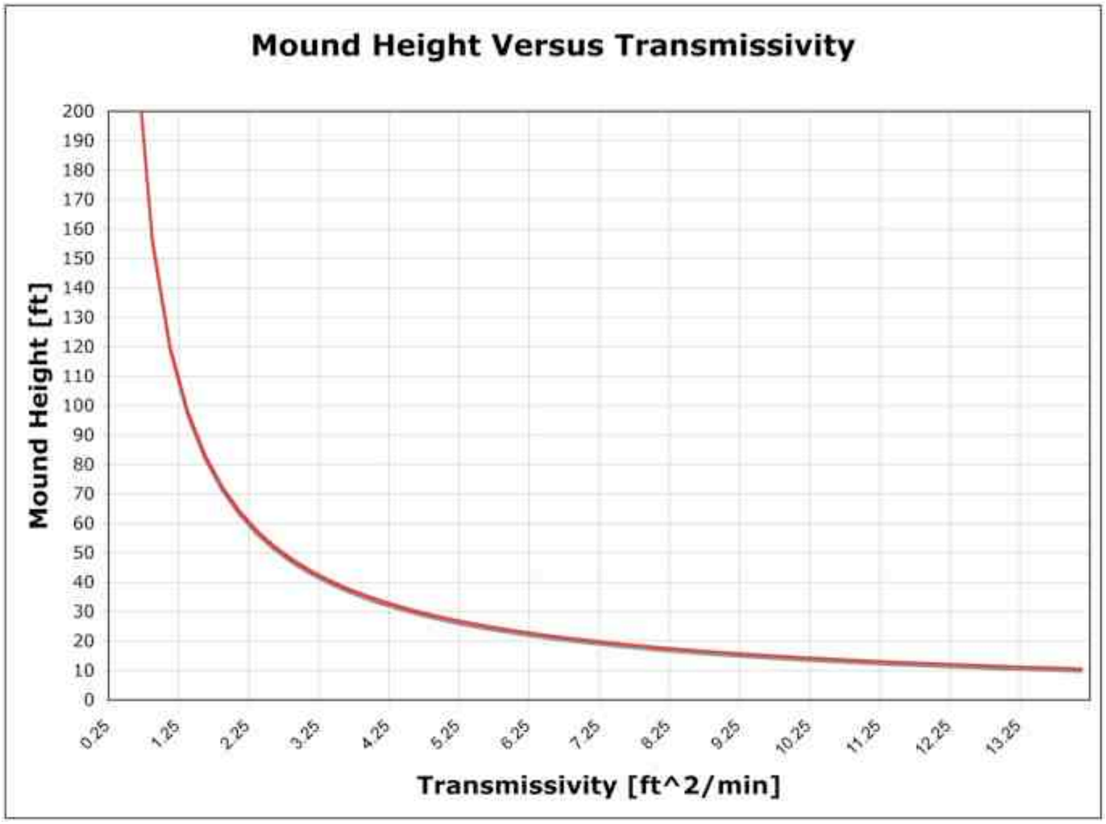


Figure 2-4: Mound Height Versus Aquifer Transmissivity

This analysis indicates that an aquifer with high transmissivity (high hydraulic conductivity) is needed. Figure 2-4 shows a plot of mound height versus transmissivity, holding the other values given above constant. This plot demonstrates the trend of decreased mound height as transmissivity increases.

Based on this analysis, the original hypothesis of whether the same flow that can be yielded by pumping can be re-injected into a well has been tested. The result depends on the aquifer transmissivity and the depth to water. In many cases, the same flow that can be pumped out can indeed be re-injected, however, the hydraulic head available for turbine operation is reduced. Injection results in a mound that can reach the surface in some cases. In comparing this to the pumping cycle, if the pump depth below the water datum level is the same as the depth from the surface to the water datum level, the mound of injection will just reach the surface, negating the ability to produce power from the injection flow using a turbine.

This modeling exercise indicates that the aquifer UPHS system must be designed with aquifer transmissivity, mound height, and depth to water as major design parameters. The transmissivity must be relatively large so that the mound of injection remains low enough to reserve sufficient hydraulic head for turbine power generation. In the case of the 200 foot (61 meters) water depth example, if the transmissivity of the aquifer is 6.5 ft^2/min (100.6 cm^2/s), then there is a remaining 182 feet (45.7 meters) of head for turbine operation.

This situation can be modeled as a simple electrical circuit with a voltage source representing the total hydraulic head potential, and resistances representing the “head drop” for the turbine and for the aquifer injection mound. The current in the circuit represents water flow. The resistance associated with the turbine correlates to the resistance to water flow in the pipe and in the turbine. The injection resistance correlates to the transmissivity (resistance to water flow) encountered in the aquifer. Figure 2-5 is a diagram of the electric circuit model for system head. This electrical model gives accurate insight into the interactions of the design parameters. Holding the total head constant, a transmissivity increase correlates to a reduction in the injection resistance. A reduction in the injection resistance is coupled with an increase in the turbine resistance, keeping total flow constant, but increasing the power dissipation in the turbine. Alternately, decreasing the flow while holding total head and transmissivity constant will decrease the injection head. Then, more head (voltage) will drop across the turbine. Alas, because the flow has been decreased, the total power dissipation from the turbine would remain constant. Using the correlation between Ohm's law and equations governing the flow, head and hydraulic resistance, design trade-offs can be calculated.

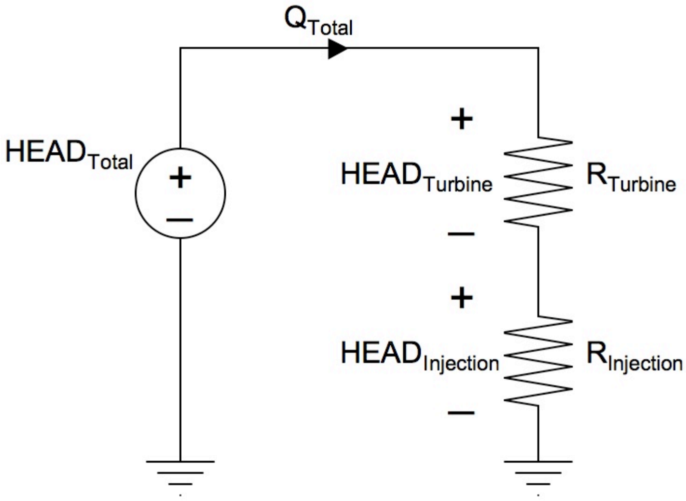


Figure 2-5: Electrical Circuit Model for Hydraulic Head

The basic equations governing the linear behavior of the electric circuit (Ohm’s Law) of Figure 2-5 are:

$$\mathrm{HEAD}_{\mathrm{Total}} = \mathrm{HEAD}_{\mathrm{Turbine}} + \mathrm{HEAD}_{\mathrm{Injection}}$$
$$\mathrm{HEAD}_{\mathrm{Turbine}} = Q_{\mathrm{Total}} * R_{\mathrm{Turbine}}$$
$$\mathrm{HEAD}_{\mathrm{Injection}} = Q_{\mathrm{Total}} * R_{\mathrm{Injection}}$$
$$\mathrm{POWER}_{\mathrm{Turbine}} = Q_{\mathrm{Total}} * \mathrm{HEAD}_{\mathrm{Turbine}}$$

Given the resistances associated with the turbine piping and aquifer hydraulics, the relative trade-off between flow, head, and power output can be modeled using these equations. Also, a correlation can be derived relating the transmissivity in the hydraulic circuit to the resistance in the equivalent electric circuit. The allowable flow (current) through the circuit is proportional to the transmissivity (resistance) in the circuit. The equations to determine the resistance and conductance in an electrical circuit are:

$$R = \frac{l}{\sigma \cdot A}; \quad G = \frac{1}{R} = \frac{\sigma \cdot A}{l}$$

where;

R = resistance [Ω]

G = conductance [S]

l = length [m]

σ = conductivity [S/m]

A = area [m^2]

The analogous equation in hydraulics for transmissivity is:

$$T = \frac{k \cdot A}{r}$$
$$T = k \cdot b$$
$$T = \frac{\kappa \cdot \gamma \cdot b}{\mu}$$

where;

T = transmissivity [m^2/s] or [ft^2/min]

k = hydraulic conductivity [m/s] or [ft/min]

A = area [m^2] or [ft^2]

r = radius [m] or [ft]

b = aquifer thickness [m] or [ft]

κ = intrinsic permeability, [m^2] or [ft^2]

γ = specific weight of water, [1000 kg/m^3 (at 4°C)]

μ = dynamic viscosity of water, [0.00089 Pa/s]

Comparison of these two equations shows that electrical conductance is the corollary to transmissivity, and electrical conductivity is the corollary to hydraulic conductivity. Transmissivity has units of area per time, and is usually calculated as the hydraulic conductivity times the aquifer thickness.

The next step would be to derive an expression for the transmissivity in an aquifer experiencing recharge flow through a well. Although not included here, the result of this derivation is expected to match the governing equation for hydraulic flow in an aquifer used above.

Transmissivity (T) is a measure of the volume of water flowing through a cross-sectional area of an aquifer (for example 1 ft times the aquifer thickness (b)), under a hydraulic gradient (for example 1 ft / 1 ft) in a given amount of time. Transmissivity is a parameter used to calculate water flow in aquifers, and is equal to hydraulic conductivity (k) times aquifer thickness (b), as shown in the equation above. Hydraulic conductivity (and therefore transmissivity) depend on the permeability of the medium, specific weight (of water) and the dynamic viscosity (of water). The equation for hydraulic conductivity is found from application of Darcy's law.

Transmissivity therefore depends on the above quantities, including another length dimension, aquifer thickness. In this paper, the quantity of transmissivity is used to evaluate the water flow and aquifer performance. It should be noted that transmissivity can be related back to the basic properties of aquifer materials. Another common material property, porosity, is the ratio of the amount of empty space volume to the total volume in a material. Porosity can change with depth, because the weight of material from above compresses the voids between particles. While porosity of a material can effect the intrinsic permeability, these quantities are not necessarily related.

2.3 System Components

2.3.1 Water Pump-Turbine Motor-Generator

The core of the aquifer UPHS system is an integrated pump-turbine/motor-generator unit. As the name suggests, this single unit performs the functions of both pumping water using electrical power and generating electricity from water power. This type of integrated machine exists commercially for large pumped hydroelectric installations, normally employing a Francis reaction type turbine coupled to a synchronous AC electric machine. A unit sized and designed for the proposed aquifer UPHS application is not commercially available. In this section, the important design considerations for the integrated pump-turbine/motor-generator unit for use in the aquifer UPHS system are described.

2.3.1.1 Pump-Turbines

Reaction type turbines, such as Kaplan or Francis designs, are capable of accomplishing both pumping and turbine functions at efficiencies that increase with the unit’s size. Kaplan or propeller style turbines are used in low head, high flow applications, while

Francis turbines and “pump-as-turbine” designs are applied in high head, high flow situations. Typical efficiencies for very large Francis turbines can approach 95% [2]. For smaller sized units, lower efficiencies in the range of 70% to 90%, depending on head, flow and specific speed, can be expected. In standard Francis turbine designs, the water enters or leaves a scroll-shaped vane housing that is at a right angle to the rotation of the drive shaft. This characteristic may pose a design challenge in installing such a unit in a vertical shaft well.

Another option for the design of the aquifer UPHS pump-turbine is the use of standard centrifugal or “vertical turbine” well pump in the forward direction for pumping and in reverse for turbine operation [2]. Example images of these types of pumps are shown in Figure 2-6. This use of the pump is referred to as a pump-as-turbine (PAT) design. A first order estimation of the turbine efficiency of a centrifugal pump is that it is the same as the pump efficiency [3]. Although originally designed as a pump, a centrifugal pump may be capable of operating in reverse as a turbine at efficiencies in the range of 65% [4] to perhaps 85%. This method is proposed as a preferred option for the aquifer UPHS situation because it uses existing technology, is commercially available, and would be a low cost solution. Because of the difficulty in predicting turbine performance of a given centrifugal pump [3], testing is required to characterize the flow capability, water velocity range, and turbine efficiency. The selected centrifugal pump design will need to employ a keyed shaft to accommodate shaft torque in either direction.

Centrifugal motor pumps are a common item used for pumping water in many situations. They are available in submerged or non-submerged designs. There are a wide range of available head ratings, flow ratings, and power ratings for commercial motor pumps. These

Figure 2-6: Sample Images of Centrifugal Pumps; (a) Vertical Turbine Pump, (b) Submersible Vertical Turbine Pump

units are commonly centrifugal or vertical turbine pump designs, integrated with an AC induction motor. The industry standard estimation of pump efficiency is 55%, however, with proper system design, a centrifugal pump could run as high as 85% efficient. The efficiency for either the pumping cycle or the turbine cycle can be optimized, but not both simultaneously. In the case of aquifer UPHS, the turbine efficiency must be optimized. The very rough range of attainable turbine efficiency used in this paper is 70% to 85%, and pump efficiency range of 65% to 80%. These numbers are estimates adopted from research on modern PAT pumps, centrifugal pumps, and turbines. Unfortunately no concrete data on the pumping and turbine efficiency of a PAT unit was uncovered.

2.3.1.2 Motor-Generators

Motor-generator units that operate with relatively high efficiency are a mature and available technology. As with pump-turbines, the efficiency increases with size and rating. Some large motor-generators can operate at greater than 96% efficiency. For the application in question, efficiencies between 90% and 95% can be expected.

Well motor-pumps commonly employ an AC induction motor or a synchronous wound-rotor AC motor for larger machines. Although commercial designs assume the unit will be used as a motor only, modifications can be made to produce efficient operation as a generator also. In the case of a synchronous wound-rotor AC machine, an interface to the machine's rotor windings that provides excitation current during generating operation is needed. It is a relatively simple modification to implement with or without the use of power electronics. If power electronic control of the winding is used, the frequency of the generator output can be regulated.

For AC induction machines, perhaps the most common and simple modification involves connecting excitation capacitors to the three phase leads of the machine [5]. These capacitors provide excitation current which is 90 degrees out of phase with the primary generation current waveform. This excitation current induces currents in the rotor of the machine which allow it to operate as a generator. Another possible modification technique involves the use of power electronics to synthesize this excitation current. In this case, the same electronics used to drive the machine as a motor are used to control excitation of the machine. To implement this method, a more complicated control loop is programmed into the machine controller software. Figure 2-7 shows a schematic indicating the connections of the excitation capacitors and the basic inverter/rectifier power electronic switches.

For the aquifer UPHS system, a centrifugal well pump with an induction motor is recommended. This option represents the least cost solution, however, efficiency during the generating cycle may not be optimized. For the final system design, a full-sized unit should be procured and tested to determine the actual performance capabilities. Care must be taken to select a unit that will operate with the required flow and range of attainable water velocities.

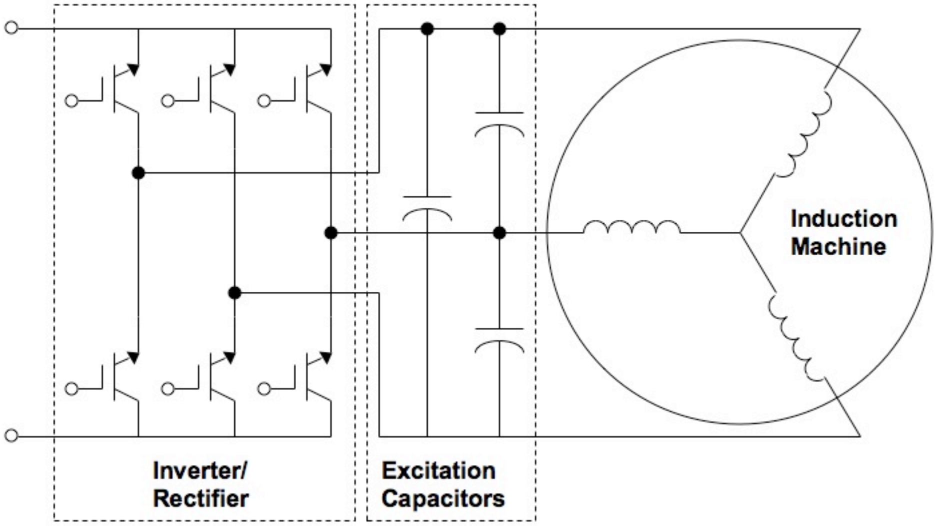


Figure 2-7: Schematic of Induction Machine Connections For Generator Modifications

2.3.2 Electrical Control System Design

2.3.2.1 Electrical System Overview

An electrical system is needed to implement the aquifer UPHS function and interface it with energy sources, user loads, and the utility grid. Its main functions include:

- Power electronics motor drive to energize motor pump during the up-cycle

- Generator exciter and rectifier to extract electricity from the turbine generator during the down-cycle
- Grid tie inverter to condition the power to 60 Hz, 480 Vac
- The grid tie inverter also has a rectifier function in the case of a local wind turbine power source
- A 480 Vac circuit breaker panel for protective functions and power routing
- A transformer to convert 480 Vac to 220 Vac and 120 Vac for user load power
- A 220 Vac and 120 Vac circuit breaker panel for protection and power routing to user loads
- A system control, monitoring and user interface panel that regulates and controls the entire system

Figure 2-8 gives a block diagram of the connections of the electrical system. Each of the components introduced above and shown in Figure 2-8 are described in more detail in the following discussion. The details of the solar and wind turbine equipment, including control interfaces, is not treated in this paper. In reality, a system would likely only have one local renewable energy source, such as solar panels or a wind turbine. Also, it is possible that this system could be run “off-grid”, however, emergency back-up power provisions, such as batteries, may be required. In general, the functional components of this system are available commercially, except the system controller. Further detailed engineering design work is required to correctly interface and control these components in a concerted and safe manner.

