Final Report

Energy Storage

Presented to

The Colorado Department Of Agriculture

February 2010

International Center for Appropriate & Sustainable Technology (iCAST)
8745 W. 14th Ave, Suite 220
Lakewood, CO 80215
(866)-590-4377

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Overview

Background

As environmental concerns have heightened and energy costs have continued to rise, the public's interest in renewable energy has grown drastically. Even though it seems that agricultural producers can benefit substantially simply from utilizing renewable energy technologies, an underlying problem still exists – the lack of an economically viable means of storing the produced energy. Many owners of renewable energy sources attempt to accumulate "green" credits from their renewable energy source only to quickly turn around and deplete these credits when needing to rely on utility power. Conversely, when renewable energy is not a feasible option, the agricultural community may prefer to build larger power generation systems (>25kW) – but then cannot easily interconnect to the grid to gain credits. This offsets the economic benefits of operating a large renewable energy system and forces the agricultural community to rely on traditional utility power.

According to the American Wind Energy Association, wind energy capacity in the United States raced past the 20,000MW mark in September 2008. Additionally, this capacity is growing at an astounding rate and has more than doubled over the last two years. Rapid policy changes have provided countless opportunities for advancements in renewable technology. The iCAST Compressed Air Energy Storage (CAES) project is focused on making small wind turbines more economically viable so that agricultural producers are able to take advantage of such an abundant Colorado natural resource.

*i*CAST's Compressed Air Energy Storage (CAES) model is focused on decreasing Colorado farmers' reliance on utilities by allowing them to store energy during off-peak hours. The CAES 2010 pilot will build upon the success of the prototype (2007-CDA-ACRE grant), which was developed in partnership with the University of Colorado-Boulder and Colorado School of Mines. Agriculture producers' ability to store their own energy contributes to Colorado's economic security by decreasing reliance on imported energy, while decreasing production costs and deferring the affects of load-control.

Current energy production has to be "readily available" from the utility through its own grid (via peaking plants). Without an energy storage device, agricultural producers are forced to buy energy from the utility at "peak" prices and to sell back at "off peak" prices. Additionally, renewable energy production is intermittent and not always available when needed. The ideal storage system will provide an agricultural producer the option of either (a) using the energy stored, as needed, to power large loads such as irrigations pumps, or (b) selling excess or stored energy back to the utility during peak load. Lastly, an underlying requirement of *i*CAST's CAES pilot was to provide the agricultural community an affordable energy storage solution utilizing "off-the-shelf" parts – to make it fairly easy and cost-effective for the typical agricultural worker to commission, operate and repair the equipment.

Project Goal & Key Accomplishments Summary

The project's goal is to provide Colorado's agricultural community with a solution that maximizes the benefits of storing energy by:

- Increasing operational efficiencies in renewable distributed energy production and use.
- Enabling stored renewable and lower-cost energy to be available at any time of the day.
- Enabling Demand Side Management (i.e. peak shaving) by using off-peak energy during peak pricing hours.
- Allowing the agricultural community to sell energy back to the utility, when appropriate.
- Decreasing agriculture producer's dependency on over-priced utility rates.

The previous Research Energy Storage Grant (ACRE) funded the design and development of a compressed air energy storage prototype (operation can be viewed at http://www.youtube.com/watch?v=YOsejFBEXTY) by the University of Colorado at Boulder in 2008-2009. This is the inspiration for the pilot system to be installed at the Irrigation Research Facility (IRF) in Yuma, Colorado. The lack of economical energy storage is a major impediment which prevents renewable energy from being fully developed and widely adopted. Although there is much research being focused on advanced energy storage systems, it is primarily focused on utility-scale applications (i.e. more attractive in for-profit sectors). iCAST has built strong partnerships with the Yuma Conservation District, the Irrigation Research Foundation (IRF), Y-W Electric Association and Tri-State Generation & Transmission to incorporate design principles that are simple and hopefully relevant to any usage application: agricultural, industrial/commercial, and demand-side management (i.e. utility substations). At this point in the project, the team will focus on integrating energy storage for small-scale renewable energy systems tied to irrigation applications – for the purpose of shaving Colorado producer costs through sustainable energy technologies.

KEY ACCOMPLISHMENTS of the project are summarized below and then further detailed in the following section (pages 6-18).

- **Comprehensive Evaluation of Energy Storage Technologies and Selection of Compressed Air** (Aug-Dec 2008). Numerous advanced storage technologies (from flywheels to vanadium redox flow batteries) were evaluated by the engineering team from the University of Colorado-Boulder. Using selection criteria such as scalability, ease-of-implementation, availability and cost, it was decided that compressed air energy storage satisfied overall project requirements. In addition, the team completed initial design of the CAES prototype and control system.
- **Design, Development and Construction of CAES Prototype** (Jan-May 2009). The following tasks were successfully completed:
    - Iterative testing of efficiency performance of Tesla turbine and alternator.
    - Control and main CAES system design and construction.
    - System efficiency testing and output power measurements.
    - Efficiency testing using preheated water in turbine and thermal storage design.

    - Identification of CAES system areas needing further research during next phase.
- **Design and Development of CAES (Pilot) Control System** (May-July 2009). This was completed for an irrigation pump, a relatively high-energy demand application. Energy storage occurs via wind turbine or during off-peak hours. CAES energy release occurs during start of peak-hour to "peak-shave" demand curve. Additionally, the system bill of materials (BOM) was developed, including estimated component costs.
- **Design of CAES (Utility-Scale) Control System** (May-July 2009). Although based on the 10kW system design, a utility-scale CAES requires more complex monitoring and safety components, depending on the specific utility requirements. Further refinement of this design will be conducted with direct input from utilities and municipalities. Full design was completed using LabVIEW, a developmental software tool for measurement and automation.
- **CAES Market Validation from Community Outreach and Education** (June-July 2009). iCAST and the student team attended two agricultural community events (Akron Research Station Ag Days and the Southern Colorado Sustainability Conference) to showcase the CAES prototype and gather user feedback. The audience, agricultural producers, was extremely positive to the concept of using compressed air to reduce utility demand charges and approved of the simplicity of the CAES concept. Most were very familiar with the hardware components and were confident in their ability to service the equipment.
- **Identification and Formation of Co-Sponsor Project Team** (Aug-Dec 2009). Four organizations were identified, contacted and have agreed to support iCAST throughout the next phase of the CAES project. These organizations will contribute technical and application expertise – to increase likelihood for project success.

    - The Irrigation Research Foundation (IRF)
    - Y-W Electric Association, Inc.
    - Tri-State Generation and Transmission Association, Inc.
    - Active Power, Inc.

  The IRF will provide expertise on irrigation applications and others relevant to the agricultural community. Y-W Electric and Tri-State G&T will provide interconnection expertise and consumer energy usage insight for various types of customers. Active Power has commercialized a compressed air energy storage system for use in conjunction with their flywheel-based uninterruptible power supply (UPS) systems. The iCAST team intends to work closely with these organizations to benefit from their past experiences and market knowledge.
- **Interconnection Research** (Aug-Dec 2009). During discussions with Y-W Electric and Tri-State Generation & Transmission Association, we were informed that, due to the popularity of renewable energy sources over the past decade, interconnecting to the utility grid has become a relatively straightforward process. The necessary documentation to better understand this process has been gathered and is ready for implementation. We do not foresee utility interconnection being a project barrier.

Key Accomplishments (Detail)

Evaluation of Energy Storage Technologies and Selection of Compressed Air

Initially, flywheels and vanadium redox flow batteries were the University of Colorado-Boulder team's top picks as feasible small scale energy storage solutions. Flow batteries were decided against for two reasons. First, designing and building one was not viable given the time, resources, and experience of the team. Second, purchasing an off-the-shelf vanadium redox battery was not an option considering the price of a 5KWh VRB battery approaches $50,000. Flywheels provide a large amount of power, albeit for a short period of time, and are reliable. In addition, the team's mechanical experience background allows for a successful flywheel design. However, iCAST deemed the flywheel design did not fulfill the project requirements and was also too complicated for a student team to tackle in a semester.

An extensive amount of research has shown compressed air energy storage (CAES) is the best alternative. CAES is scalable, easy to implement on a small scale, and within the CU-Boulder team's means to design and build a system and prototype in the given time constraints. Initial estimates show CAES systems are more cost effective than other storage solutions. Furthermore, there are vast storage resources in eastern Colorado. Large scale compressed air systems have used old gas wells as storage caverns. If natural storage caverns are not available, high pressure storage tanks may be a suitable option.

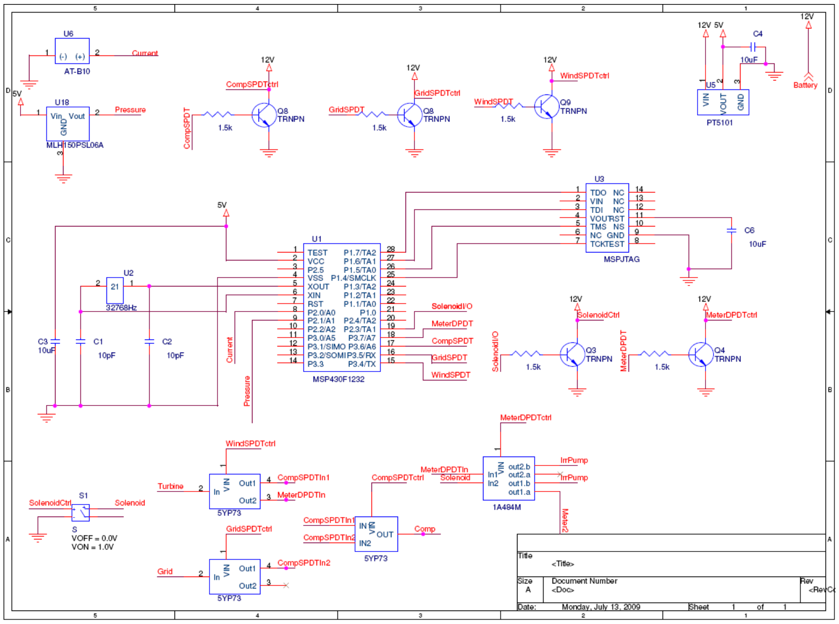
Design and Development of CAES Prototype

A small-scale prototype [Figure 1] was researched, designed and constructed by iCAST and a student engineering team from the University of Colorado at Boulder, Department of Mechanical Engineering. Significant amount of time was spent determining the various system components needed to satisfy project requirements.