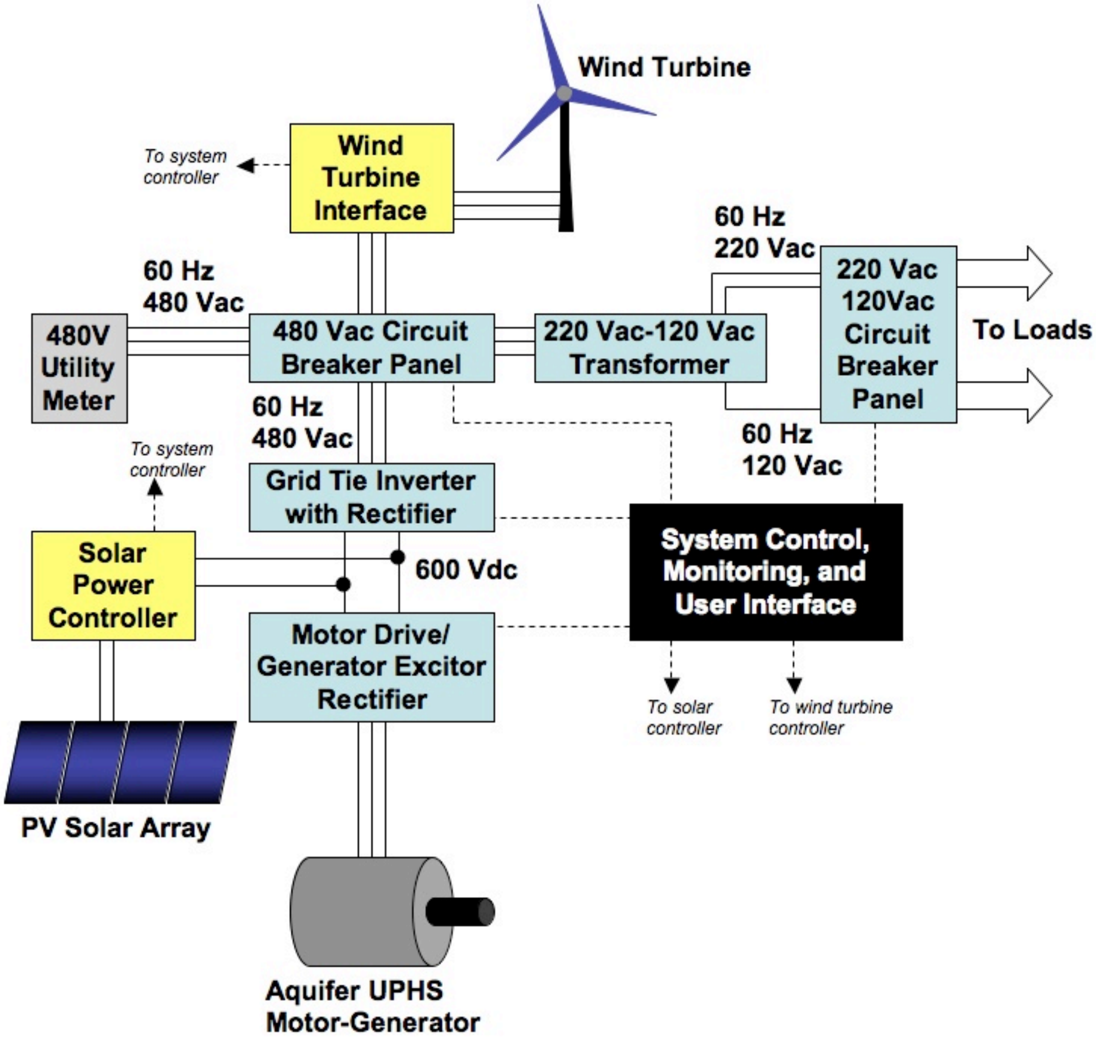


Figure 2-8: Electrical System Block Diagram

2.3.2.2 Pump Motor Drive / Generator Controller

As indicated in a previous section, a power electronics controller is required to interface the motor-generator. This controller has two main functions:

1. The controller must electrically drive the motor during pumping operation. This involves inverting the 600 Vdc using a PWM, six-step, trapezoidal, or other motor drive strategy to control a 3-phase IGBT inverter. The impedance and voltage drop in the long lines between the inverter and the motor (which is located near

the bottom of the well) must be taken into account. This inverter could be designed to drive the motor at only a single speed (simpler implementation) or at variable speeds. A variable speed drive has the advantage of being able to use lower power input (such as when the solar or wind source is minimal) and thereby increasing the efficiency of the pumping cycle. Additionally, it is possible to further optimize the pumping cycle by matching the photovoltaic solar voltage and current characteristic to the pump characteristic using a method such as maximum power point tracking (MPPT) [6].

2. The controller must excite the motor-generator and rectify the output. In a previous section, two methods of exciting the generator are discussed. It is recommended here to employ the scheme involving advanced control of the IGBT switches to simultaneously excite the machine and rectify the output. The excitation capacitors are eliminated, reducing cost and increasing reliability. Figure 2-9 gives a schematic of the proposed unit, utilizing position feedback sensed directly from the machine shaft.

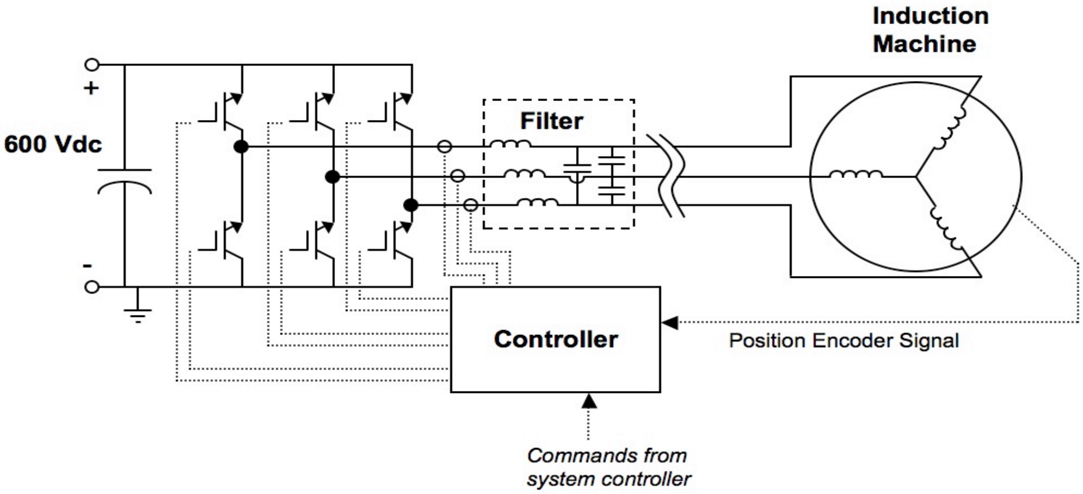


Figure 2-9: Motor Control Inverter/Rectifier Schematic

A filter must be employed between the induction machine and the inverter. This filter attenuates the voltage spikes that occur on the lines due to their long length, and therefore, large impedance. A DC link capacitor is connected to stiffen the 600 Vdc bus, and improve transient performance.

2.3.2.3 Grid Tie Inverter / Rectifier

The function of the grid tie inverter/rectifier is twofold. It is intended to operate as a commercial grid tie inverter to convert the 600 Vdc power into 60 Hz, 480 Vac grid-compatible power. In addition, the unit must step up and rectify incoming 480 Vac power into 600 Vdc power to supply the motor drive controller. The step up function can be accomplished using a transformer or by using a DC-DC boost converter. Both methods are efficient. The complexity of the DC-DC conversion is greater than the transformer method, however, the transformer may be a more costly implementation.

2.3.2.4 Circuit Breaker Panels and Transformer

Circuit breaker panels that protect and control the 480 Vac, 220 Vac and 120 Vac systems are required. The circuit breakers should be implemented using appropriate relays or contactors so that power routing can be accomplished by the system controller. These relays also function as protective circuit interrupt elements. In the case of tying the grid tie inverter to the utility meter, the system controller must monitor and verify that the frequency and voltage waveforms are compatible with the grid. At that point, the system controller will close the circuit breaker connecting the system to the grid.

A transformer with its primary winding connected to the 480 Vac system is utilized to provide 220 Vac and 120 Vac 60 Hz power to the low voltage circuit breaker panel. This panel houses either traditional passive circuit breakers for the user loads, or externally controlled relays (or contactors) if additional automation is desired.

2.3.2.5 System Control and Monitoring

The system controller is responsible for the overall control and protection of all the other elements of the electric system. It has several important functions, with its primary job to appropriately route power to or from the storage system, the local power sources, and the loads. To implement energy storage management, the controller monitors the amount of power being generated by the local power sources, the load demand power present, and estimates the status of the energy storage system (full, empty, 50% full, etc.). Based on this information, the controller initiates one of the following actions:

1. If there is energy being generated but not used by the loads, power is routed to the motor pump drive and water is pumped to the surface.
2. If there is power demanded by the loads, but no power being generated, stored energy is released by putting the storage system into generating mode.
3. If power is demanded by loads, the energy storage is depleted, and there is no local power generation online, electricity is routed from the utility grid to supply the load demand.
4. If there is more power being produced by the local energy source than is being used, and the storage reservoir is full, power will be “net-metered” or routed to the grid.

5. Direct energy from the utility grid can also be stored. This option would be used if “time-of-day” pricing of grid electricity is in effect. That is, if less expensive grid electricity is available at night than during the day, this inexpensive electricity can be stored and later used when grid prices rise. The efficiency of the storage system must be traded against the cost differential of the time-of-day pricing to determine if this is an economically beneficial choice.

In addition to energy storage management, the system controller performs monitoring, protection, and power routing functions. System status including which circuit breakers are closed and open, which units are operating and in which direction, power flow data, and other parameters are continually monitored. Each individual electrical system component has provisions for self protection against overloads and overheating, but it the job of the system controller to ensure no system configuration is enabled that may damage equipment.

The user interface to the operation of the overall system is housed in the system controller. This interface tells the user the status of the system, including the output from local power sources, the status of the energy storage, the loads that are energized, and the power flow specifics. The interface also allows the user to configure the system in certain ways, as well as to shut down components or sections of the system.

2.3.3 Water Well

The aquifer UPHS system utilizes a deep, high flow capacity water well to accomplish energy storage. The power capacity of the turbine is a function of available head (depth) and flow (transmissivity). Analysis from previous sections show how the trade-off between head, flow, mound height, and aquifer transmissivity affects the system design. In this section, well characteristics are reviewed and methods to increase the system power by modifying wells, or by using an infiltration pit are described.

Water well characteristics vary greatly in installations across the country, world, and also within the same aquifer system. The main characteristics of importance to the aquifer UPHS system are:

- Transmissivity or hydraulic conductivity of the surrounding geologic formation
- Depth to water
- Well diameter
- Well casing
- Confined or unconfined aquifer

As indicated in earlier sections, a well having greater than 1000 gal/min (0.063 m^3/s) injection flow capacity and 300 feet (91 meters) of head for turbine power generation is targeted. To achieve this, for example, an aquifer with 350 feet (107 meters) depth to water must have transmissivity of about 2.6 ft^2/min (40.3 cm^2/s) or greater. Does this type of well exist? What can be done to retro-fit a well to achieve the necessary parameters?

Given certain limits on the typical flow capability of existing irrigation wells, it follows that one would consider ways to increase the injection flow capability of a well in order to extract the maximum possible power. Aquifer recharge (AR) and Aquifer Storage and Recovery (ASR) wells exist in Colorado and elsewhere. To quote one source; “Currently, more than 60 aquifer storage and recovery (ASR) sites are in operation around the U.S.

These projects range from a single well to networks of 30 wells, with recovery capacities ranging from 500,000 gallons per day from single wells to 100 million gallons per day from well fields (Tampa Water Dept., 2003).” ([9], Page 28).

Recharge wells are designed to replace water in an aquifer or underground structure by flowing water backwards into a water well, thereby “recharging” the aquifer. In the case of ASR wells, water is both injected and removed depending on seasonal cycles and water use obligations. This type of well sets the precedent for an aquifer UPHS installation, though Aquifer UPHS cycles are much more frequent. Modified AR and ASR 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 [9]. Figures 2-10 and 2-11 show options for modified wells to increase the recharge flow capacity. To quote Topper et. al.; “ASR wells have proven to be cost-effective, and can be readily implemented within existing water utility facilities using well fields.” ([9], Page 19).

Essentially, these concepts serve to increase the injection flow possible by increasing the completed surface area in contact with the aquifer, or by increasing the diameter of the well. Horizontal screen pipes or radial screen pipes or horizontally dug wells are proposed by Topper et. al. to increase injection flow capacity. To quote Topper et. al. regarding the radial well concept; “These installations potentially increase the surface area open to the aquifer as well as the radius of influence of a well allowing higher injection or extraction rates than a traditional well.” [9]

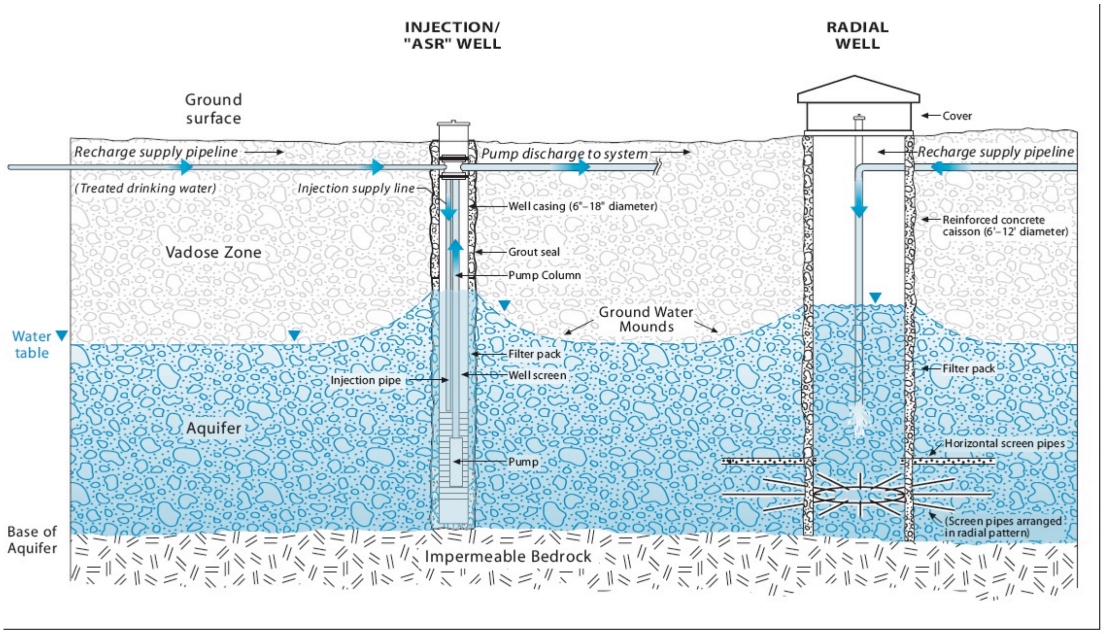
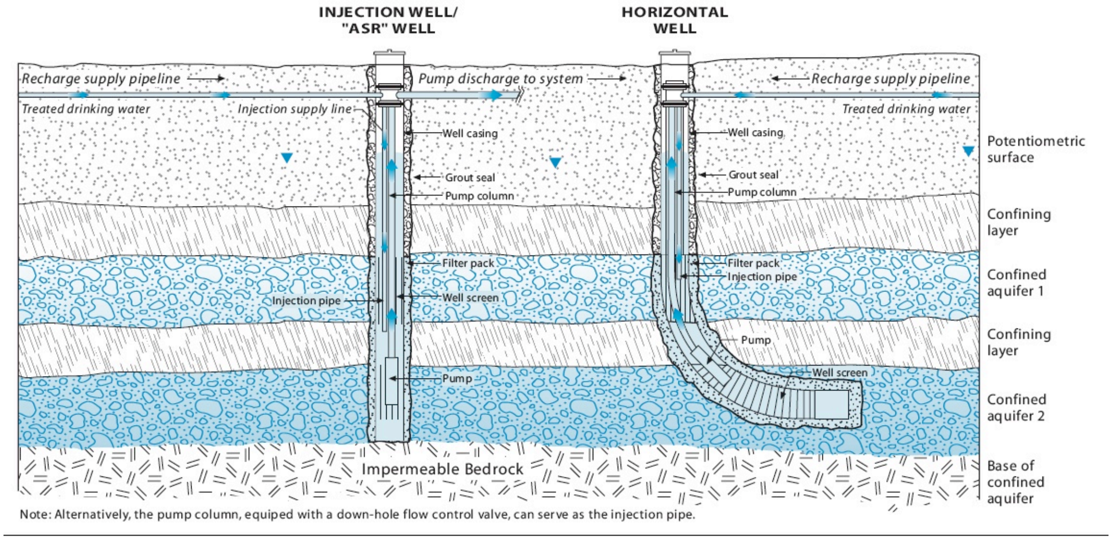


Figure IV-3. Direct injection in an unconfined aquifer. Water for recharge is injected through a well directly into the saturated aquifer raising the water table in a conical mound around the well. The well can also be used for recovery of the injected water as an ASR well. Injection can use a dedicated 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.

Figure 2-10: Direct Injection Radial Unconfined Aquifer Well Concept [9]



Note: Alternatively, the pump column, equiped with a down-hole flow control valve, can serve as the injection pipe.

Figure IV-4. Direct injection in a confined aquifer. Water for recharge is injected through a well directly into a confined aquifer raising the potentiometric surface 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 horizontal well increases the area of the well open to the aquifer and can potentially increase well yields and/or injection rates.

Figure 2-11: Direct Injection Horizontal Confined Aquifer Well Concept [9]

Another option for increasing well injection flow may be the use of an “infiltration pit” dug out near the bottom of a well. An infiltration pit could be used to increase to surface area of contact of the well to the aquifer, in both saturated and unsaturated regions. This option may complicate well completion procedures and increase cost, as it is an unused and unproven concept. Figure 2-12 illustrates the infiltration pit well concept.

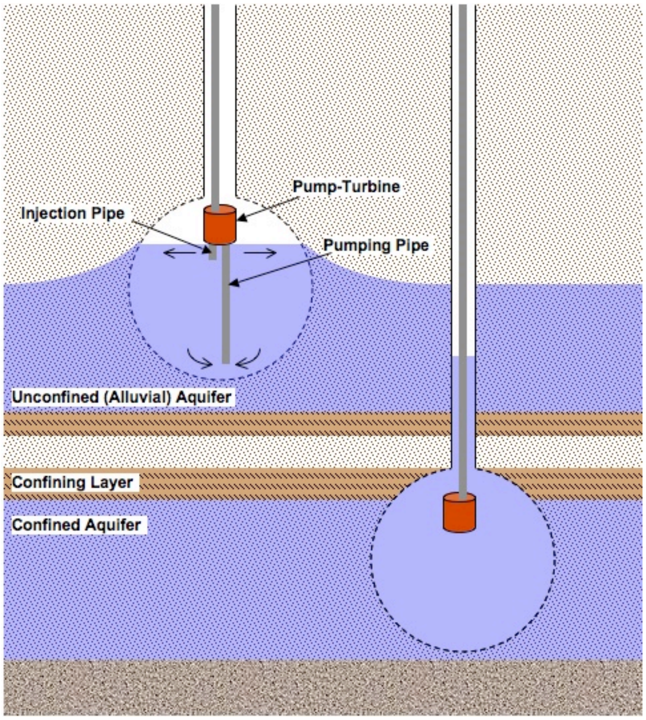


Figure 2-12: Infiltration Pit Well in Confined and Unconfined Aquifers

The infiltration pit option has different implementation challenges depending on whether it is used in a confined or unconfined aquifer. Figure 2-12 shows the characteristic mound of injection in the unconfined case. One main design consideration here is where to place the pump-turbine unit. The water level in the well will change significantly for pumping versus injection modes. To alleviate the problem of a “dry” pumping situation, an extension pipe is installed that reaches toward the bottom of the completion. Alternately, during turbine operation, it is desirable to allow “free flow” of water at the exit of the turbine. To accomplish this, a short pipe that dumps water into the air above the water level in the well is proposed. This allows maximum water velocity through the turbine, increasing generating efficiency. In the unconfined aquifer, the situation is more difficult. It is likely not possible to operate the turbine such that its exit water dumps into free air. Thus, the velocity of water through the turbine may not be ideal.

It is difficult to compare the performance of the infiltration pit well to the other completion options. Many factors are involved including pit size and dynamic flow patterns in the wells. Testing to find out the performance trade-offs of the well completions is recommended, and this is outside the scope of this paper.

Well modifications of the type outlined in this section are proposed for use in implementing aquifer UPHS. They include increased well radius, horizontal pipe completions, radial completions, horizontal “bending” well geometry, and infiltration pits. The best method of increasing well flow rates will depend on site specific geology and aquifer characteristics, the availability of technology and tools to implement these advanced completions, as well as budget and power requirements.

2.3.4 Surface Reservoir

A surface water reservoir is needed to contain the water pumped up from the aquifer until it is used. Water pumped and held at the surface represents stored potential energy with respect to the aquifer. This energy can be converted back into electricity, using a turbine-generator, or it can be partially allocated to some other use, such as irrigation. Surface ponds are not uncommon structures found at farms, though they are more prevalent in Midwestern regions than in Colorado. Permitting, design, construction, and use of surface reservoirs is well understood, and should pose no engineering challenge for implementation in most cases. The cost of excavating and lining a new surface reservoir, and the challenge of maintaining sufficient water quality levels are the major foreseeable hurdles.

The most suitable type of reservoir will vary depending on site characteristics such as topography, soil composition, and local regulations. The main types of reservoir (pond) designs are excavated, embankment, or a combination of the two. Excavated ponds are more common on flat terrain, while embankment ponds are commonly used with sloping terrain. Figure 2-13 illustrates these types of pond excavations.

In an aquifer UPHS system, the water level in the pond will rise and fall frequently. The magnitude of this change will depend on the volume and surface area of the reservoir with respect to the amount of water being pumped or injected. If the pond water is to be used directly for crop irrigation, the volume of water must be sufficient to support both irrigation and aquifer injection volumes. As a reservoir surface area increases, however, evaporation losses also increase. The reservoir volume and depth must be traded with the allowable water level change. A reservoir owner must have enough water rights to account for any losses due to evaporation.

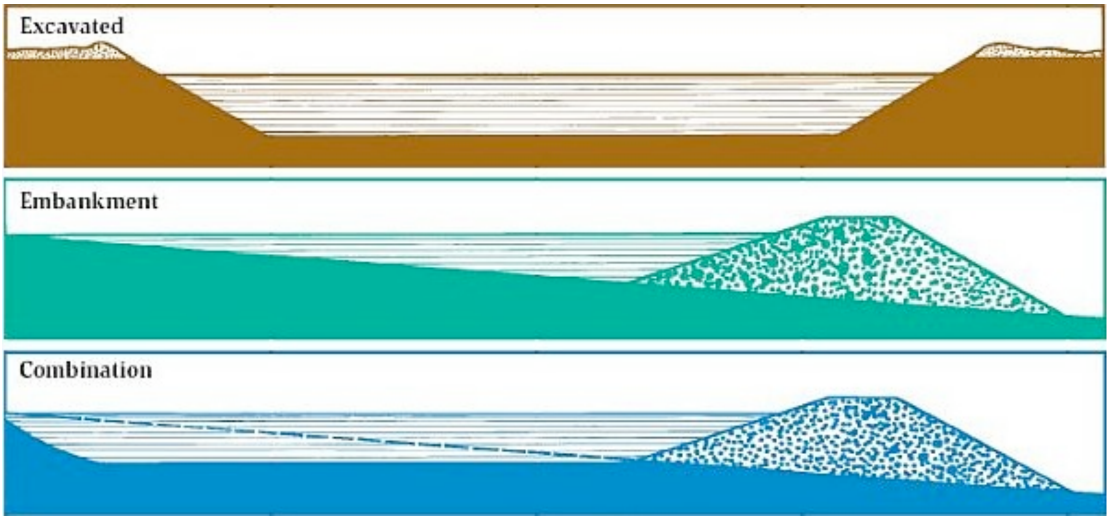


Figure 2-13: Major Types of Pond Excavations [12]

Excavation costs can range widely depending on the soil type, size, and local labor rates and economics. As an estimation, one may expect costs for pond excavation between $0.75 and $2.50 per cubic yard of material excavated [12], [13]. A cost of $2.00 per cubic yard is used in this paper. In addition to excavation costs, importing materials for lining the pond has an expense typically in the range of $10,000 to $20,000 [13].

Finally, a hydraulic interface that allows water to be pumped in and out of the reservoir is required for aquifer UPHS. This will necessitate the installation of underground or above ground water piping and valves interfacing the reservoir to the well.

2.4 System Efficiency

The efficiency of the operation of the aquifer UPHS system is an important measure of its feasibility. In this section, estimates of the efficiencies of the components are provided, and the resulting system efficiencies. In previous sections, discrete component efficiencies are introduced. These values are summarized in Table 2-1. The pump or turbine is the single component that has the majority of the impact on system efficiency. Electrical system components, including the motor-generator have relatively high efficiencies. One should note that the round trip efficiency is not the figure of merit for aquifer UPHS. Rather, the turbine operation efficiency should be emphasized. This is because during pumping, energy that would otherwise be unused is used to pump water. Therefore, the pumping cycle can be viewed as “free” and the generating cycle viewed as the efficiency of merit for the system.

	EFFICIENCY			
COMPONENT	LOW	TARGET	HIGH	
VFD Pump Drive	94%	95%	97%	PUMPING
Power Wires	96%	98%	99%	
Motor	94%	96%	97%	
Pump	60%	70%	75%	
Pipe Friction	96%	97%	98%	
TOTAL	**49%**	**61%**	**68%**	
Pipe Friction	96%	97%	98%	GENERATING
Turbine	70%	80%	85%	
Generator	93%	95%	96%	
Rectifier	95%	97%	98%	
Inverter	94%	96%	97%	
TOTAL	**56%**	**69%**	**76%**	
Round-Trip Efficiency	27%	**42%**	52%	

Table 2-1: Estimated System and Component Efficiencies

3 Hydrogeology, Irrigation and Regulations

The success of an aquifer UPHS installation depends on the occurrence of favorable hydrogeologic conditions, on a practical and economical use or reason for storing electricity, and on the ability to follow all legal regulations. For this reason, aquifer hydrogeology as well as irrigation practices in the state of Colorado are reviewed in this section. In addition, current irrigation practices and projected needs of the agricultural community in the state will be examined. Further, areas of the state that foster both intensive irrigation and compatible aquifer geologies will be highlighted. These include the northeastern plains and the San Luis Valley. Finally, important regulations, procedures, and permitting requirements are addressed as an aspect of the feasibility of installing aquifer UPHS.

3.1 Colorado Aquifer Hydrogeology

Aquifers fall into two major categories; unconfined and confined. Unconfined aquifers are also called water table aquifers or phreatic aquifers, because their upper boundary is the water table. Usually, the most shallow aquifer at a given location is unconfined, with confined aquifers occurring below. Unconfined and confined aquifers are separated by confining layers called aquitards or aquicludes, which are geologic formations of very low hydraulic conductivity. Unconfined aquifers generally receive recharge water from direct precipitation or from a body of surface water such as a river or lake [13]. Confined aquifers have a water table above their upper boundary, thus a well dug into a confined aquifer may find pressurized water, or even artesian flow to the surface.

The storage coefficient is an important characteristic that distinguishes confined and unconfined aquifers. Confined aquifers have very low storage coefficient values (generally less than 0.01, and as little as 10^{-5}) [13]. These values indicate that the confined aquifer is storing water using the mechanisms of aquifer matrix expansion and the compressibility of water, which typically are both quite small quantities. Unconfined aquifers have storage coefficients (specific yields) that are normally greater than 0.01, and they release water from storage by the mechanism of actually draining the pores of the aquifer, which releases relatively large amounts of water [13].

Both unconfined and confined aquifers are candidates for aquifer UPHS installation. Confined aquifers have the advantage of being much deeper (farther below the surface) than unconfined aquifers. However, the specific yield of confined aquifers is decidedly lower than unconfined. Alternately, while unconfined aquifers have high specific yield capacity, they are generally much shallower, or closer to the surface. Here again, we see a design trade-off between a high head, low flow option and a low head, high flow option. Another important note is that water quality requirements are more stringent for unconfined aquifers. Table 3-1 gives a qualitative comparison of the two types of aquifers.

	UNCONFINED AQUIFER	**CONFINED AQUIFER**
Hydraulic Conductivity	med to high	low to med
Storage Coefficient	med to high	low
Transmissivity	med to high	low to med
Depth to Water	low to med	low to high
Specific Yield	high	low to med
ADVANTAGES	- existing irrigation wells - high flow yield	- possible very high head - easier to meet water quality specs
DISADVANTAGES	- stringent water quality specs - water rights more difficult to get - typically shallow depth to water	- low flow yield - more difficult to use advanced completion

Table 3-1: Qualitative Comparison of Aquifer Types

Unconfined aquifers occur across the state, and are prevalent in the eastern plains areas and in valleys, most notably the San Luis valley. An unconfined aquifer will exhibit a shallow depth to water near a river, stream or lake system. If the topology is such that surface elevation rises as one moves away from a surface water source, the depth to water may be found to increase.

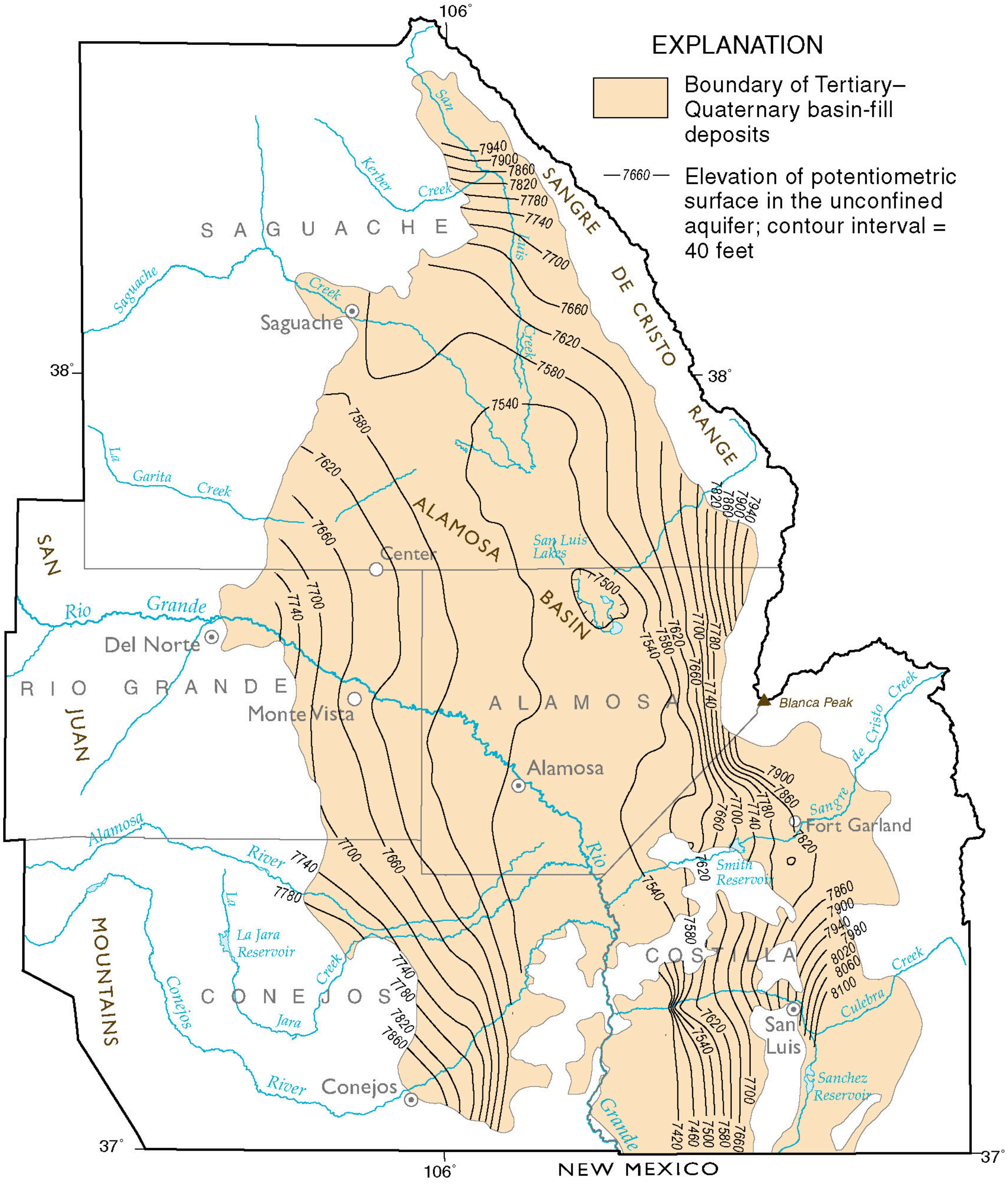


Figure 3-1: Unconfined Aquifer Depth Contours in the San Luis Valley

This is not always the case, but it can be used as a first order "rule of thumb" when assessing potential well sites for aquifer UPHS. Figure 3-1 is a map of the unconfined aquifer potentiometric water surface level contours in the San Luis valley [10]. This information is useful when compared with a topographic map (Figure 3-2) of the area in identifying potential high-head sites. The convolution of the two maps will give an idea of depths to water in the unconfined aquifer across the valley.