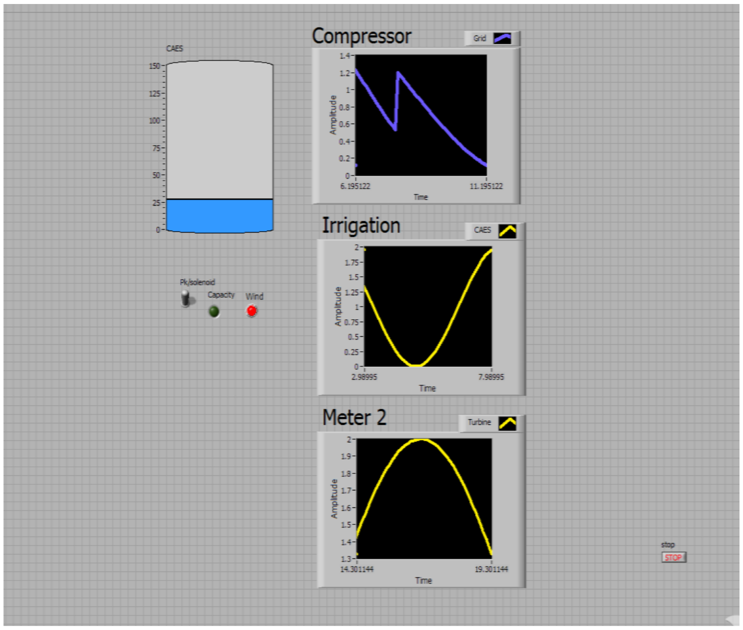
[Figure 1]: CAES Prototype

Design and Development of CAES (Pilot) Control System

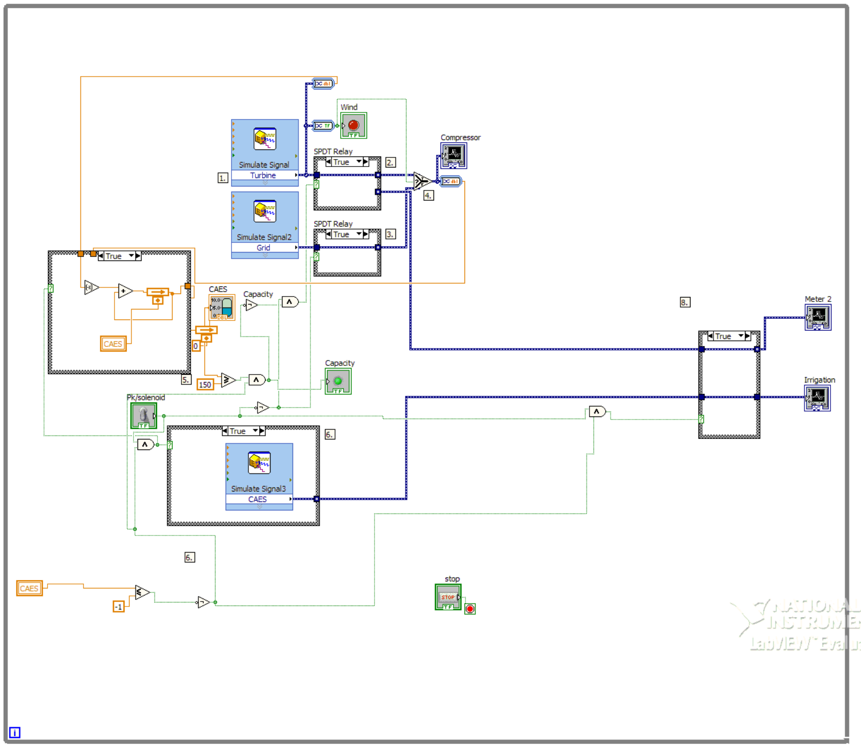
A control system was designed to allow (1) the CAES system to be powered by a wind turbine and then (2) the power to be used by the customer during peak hours. An irrigation pump was the load targeted for this system, although the system can be applied to any load. [Figure 2] shows the completed printed circuit board schematic and [Figure 3 & 4] show LabVIEW model screen shots.



[Figure 2]: Control System, Printed Circuit Board Schematic



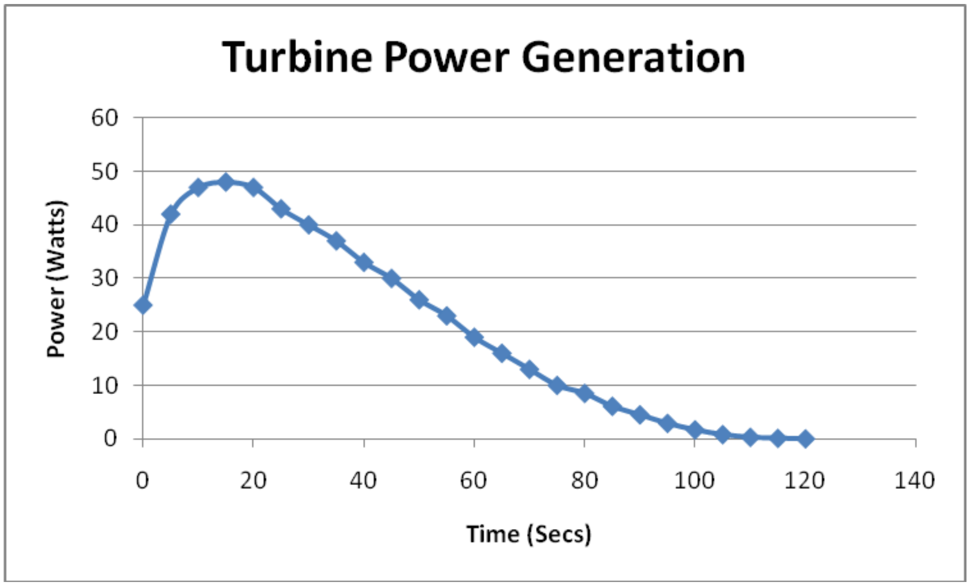
[Figure 3]: CAES LabVIEW Front Panel



[Figure 4]: CAES LabVIEW Block Diagram

The system was designed and then simulated in LabVIEW. The CAES LabVIEW Front Panel screen shot shows the main components of the CAES system. There is a tank for the compressed air, LEDs showing logic states, and three waveform graphs to show the power of the compressor, and power released to the irrigation pump, and the power that is released to a second meter (possibly a house meter or another agricultural meter). It was decided to use two target meters with the irrigation pump being the primary meter because it was the most practical way to use both the CAES power and the wind turbine power simultaneously. Combining the power from both in parallel or series would not be feasible either for technical or financial reasons, and would only complicate the system further. With two meters, it is possible to release power from the compressor to the irrigation pump during peak times while also using the power being produced from the wind turbine on a second meter so no resource goes to waste.

Although fully functional, the CAES prototype did not achieve the desired efficiencies to justify proceeding to a utility-scale pilot. The University of Colorado-Boulder team performed initial testing and found the efficiency of the system to be only about 2%. The power leaving the system was determined by draining the tank (with the pre-determined ideal load on the generator), and measuring turbine voltage and current. Values were recorded every five seconds until the tank was empty. These voltage and current values were multiplied together to determine instantaneous power. The power values were integrated to determine the total energy output of the system. A power generation curve for the generator during a full drain of the air tank is shown in [Figure 5]. Overall efficiency was calculated by dividing the total energy output by the energy needed to charge the system.



[Figure 5]: Turbine Power Output at Optimum Load

Design of CAES (Utility-Scale) Control System

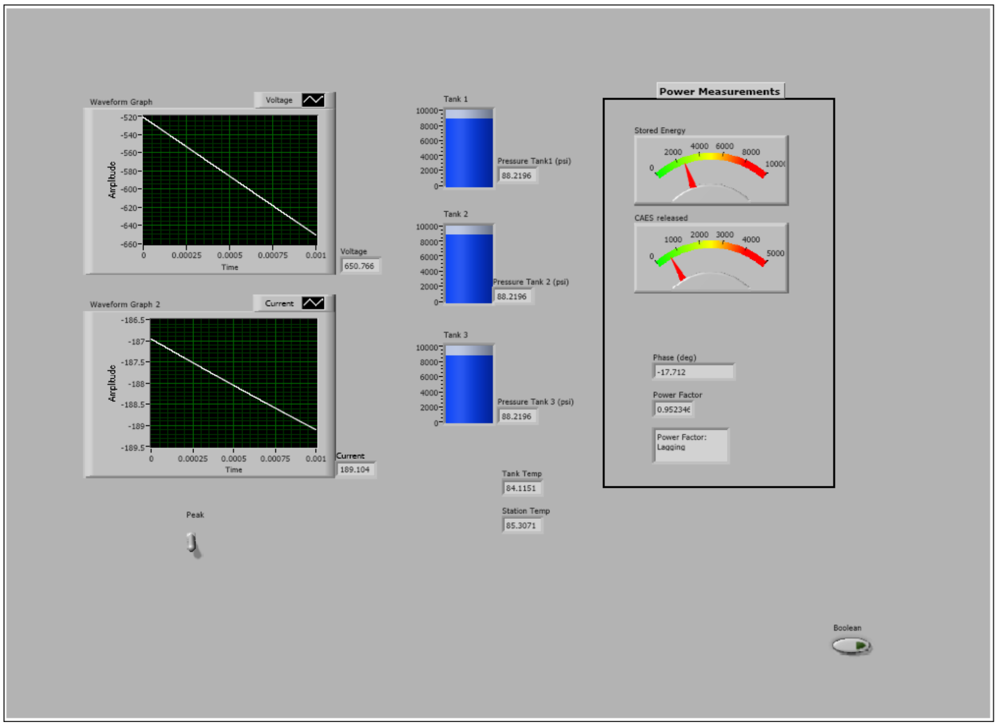
A utility-scale CAES control system was also designed. It was designed for small rural electric associations to help them with demand management and load leveling. This was more complicated than the 10kW system because it is a larger system (in the mega-watts), and requires more conditions monitored and to control the output of the compressors. To store the required amount of air, the system would probably use multiple tanks hooked up to one inverter, or using micro-inverters. These tanks would be charged using utility power during off peak hours, and then released during the day either at a predetermined time, or when the power demand exceeded a threshold level. These controls would be determined by the utility company since they would be specific to each substation and each utility. The CAES system was hypothetically set at a distribution substation and was again designed and tested using LabVIEW.

[Figures 6 & 7] show the LabVIEW Front Panel and Block Diagram for a utility-scale CAES system. The front panel shows the major components, such as pressure tanks, and various measurements and monitored values. For simplicity's sake, only the temperatures of the tank and overall substation (which would encompass transformer and controls temperature) were simulated. The waveform graphs show the monitored voltage and current coming into the substation, and the values to the right of the graphs are the measured volts and amps. Within the “Power Measurements” box, there are calculated quantities such as phase angle, power factor, and whether the power factor is leading or lagging. These measurements are important to assure power quality. There are also indicators for the total amount of stored energy in the tanks, and the difference between the energy being supplied from the grid and the CAES energy. Ideally, this would stay at a certain threshold or below. For example, if the distribution station was a 3MW station, but demand starting getting around or above that level, an amount of CAES could be released to compensate. This demands control of variable or proportional solenoid valves which can open to release air at diameters proportional to the electric signal. This way, the compressed air can be used most effectively over the day and not just all at once.