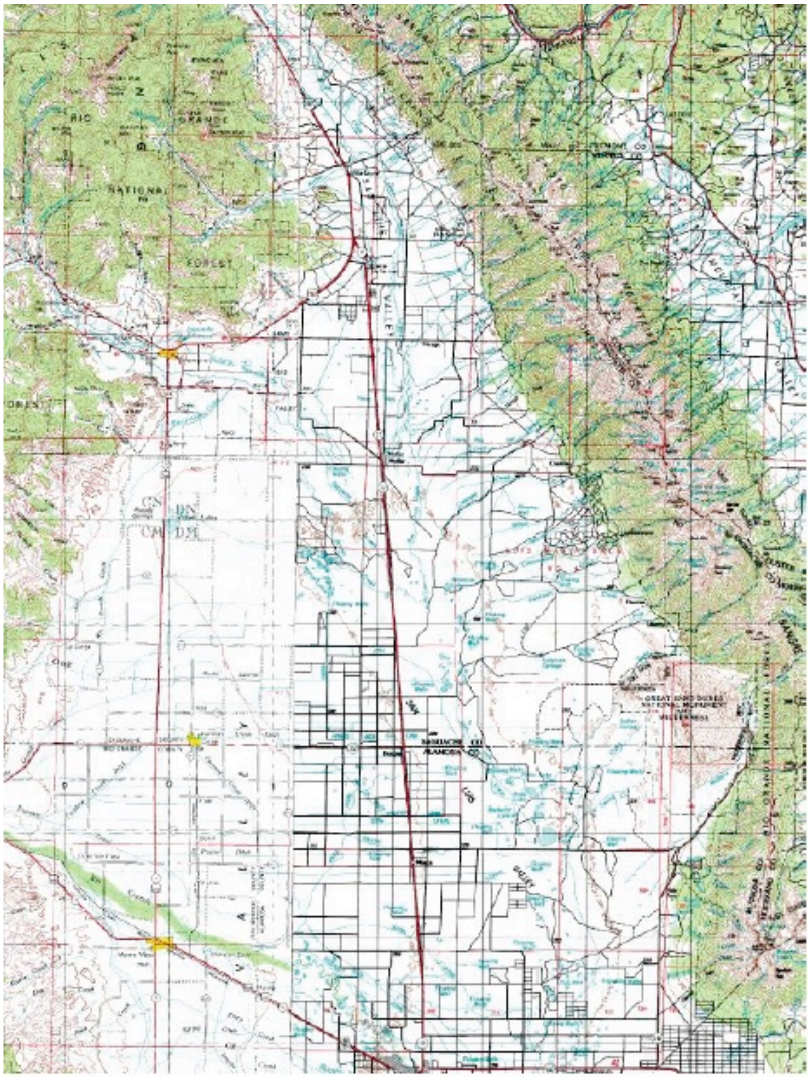


Figure 3-2: Topographic Map of the San Luis Valley

Closer inspection of the topographic surface elevation of the land in comparison to the water table elevation reveals generally small depths to water in a large portion of the valley. Water table elevation rises with surface elevation in closer proximity to the mountains bordering the valley, though the surface elevation gradient is generally greater. This is an indication that potential high-head sites lie around the border of the valley. Well data presented in a previous section indicates that deeper water table regimes can be found on a site-by-site basis. Therefore, in order to accurately pinpoint a viable site, a measurement of water table depth must be taken at that site, or data from nearby wells must be reviewed.

Considering the minimum requirements for an aquifer UPHS system, for a 200 ft (60.1 m) thick aquifer, a transmissivity of 2.6 ft^2/min (40.3 cm^2/s) translates to a hydraulic conductivity of 0.013 ft/min (0.0066 cm/s). The following Table 3-2 summarizes the typical range of hydraulic conductivity and transmissivity values for different geologic materials [7].

Material	**k [cm/s]**		**k [ft/min]**		**Transmissivity [cm^2/s] (aquifer depth = 61 m)**		**Transmissivity [ft^2/min] (aquifer depth = 200 ft)**	
	min	max	min	max	min	max	min	max
Unconsolidated								
Gravel	1.0E-01	1.0E+01	2.0E-01	2.0E+01	610	60960	39	3936
Sand	1.0E-04	1.0E+00	2.0E-04	2.0E+00	0.610	6096	0.039	394
Silt	1.0E-07	1.0E-03	2.0E-07	2.0E-03	0.001	6.096	0.000039	0.394
Clay and Glacial Till	1.0E-11	1.0E-06	2.0E-11	2.0E-06	0.0000000610	0.006	0.000000004	0.000394
Sedimentary Rock								
Sandstone	1.0E-08	1.0E-03	2.0E-08	2.0E-03	0.000061	6.096	0.000004	0.394
Limestone, Dolomite	1.0E-07	1.0E-01	2.0E-07	2.0E-01	0.001	610	0.000039	39
Karst Limestone	1.0E-04	1.0E+00	2.0E-04	2.0E+00	0.610	6096	0.039	394
Shale	1.0E-11	1.0E-06	2.0E-11	2.0E-06	0.0000000610	0.006	0.0000000039	0.000394
Crystalline Rock								
Basalt	1.0E-09	1.0E-05	2.0E-09	2.0E-05	0.000006	0.061	0.0000003936	0.004
Fractured Basalt	1.0E-05	1.0E+00	2.0E-05	2.0E+00	0.061	6096	0.004	394
Dense Crystalline Rock	1.0E-12	1.0E-08	2.0E-12	2.0E-08	0.0000000061	0.000061	0.0000000004	0.000004
Fractured Crystalline Rock	1.0E-06	1.0E-02	2.0E-06	2.0E-02	0.006	60.960	0.000394	3.936

Table 3-2: Typical Ranges of Hydraulic Conductivity and Transmissivity in Aquifer Materials

Based on the ranges in Table 3-2, unconsolidated gravel and sand, sedimentary limestone, dolomite, Karst limestone, and crystalline fractured basalt aquifer geologies are candidates for aquifer UPHS.

In the San Luis Valley, reported aquifer transmissivity values reach as high as 225,000 gallons per day per foot (20.9 ft^2/min, 323.4 cm^2/s) and well yields can be as high as 3,000 gal/min (0.189 m^3/s), giving the unconfined aquifer favorable characteristics for large-scale irrigation [9].

Hydraulic conductivities in the high plains Ogallala aquifer generally lie in the range of 25 to 100 feet per day (0.017 ft/min to 0.07 ft/min, 0.0086 cm/s to 0.036 cm/s) with an average estimated at 51 feet per day (0.035 ft/min, 0.018 cm/s) [1]. In addition, the maximum thickness of this aquifer can exceed 700 feet (213.4 m) [1]. Using these ranges, the transmissivity for several cases is calculated and shown in Table 3-3. The table selects a minimum, maximum, and median value within the above ranges for hydraulic conductivity and thickness. From these entries, an average expected transmissivity is calculated to be 17.4 ft^2/min (269.4 cm^2/s).

k [ft/day]	k [ft/min]	thickness [ft]	T [ft^2/min]
25	0.017	100	1.74
25	0.017	400	6.94
25	0.017	700	12.15
50	0.035	100	3.47
50	0.035	400	13.89
50	0.035	700	24.31
75	0.052	100	5.21
75	0.052	400	20.83
75	0.052	700	36.46
100	0.069	100	6.94
100	0.069	400	27.78
100	0.069	700	48.61
		average	17.36

Table 3-3: Transmissivity Averaging Calculations for Ogallala Aquifer

The depth to water and flow yield of a well are important parameters to lead the search for a suitable aquifer UPHS site. Data is available from the Division of Water Resources' Colorado Decision Support System (CDSS) for millions of wells in the state of Colorado. However, data can be extracted for only 25 wells at one time, for only a specified 30 mile by 30 mile (48.3 km by 48.3 km) area of the state per query. This makes it very difficult to perform a comprehensive survey of Colorado wells. The full set of data is available to purchase from the Colorado DWR for at a considerable cost.

The author attempted to find viable wells, based on depth to water and yield data, using the CDSS system. This search was limited compared to the total amount of data available. Even so, a small sampling of wells in the eastern plains of Colorado and in the San Luis Valley indicate that both high yield wells are common (greater than 1000 gal/min = 0.0631 m^3/s) and also that deep water tables occur (greater than 300 ft (91 m) depth to water). In searching for candidate wells, several wells having greater than 2000 gal/min (0.126 m^3/s) yield rates were found, though the vast majority of these operate with very small depths to water. In addition, a few wells with depths of greater than 300 ft (91 m) were identified in the Ogallala aquifer. It makes sense that not many installations with both high head and flow exist, because of the increasing cost to pump high yields with high heads. Because of this fact, and the sheer number of wells to search, only few reported potentially suitable wells were found. One such well is located in the southern high plains, and another in the southern San Luis valley of Colorado. The data for these wells, and a sampling of some other reported wells from the CDSS are given in Table 3-4. These data suggest that the necessary characteristics for an aquifer UPHS well do exist, and therefore required wells could potentially be modified or dug to support aquifer UPHS installations.

PERMIT NO	USE	AQUIFER	WELL_YIELD	WELL_DEPTH	WELL_LEVEL	COUNTY	REGION
5118	IRRIGATION	ALL UNNAMED AQUIFERS	2800	80	50	CONEJOS	San Luis
14246	IRRIGATION	ALL UNNAMED AQUIFERS	1500	320	290	COSTILLA	San Luis
14246	**IRRIGATION**	**ALL UNNAMED AQUIFERS**	**1500**	**320**	**290**	**COSTILLA**	**San Luis**
14573	IRRIGATION	ALL UNNAMED AQUIFERS	1250	280	232	PHILLIPS	Northeast
15919	**IRRIGATION**	**ALL UNNAMED AQUIFERS**	**1400**	**300**	**270**	**PHILLIPS**	**Northeast**
84282	DOMESTIC	ALL UNNAMED AQUIFERS	15	743	359	LINCOLN	Northeast
5934	IRRIGATION	ALL UNNAMED AQUIFERS	1000	741	341	BACA	Southeast
12287	IRRIGATION	ALL UNNAMED AQUIFERS	1200	612	288	BACA	Southeast
5935	IRRIGATION	ALL UNNAMED AQUIFERS	500	698	320	BACA	Southeast
210417	DOMESTIC	CHEYENNE	15	720	580	KIOWA	Southeast
146445	STOCK	DAKOTA	21	900	540	CROWLEY	Southeast
35123	STOCK	ALL UNNAMED AQUIFERS	5	1730	1480	PUEBLO	Southeast
25629	STOCK	ALL UNNAMED AQUIFERS	8	675	440	OTERO	Southeast

Table 3-4: Sampling of Well Data from DWR CDSS [8]

The search for aquifer UPHS sites can be guided by a general knowledge of existing well characteristics. It should be noted that there is potential for high-head wells in many areas around the state. Table 3-5 provides a compilation of reported well data available on hydraulic characteristics of the major unconfined alluvial aquifer systems in Colorado [10]. In addition, reported values of transmissivity in the San Luis Valley aquifer range from about 0.5 ft^2/min (7.74 cm^2/s) to 20.4 ft^2/min (315.9 cm^2/s). Existing wells may not occupy the sites that are best suited for aquifer UPHS. Based on this information, and the intensity of agricultural operations, the Lower South Platte River region and the San Luis valley are targeted as reasonable places to search for suitable sites. As a side note, the southeastern plains of Colorado also harbor existing wells with large depths to water in the unconfined aquifer. This is evidenced by the well data Table 3-4.

	Depth to Water [ft]		Yield [gpm]		Hydraulic Conductivity [ft/min]		Transmissivity [ft^2/min]	
	Min	Max	Min	Max	Min	Max	Min	Max
Lower Arkansas River	5	30	10	4000	0.049	0.833	1.389	41.667
Upper Arkansas River	5	58	1	500				
Lower South Platte River	0	215	1	3000	0.069	1.389	2.778	76.389
Beebe Draw					0.278	2.222	8.333	83.333
Box Elder Creek					0.076	0.438	2.222	13.889
Cache La Poudre					0.229	1.458	4.167	46.528
Clear Creek					0.031	0.278	0.653	1.667
Lone Tree Creek					0.194	0.625	2.778	34.028
Cherry Creek					0.139	0.486	8.333	21.528
Upper South Platte River	0	80	1	100				
Colorado River Basin	1	70	1	1600				
Yampa River Basin	0	45	1	15	0.001	0.020		
White River Basin	3	90	2	600			0.597	64.583
Gunnison River Basin	2	63	1	750	0.003	0.069	0.003	0.556
Republican/Arikaree Basin	5	64	1	1000	0.021	0.188		
San Luis River System	1	181	1	50	0.000	0.139		
Dolores River Basin	2	90	1	200				

Table 3-5: Aquifer Properties From Reported Well Data [10]

3.2 Colorado Agriculture and Irrigation

Agriculture in Colorado predominates in the eastern plains, the San Luis valley and in the west near Grand Junction. Corn, hay, wheat and potatoes dominate the crop profile for the state, with much of this produce used to feed livestock.

In the northeastern plains of Colorado, significant agricultural activity exists that utilizes the Republican/Arikaree River basin aquifer system. The many irrigation wells in the area experience rather shallow depths to water. This aquifer is part of the Ogallala system, and has relatively high transmissivity and hydraulic conductivity because of the unconsolidated sediment that makes up portions of the aquifer [10].

The San Luis valley is an agricultural hotbed, growing potatoes, corn, hay and alphalpha in large quantity. The aquifer underlying the valley supplies a great deal of the water used for irrigation. Figure 3-3 shows a satellite image of crop circles north of Alamosa, Colorado. The dominant method of irrigation is by use of center-pivot irrigation systems.

The northeastern plains of the state also harbor significant irrigation activity for agriculture. Utilizing the South Platte River and the Republican/Arikaree River systems, nearly all of the irrigation water comes from underground sources. Figure 3-4 is a satellite image of crop circles in Yuma County, Colorado.

While surface water irrigation is more common across the state as a whole, a significant amount of groundwater irrigation occurs in the San Luis valley and along the eastern plains. Figure 3-5 shows the ratios of groundwater irrigation to surface water irrigation for regions across the state [10].