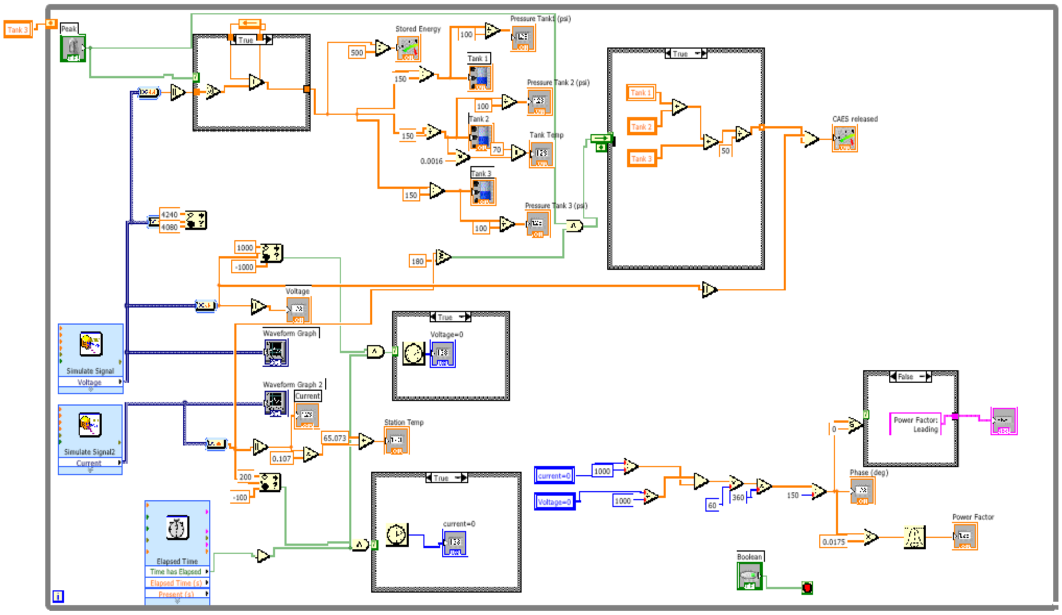
The block diagram shows the actual modeling and programming for the rural electric utility-scale CAES. It consists of simulated signals for the voltage and the current, which are fed through different loops and calculations to obtain the measured values and to fill the tanks. The current is measured so that when it is above a threshold (this would be done using a current transducer), it creates a logic control that signals the compressed air to release until the power going through the substation returns to a normal level.

The basic idea of the utility-scale CAES is that the tanks would release energy proportional to the amount of energy demanded above a threshold level. For example, at a 3MW substation of a rural electric association, if the power limit was being approached, the compressors might release 5kW or 10kW of energy to reduce the strain on the equipment and on the generation station. However, if more than 3MW was being demanded, the compressors might release 500kW of energy or more.

Another application for utility-scale energy storage is that it can be used at larger stations for spinning reserve. Energy storage, especially compressed air, is able to be charged and released quickly, and so is useful not only when peak demand of energy goes up, but when a power supply goes down.



[Figure 6]: Utility-Scale CAES LabVIEW Front Panel



[Figure 7]: Utility-Scale CAES LabVIEW Block Diagram

CAES Market Validation from Community Outreach and Education

Very positive anecdotal feedback and user acceptance was collected at two events: Akron Research Station Ag Days and the Southern Colorado Sustainability

Conference (November 3-4, 2009). In summary, the agricultural community supports and understands the concept of CAES. The technology is familiar to them, they are confident that they could perform minor system repairs and they would value the opportunity to reduce their energy costs.

Identification and Formation of Co-Sponsor Project Team

Four organizations – The Irrigation Research Foundation (IRF), Y-W Electric Association, Tri-State Generation & Transmission Association and Active Power, Inc. – have agreed to support iCAST throughout the next phase of the CAES project. Active participation from these organizations is critical to the success of the project. We intend to lean on these organizations for technical and application expertise, as well as solicit them for resource contributions, as needed.

Irrigation Research Foundation (IRF)

Contact: Charles Corey - Farm Director
(970) 848-3043, irf@plains.net
PO Box 396 Yuma, CO 80759

The IRF is located on a section of land 2 1/4 miles of Yuma, Colorado beside Highway 59 by the western edge of Yuma County. Yuma County is central to the Golden Plains area of northeastern Colorado. The Golden Plains covers 40% of the state, of which a majority sits atop the Ogallala Aquifer. The Golden Plains has always been a leader, not only in Colorado but nationwide in agricultural productivity. The Ogallala Aquifer allows this area to be one of the most intensely irrigated areas in the entire nation, each year producing large yields of corn, alfalfa, beans, potatoes, sorghum, sugar beets, sunflowers & wheat.

The Irrigation Research Foundation provides research cooperators an opportunity to develop extensive studies on a variety of soil types, water and fertilizer applications, different hybrid varieties of various crops, and low energy costs to produce the maximum amount of net income per acre. At the IRF site, there are five (5) sprinkler systems and two (2) drip irrigation systems that all draw from the same deep well and each sprinkler can be operated independently. *i*CAST's pilot CAES will be an operative energy source for the pump located at the hub of the 5 sprinkler system. With the IRF's assistance in operation, data collection and observation, *i*CAST will be able to improve efficiencies and sustainability of product.

Y-W Electric Association, Inc.

Contact: Terry Hall - Northeast Colorado Cooperative Manager
(970) 345-2291, terryh@ywelectric.coop
250 Main Avenue Akron, CO 80720

Y-W Electric Association, Inc. is dedicated to providing high quality, reliable electric service and related products to members at competitive prices. Y-W provides electric service to most of Yuma and Washington Counties, Colorado. They believe members deserve and should receive quality service unexcelled in the utility industry. Y-W Electric Association is in support of *i*CAST's CAES pilot and has committed to supplying this project with data that will help in defining and understanding local service loads and system cycles.

Tri-State Generation and Transmission Association, Inc.

Contact: James Spiers - Senior Manager Energy Strategies
(303) 452-6111, jspiers@tristategt.org
PO Box 33695 Denver, CO 80233

Tri-State Generation and Transmission Association is a wholesale electric power supplier owned by the 44 electric cooperatives that it serves. Tri-State generates and transmits electricity to its member systems throughout a 250,000 square-mile service territory across Colorado, Nebraska, New Mexico and Wyoming. Serving more than 1.4 million consumers, Tri-State was founded in 1952 by its member systems to provide a reliable, cost-based supply of electricity. Headquartered in Westminster, Colo., more than 1,100 people are employed by Tri-State throughout its four-state service area.

Tri-State Supplies energy to people in small towns and rural communities in the West and is dedicating to finding sustainable means of fulfilling it's member's production requirements. By investing in renewable energy from clean and green sources in new technology and improving energy efficiencies, Tri-State strives to provide reliable, affordable electricity. Tri-State recognizes *i*CAST's efforts and potential in this field and has volunteered their expert counsel and support in the production of the CEAS pilot.

Active Power, Inc.

Contact: Martin T. Olsen, VP - Business Development
(401) 441-6660, (512) 744-9215, (508) 981-9588 cell, molsen@activepower.com
2128 W. Braker Lane, BK12, Austin, Texas 78758

Active Power is an established provider and manufacturer of *efficient*, *reliable* and *green* critical power solutions that ensure business continuity in the event of power disturbances. Active Power's expert system engineers and worldwide service and support teams ensure that enterprises around the globe have the power to perform. Founded in 1992, Active Power protects operations in more than 40 countries on six continents with their flywheel-based UPS systems and turnkey power solutions. Active Power has developed and commercialized a revolutionary Thermal & Compressed Air Energy Storage (TACAS) technology, which utilizes compressed air to provide extended power backup time for 3-phase Uninterruptible Power Supply (UPS) applications. Active Power supports iCAST's CAES pilot and has committed to provide engineering support, technology and hardware, depending on availability and need.

Yuma Conservation District

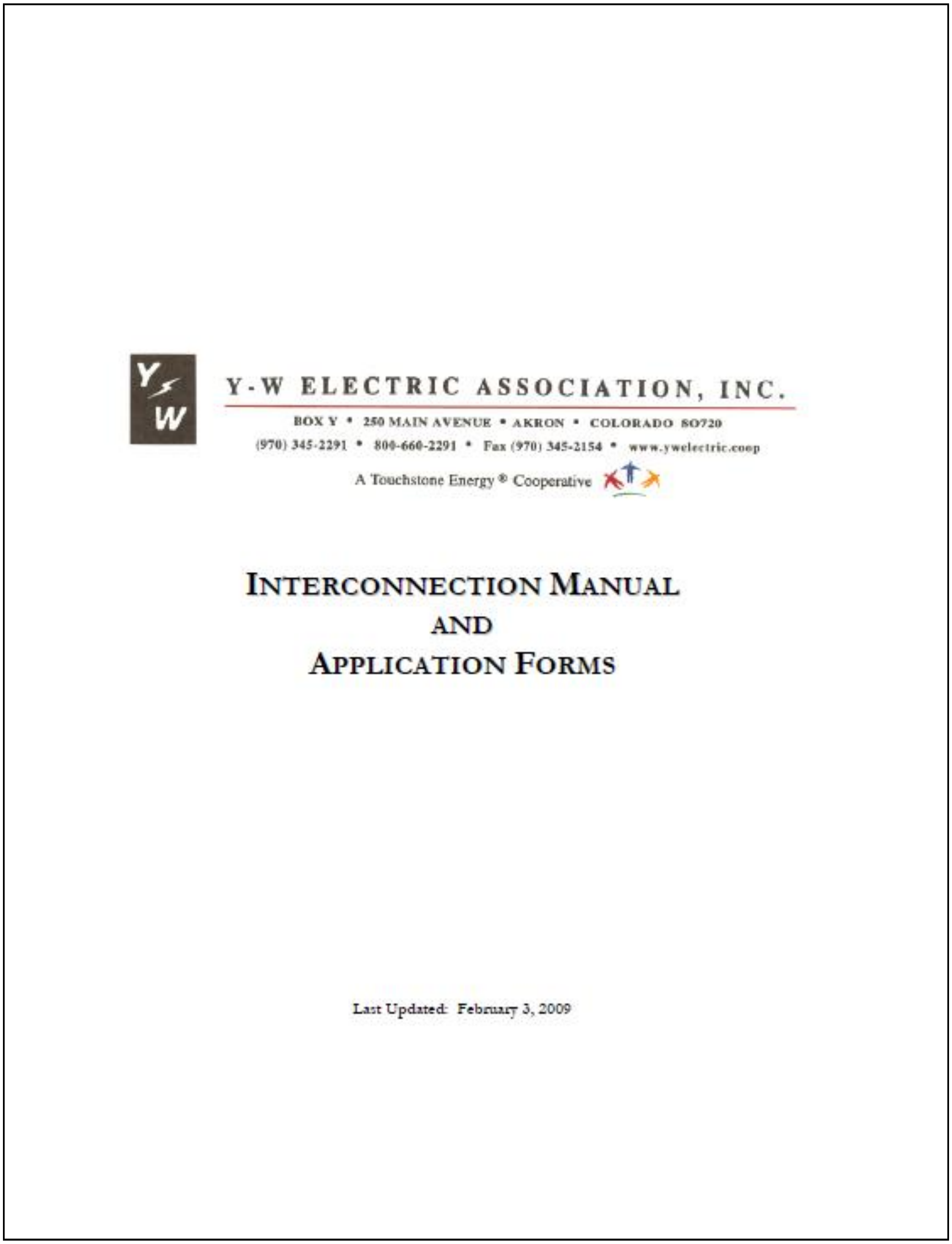
Contact: Brian Starkebaum
508 E. 8th Avenue, PO Box 116, Yuma, Colorado 80759
(970) 848-5605, Fax (970) 848-5613

The Yuma Conservation District is one of 66 Conservation Districts in Colorado, organized as a special government created by the Soil Conservation Act of Colorado. The district was formed by local agriculture producers in 1958. The District oversees a comprehensive program of natural resource conservation under the direction of a locally-elected volunteer Board of Supervisors made up of Milton "Bud" Mekelburg (President), Fred Raish (Vice President), Ross Tuell (Secretary/Treasurer), John Deering and Dan Walter (District Staff), Bethleen McCall (District Manager), Brian Starkebaum (Pathways Project Director), Katie Haerr (P2M Coordinator). In the past, the focus has been on soil conservation, with the widespread adoption of soil conserving practices adopted by our producers, the district is now able to devote time toward other natural resource concerns including: energy, water quality and quantity, agro-forestry and rangeland health. The Yuma Conservation District fully support iCAST's CAES project and will provide local support in securing partnerships and building more confidence amongst the local agricultural producers and community.

Interconnection Research

Although grid interconnection has been widely recognized by industry groups as the most significant barrier to the adoption of distributed generation technologies, we don’t foresee interconnection as a major hurdle. During our discussions with YW Electric Association and Tri-State Generation & Transmission Association, we were informed that, due to the popularity of renewable energy sources over the past decade, interconnecting to the utility grid has become a relatively straightforward process.

All information pertaining to interconnecting to Y-W Electric Association’s utility grid can be found in the document: “Interconnection Manual and Applications Forms.” This document was provided by Terry Hall - Northeast Colorado Cooperative Manager, Y-W Electric Association. See [Figures 8-11].



Y-W ELECTRIC ASSOCIATION, INC.

BOX Y • 250 MAIN AVENUE • AKRON • COLORADO 80720
(970) 345-2291 • 800-660-2291 • Fax (970) 345-2154 • www.ywelectric.coop

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INTERCONNECTION MANUAL
AND
APPLICATION FORMS

Last Updated: February 3, 2009

[Figure 8]: Interconnection Manual (cover)

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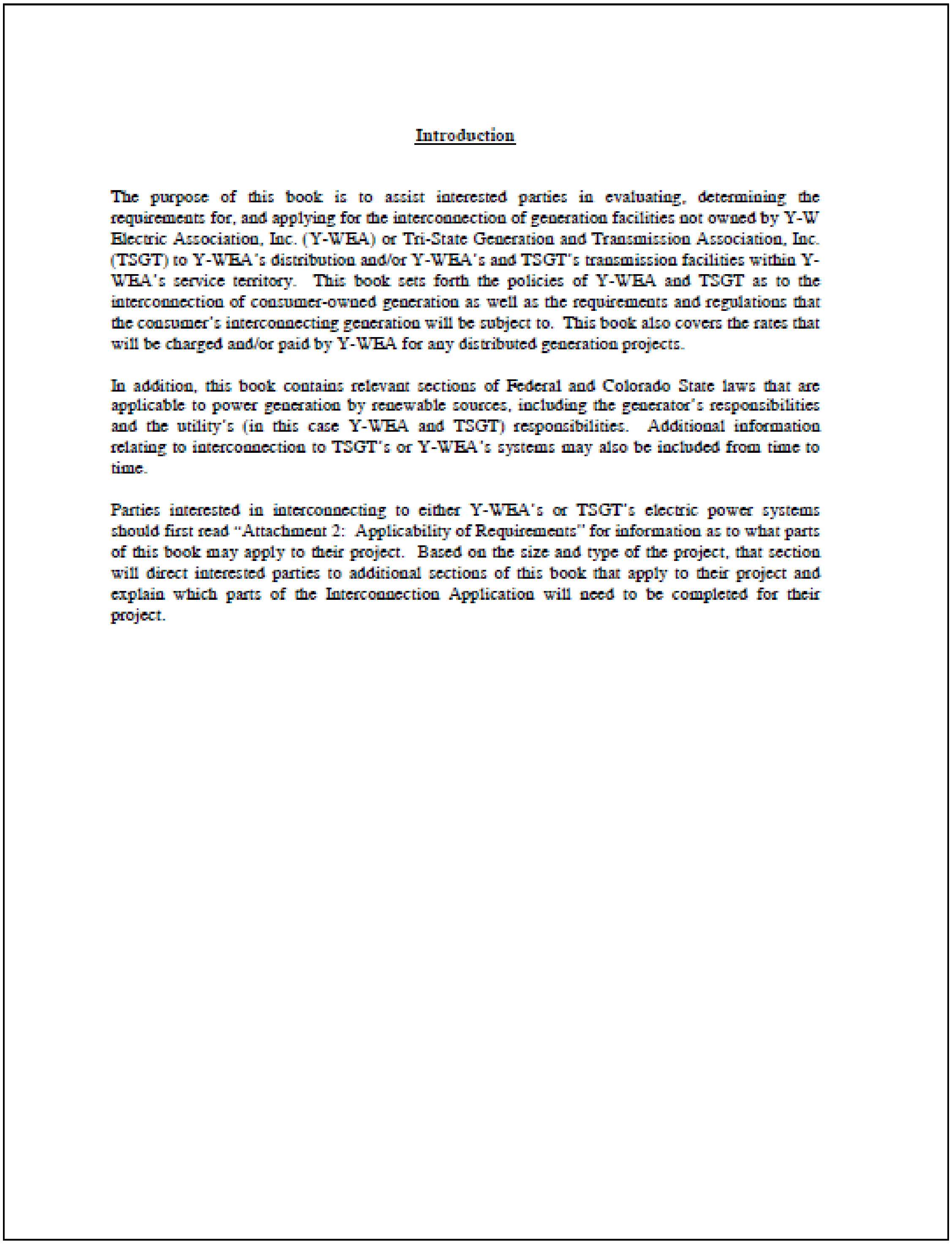
[Figure 9]: Interconnection Manual (Table of Contents)



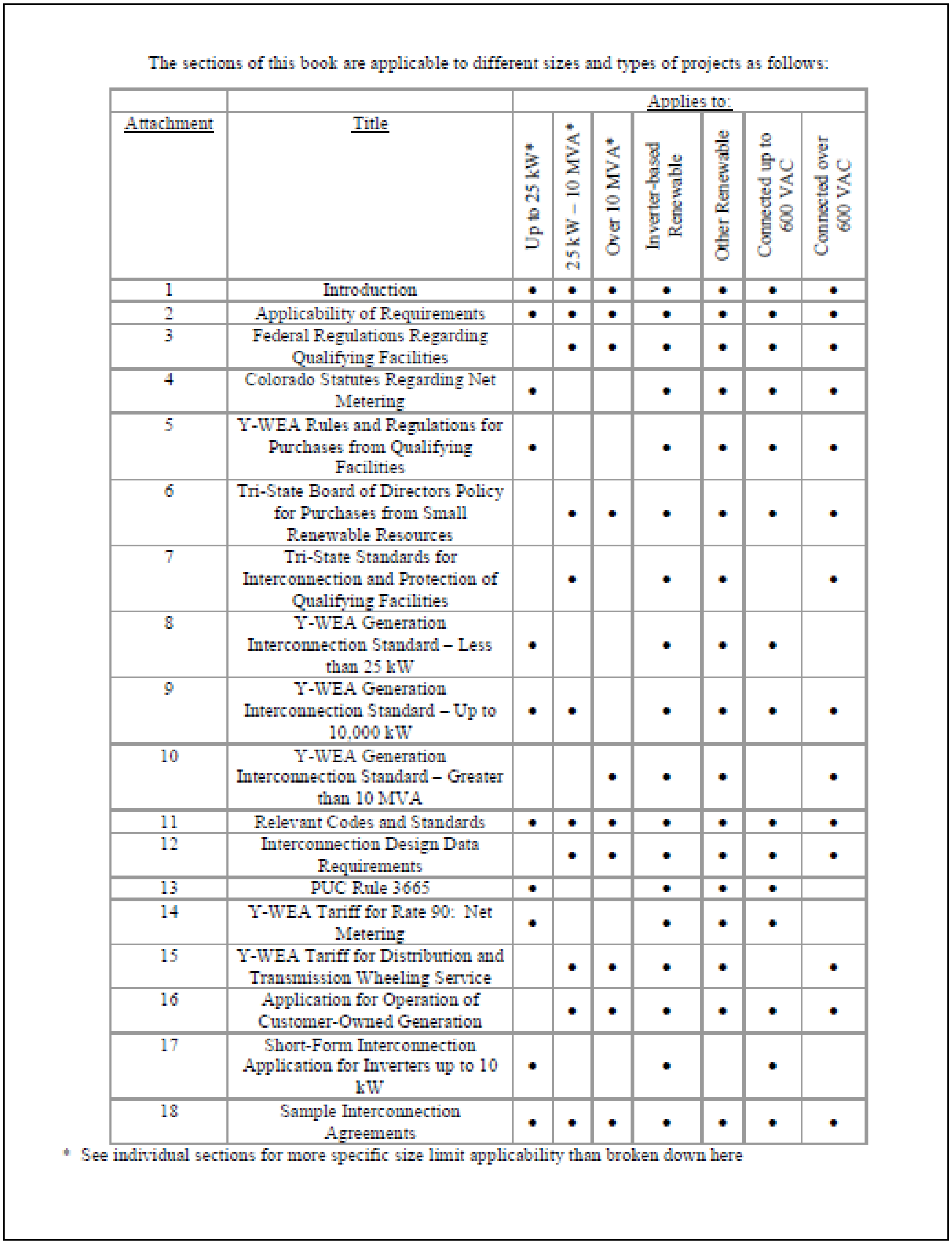
Introduction

The purpose of this book is to assist interested parties in evaluating, determining the requirements for, and applying for the interconnection of generation facilities not owned by Y-W Electric Association, Inc. (Y-WEA) or Tri-State Generation and Transmission Association, Inc. (TSGT) to Y-WEA's distribution and/or Y-WEA's and TSGT's transmission facilities within Y-WEA's service territory. This book sets forth the policies of Y-WEA and TSGT as to the interconnection of consumer-owned generation as well as the requirements and regulations that the consumer's interconnecting generation will be subject to. This book also covers the rates that will be charged and/or paid by Y-WEA for any distributed generation projects.

In addition, this book contains relevant sections of Federal and Colorado State laws that are applicable to power generation by renewable sources, including the generator's responsibilities and the utility's (in this case Y-WEA and TSGT) responsibilities. Additional information relating to interconnection to TSGT's or Y-WEA's systems may also be included from time to time.

Parties interested in interconnecting to either Y-WEA's or TSGT's electric power systems should first read "Attachment 2: Applicability of Requirements" for information as to what parts of this book may apply to their project. Based on the size and type of the project, that section will direct interested parties to additional sections of this book that apply to their project and explain which parts of the Interconnection Application will need to be completed for their project.

[Figure 10]: Interconnection Manual (Introduction)



The sections of this book are applicable to different sizes and types of projects as follows:

		Applies to:						
Attachment	Title	Up to 25 kW*	25 kW – 10 MVA*	Over 10 MVA*	Inverter-based Renewable	Other Renewable	Connected up to 600 VAC	Connected over 600 VAC
1	Introduction	•	•	•	•	•	•	•
2	Applicability of Requirements	•	•	•	•	•	•	•
3	Federal Regulations Regarding Qualifying Facilities		•	•	•	•	•	•
4	Colorado Statutes Regarding Net Metering	•			•	•	•	•
5	Y-WEA Rules and Regulations for Purchases from Qualifying Facilities	•			•	•	•	•
6	Tri-State Board of Directors Policy for Purchases from Small Renewable Resources		•	•	•	•	•	•
7	Tri-State Standards for Interconnection and Protection of Qualifying Facilities		•		•	•		•
8	Y-WEA Generation Interconnection Standard – Less than 25 kW	•			•	•	•	
9	Y-WEA Generation Interconnection Standard – Up to 10,000 kW	•	•		•	•	•	•
10	Y-WEA Generation Interconnection Standard – Greater than 10 MVA			•	•	•		•
11	Relevant Codes and Standards	•	•	•	•	•	•	•
12	Interconnection Design Data Requirements		•	•	•	•	•	•
13	PUC Rule 3665	•			•	•	•	
14	Y-WEA Tariff for Rate 90: Net Metering	•			•	•	•	
15	Y-WEA Tariff for Distribution and Transmission Wheeling Service		•	•	•	•		•
16	Application for Operation of Customer-Owned Generation		•	•	•	•	•	•
17	Short-Form Interconnection Application for Inverters up to 10 kW	•			•		•	
18	Sample Interconnection Agreements	•	•	•	•	•	•	•

* See individual sections for more specific size limit applicability than broken down here

[Figure 11]: Interconnection Manual (section cross reference table)

Key Findings

Summary

The following key findings are relevant for the design, construction and implementation of the next-phase, small-scale pilot at the Irrigation Research Foundation (IRF).