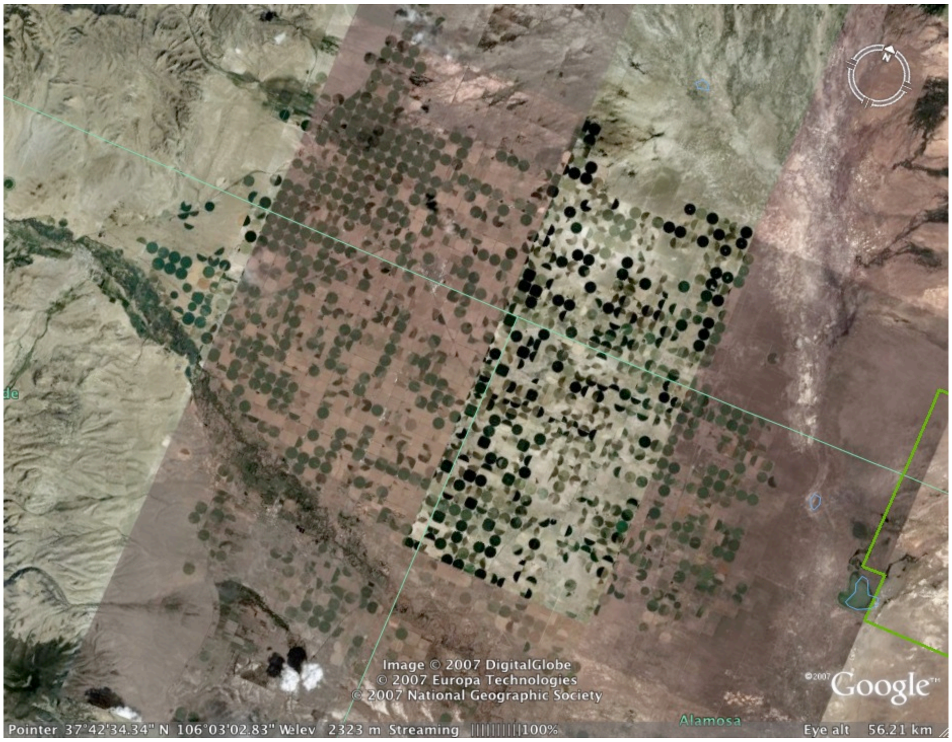


Figure 3-3: Satellite Image of Crop Circles in the San Luis Valley

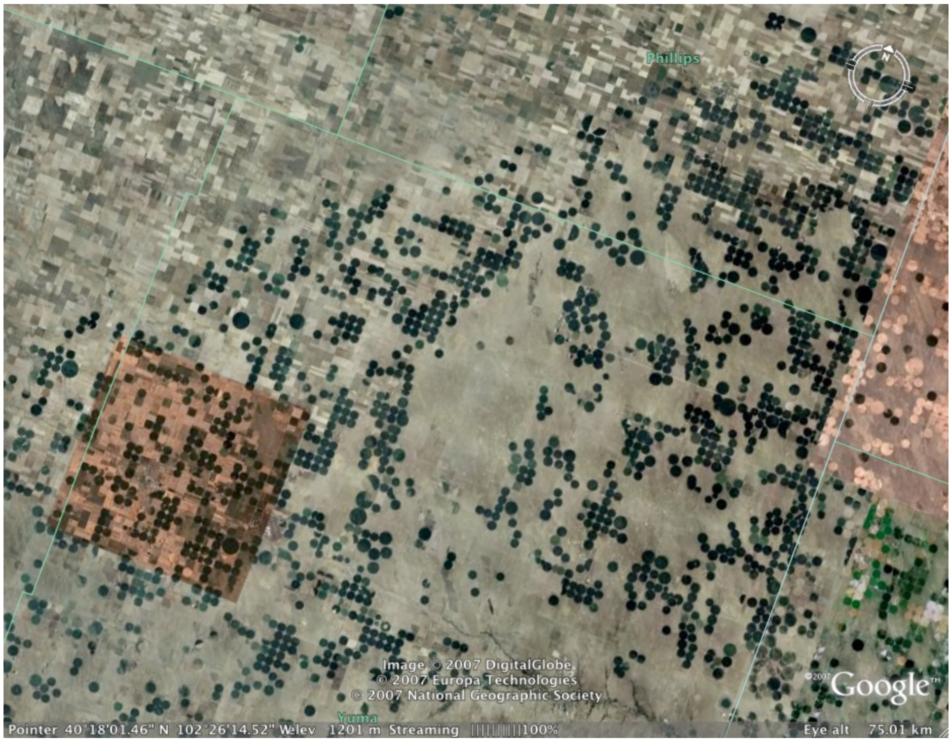


Figure 3-4: Satellite Image of Crop Irrigation in Colorado's Yuma County

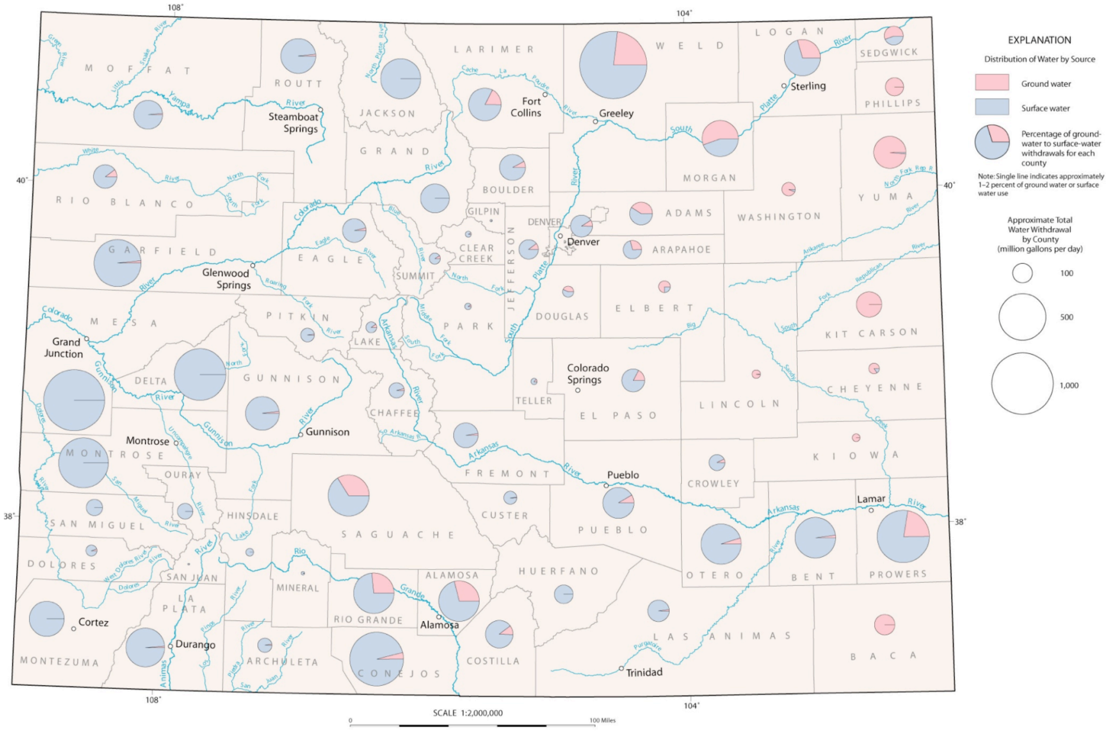
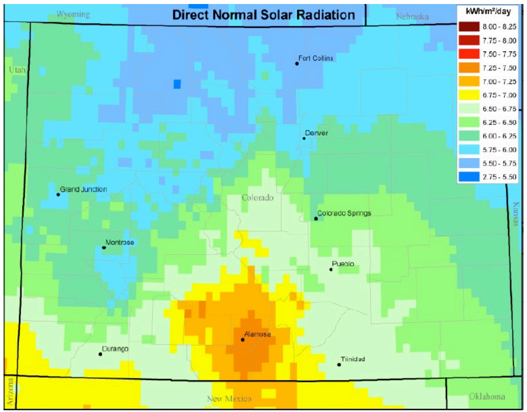


Figure 3-5: Irrigation Water Sources in Colorado [10]

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. Figure 3-6 shows the incident solar insolation intensity for the state of Colorado.



Source: NREL website, Concentrating Solar Power Resource Maps, http://www.nrel.gov/csp/pdfs/csp_co_nrel_11x17.pdf, 06-05-18.

Figure 3-6: Solar Insolation Map of the State of Colorado

Furthermore, a relatively large percentage of irrigation water in the valley is pumped from underground sources. The following passage summarizes the nature and use of the underground water resource in the San Luis Valley. This passage is taken from the Groundwater Atlas of Colorado [10]:

> *"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…*
>
> *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."* [10]

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, 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. Depending on the depth to water and the flow requirements, pumping water using grid electricity can be expensive. One agriculturalist in the San Luis valley reported an annual electrical bill of about $90,000 for irrigation pumping for ten 160 acre center-pivot irrigated crops.

To correctly size an energy source and energy storage system, crop irrigation requirements were studied. While there is no set irrigation schedule, the seasonal water needs can be assessed and averaged per day, per week and per month. A potato crop was assumed, requiring approximately 12 inches of water (in addition to sparse rainfall) per season. The total water need was increased to account for evaporation and runoff. The growing season is assumed to be five months long, April through August. Table 3-6 summarizes the potato crop irrigation requirements and average irrigation time per day, per month and per season. A standardized irrigation water flow of 850 gallons per minute (0.054 m^3/s) was assumed. Assuming a crop area of 130 acres (526091 m^2) takes 6 hours to impart 0.1 inches (0.254 cm) of water, the average irrigation time for each segment is also estimated in Table 3-6.

Seasonal Water Needed	16 inches
Monthly Water Needed	3.2 inches
Weekly Water Needed	0.8 inches
Daily Water Needed	0.11 inches
Irrigation Time Per Season	960 hours
Irrigation Time Per Month	192 hours
Irrigation Time Per Week	48 hours
Irrigation Time Per Day	6 hours

Table 3-6: Estimated Water Needs of Potato Crop in the San Luis Valley

3.3 Legal Considerations [14]

A detailed analysis of the legal and regulatory considerations involved with the proposed aquifer UPHS system was preformed by the University of Colorado at Boulder School of Law as part of this research project [14]. The information and findings presented in this section are taken directly from the text of this report. The findings and recommendations of the authors of [14] are found in section 3.3.4 below.

3.3.1 Water Rights and Usage

"Tributary ground water is considered 'water of every natural stream' as the phrase is used in the Colorado Constitution and is thus subject to appropriation (see C.R.S. § 37-82-101). The basis for this classification is the hydrological connection of this ground water to surface water. Legally, it is generally treated the same as surface water (e.g., rivers and streams). The provisions of the Water Right Determination and Administration Act of 1969, as modified since original enactment, govern the use of natural stream water within the state, including tributary ground water. Thus, tributary ground water is subject to the prior appropriation scheme.

There is a presumption that all ground water is tributary. Stonewall Estates v. CF & I Steel Corp., 592 P.2d 1318, 1320 (Colo. 1979). Thus, one must prove to the court that ground water is non-tributary in order to receive that designation. If so designated, non-tributary ground water is subject to a different set of rules. However, it is difficult to prove that ground water is not tributary to a stream. While tributary water is annually replenished, non-tributary water is 'subject to eventual depletion'.

Because tributary aquifer ground water is water contained in an aquifer that is directly connected to the local stream system, *generally, the water table in such an aquifer is relatively shallow. On the other hand, deep aquifer ground water is not so directly connected to the surface stream system (i.e., non-tributary ground water is more likely to be deep aquifer ground water). Thus, typically, a site using non-tributary ground water (may) better meet the needs (i.e., head requirement) for the aquifer UPHS system. Further, there are other advantages associated with the non-tributary regulatory scheme, such as the manner in which water rights are allocated and the accounting mechanism for water use.*

Because aquifer UPHS will be putting water to a different use, a change of water right (a.k.a. "change of use") must be undertaken for both tributary and non-tributary ground water. An application for a change of water right must be pursued through the water court.

If some of the water used for (aquifer UPHS) is not designated as agricultural (which may include the water necessary to impound for drainage/energy production and any associated evaporation), this water will not enjoy Article XVI protection in times of shortage.

Where tributary ground water is being used and the well does not have an associated right sufficient for the desired use, the well will be taking water out-of-priority (because it is too junior in the system). Here, a plan for augmentation must by applied for through the water court. Non-tributary ground water is treated somewhat differently in that the amount of water that can be withdrawn under the permit is the amount determined by the court decree of rights.

It is assumed in this analysis that a permitted well already exists. As a result, the well may already have an augmentation plan associated with it if it does not have rights sufficiently senior so as to not be out-of-priority. An augmentation plan decree includes *an identification of the beneficial uses that the plan is augmenting (Empire Lodge, 39 P.3d at 1150–51). It likely follows then that where the augmented beneficial uses change, some sort of notification, application, or amendment needs to be made to the water court. It is possible to have more than one plan for augmentation on a well at one time. Having a separate plan preserves the original use in case the new use ceases sometime in the future. Therefore, the water right holder may opt not to change an existing augmentation plan and to instead develop a new and separate plan. (Email from Dick Wolfe, Assistant State Engineer, July 1, 2007, on file with authors).*

Non-tributary water does not have the same difficulties of replacing out-of-priority depletions because it is not governed by prior appropriation. As a result, it is considered 'developed water' (the phrase normally refers to water imported from another basin) and can be used and reused by the appropriator. Instead of by prior appropriation, it is allotted based on overlying land ownership. Another benefit to having and using non-tributary ground water is that the landowner can 'bank' the supply of ground water, saving any unused allotment for use in future years.

Another question that arises is whether a storage right must be obtained for the surface impoundment. Because (aquifer UPHS) will be utilizing the water by storing in the surface impoundment for later use rather than putting it directly to use (such as for irrigation), it may be that a storage right is necessary. However, if the plan for augmentation or the change of water right, or both, clearly describe the process to be used and clearly accounts for all losses (like evaporation and seepage), one likely does not need to file for a storage right (Email, Wolfe, supra).

3.3.2 Well Permitting

If the equipment in a well is changed, such as that required for the (aquifer UPHS) system, it appears that a new well permit must be obtained. The State Engineer requires that a new well permit be obtained prior to:

1. *changing the producing interval of an existing well,*
2. *installing certain dewatering systems as specified by the State Engineer,*
3. *installing pumping equipment that will withdraw ground water for beneficial use, or*
4. *installing pumping equipment having a sustained production rate in excess of the permitted production rate.*

Further, there may be well construction requirements, pursuant to federal laws and regulations applicable to re-injection of water into underground sources. Underground injection permitting will be required for the aquifer UPHS system. The EPA Site Information Request Fact Sheet form for injection well permitting is included in Appendix A.

3.3.3 Water Quality

The drainage of water from the surface impoundment down to the underground source, or aquifer, implicates laws and regulations regarding water quality.

3.3.3.1 Federal Regulations

Class V injection well requirements under the federal Safe Drinking Water Act (SDWA) will apply. Protection of other water rights, including the quality of water of that right, is required.

Underground injection is the technology of placing fluids underground through wells. Because of ground water contamination occurrences in the 1960-1970s as a result of underground injection, Congress passed the Safe Drinking Water Act (SDWA) in 1974 which required the US EPA to establish a system of regulations for injection activities (42 U.S.C. §§ 300h to 300h-8 - Part C of the SDWA). The regulations are designed to establish minimum requirements for controlling all injection activities and provide mechanisms for implementation and authorization of enforcement authority and also provide protection for underground sources of drinking water.

Historically, the SDWA has applied to water returned to an underground source through aquifer recharge or aquifer storage recovery (ASR) wells. However, based on the definition of 'well' and the lack of any applicable exclusion, it appears that this Act would apply to the (aquifer UPHS) system contemplated here as a Class V well. The Underground Injection Control (UIC) program defines a well as any bored, drilled or driven shaft or a dug hole, where the depth is greater than the largest surface dimension that is used to discharge fluids underground (see 40 C.F.R. §144.1(g)(1)(ii)).

The decision to deliberately subject all underground injection wells to regulation is repeated in Subpart B, General Program Requirements of Part 144: 'Any underground injection, except into a well authorized by rule or except as authorized by permit … is prohibited.' (50 C.F.R. §144.11). Injections of fluids without regulation could potentially contaminate ground water and drinking water sources. Because the contamination of ground water would be very difficult to remediate, it is important to ensure that contaminants do not enter the ground water in the first place.

To comply, the owner or operator of a Class V well is required to submit basic inventory information and is required to operate the well such that a USDW is not endangered. Of great interest to this project is that because ASR and aquifer recharge wells are authorized by rule, they do not have to obtain a permit unless required to do so by the Underground Injection Control (UIC) Program Director under 40 CFR §144.25

3.3.3.2 State Regulations

The water courts and the Water Quality Control Commission (WQCC) created by the Water Quality Control Act (WQCA) both have authority with respect to water quality, but their authorities do not overlap. This dual system limits both water courts and the WQCC in their authorities with respect to water quality issues. This result unfortunately leaves some gap where issues may not be addressable by either the court or the agency. The second 'system' in Colorado's dual system governing water quality is the court system. While the majority of water quality issues are delegated to the WQCC, Denver Application, 44 P.3d 1019, water courts still retain exclusive authority with respect to the determination and administration of water rights. 'Any substituted water shall be of a quality and quantity so as to meet the requirements for which the water of the senior appropriator has normally been used.'

Thus, if the change in quality of the water does not affect the use that the downstream appropriators are entitled to, then there is no pollution and no injury with respect to the augmentation plan or re-injection of water. Water sources under consideration for (aquifer UPHS) will likely be under the standard to protect existing quality.

The key issue will be what changes occur to the water while it is impounded and whether it will introduce 'pollutants' into the underground source when it is drained, or re-injected, back down. This in turn will depend on a number of factors, for example: the length of time the water remains stagnant in the impoundment; composition of material the impoundment is made of; the height of the barrier and whether it permits runoff to enter; whether the surface of the impoundment is closed or open; what kind of airborne pollutants are in the area; and if the water is filtered before re-injection. The type of impoundment will also affect the amount of water necessary to implement the (aquifer UPHS) system, (i.e., the evaporation rate). Therefore, the cost of compliance with water quality standards would need to be assessed on a case by case basis.

3.3.4 Legal Recommendations

Some generalities can be made about site preferences for the (aquifer UPHS) system. Designated basins, for a number of reasons, will probably not be advantageous sites for implementation of the system. The reasons include: the depth of wells associated with designated basins are typically too shallow for the necessary head; these are typically over-appropriated water sources; and there is a more involved permitting process. Between tributary and non-tributary sources, non-tributary sources appear to be more advantageous because of the manner in which water rights are allocated and the accounting mechanism for water uses. In addition, wells for non-tributary water sources will usually be deeper. However, for testing purposes, substitute supply plans (SSP) are an option for tributary water sources. The SSP provides an expedited permitting process for temporary projects that meet certain criteria." [14].

4 Case Study Analysis

To further develop understanding of the aspects of installing and using the proposed aquifer UPHS system, a case study analysis is undertaken in this chapter. The purpose of this exercise is to provide a practical example of design trade-offs and cost estimations likely to be encountered in implementing this system. Actual well sites in the San Luis valley and Yuma County, Colorado are used as a starting point. The basic characteristics for these sites draw from the information presented in prior chapters of this paper, and from actual well record information. The system implementation and operation is discussed, and an economic analysis of the example aquifer UPHS system is provided. In addition, a proposed test plan to determine the operating characteristics of a potential aquifer UPHS site is included in Appendix B.

4.1 Well Site Selection

A search of well record data in the Colorado Division of Water Resources CDSS [8] system turned up two candidate wells for aquifer UPHS modification. One well is in the southern part of the San Luis valley (site 1), and one is in Philips county in northeastern Colorado (site 2). Both sites were selected because of their reported high flow and head. Figure 4-1 shows a satellite image locating site 1, with Table 4-1 giving the reported well parameters. Figure 4-2 locates site 2 and Table 4-2 lists the reported well parameters. It was not possible for the author to search every well in these regions, and in many cases well data is incomplete. It is therefore likely that even better candidate wells (i.e. higher head) for aquifer UPHS exist in these regions.

Figure 4-1: Location of Site 1 in the San Luis Valley of Colorado

Permit Number	**14246**
Division	3
City	ALAMOSA
Water District	24
Name	RIO GRANDE RANCHES OF COLO
Address 1	PO BOX 724
City	ALAMOSA
State	CO
Zip	81101
Aquifer 1	ALL UNNAMED AQUIFERS
Use 1	IRRIGATION
Yield (gal/min)	**1500**
Depth (feet)	320
Level (feet)	**290**
Meridian	C
Township	2
Township Dir	N
Range	74
Range Dir	W
Section	32
Qtr 160	NE
Qtr 40	SE
Coords NS (feet)	1520
Coords NS Dir	N
Coords EW (feet)	955
Coords EW Dir	E

Table 4-1: Reported Data for Site 1 Well

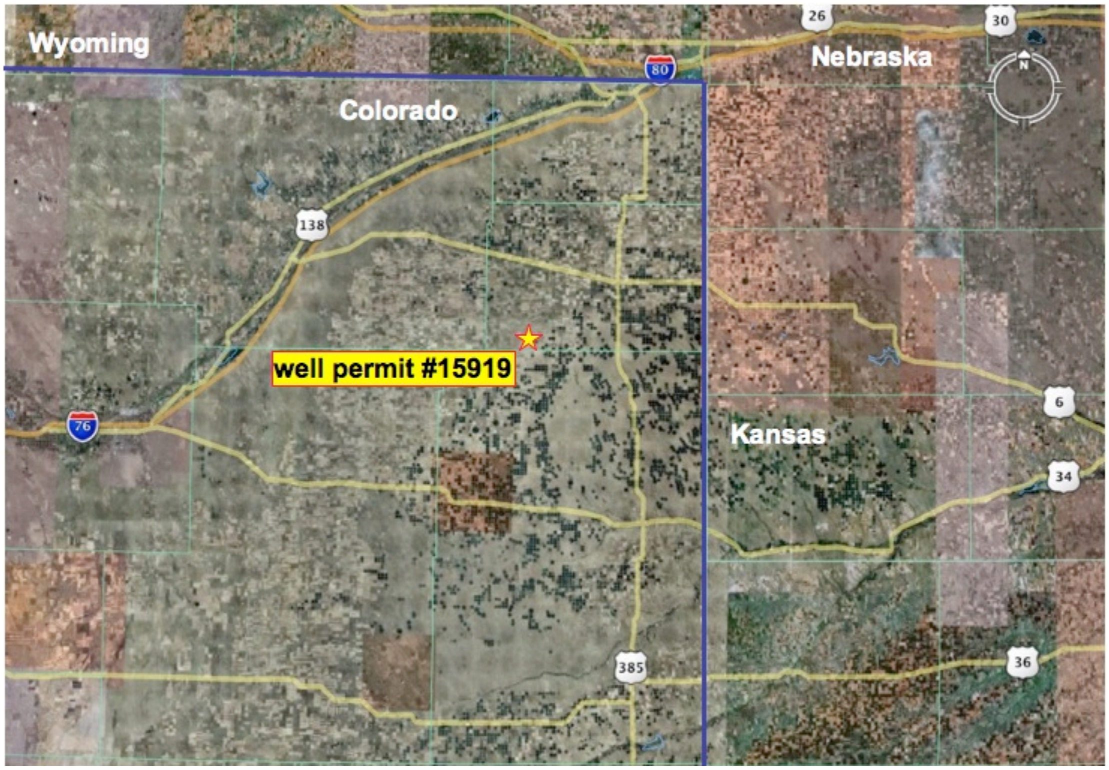


Figure 4-2: Location of Site 2 Well in Philips County, Colorado

Permit Number	**15919**
Division	8
City	ECKLEY
Water District	65
Designated Basin	NORTHERN HIGH PLAINS
Management District	FRENCHMAN
Name	TUELLAND INC
Address 1	15742 CR 48
City	ECKLEY
State	CO
Zip	80727-
Aquifer 1	ALL UNNAMED AQUIFERS
Use 1	IRRIGATION
Yield (gal/min)	**1400**
Depth (feet)	300
Level (feet)	**270**
Meridian	S
Township	6
Township Dir	N
Range	46
Range Dir	W
Section	32
Qtr 160	NE
Qtr 40	SW
Coords NS (feet)	1330
Coords NS Dir	N
Coords EW (feet)	1330
Coords EW Dir	E

Table 4-2: Reported Data for Site 2 Well

4.2 Energy and Water Use Assumptions

Given the high yield of the chosen wells, it is likely that the water is used for irrigation of two moderately water intensive crops. Further, based on the satellite images, it is very likely that these crops are the standard 130 acre (526091 m^3) center-pivot irrigated plots. Assumptions about the water required for irrigating potato crops, as introduced in section 3.2, support these assertions. A peak water flow per plot of 850 gal/min (0.054 m^3/s) is assumed, however the total flow yield may be shared between the two plots during non-peak conditions.

The major power consumer for conventional irrigation is typically a 50 to 75 horsepower (37 kW to 56 kW) well/pressurization pump that draws water from the aquifer and provides pressurized water to the irrigation distribution system. Several motor wheel drives move the irrigation arm in a circle. Chemigation and fertigation pumps may be used to feed chemicals and fertilizer into the irrigation water, though these installations are not included in this analysis. Household and shop electrical demand are included as loads to be supplied by the aquifer UPHS system. The connected electrical load ratings assumed and average electrical load requirements are summarized in Table 4-3.

Load Description	**KW**	**QTY**	**TOTAL kW**	**Duty Cycle**	**Avearge kW**
Main well and irrigation AC pump (50hp)	37.3	2	74.6	100%	74.6
Pivot arm wheel drive (1.25hp)	0.9	4	3.7	75%	2.8
Pivot arm wheel drive (1.25hp)	0.9	4	3.7	75%	2.8
Pivot arm wheel drive (1.0hp)	0.7	4	3.0	75%	2.2
Pivot arm wheel drive (1.0hp)	0.7	4	3.0	75%	2.2
Pivot arm wheel drive (1.0hp)	0.7	4	3.0	75%	2.2
Pivot arm wheel drive (0.75hp)	0.6	4	2.2	75%	1.7
Pivot arm wheel drive (0.75hp)	0.6	4	2.2	75%	1.7
Pressure Boost Pump (25 hp)	18.7	2	37.3	75%	28.0
Household heat, light, misc	10.0	1	10.0	50%	5.0
Shop Power	5.0	1	5.0	25%	1.3
Total (without main well pump)	**38.9**		**73.2**		**49.9**

Table 4-3: Electrical Load Analysis for Agricultural Operations

Because the pump-turbine unit has the job of either pumping water or generating power, it does not need to be sized for the entire sum of the loads in Table 4-3. Rather, it is sized to produce enough power to supply all of these loads except the main well pump. The job of the conventional main well/pressurization pump is to provide the rated flow yield of water at 50 psi (344.7 kPa) to the irrigation systems. In the aquifer UPHS installation, the well pump must only provide rated flow to the surface, overcoming gravity. To calculate the power input required to the aquifer UPHS main pump, the basic fluid power equation is used:

$$P = Q \cdot H \cdot \rho \cdot g \cdot \eta$$

where;

$Q = 0.095\ m^3/s = 1500$ gal/min

$H = 88.4$ m $= 290$ ft

$\eta = 65\%$

This calculation for site 1 gives 53.5 kW (71.7 hp) for maximum pumping power during the up-cycle. For turbine operation during the down-cycle, the load analysis of Table 4-3 shows an average requirement of 49.9 kW. The designer must at this point decide whether the turbine should be sized to accommodate the average load or the peak load. If the user can adapt to not having all loads running simultaneously at rated power, the system could utilize a smaller turbine. To optimize cost and utilization of the pump-turbine unit, it is recommended to size the turbine for the average load, 50 kW. This matches nicely with the pumping power requirement from the conventional case. Since the pump-turbine is a combined unit, this design fully utilizes the pump and turbine ratings.

Once the water has been pumped to the surface by the main well pump, flow and pressure must be supplied to the irrigation system using boost pumps. The conventional center-pivot irrigation systems are typically pressurized at 50 psi (344.7 kPa). As established previously, the wells in question are used to supply 850 gal/min (0.054 m^3/s) peak to each crop plot. This indicates the use of two boost pumps that pump surface water to the irrigation heads at 50 psi (344.7 kPa). To calculate the power rating of these pumps, the following fluid power equation is used:

$$\text{Power[hp]} = \frac{Q[\text{gpm}] * P[\text{psig}]}{1714} = \frac{850 * 50}{1714} = 24.8\text{hp} = 18.5\text{kW}$$

The system requires two boost pumps, each rated at 18.5 kW (24.8 hp).

Significant energy and power can be saved by using efficient, low pressure irrigation methods. Low elevation precision application (LEPA) and low energy spray application (LESA) systems can operate are pressures as low as 6 to 10 psi (41.4 kPa to 68.9 kPa) [15]. They can save between 20% and 40% of the energy consumed by a conventional 50 psi (344.7 kPa) spray system. These methods are options for agriculturalists to greatly reduce the power and energy required for the boost pumps, potentially reducing cost in other parts of the system.

4.3 Well Characteristics and Modifications

Two wells were selected for this case study. They have similar head and flow characteristics, and likely have comparable aquifer properties. In this section, design parameters will be calculated or assumed for each well, and recommendations for modifications are made for each.

The site 1 well is an irrigation-grade well in the San Luis valley that yields 1500 gal/min (0.095 m^3/s), and has a depth to water of 290 feet (88.4 meters). This flow rate and head would be sufficient for the required 50 kW (67 hp) of turbine power generation only if the entire head drop (290 ft) could be used for power generation. This is not the case, because as indicated in Chapter 2, a mound of injection will form which reduces the effective head of the turbine. The height of this mound depends on the transmissivity the aquifer, storage coefficient, and flow. From section 3.1, the probable range of transmissivity for this aquifer is 0.4 ft^2/min (6.2 cm^2/s) to 20.4 ft^2/min (315.9 cm^2/s). For this analysis, a middle value of 10 ft^2/min (154.8 cm^2/s) is used. This value assumes that a well is completed through the entire thickness of the aquifer, and that the aquifer is relatively thick (approximately 200 ft (60 m) or greater). Flow is determined using the groundwater drawdown equation from Chapter 2 with an iterative calculation model to find the flow that maintains a power output of 50kW (with increasing injection mound height). The following parameters are held constant in the model:

storage coefficient = 0.05
transmissivity = 10 ft^2/min = 154.8 cm^2/s
well radius = 1 ft = 0.305 m
time = 360 min

The model finds that a flow of 1550 gal/min (0.098 m^3/s) creates a mound of injection 19.4 feet (5.9 m) high, and a turbine operating at 65% efficiency can produce 50.6 kW (68 hp). The resultant effective head for the turbine is 270.6 feet (82.5 m).

Using the same model, the effect of transmissivity on mound height and power output is investigated. The model finds that there is no flow solution that yields 50 kW for transmissivities less than 2.2 ft^2/min (34.1 cm^2/s).

Since the flow increase to support aquifer UPHS in this case is small (25 gal/min, 0.0016 m^3/s), it is likely that no modifications are required to increase the flow of the well. We must remember that this analysis assumes the well is completed through the entire thickness of the aquifer. If this is not the case for the existing well, then this modification should be made.

The site 2 well is also an irrigation-grade well, but it is located in northeastern Colorado, drawing from the Ogallala aquifer. It has a depth to water of 270 feet (82.3 m) and a yield of 1400 gal/min (0.088 m^3/s). In the absence of a mound of injection, a turbine powered by this flow and head would produce about 46 kW (61.7 hp). Therefore, it is clear that the injection flow into the aquifer through this well will have to be increased beyond its rated yield. In section 3.1, an average transmissivity for the entirety of the Ogallala aquifer was found to be 17.4 ft^2/min (269.4 cm^2/s). For this analysis, a conservative transmissivity value of 10 ft^2/min (154.8 cm^2/s) is used. This value assumes that a well is completed through the entire thickness of the aquifer. The iterative modeling method used above is applied to this case, with the same constant parameters. It finds that the injection flow should be increased to 1650 gal/min (0.104 m^3/s), at which point 50.4 kW (67.6 hp)can be generated with an injection mound of 21.0 feet (6.4 m). This gives an effective head for the turbine of 249.0 feet (75.9 m).

Again, the effect of transmissivity is investigated with the goal of finding the lowest transmissivity value that yields a flow solution. The model indicates that transmissivities of less than 2.6 ft^2/min (40.3 cm^2/s) have no flow solution that gives 50 kW.

In this case, the flow must be increased by 250 gal/min (0.016 m^3/s) compared to the rated pumping yield. This well may require the use of radial pipes in the aquifer to increase the surface area of contact with the aquifer. Another option is to excavate an infiltration pit to reduce the height of the injection mound. As before, it is assumed that this well is completed through the entire thickness of the aquifer.

4.4 Surface Reservoir

The surface reservoir design depends on the amount of energy to be stored, manifested in the generating cycle flow rate, and the amount of water used for irrigation. In previous sections, the volume, rate, and schedule of irrigation water required by the assumed crops, has been established. An irrigation water flow of 850 gal/min peak for each crop at a peak of 6 hours per day has been assumed. At 50 kW, the reservoir must store 300 kWh of gravitational potential energy with respect to the water table. For the wells in question, the peak flow cannot be supplied to each crop simultaneously, and the available flow yield from the well is shared between them. The volume of water required per day is calculated as flow multiplied by time. The result for each site is:

Site 1: (1500 gal/min)*(360 min) = 540,000 gal = 1.66 acre-ft

(Site 1: (0.095 m^3/s)*(360 min) = 2052 m^3)

Site 2: (1400 gal/min)*(360 min) = 504,000 gal = 1.55 acre-ft

(Site 2: (0.088 m^3/s)*(360 min) = 1901 m^3)

To avoid running the reservoir dry, the reservoir should store enough water for 3 six-hour irrigation cycles. This results in a volume of 5.0 acre-ft (6167 m^3) for site 1 and 4.7 acre-ft (5795 m^3) for site 2.

The second major demand for water volume is the energy storage system. The system is designed to supply 50 kW for 6 hours when the primary energy source is not available. The flow rates giving this power output were calculated in the previous section. Here, the volume of water per day (or 6 hour cycle) is calculated:

Site 1: (1525 gal/min)*(360 min) = 549,000 gal = 1.68 acre-ft

(Site 1: (0.096 m^3/s)*(360 min) = 2074 m^3)

Site 2: (1650 gal/min)*(360 min) = 594,000 gal = 1.82 acre-ft

(Site 2: (0.104 m^3/s)*(360 min) = 2246 m^3)

To provide enough water volume for three of these generating cycles, the total water volume capacity stored in the reservoir is 5.0 acre-ft (6167 m^3) for site 1 and 5.5 acre-ft (6784 m^3) for site 2.

The reservoir size should be large in proportion to the volume of water draw out to minimize water level fluctuations. In addition, the depth of the reservoir can be minimized to accomplish the same goal. The author recommends that the reservoir volume be twice the expected volume change due to water usage operations.