- Equipment size ratio may be an issue for increasing to pilot-scale
- Sustaining output power for (ideal, 15 minute) duration may be an issue
- Exit pressure without combustion was not meeting desired compression ratio
- Considering the low efficiencies of the portable prototype, more research and planning are needed before utility-scale CAES can be considered viable
- Agricultural producers understood and supported the CAES concept; the overall simplicity of the technical design was well-received.

One of the key findings of the research to-date was that the size ratio may be an issue for scaling the demo unit to that needed for the pilot. Also, smaller scale systems (1-500kW) may suffer from inefficiencies and lack of technology. Hence, sustaining the output power for the expected duration may also be a concern. This was primarily due to the exit pressure, without combustion, was not meeting the required compression ratio.

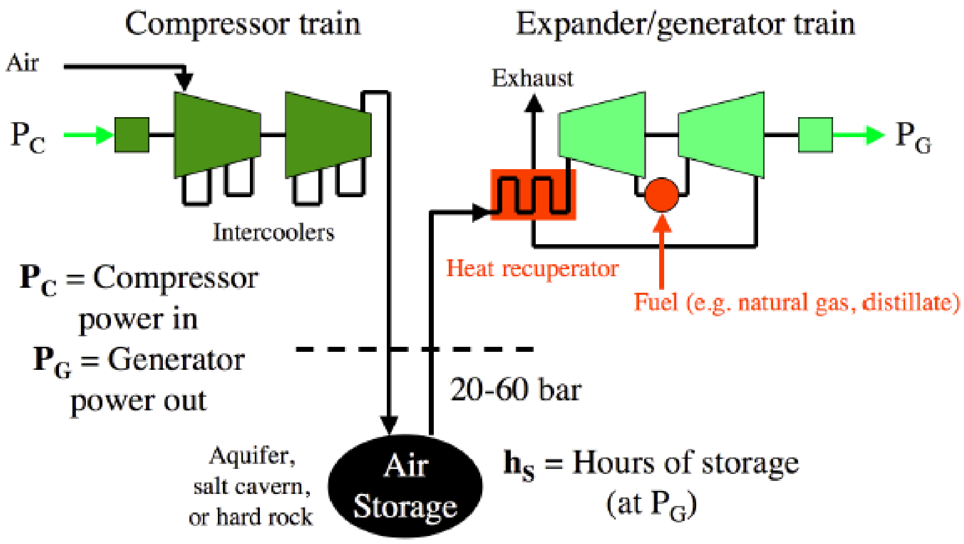
Full Scale (Pilot) System Design

Introduction of a 10kW / 80kWh CAES System

The main differences between the prototype that was build and a full-scale (pilot) system are the turbine and the heat addition. The turbine used in the prototype was a Tesla Turbine custom-made for the prototype's application. Larger systems may use pre-manufactured turbine systems designed to run in combination with a heat source such as natural gas or propane. A cycle including natural gas is suggested for any system that has access to the fuel.

This particular layout is designed for a wind turbine (or set of solar panels) rated at 10kw. For simplicity, it is assumed that 10kw is produced constantly. Ideally, this would be stored for use during peak hours. Assuming the wind blew for 8 hours at 10kw of production, the system needs to be able to hold 80 kW-hours of energy.

Compressed Air Energy Storage (CAES) systems have a variety of layouts. The majority includes a compressor stage that includes intercoolers, after coolers, fuel combustors and high- and low-speed turbines. [Figure 12] is an example of what a system layout might look like.



[Figure 12]: CAES System (from Princeton University)

System Components

Below[1] are the estimated system component specifications for a 10kw/80kwh system. These were calculated using ideal gas equations and fluid analysis. The parameters presented are based on scaled down specifications from two functionally operational plants. Because the larger systems are more efficient, it should be noted that the estimates for the 10kW system are somewhat optimistic. Nevertheless, these estimates give good insight into existing hurdles of designing and constructing a 10kw system.

Compressor

The chosen compressor will need to be at least a 2-stage compressor capable of 600-1200 psi charges. Higher psi levels allow for more power generation, yet more storage space will be needed. Lower psi levels may lead to a more sustained, yet lower level, energy. Airflow is also an important factor. This system should use around 6-10 SCFM. However this flow rate needs to be constant, something difficult to achieve.

Storage

The storage size depends on how long the system needs to run. Assuming 80kWh is the needed storage capacity, approximately 300 cubic feet of storage space is needed. Multiple tanks could be used as long as they are safely rated at the high pressures required.

Heat addition

Both currently operational plants add approximately 4100 BTU/kWH of heat during operation. Based on $.19 per 1000 ft^3 of natural gas and 80kwh of energy, it would cost a user $20/day to run a 10kW size system. This increases efficiency but at a significant cost and increased complication of design. A custom designed system could use the excess heat from

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[1] Final Report: iCAST Renewable Energy Storage System; University of Colorado at Boulder, Department of Mechanical Engineering, 04/31/2009; page 42

compression to aid in the expansion cycle. A fully operational system in Alabama (the McIntosh Plant) uses a heat recuperation method that cuts fuel usage by 25%.

Future systems could also incorporate steam as a working fluid. Various prototypes have been made that output significant power. The density and moisture from the steam allows it to grip the blades of the Tesla Turbine more effectively and steam provides a higher velocity at the same pressure and volumes.

Turbine

The turbine is a difficult part to specify mainly because companies do not currently make turbines for this scale of energy. Turbines will have to be custom designed specifically for this purpose until companies start creating turbines for small scale power production. Each turbine should be matched to the psi and scfm rates. A company such as Dresser-Rand should be contacted for available options.

One possibility may be to modify an existing turbine system such as the Dresser-Rand 70kW micro turbine. These turbines are currently designed to run strictly on natural gas (or a similar fuel). Modifying a system, such as this, to run on a combination of fuel and compressed air could drastically increase the turbine's output power. A normal gas turbine that produces 100MW is able to produce 200 - 300MW when combined with compressed air. CAES in combination with traditional fueled turbines can produce 2-3 times more power than the fueled turbine alone.

Below is a summary of highlights for each of the various progress reports.

- Dec 30, 2008 Progress
    - Various storage technologies were evaluated; CAES was deemed the best alternative.
- March 25, 2009 Progress
    - Completed assembly of CAES core power generation system (w/o UI)
    - Testing and monitoring system efficiency
    - Contacted several resource conservation districts re: market validation and acceptance.
    - Defining Summer 2009 project and forming intern team
- July 27, 2009 Progress
    - CAES assembly completed and tested (electronic UI installed and tested)
    - Turbine power output did not achieve desired efficiency necessary for a full-scale system
    - Tested system by adding preheated water to storage unit and system efficiency, surprisingly, decreased.
- Summer 2009 Intern Work
    - Design control system to power CAES from wind turbine
    - Design control system to transfer energy from CAES to grid (not including interconnection)

    - Pricing research for control system components
    - Assist in presentations for community outreach
- Community Outreach and Education (two events)
    - Market validation and acceptance; positive response from audience; understand technology

Next Steps

[Table 1] below is a project timeline, followed by a summary overview of the major next steps. Keep in mind that many tasks will be worked in parallel to help reduce the overall timeframe.

Project Timeline

	Months			
TASKS	**6**	**12**	**18**	**24**
Phase I: Design & Site Preparation	🟦	🟦		
1. Design turbine placement on new compressor tank equipment	🟦			
2. Correspond with Tri-State, YW Electric, and IRF on interconnection strategy	🟦	🟦		
3. Complete drawings and specs for CAES unit		🟦		
4. Obtain parts and construct CAES control system	🟦	🟦		
5. Prepare site for CAES construction		🟦		
Phase II: Implementation			🟦	🟦
6. Obtain equipment and construct pilot			🟦	
7. Monitor performance and electricity savings				🟦
8. Optimize design for maximum efficiency				🟦

[Table 1]: CAES Project Timeline

Next Steps: Detail

1. **Design turbine placement on new compressor tank equipment**

   With professional oversight, a mechanical engineering student team at Colorado School of Mines will design and build an optimized thermal storage unit and mounting bracket for the air turbine. Understanding thermal storage systems and knowledge of existing systems will be instrumental in creating an improved design. Professional guidance will be provided to achieve an optimal technology design for the rural farming scenario. Careful selection of the heating medium within the thermal storage container needs to be taken into account, given the limited resources in rural Colorado.

2. **Design interconnections strategy and develop application use cases leveraging Tri-State G&T, YW Electric Association, and the Irrigation Research Foundation (IRF).**

   Although grid interconnection has been identified by industry groups as the most significant barrier to the adoption of renewable energy technologies, over the years interconnection has become more common – and thus less of a project barrier. Electric utilities have understandably always placed a high priority on the safety of their workers and the reliability of their electrical systems; faced with the interconnection of potentially large numbers of distributed generators owned and operated by utility customers, some members of the utility industry have perceived distributed generation as a threat to both. Both Tri-State and YW Electric (project co-sponsor partners) will provide the power systems expertise for a successful grid interconnection.

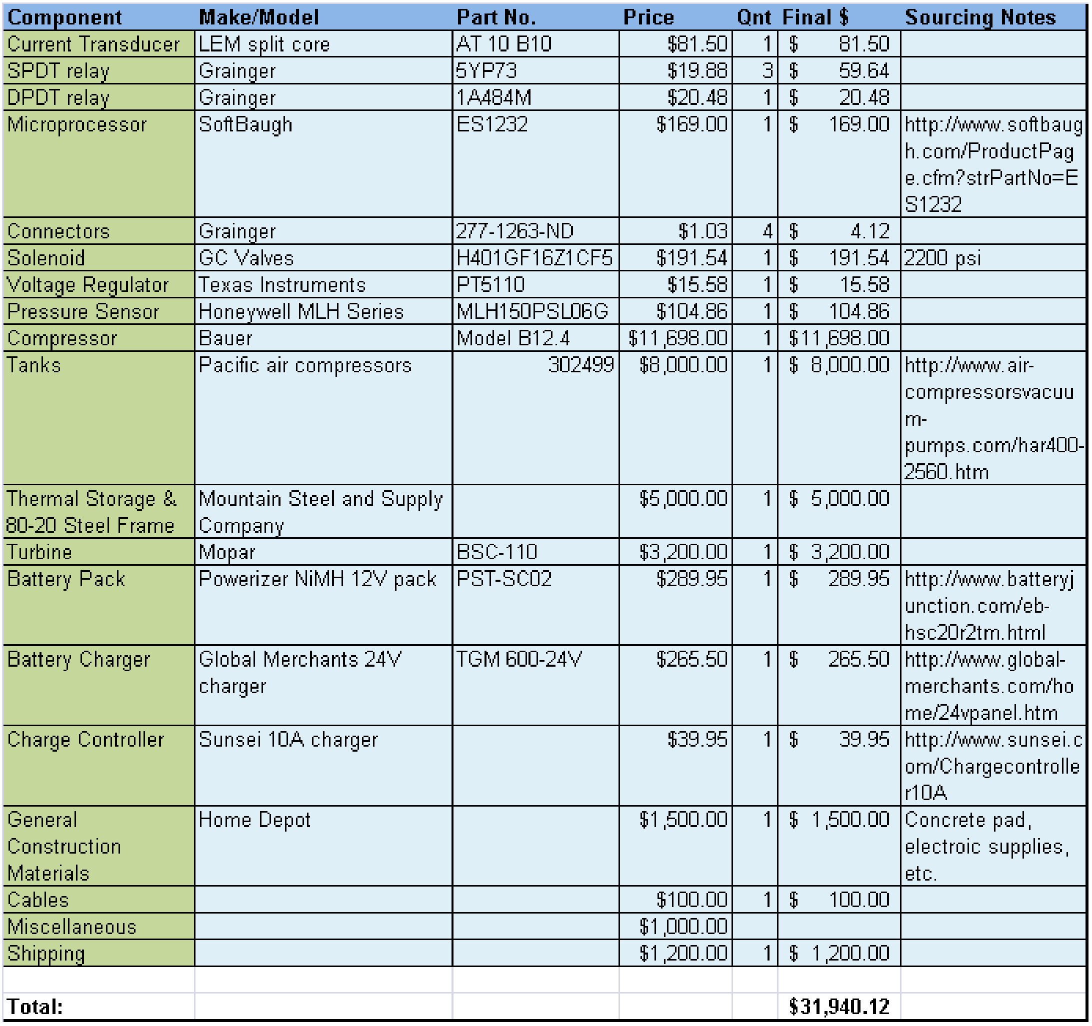
3. Complete drawings and specifications for CAES unit

With the thermal storage unit and turbine designs completed, the whole system will be evaluated and designed to optimize the process. This includes specifying component types and sizes based on calculations and simulations, and may include selecting efficient piping and valves. This is an important part of this project, as the full scale designs will be based on existing designs. The final deliverable of this project should provide a framework for a pilot system offering the full benefits of energy cost savings, energy diversity, and energy security to rural farmers.

Consideration of the size and scale are important for both of these components to minimize the physical size of the full pilot system. Also, consideration of tank size, volume and air pressure are important to maximize the energy produced. Achieving the correct duration of cycle time over which the energy is stored and released is also paramount to gain the most savings.

4. Obtain parts and construct CAES control system.

The assembly of the CAES control system can be performed in parallel with other tasks on this list. The CU-Boulder student team has completed the (a) Bill of Material (BOM) and costing of the required parts [Table 2] and (b) design of the control system – so this task should not be a project bottleneck.



Component	Make/Model	Part No.	Price	Qnt	Final $	Sourcing Notes
Current Transducer	LEM split core	AT 10 B10	$81.50	1	$ 81.50	
SPDT relay	Grainger	5YP73	$19.88	3	$ 59.64	
DPDT relay	Grainger	1A484M	$20.48	1	$ 20.48	
Microprocessor	SoftBaugh	ES1232	$169.00	1	$ 169.00	http://www.softbaugh.com/ProductPage.cfm?strPartNo=ES1232
Connectors	Grainger	277-1263-ND	$1.03	4	$ 4.12	
Solenoid	GC Valves	H401GF16Z1CF5	$191.54	1	$ 191.54	2200 psi
Voltage Regulator	Texas Instruments	PT5110	$15.58	1	$ 15.58	
Pressure Sensor	Honeywell MLH Series	MLH150PSL06G	$104.86	1	$ 104.86	
Compressor	Bauer	Model B12.4	$11,698.00	1	$11,698.00	
Tanks	Pacific air compressors	302499	$8,000.00	1	$ 8,000.00	http://www.air-compressorsvacuum-pumps.com/har400-2560.htm
Thermal Storage & 80-20 Steel Frame	Mountain Steel and Supply Company		$5,000.00	1	$ 5,000.00	
Turbine	Mopar	BSC-110	$3,200.00	1	$ 3,200.00	
Battery Pack	Powerizer NiMH 12V pack	PST-SC02	$289.95	1	$ 289.95	http://www.batteryjunction.com/eb-hsc20r2tm.html
Battery Charger	Global Merchants 24V charger	TGM 600-24V	$265.50	1	$ 265.50	http://www.global-merchants.com/home/24vpanel.htm
Charge Controller	Sunsei 10A charger		$39.95	1	$ 39.95	http://www.sunsei.com/Chargecontroller10A
General Construction Materials	Home Depot		$1,500.00	1	$ 1,500.00	Concrete pad, electroic supplies, etc.
Cables			$100.00	1	$ 100.00	
Miscellaneous			$1,000.00			
Shipping			$1,200.00	1	$ 1,200.00	
Total:					**$31,940.12**	

[Table 2]: CAES Bill of Material

5. Prepare site for CAES construction.

The pilot site has been selected and approved by the Irrigation Research Foundation (IRF). The IRF provides research cooperators an opportunity to develop extensive studies on a variety of soil types, water and fertilizer applications, different hybrid varieties of various crops, and low energy options to produce the maximum amount of net income per acre. At the IRF site, there are five (5) sprinkler systems and two (2) drip irrigation systems that all draw from the same deep well. Each sprinkler system can be operated independently. *i*CAST's CAES pilot will be an operating energy source for the pump located at the hub of the five (5) sprinkler system. With the IRF's assistance in operation, data collection and monitoring, *i*CAST will be able to improve system efficiencies and record application requirements. Site preparation will include working closely with the IRF to ensure safety procedures are followed and that physical space limitations are taken into consideration.

6. Obtain equipment and construct pilot.

Based upon the equipment specifications calculated from Task #3 above, the project team shall purchase/obtain the necessary equipment [Table 2] and then construct the CAES pilot at the IRF site. The project team shall contact grant co-sponsor partners – such as Active Power, YW Electric Association or Tri-State Generation & Transmission – for donation of equipment, moneys and/or technical expertise. The parties responsible for site construction and oversight shall be determined with direct input from YW Electric Association and the IRF – to ensure operational safety as well as interconnection compliance.

7. Monitor performance and electricity savings.

The iCAST project team will work closely with the IRF to monitor and record onsite power usage and system parameters of the CAES system. Parameters measured will include CAES power output (watts), CAES run duration, load (pump) input current and voltage – all measured in increments to allow for a comprehensive power system analysis.

For Colorado's demand charge structure, the highest 15-minutes of power consumption in the monthly billing period is the most important peak to shave with energy storage. If peak demand from agricultural operations is not shaved for the entire 15-minute period, the peak charge remains high and the farmer is charged a large demand fee. Therefore, an energy storage system that targets this 15-minute peak is necessary to be of the most use to rural farmers.

8. Optimize design for maximum efficiency.

The power output, power density (ratio of power output to maximum specific volume in the cycle) and thermal efficiency of the cycle are used to determine the overall efficiency and operation of the CAES pilot. For future efforts, consider researching various scenarios to develop a higher efficiency turbine design – requiring professional machining and engineering analysis.

Final Accounting of Project Expenditures

Funds from CAVADB Energy Grants Program

Salaries, Taxes & Fringe	$	23,635
Paid Student Teams & Consultants		24,939
Travel		1,426
Indirect		-
Total Grant Funds	$	50,000

Matching cash and in-kind contributions

Cash Match		
Salaries & Personnel	$	16,115
Travel		-
Indirect Costs		7,245
Total Cash Match	$	23,360
Student Team and Consultant in-kind Contribution		32,072
Total matching cash and in-kind contributions	$	55,432
Total Project	$	105,432

Appendix

Appendix A – Progress Reports (Previously Submitted)

Progress as of December 30, 2008

Initially, flywheels and vanadium redox flow batteries were the University of Colorado-Boulder team's top picks as feasible small scale energy storage solutions. Flow batteries were decided against for two reasons. First, designing and building one was not viable given the time, resources, and experience of the team. Second, purchasing an off the shelf vanadium redox battery was not an option considering the price of a 5KWh VRB battery approaches $50,000. Flywheels provide a large amount of power, albeit for a short period of time, and are reliable. In addition, the team's mechanical experience background allows for a successful flywheel design. However, iCAST deemed the flywheel design does not fulfill the project requirements and was too complicated for a student team to tackle in a semester.

An extensive amount of research has shown compressed air energy storage (CAES) is the best alternative. CAES is scalable, easy to implement on a small scale, and within the CU-Boulder team's means to design and build a system and prototype in the given time constraints. Initial estimates show CAES systems are more cost effective than other storage solutions. Furthermore, there are vast storage resources in eastern Colorado. Large scale compressed air systems have used old gas wells as storage caverns. If natural storage caverns are not available, high pressure storage tanks are a suitable option.

Worldwide, CAES has been implemented on the megawatt scale in two full size power plants. However, both of these operations include non-renewable gas turbine cycles. In these designs, compressed air is used to increase efficiencies of traditional power generation methods, but fossil fuel combustion is still required. This project's requirement for a renewable solution conflicts with existing CAES designs. However, it is believed that reasonable efficiencies can still be achieved using only compressed air for smaller systems, therefore, eliminating the need for fossil fuels.

A full scale traditional system is comprised of renewable energy source, a compressor, an air storage cavern or tank, a turbine and a generator. The team's large scale design excludes the use of combustion and recuperation. Electricity generated by wind turbines drives the compressor. The compressed air is forced under pressure into a storage cavern or tank until it is needed. During peak hours the controlled release of compressed air drives a Tesla turbine. The mechanical energy from the turbine is converted back into electricity by the generator. One advantage of this storage device is that the air can be held for extended periods of time without any additional losses in efficiency.

The team's intention is to create a prototype that effectively demonstrates their design for a large scale CAES system. The goals of this prototype are to demonstrate CAES to the Colorado Department of Agriculture, agricultural producers with renewable technologies, and develop proof of concept to obtain future funding to build the large scale system on a Colorado farm. This prototype needs to be fully portable, self contained, and easy to operate.

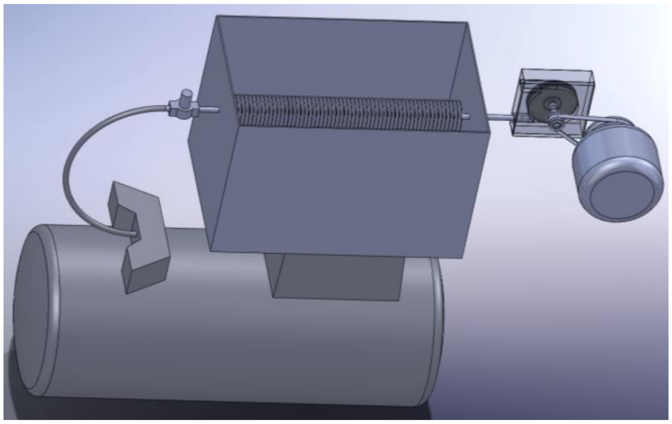


Figure 1: CAD design of prototype CAES system will be built be University of Colorado-Boulder senior engineers this spring

The student team's prototype design of a CAES system consists of seven major parts. The parts are laid out in the following order: compressor, storage tank, solenoid valve, thermal storage system, Tesla turbine, generator, and water pump.