Finally, evaporation losses should be taken into account in sizing of the reservoir. While the depth of the reservoir should be minimized to maintain turbine head, the surface area should be minimized to lessen the evaporation loss. This is a design trade-off that must be considered by the designer. If a general assumption of 10% loss of water due to evaporation is made, the entire volume of the reservoir should be increased by 10%.

The final reservoir volumes recommended for each of the case study sites are:

Site 1: ((5.0 + 5.0)*2)*1.10 = 22.0 acre-ft (27137 m^3)

Site 2: ((4.7 + 5.5)*2)*1.10 = 22.4 acre-ft (27630 m^3)

4.5 Electrical and Mechanical Systems

The electrical system needed to implement aquifer UPHS for the examples of the case study sites follows Figure 2-9. Some electrical functionality may be added or deleted as dictated by the user needs.

The electrical component design details, other than expected voltage levels and power ratings, are not included in this paper. However, an estimation of the costs to procure the components and perform the system integration design and controls is included in a following section.

A major design concern is the speed of the shaft of the pump-turbine motor-generator unit. This case study assumes the use of a centrifugal pump-as-turbine, as described in Chapter 2. If this type of unit is used, the pump was designed for some optimum efficiency at a certain water velocity. Because of the lack of literature and analysis available on the operation of centrifugal pumps as turbines, it is unclear what velocity of water, shaft speed and head give the maximum efficiency point for turbine operation. The designer is recommended to test a candidate pump as a turbine to determine the head, flow and water velocity, and the maximum efficiency point. As indicated in Chapter 2, the turbine efficiency is to be optimized for aquifer UPHS, with pumping efficiency as a secondary goal.

4.6 Cost Estimation

In this section, an attempt to estimate the cost of an aquifer UPHS system as described in this case study is made. A maximum and minimum cost estimate is made for each site using probable ranges in the expense of each component. This is done in an attempt to bracket the cost range of the system. Table 4-4 lists and sums the cost estimates for all major components of the system. This analysis also includes an estimate of engineering and overhead costs.

Cost estimates for each component are not easily available. In most cases, because of the relatively large ratings of the equipment, a price quote from a manufacturer is required. While various quotes were requested, few were returned. Internet searches for component prices were used where available. Many of the entries in Table 4-4 are engineering estimates made by the author. It is expected that the cost estimates for these items are accurate to within 50%.

The major expected costs for the system are likely the electrical system components. If major well modifications are required, however, these costs may eclipse other costs to install aquifer UPHS. In Table 4-4, the entries in red are the engineering estimates provided by the author.

			SITE 1		SITE 2	
	Rating	Quantity	$ MIN	$ MAX	$ MIN	$ MAX
ELECTRICAL COMPONENTS			$65,450	$105,856	$65,450	$105,856
Well Motor Drive[1]	50 kW	1	$3,450	$4,686	$3,450	$4,686
Generator Excitor and Rectifier	50 kW	1	$2,000	$3,000	$2,000	$3,000
Grid Tie Inverter[2]	50 kW	1	$40,000	$46,170	$40,000	$46,170
Rectifier	50 kW	1	$1,000	$2,500	$1,000	$2,500
480 Vac Circuit Control Panel	120 Amps	1	$1,000	$3,000	$1,000	$3,000
220/110 Vac Transformer	12 kW	1	$500	$1,500	$500	$1,500
220/10 Vac Circuit Control Panel	50 Amps	1	$500	$1,000	$500	$1,000
System Controller and Interface	N/A	1	$15,000	$40,000	$15,000	$40,000
Electrical Wiring	Various	1	$2,000	$4,000	$2,000	$4,000
MECHANICAL COMPONENTS			$13,500	$27,700	$13,500	$27,700
Centrifugal Motor-Pump	55 kW	1	$9,000	$20,000	$9,000	$20,000
Flow Valves	2000 gpm	3	$600	$800	$600	$800
Water Quality Filtration System	N/A	1	$1,500	$3,000	$1,500	$3,000
Irrigation Boost Pumps	20 kW	2	$400	$900	$400	$900
Various Equipment Mountings	N/A	12	$2,000	$3,000	$2,000	$3,000
IRRIGATION WELL			$13,000	$36,000	$43,000	$91,000
Well Pump Remove/Replace[3]	N/A	1	$10,000	$30,000	$10,000	$30,000
Well Depth Extension Modification	N/A	1	$0	$0	$15,000	$25,000
Infiltration Pit Excavation	N/A	1	$0	$0	$15,000	$30,000
Well Pump Mounting	N/A	1	$2,000	$3,000	$2,000	$3,000
Water Tubing	2000 gpm	1	$1,000	$3,000	$1,000	$3,000
SURFACE RESERVOIR			$40,000	$60,000	$40,000	$60,000
Embankment Excavation[3]	N/A	1	$30,000	$40,000	$30,000	$40,000
Lining Material Transport	N/A	1	$10,000	$20,000	$10,000	$20,000
OVERHEAD/OTHER			$42,000	$155,000	$42,000	$155,000
Electrical Engineering Design	N/A	1	$10,000	$50,000	$10,000	$50,000
Civil Engineering Design	N/A	1	$10,000	$50,000	$10,000	$50,000
Well Testing	N/A	1	$2,000	$5,000	$2,000	$5,000
Installation Labor	N/A	1	$20,000	$50,000	$20,000	$50,000
TOTALS			**$173,950**	**$384,556**	**$203,950**	**$439,556**
			$ MIN	$ MAX	$ MIN	$ MAX
			SITE 1		SITE 2	

	PRICE SOURCE
Well Motor Drive[1]	http://www.driveswarehouse.com/c-30-variable-torque-vfd.aspx?categories_id=&ManID=&Horsepower=&IVoltage=&OCurrent=&pagenum=4
Grid Tie Inverter[2]	http://www.affordable-solar.com/related_1697.htm
Embankment Excavation[3]	http://www.aquahabitat.com/techfaqs.html

Table 4-4: Cost Estimation for Aquifer UPHS System

The aquifer system analyzed in this case example provides 300 kWh of energy per cycle, with a 50 kW power rating. It is not an even comparison to compare the estimated cost of the aquifer UPHS system to an energy storage system using, for example, inexpensive lead-acid batteries. The reason for this is that much of the equipment and infrastructure in the aquifer UPHS system would be required for irrigation even in the absence of an energy storage system. Nonetheless, an estimated cost of a 300 kWh, 50 kW lead-acid battery installation is about $100,000 [18]. The lifetime of lead-acid batteries is roughly 25% that of an aquifer UPHS system. Deep cycling of the batteries will further decrease their lifetime, so additional batteries would have to be added to avoid deep cycling. This could add 50% to 100% additional cost on the $100,000 estimate. Thus, the cost of the aquifer UPHS system appears to be competitive with an inexpensive battery system, especially when one considers site characteristics, water use, utilization of irrigation infrastructure, and lifetime.

The results of the cost estimation exercise indicate that the cost can be very dependent on site characteristics. The amount of well modification required, the presence of an existing surface reservoir, and the possibility of using existing irrigation machinery could all significantly reduce the total system cost. Significant engineering costs would be required for design of the electric system controller, well, and surface reservoir system. This is a non-recurring cost that eliminated as additional aquifer UPHS systems are installed. Site characteristics such as transmissivity and depth to water have very important effects on the cost of the system. Designers must strive to locate aquifer UPHS systems in areas where these parameters are maximized.

The synthesis of a levelized cost estimation for the aquifer UPHS system may be instructive, though the result is heavily dependent on the assumptions made. Herein, an attempt is made to suggest the expected levelized cost of energy associated with this energy storage system. Levelized cost is defined as the cost per unit energy of the installation, averaged over its lifetime. System cost ranges for the aquifer UPHS system are estimated above, for a system sized to provide up to 300 kWh of energy per cycle. It should be noted that this is an energy storage system, so rather than producing energy, it consumes a small amount (due to efficiency losses). Thus, the levelized cost calculated here is applicable to an energy storage system only, one that is not coupled to a generating source, and one that does not produce electricity. Following is a list of assumptions made for the purpose of levelized cost estimation:

- System rated power = 50 kW
- System rated energy = 300 kWh per cycle
- Number of cycles per day = 1
- Number of days operating per year = 150
- Operating lifetime of system = 35 years
- System lifetime capital and operating cost = $300,000
- System round-trip efficiency = 50%
- Photovoltaic solar system levelized cost = 0.03$ per kWh [19]

The levelized cost the stand-alone system is found by summing the total energy (stored) over the lifetime of the system and then dividing the total costs by this energy result. The calculation is shown here:

(300 kWh) * (150 days) = 45,000 kWh per year

(45000 kWh/year) * (35 years) = 1,575,000 lifetime kWh

($300,000) / (1,575,000 kWh) = **$0.19 per kWh stored**

This result, a levelized cost of 19¢ per kWh, is higher than the cost of energy from most generating sources. However, this cost cannot be directly compared to the costs for generating sources, because this system does not generate. The value of the storage system lies in the ability to capture variable or low cost energy and deploy it as needed.

5 Conclusions

A new method of storing electrical energy in an agricultural setting for irrigation application has been analyzed in this paper. System design analysis, modeling methods, operation reviews, and aquifer hydrogeology research demonstrates that this is a feasible method for storing energy on-site. Various design trade-offs and installation decisions are outlined that must be considered by the system designers and users. These include depth of well and injection flow capacity, aquifer transmissivity, advanced well completions, pump-turbine sizing, and surface reservoir sizing. The information provided is intended as a guide for selection and analysis of potential aquifer UPHS sites.

A rough cost estimation of the aquifer UPHS system suggests that it is cost-competitive with a lead-acid battery storage system of similar energy capacity. The cost estimation finds wide ranges in expected costs for different sites. In addition, non-recurring costs such as engineering design, and the availability of a well or surface reservoir compatible with the energy storage needs can significantly reduce the system cost.

The next step in development of this concept is component and field testing. A centrifugal pump should be procured and tested to determine the maximum efficiency head, flow and shaft speed for both pump and turbine operation. Geologic sampling tests of candidate sites should be analyzed for transmissivity and storativity values. Finally, an actual field installation should be tested for performance to fully verify the analysis in this paper.

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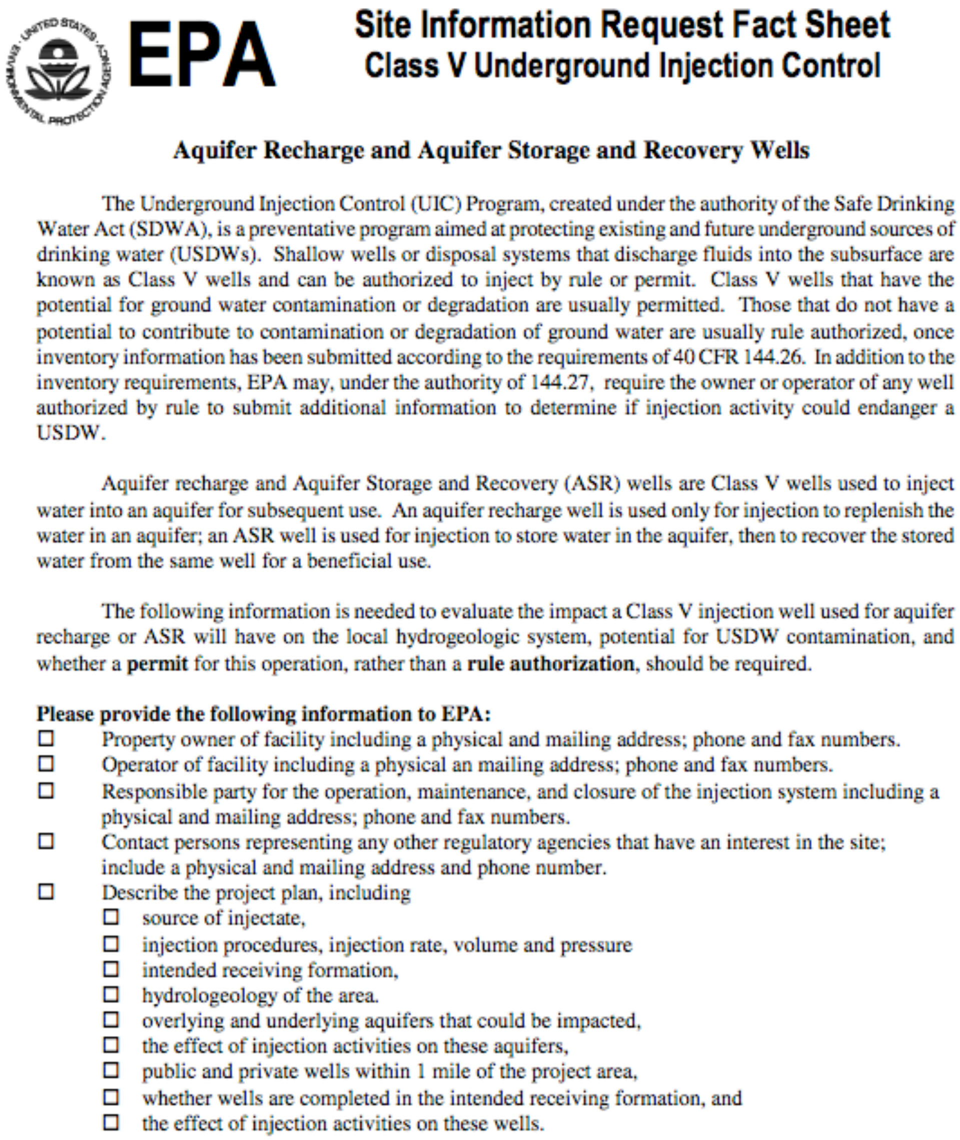
Appendix A



EPA

Site Information Request Fact Sheet
Class V Underground Injection Control

Aquifer Recharge and Aquifer Storage and Recovery Wells

The Underground Injection Control (UIC) Program, created under the authority of the Safe Drinking Water Act (SDWA), is a preventative program aimed at protecting existing and future underground sources of drinking water (USDWs). Shallow wells or disposal systems that discharge fluids into the subsurface are known as Class V wells and can be authorized to inject by rule or permit. Class V wells that have the potential for ground water contamination or degradation are usually permitted. Those that do not have a potential to contribute to contamination or degradation of ground water are usually rule authorized, once inventory information has been submitted according to the requirements of 40 CFR 144.26. In addition to the inventory requirements, EPA may, under the authority of 144.27, require the owner or operator of any well authorized by rule to submit additional information to determine if injection activity could endanger a USDW.

Aquifer recharge and Aquifer Storage and Recovery (ASR) wells are Class V wells used to inject water into an aquifer for subsequent use. An aquifer recharge well is used only for injection to replenish the water in an aquifer; an ASR well is used for injection to store water in the aquifer, then to recover the stored water from the same well for a beneficial use.

The following information is needed to evaluate the impact a Class V injection well used for aquifer recharge or ASR will have on the local hydrogeologic system, potential for USDW contamination, and whether a **permit** for this operation, rather than a **rule authorization**, should be required.

Please provide the following information to EPA:

☐ Property owner of facility including a physical and mailing address; phone and fax numbers.
☐ Operator of facility including a physical an mailing address; phone and fax numbers.
☐ Responsible party for the operation, maintenance, and closure of the injection system including a physical and mailing address; phone and fax numbers.
☐ Contact persons representing any other regulatory agencies that have an interest in the site; include a physical and mailing address and phone number.
☐ Describe the project plan, including
    ☐ source of injectate,
    ☐ injection procedures, injection rate, volume and pressure
    ☐ intended receiving formation,
    ☐ hydrologeology of the area.
    ☐ overlying and underlying aquifers that could be impacted,
    ☐ the effect of injection activities on these aquifers,
    ☐ public and private wells within 1 mile of the project area,
    ☐ whether wells are completed in the intended receiving formation, and
    ☐ the effect of injection activities on these wells.

Appendix A (continued)

☐ Determine the aerial extent of the aquifer(s) (i.e. fill-up volume) that would be impacted by the proposed injection based on the proposed injection volumes and rates. Identify all outcrops of the formation to receive injectate and any potential to create artificial springs. Identify mechanisms which will increase the volume of ground water infiltration into nearby surface water bodies. Identify all erosional intersections between the proposed formation to received injectate and potentially affected surface water drainage systems.

☐ Map of the site location (1:24,000 topographic map or similar)

☐ Hydrogeologic description, location, depth, and current use (if any) of the receiving formations.

☐ Aquifer characteristics: transmissivity, storage coefficient, hydraulic conductivity, saturated thickness, information from drawdown tests and specific capacity

☐ If injection is into an alluvial aquifer, provide locations of surface water bodies, i.e. rivers, streams, and lakes, within one mile of injection site (may substitute topographic map).