A 33 gallon Craftsman air compressor fits within the size requirements and fulfills the energy storage needs to operate the water pump. This compressor is rated at a maximum of 150 psi, with an average flow rate of 5 scfm. A hose will connect the outlet of the storage tank to a solenoid valve which will be used to regulate the air flow. The regulated flow is then directed through a pipe that runs through the thermal storage system into the Tesla turbine. This pipe will have a quarter inch inner diameter and a series of sixty, 3 inch diameter fins to conduct heat back into the compressed air before reaching the turbine.

The thermal storage system is comprised of three elements. There is a thermal storage box, the thermal medium, and a heat reclamation pipe. The thermal storage container will be made out of an outer and an inner box separated by an insulating layer. The external box will be made of sheet metal, and the internal box will be made from polycarbonate sheet. Highly insulating foam will be used between the two boxes to minimize heat loss. The storage medium will be ceramic bricks with water as the transfer medium. The medium will be placed in the box after it is attached to the compressor and the heat pipe. The metal pipe will have machined metal fins adhered to the outer diameter to increase the rate of heat transfer to the air.

The Tesla turbine will output power via a drive shaft with a pulley attached. A belt will connect the turbine and a generator with a 4:1 gear reduction. This will allow the generator to operate at a lower, optimize range of revolutions per minute. The generator will also experience a higher torque which is necessary for it to start rotating.

For demonstrational purposes the electricity output from the generator will be used to power a water pump. This will show how a CAES system can ease the utility burdens of common agricultural applications that require a significant amount of power. A closed loop will be used to demonstrate the amount of water that can be pumped even with a small system.

The control system is designed to electronically manage all important aspects of the system and collect data. Ultimately, it allows for timed actions to shave peak electricity use. A microcontroller (Basic Stamp II) is responsible for processing all inputs and controlling the system based on current conditions. A real time clock and resonance crystal tracks the time of day. An on/off toggle switch allows for manual shutdown of the system and is directly wired to the emergency shutoff relay. If pressures become exceedingly high, or a major component fails, the emergency shutoff relay will activate. The Micro Processor monitors the tank pressure using the built in compressor transducer. A simple on/off solenoid valve allows for the outflow of the air to be controlled. The final circuitry will be etched onto a printed circuit board, and will be housed in a weather proof containment box. Ultimately, the control system can be expanded to monitor efficiencies and determine the current state of electricity generation from wind turbines.

The project is on schedule and the student team is anxious to start testing and building the prototype in the beginning of January. They have been working with several CU faculty members who are conducting research on CAES for large scale operations, Integrity Wind Inc. engineers out of Boulder, CO, and an NREL compressed air specialist.

Progress as of March 25, 2009

The student team has completed assembling the CAES prototype and is currently testing the power generation and efficiency of the system. They have decided to add a second Tesla turbine and alternator to increase the power output of the prototype that will power an irrigation pump. This will be a powerful demonstration aspect of the prototype that should appeal to the agriculture community.

The electronics for the prototype have been completed and will be installed on the prototype next week. The digital display shows the time, date, whether or not the small wind turbine is operating, whether or not the time is during peak or non-peak hours, and the percentage of tank capacity filled during the compression stage. The manual controls will still be readily accessible next to the electronics storage box in case an emergency shutdown needs to be performed.

The only problem the team has faced is correctly sizing the proper solenoid valve to regulate the air flow into the Tesla turbines. They plan to upgrade the valve in order to raise the efficiency. This will require more financial assistance from iCAST than originally budgeted but it will be essential towards the prototype's success.

At iCAST, we have contacted several resource conservation districts about demonstrating the CAES system at their agriculture events this summer. We plan to establish a scheduled tour of these events to reach a wide audience around the state interested in energy storage for their renewable energy systems. These appearances will be crucial in establishing relationships with current agricultural producers who are interested in implementing the full scale pilot CAES plant that the student team is designing to mimic their prototype. The next step in this project is to implement an actual CAES system that will be able to generate the storage capacity to offset peak usage for producers with a renewable source on their property. Allowing producers to see the basic mechanical operation of the CAES system will be imperative to them buying into the value of energy storage.

Currently, we are interviewing intern applicants with the knowledge of power systems and an honest desire to help the under-served.   Additionally, we are requiring a technical understanding of renewable energy technologies that will interact with the CAES system. The iCAST team and mentors will be able to assist in their understanding, but applicants will need prior experience. Knowledge of renewable energy policy and financing mechanisms, such as net metering and tariff structures will be a strongly considered asset.

The deliverables for the summer intern will be as followed:

1. Using the demonstration CAES system and with support from the iCAST team and community partners, perform presentations to the agricultural community;
2. Determine how the CAES system can best connect to the power grid and the wind turbine:
    a) The intern will assess the site of producers for proper power generation to test the energy storage device and secure grid connections to connect the device. This assessment will include the producer's average annual electricity usage, the normal peak electricity demand, the average annual electricity cost, the grid connection capacity and capacity factors;
    b) Energy can lose some efficiency as it travels from its source to the load it powers. These losses are based on the distance traveled, the size of wires the current travels, the power loads, resistance, and the energy storage device itself. The intern will need to assess these variables to prevent damage to the energy storage device and to the producer's renewable energy source;
3. Determine reaction time between needing power and accessing it from the storage system;
4. Source and price out individual components of large scale system design to generate the necessary budget to build a full pilot scale CAES system;
5. Determine the economics of the full scale design and whether it makes sense for agricultural producers to invest in the technology;
6. Complete initial CAD drawings of the CAES system.

The student team at the University of Colorado-Boulder will have until April 20th to test the prototype before their senior design fair when they plan to have completed the prototype and full system design.

Progress as of July 27th

The prototype Compressed Air Energy Storage (CAES) system was completed in May by the University of Colorado-Boulder team. The completed system is demonstrated on YouTube (http://www.youtube.com/watch?v=YOsejFBEXTY). The video shows the whole assembled system, which includes the compressor and storage tank, thermal storage unit, Tesla turbine, control system, and the light panel. The video demonstrates the functionality of the system. When the video starts, the compressor is filling the tank. As the video pans to the control box, the light marked "wind" is on, indicating that the compressor is filling. The compressor for the prototype system is powered by grid power, however this simulates the power that will be coming from a wind turbine in the full scale system. Below is a table that shows the logic for the prototype control system.

Input Variables State		**Output Variables State**		**Overall Result**
Wind	Peak Power	Compressor Relay	Solenoid	
Low (No Wind)	Low (Off-Peak)	Low (Off)	Low (Closed)	System is not charging and not releasing stored energy
Low (No Wind)	High (On-Peak)	Low (Off)	High (Open)	System is not charging and is releasing stored energy
High (Wind)	Low (Off-Peak)	High (On)	Low (Closed)	System is charging and not releasing stored energy
High (Wind)	High (On-Peak)	Low (Off)	High (Open)	System is not charging and is releasing stored energy

Table X – CAES control logic

In the video, the LED display shows the time and date, and reads "W: Y, P: N", signifying that the wind turbine is powering the compressor and it is off peak. A toggle switch controls the logic that determines if there is wind or not. In the video, the switch is turned off, which turns the compressor off. Looking at the logic table, when there is no wind and it is on peak, the compressor is off and air is released through a solenoid valve. The video shows this scenario happening. Finally, the video shows the light display powered and lit up by the Tesla turbine. Figure X shows the Final control system circuit board.

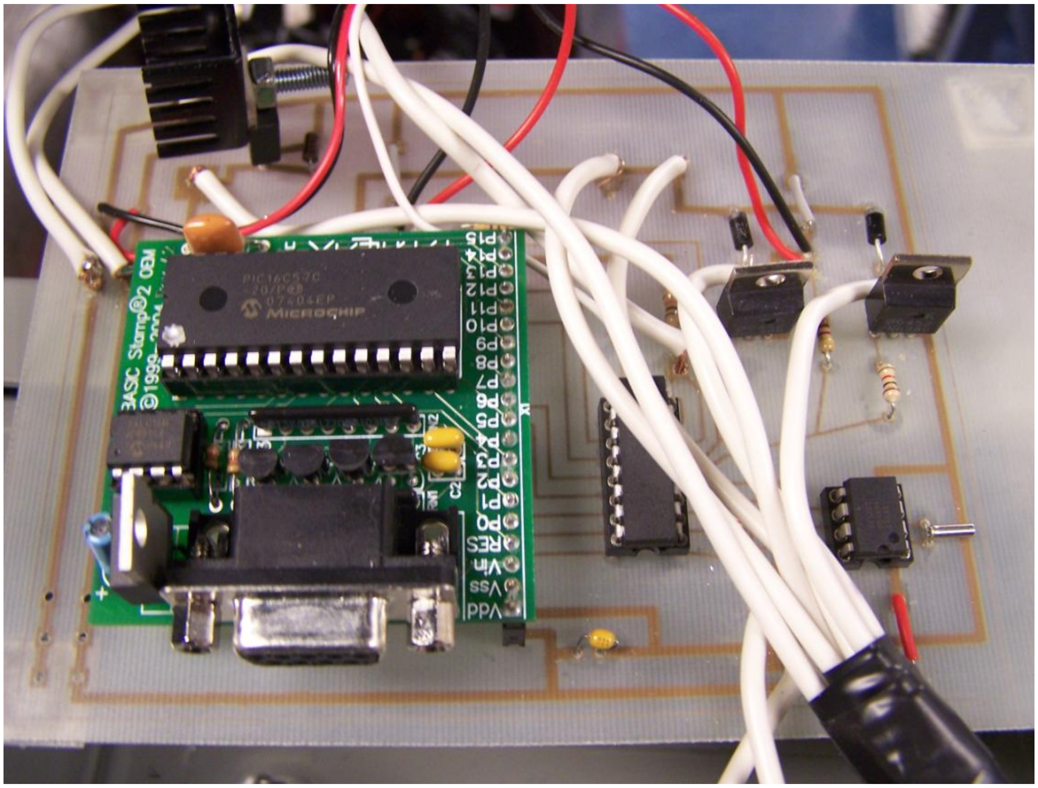


Figure X: Printed Circuit Board

The CAES demonstration unit is fully functional, yet does not achieve the desired efficiencies necessary for a full scale system. The University of Colorado-Boulder team did initial testing and found the efficiency of the system to be only about 2%. The power leaving the system was determined by draining the tank with the pre-determined ideal load on the generator, and measuring voltage and current generated by the turbine. Values were recorded every five seconds as the tank was drained until empty. These voltage and current values were multiplied together to determine instantaneous power. The power values were integrated to determine the total energy drained from the system. A power generation curve for the generator during a full drain of the air tank is given in Figure X. Overall efficiency was calculated by dividing the total energy output from the turbine by the energy needed to charge the system.

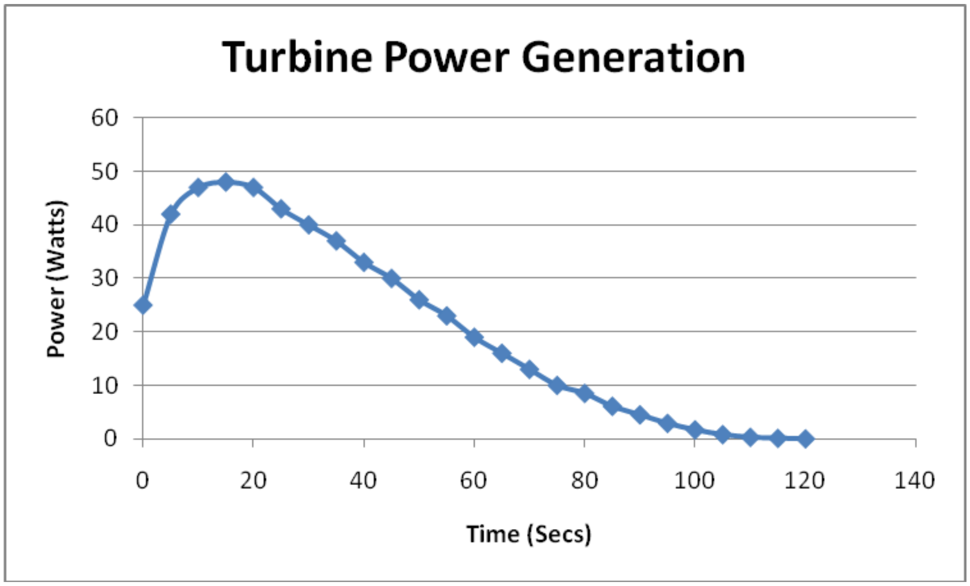


Figure X: Turbine Power Output at Optimum Load

Future design research and development will focus on the turbine and thermal storage design. These were the only two components that were specially designed and constructed by the University of Colorado-Boulder team as opposed to being bought off the shelf. The results of the initial testing for the thermal storage are rather surprising. The testing was done by adding preheated water to the storage unit. In most power generation cycles, heat recupperation increases the energy in the fluid, leading to higher power generation. However, most power generation use steam instead of pure air. Because the turbine discs depend on the air "sticking" to them, heating the air actually made the turbine less effective. As the density of the air decreased and its velocity increased (due to higher temperatures), it was less effective at developing laminar flow in the Tesla Turbine. The efficiency of the system with 170 degree Fereignheight water heating the storage unit was 0 .3%, while with just 70 degree ferenhite had efficiency of 0.4%.

The use of another design for the turbine coupled with a molten salt energy storage tube might produce higher efficiency ratings. The molten salt is a combination of sodium and potassium nitrate, with a melting temperature of 460°F. In the liquid state, molten salt has the viscosity and the appearance similar to water. It is a non-toxic, readily available material, similar to commercial fertilizers. Further research needs to be conducted to match the efficiencies of the utility scale CAES plants that utilize natural gas.

Worldwide, CAES has been implemented on the hundreds of megawatts scale in two full size power plants, one in Alabama, the other in Germany. Both of these operations use thermal storage. Both currently operational plants add approximately 4100 BTU/kWH of heat during operation. Based on \$0.19 per 1000 ft^3 of natural gas and 80kwh of energy, it would cost a user \$20/day to run a 10kW size system. This increases efficiency but at a significant cost and increased complication of design. A custom designed system could use the excess heat from compression to aid in the expansion cycle. A fully operational system in Alabama (the McIntosh Plant) uses a heat recuperation method that cuts fuel usage by 25%. Future system research and development will incorporate steam as a working fluid.

The turbine is a Tesla turbine and used hard drive platters for blades. However, the turbine is a major area for future research and development to increase efficiencies. The turbine is a difficult part to specify mainly because companies do not currently make turbines for this scale of air pressure exiting the storage tank. We will be able to use manufactured turbines, such as a modified automobile turbo turbines, in the scaled up version of the CAES system. Each turbine utilized should be matched to the psi and scfm rates. However, many presently manufactured turbines usually run with the additional of some type of fuel, such as natural gas and fossil fuel dependency is not part of iCAST's vision for the CAES system.

Summer Intern Work 2009

The summer intern's assignment was to complete a design for a more advanced control system to connect the large scale (10kW) CAES system to the wind turbine and a farm meter. The deliverables included:

- Design control system to power CAES from wind turbine
- Design control system to transfer energy from CAES to grid
- Price out components for control system
- Assist in presentations for community outreach

The first deliverable accomplished was designing a control system to have the CAES system powered by a wind turbine and then have power released to a farm power meter during peak hours. An irrigation pump was the load that was specifically targeted for this system, although the system can apply to any load that needs to be powered during peak hours. Appendix A shows the completed printed circuit board schematic and LabVIEW model screen shots.

The system was designed and then simulated in LabVIEW. The CAES LabVIEW Front Panel screen shot shows the main components of the CAES system. There is a tank for the compressed air, LEDs to show logic states, and three waveform graphs to show the power of the compressor, and power released to the irrigation pump, and the power that is released to a second meter (possibly a house meter or another agricultural meter). It was decided to use two target meters with the irrigation pump being the primary meter because it was the most practical way to use both the CAES power and the wind turbine power simultaneously. Combining the power from both in parallel or series would not be feasible either for technical or financial reasons, and would only complicate the system further. With two meters, it is possible to release power from the compressor to the irrigation pump during peak times while also using the power being produced from the wind turbine on a second meter so no resource goes to waste.

The two LED's on the front panel represent two measured quantities: a pressure transducer for tank capacity and a current transducer for measuring how much wind power is being produced. Once the tank gets to its maximum pressure, it will manually shut off. However, in order to make a more robust system without any detrimental feedback loops, it is necessary to use this logic input to program the relay that controls where the wind power goes. The pressure transducer is also used to indicate when the tank is empty so the grid power can be switched to power the irrigation pump during peak hours. Wind power is measured so that, during off peak times, if the turbine is not producing enough power to charge the compressor (when the current is below a determined threshold level), a relay will switch the compressor to be powered by the grid. The toggle switch is used to simulate whether it is peak or off peak. Table X shows the logic and overall result of the large scale system. An “X” signifies a “don’t care” condition, where the resulting output variable is irrelevant or it doesn’t matter what the outcome is.

Input Variable State			Output Variable Result			Overall Result
Peak	Capacity	Wind	Compressor	Irr Pump	Meter 2	
Low (off-peak)	Low (not filled)	Low (no wind)	Grid	X	X	Compressor powered by grid, doesn't matter what powers meters
Low (off-peak)	Low (not filled)	High (wind)	Turbine	X	X	Compressor powered by turbine, doesn't matter what powers meters
Low (off-peak)	High (filled)	Low (no wind)	X	X	X	Compressor filled, doesn't matter what powers meters
Low (off-peak)	High (filled)	High (wind)	X	X	X	Compressor filled, doesn't matter what powers meters
High (peak)	Low (not filled)	Low (no wind)	X	Turbine	X	Compressor empty, Turbine powering Irr Pump
High (peak)	Low (not filled)	High (wind)	X	Turbine	X	Compressor empty, Turbine powering Irr Pump
High (peak)	High (filled)	Low (no wind)	X	CAES	Turbine	Compressor powering Irr Pump, Turbine on Meter 2
High (peak)	High (filled)	High (wind)	X	CAES	Turbine	Compressor powering Irr Pump, Turbine on Meter 2

Table X – Large Scale Control System Logic

The CAES LabVIEW Block Diagram shows the logic and programming behind the system design. The wind turbine and grid have a sinusoidal signal that simulates the AC power produced. There are two single pole, double throw (SPDT) relays. The wind turbine signal goes through one relay, and the grid power goes through the other. The wind turbines SPDT sends the wind power to the compressor when the compressor is not filled to capacity and it is off peak hours. Otherwise, the wind power is sent to another relay that determines whether the power is sent to the irrigation pump or the second meter. This is a double pole, double throw (DPDT) relay that always sends compressor power to the irrigation pump unless the compressor capacity is low, then it sends the turbine power to the irrigation pump.

A third SPDT relay controls whether the grid or wind power charges the compressor. This is determined by using the current transducer – if the wind turbine is producing enough power on off peak hours, then it charges the compressor. Otherwise, grid power charges it.

When the “Pk/solenoid” toggle is switched high, it is peak hours and the solenoid valve that controls the air output the turbine is opened. When the compressor is not empty (determined from the pressure transducer), the CAES is released and sent to the DPDT relay along with the wind power.

The printed circuit board shows the resulting control system design with its components. Appendix B shows the bill of materials for the 10kW control system. This includes all the sensors and transducers, microprocessor, relays, solenoid valve, and the mechanical components of the system like the wind turbine and compressor and tank. The large scale control system will be powered by batteries, which will be charged by a solar charger. The battery system components are also included in the bill of materials.

A utility-scale CAES control system was also designed. It was designed for small rural electric associations to help them with demand management and load leveling. This was more complicated than the 10kW system because it is a larger system (in the mega-watts), and requires more conditions monitored and to control the output of the compressors. To store the required amount of air, the system would probably use multiple tanks hooked up to one inverter, or using micro-inverters. These tanks would be charged using grid power during off peak hours, then released during the day either at a predetermined time, or when the power demand exceeded a threshold level. These controls would be determined by the utility company since they would be specific to each substation and each utility. The CAES system was hypothetically set at a distribution substation and was again designed and tested using LabVIEW.

Appendix X shows the LabVIEW Front Panel and Block Diagram for a utility-scale CAES system. The front panel shows the major components, such as pressure tanks, and various measurements and monitored values. For simplicity's sake, only the temperatures of the tank and overall substation (which would encompass transformer and controls temperature) were simulated. The waveform graphs show the monitored voltage and current coming into the substation, and the values to the right of the graphs are the measured volts and amps. Within the "Power Measurements" box, there are calculated quantities such as phase angle, power factor, and whether the power factor is leading or lagging. These measurements are important to assure power quality. There are also indicators for the total amount of stored energy in the tanks, and the difference between the energy being supplied from the grid and the CAES energy. Ideally, this would stay at a certain threshold or below. For example, if the distribution station was a 3MW station, but demand starting getting around or above that level, an amount of CAES could be released to compensate. This demands control of variable or proportional solenoid valves which can open to release air at diameters proportional to the electric signal. This way, the compressed air can be used most effectively over the day and not just all at once.

The block diagram shows the actual modeling and programming for the rural electric utility-scale CAES. It consists of simulated signals for the voltage and the current, which are fed through different loops and calculations to obtain the measured values and to fill the tanks. The current is measured so that when it is above a threshold (this would be done using a current transducer), it creates a logic control that signals the compressed air to release until the power going through the substation returns to a normal level.

The basic idea of the utility-scale CAES is that the tanks would release energy proportional to the amount of energy demanded above a threshold level. For example, at a 3MW substation of a rural electric association, if the power limit was being approached, the compressors might release 5kW or 10kW of energy to reduce the strain on the equipment and on the generation station. However, if more than 3MW was being demanded, the compressors might release 500kW of energy or more.

Another application for utility-scale energy storage is that it can be used at larger stations for spinning reserve. Energy storage, especially compressed air, is able to be charged and released quickly, and so is useful not only when peak demand of energy goes up, but when a power supply goes down.

Outreach and Education

We have presented the demonstration unit at several agricultural community events and plan to host more events in August. On June, 17th, 2009, we demonstrated the CAES unit to a large crowd of producers attending the Akron Research Station Ag Days event. A few producers had wind turbines and vocally supported our idea to capture the steady wind energy at night and utilize the more valuable commodity the next day. Many of the producers could relate to our concept of reducing their demand charge and peak usage.

On July 31st, 2009, iCAST attended the Southern Colorado Sustainability Conference in Pueblo, CO and stationed the unit under a tent just outside of the convention center. It was a beautiful day, so we were able to demonstrate the unit to most attendees at the conference. People can really buy into the simplicity of the mechanics and concept behind the unit.

We have plans to demonstrate the unit at the Yuma Farm Days and the Irrigation Research Foundation in the coming months. iCAST has a firm commitment to see this project through to the implementation phase and would like to continue to scale up the unit to pilot version actually installed on a Colorado farm.