☐ Analysis of the water to be injected including constituents regulated under the Safe Drinking Water Act (SDWA), major anions and cations, ambient temperature and pH, presented as tabular data

☐ Analysis of the fluids in the receiving formation(s) including constituents regulated under the Safe Drinking Water Act (SDWA), major anions and cations, ambient temperature and pH, presented as tabular data.

☐ To evaluate the impact of injected water on the receiving formation, plot the major anions and cations from the above analyses of the injectate, the receiving formation fluids, and mixed fluids on a tri-linear diagram or Piper diagram. Provide a brief assessment regarding the compatibility of the injected water and the receiving formation fluids.

☐ Completion diagram showing the construction plans for proposed injection well(s).

☐ A brief description of contingency plans for treating the well(s) to prevent or remediate bacterialogical or mineral buildup in the well, which could affect the injection operation

☐ Briefly describe planned treatment of injectate proposed prior to injection, such a filtering to remove particulates which might plug the receiving formation

☐ Briefly describe proposed monitoring program, including tracking of injectate volume, proposed for the operation

☐ Presence of any ground water contamination plumes near the project area that could affect or be affected by injection activity

Appendix B

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 pump-turbine hardware.

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.

An optional third test phase could involve modification of the well to increase the flow capacity.

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.
   d) 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.
   e) 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.
   f) 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.
   g) Electrical System (Phase 2). A power control center will be assembled that has the following functions:

Appendix B (continued)

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

h) Well Pump-Turbine Assembly (Phase 2)

i) 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.

ii) 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.

Well Sitting Report:

Surface-To-Aquifer Pumped Hydroelectric Energy Storage for Agriculture

Date: April, 2008

Submitted To:
The Colorado Department of Agriculture (CDA), Markets Division

Submitted By:

Dr. Frank Barnes: Project Supervisor, University of Colorado at Boulder Department of Electrical and Computer Engineering

Jonah Levine: Research Associate, University of Colorado at Boulder Department of Electrical and Computer Engineering

Gregory Martin: Past Project Manager, University of Colorado at Boulder Department of Electrical and Computer Engineering

Multiple attempts have been made to continue Surface to Aquifer Energy Storage (STAES). A description of well sitting and utilization attempts follows. No efforts yielded a usable well site.

TRIP REPORT ITF

Prepared By: **Gregory Martin**
Visit Date: **Jan 3, 2008, 3:00pm**
Organization: **Irrigation Research Foundation (IRF)**
Contact: **Charles Corey**
Address: **40161 Highway 59, P.O. Box 396**
Yuma, CO 80759
Phone: **(970)848-3043**
Fax: **(970)848-3042**
E-mail: **irf@plains.net**
Website: **http://www.irf-info.com/**

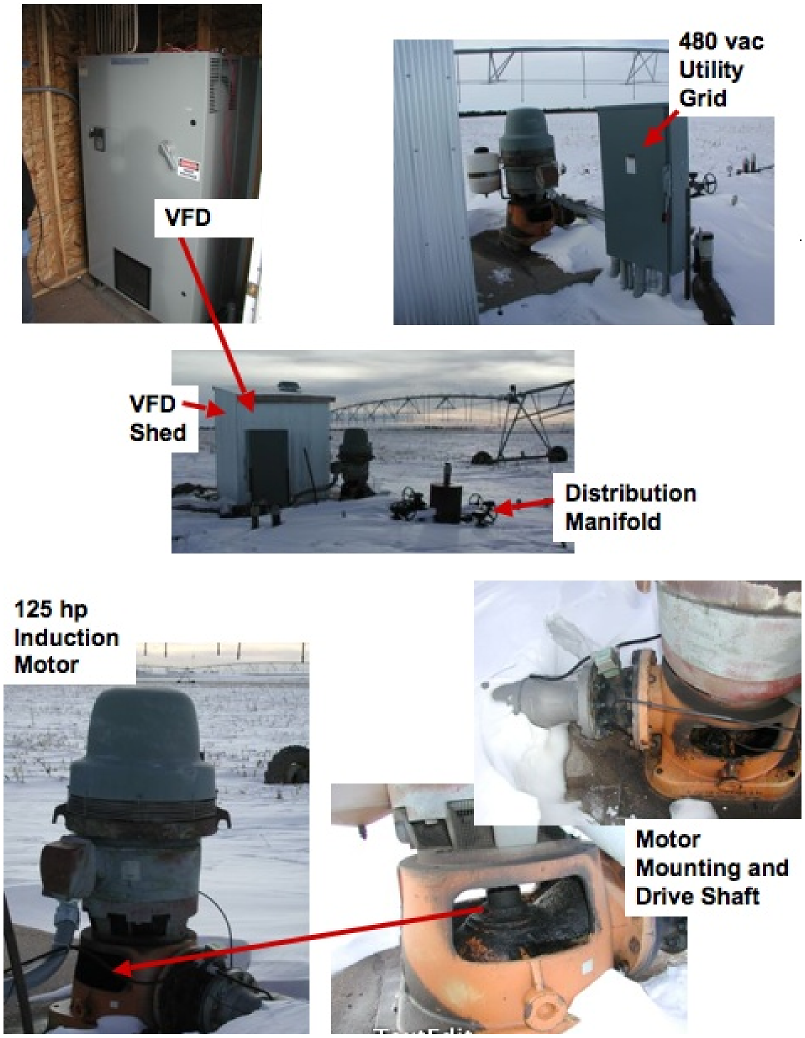
Report:

The IRF is an agricultural and irrigation research site that focuses on effects of irrigation method, fertilizer type, pesticide use, and watering cycles on the growth of a variety of crops. Our interest in this station comes from the irrigation well used. We are interested in investigating the possibility of using the well to carry out basic testing for the Aquifer Underground Pumped Hydroelectric Energy Storage project funded by the Colorado Department of Agriculture. The initial testing would consist of flowing potable water back down into the well to measure the reverse flow rate the well can accept. The mound of injection height would also be measured. This test would require dismantling the IRF well and accessing the pipe going down to the water table. It would also require a surface source of potable water in sufficient quantity to determine flow rate.

The well yields approximately 500-600 gpm and is dug to approximately 360 feet. The depth to water is generally unknown, but estimated to be greater than 150 feet. The well and irrigation system used by IRF irrigates 140 acres of crops. Several different types of crops and different styles of irrigation are used. The well is covered by a concrete block which secures the piping and water pump in the well. The pump is at an unknown depth below the surface. A large induction motor that drives the pump is secured to the concrete block and interfaces to the pump drive shaft. The motor is rated at 125 hp, for 3-phase 460 volt, 142 amp power. Utility grid 480 vac power is available at the well. This electricity is conditioned by a variable frequency drive (VFD) that powers the induction machine for pumping operations. These power electronics are located in a small shed near the well. A pipe manifold, also located at the well, is used to distribute water to the different irrigation systems. See the photo below.

Several challenges to accomplishing the proposed testing were discussed. First, the robust (and aging) mounting of the induction machine, well and pump piping, and distribution manifold would make it difficult to dismantle the system to allow direct access to the well. Next, the irrigation season extends roughly from March through September, limiting the window for test scheduling. In addition, no pond or other source of surface water is located on-site. In the event that the existing pump, motor or piping must be removed for maintenance, there may be a window of opportunity for access to the well for flow testing.

The researchers in charge of the well, while interested in the proposed research project, are concerned about the feasibility of dismantling the system for flow testing. We will remain in contact with the IRF to look for opportunities in the future for collaboration.



William Blake, Private well owner
Series of communication and partnering attempts

William Blake family has personal interest it this research topic. The Blake’s are planning to build a home on 5 acres of land in Southeast Arizona where they are planning to take advantage of solar power. The Blake’s will be putting in a well about 700 feet in depth. The Blake’s would like to be as independent as possible of commercial power sources. The ultimate finding from the Blake’s was that if they are able to mitigate variability from a grid connection the added investment in storage is not worth the added cost. From the perspective of the utility they will not incur the burden of the variability. This set of choices is consistent with many finds of this research group. Someone will have to handle the cost of variability, if the consumer passes that cost on the Utility will be forces to pick it up.

A communitarian from Bill Blake:

Thank you so much for the quick reply and link. We do not really have an idea at present what our peak power during the day would be but our plan is to use solar power to provide that. Our main concern is how to provide power at night if we are not tied to the grid. At night only our refrigerator and freezer would be the main consumers of power along with a few hours of television/DVD viewing before retiring. Using efficient refrigerators and freezers I would estimate maybe a max of 500 wh.

I am including this link that has information about transmissivity and conductivity of the aquifer in our area: http://www.tucson.ars.ag.gov/salsa/archive/publications/lacher/lacher2.htm. As I mentioned the well depth would be about 700 feet to the bottom of the aquifer. I tried to do a calculation for 500Wh but got an estimate of something like needing 336,000 gallons of water to provide this for 8 hours. Is that a correct number? If so, we probably could not provide that amount of water as it appears the wells in our area appear to produce about 400 gallons an hour max and most likely something less.

After doing some additional research, we are probably going to opt for a grid-tied system in order to avoid the use of batteries due to their environmental impacts, cost, maintenance requirements etc. However, I would still be interested to know if my calculations were correct.

I am also going to pass the link to Greg's thesis on to Dr. Paul Huddy who is the chief scientist for the Tucson Solar Alliance in Tucson, AZ. This organization is always interested in ways to reduce our reliance on fossil fuels and may find Greg's thesis of interest and use in future research for the area.

Research Team Reply:
This is an interesting energy storage application. I have included in this email an attachment with a MS Excel worksheet to do a simple calculation of energy generation using your well. To summarize, I assumed a depth to water of 262 feet (700 ft is the well depth, but I am guessing the water table is not that deep). I assumed a system that could generate 10 kW of power for 8 hours, which is 80 kWh. I find that the volume of water needed is about 180,000 gallons.

In the attached worksheet, one can enter the desired parameters into the yellow fields. I also included the equation and parameter definitions I used. I hope this helps. I would be interested in any further thoughts you have on this concept.

Research Team 2nd Reply:
Thanks for following up. My comment is that volume of water required for a fixed energy is inversely proportional to the depth of useable head so that if you went from 300 ft to 600 ft you

would cut the amount of water storage approximately in half. In any case I am glad Greg had a chance to run some numbers for you. Good luck on your construction and have fun with it.

Blake Family Reply:
Thank you so much. We would only want to provide the necessary energy from this source to power things that would need to run at night such as a refrigerator and freezer, a light or two until we retired for the evening, a TV and DVD, and then a couple of night lights (may actually adapt landscaping lights to work inside the house for this feature at night.). Therefore I used 3 KWh as the max requirement and got a requirement for 54000 gallons.

We did a google search for water storage tanks for approximately 50,000 gallons and got a quick quote of $60,000. We were planning to only store 5 to 10,000 gallons of well water for irrigation and house use, plus hope to capture and store maybe another 20,000 of rain water a year (Arizona Monsoon season is July and August). While this is an interesting concept and we have passed it on to the Tucson Solar Alliance in case someone there may be interested, we do not think this would be feasible for our needs at this time.

With your permission, may we pass on your spreadsheet to the Tucson Solar Alliance so that they could use it in any calculations they may need to perform if someone may be interested in this concept?

Sargent Family Communication
Personal Interest in project development

The communications and efforts with the Sargent family allowed the exploration of well possibilities in the San Luis Valley. The opportunity with the Sargent family became non feasible do to a curtailed pumping right.

First significant written communication
Sargent Family Communication:
I enjoyed meeting you at the poster symposium. I think Costilla County in Southern Colorado would be a good place to test your idea because of the alluvial nature of the aquifer at that end of the Valley. I know of a couple of other well owners in the Ft. Garland / San Luis area that may have a better situation for the test, and hopefully I can get you a couple of options to choose from when I go down in early Nov.
If you could let me know along with your project description:
*** about how many acre-feet of water you will need,
*** what is the anticipated duration of the test period?
*** is this test going to be run during irrigation season?
*** what kind of commitment / facility do you need from the well owner?
Is there a residual benefit for the potential project host? i.e. What strategies are you using to develop support for the project?

I look forward to assisting how I can in developing this innovative idea.
In the best possible test scenario, what kind of set would be of most use to you? Irrigation well ___gpm (minimum); surface water storage (area or size); monitoring (?); other criteria?

Let's explore.
Todd

Sargent Family Communication:
Thanks for the update on your project! Your information is correct. My current pumping right is for 300 gpm, but as you know the State of Colorado is in the process of implementing new pumping regulations going into effect on March 1, 2007. Irrigation wells are required to have a Totalizing Flow Meter on all wells by that time. This is a measure that is long overdue, but unless I can figure out how to achieve that in the next couple of weeks, my pumping right will need to move to an 'inactive' status or will be diminished to a domestic rate -- 15 gpm. I am going down to the Valley next week to see if I can accomplish this urgent task with scant resources.

This new regulation will have the effect of curtailing the relatively unbridled pumping rights of the past, but even so, if you decide that the alluvial aquifers of the southern part of the Valley would be your best bet, I may be able to provide you with some introductions to other well owners who could be a good match.
Keep my posted on your progress.

Additional contacts via open letter and personal communications:
Contact was made with two environmental education not for profit organizations:

1. Cal-Wood Education Center- www.calwood.org
2. The Plains Conservation Center- www.plainscenter.org/
   a. Associated with the West Arapahoe Conversation District www.westarapahoecd.org

While each center was interested in the project it was not feasible to pursuer testing at these locations. The open letter that was used is as follows:

Dear __________,

Per our discussion at ________________ this letter is to follow up with more information about an energy storage project to facilitate the increased ability to use renewable energy systems. The following letter contains:

- ⇒ A description of current funding or grant description
- ⇒ What we are doing
- ⇒ What are we looking for
- ⇒ Contact information

Grant Description
Ongoing research at the University of Colorado in the Electrical and Computer Engineering Department is investigating energy storage opportunities to bolster the applicability of renewable energy sources. To this end a concept called Surface-to-Aquifer Pumped Hydroelectric Energy Storage (among other projects) is being developed. The usefulness of the concept lies in the location flexibility attainable with the utilization of the gravitational potential energy in surface

water with respect to an aquifer or water table below the earth's surface. This method eliminates the required surface elevation differential needed for conventional pumped hydroelectric storage systems. Once water has been pumped from the ground into the surface reservoir, this water can be released back down into the aquifer, reversing the operation of the well pump and generating electricity. This approach to energy storage promises to be cost effective, flexible and environmentally benign. The application target of this system is to agricultural situations where power is used to pump irrigation water. This concept enables the use of renewable energy sources to supply power as needed to the user. The design and operation of such a system has endured feasibility assessment, and the next required steps include design research and development, including hardware specification and testing, geologic characterization of usable aquifer topologies and water use law applicability assessment.

What we are doing

This project is being pushed forward in three phases:

Phase 1, Feasibility Assessment
Phase 2, Specification and Laboratory Test
Phase 3, Field testing

Phase one is complete, phase two is beginning and phase three is planned to move forward by January 2008.

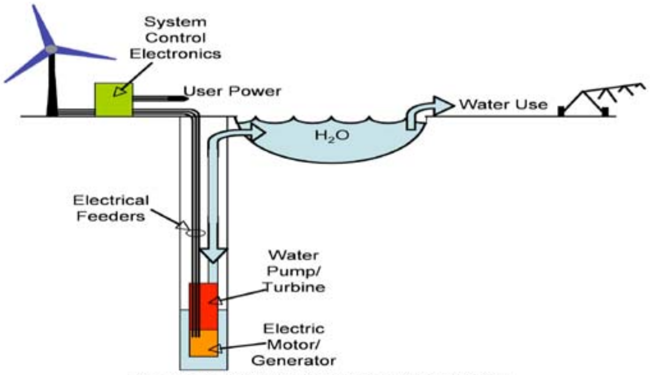


Figure 1: Surface Water Energy Storage System Diagram

What are we looking for

As our research team moves forward in phase two, we are actively seeking a site to implement phase three -testing. Phase three may provide an opportunity for Calwood and University of Colorado to collaborate. The testing of this system will be the first of its kind, and has the potential to demonstrate a technology that can change the way the modern world generates and distributes energy. A workable testing location will have or have the capability of developing a well, a surface reservoir or tank and an energy source. To identify the best testing location it would be helpful to know the following information about the potential site:

1. What is the depth of the well?
2. What is the depth to the water?
3. What is the diameter of the well?
4. What is the maximum pumping rate?

5. What are the current accretion (water) rights?
6. Is there is a surface reservoir Y/N, if Y, what is the volume and depth of that reservoir?
7. Is there power available Y/N? If Y, what is that power (110, 220, 480, other)
8. What is known about the Aquifer geology, soil type, aquifer type confined and unconfined?

Contact information
If this project is of interest do no hesitate to be in touch. Our research group would love to see this idea in practical application. Moreover, if that application can serve as a teaching mechanism to educate our community we would be thrilled. Any questions, concerns or comments are welcome.

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