Technology Performance Report

SustainX Smart Grid Program

Contract ID: DE-OE0000231

Project Type: Demonstration of Promising Energy Storage Technologies

Company Name: SustainX

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Recipient: SustainX, Inc.

Principal Investigators: Benjamin Bollinger, PhD

Project Title: Demonstration of Isothermal Compressed Air Energy Storage to Support Renewable Energy Production

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Contents

Abbreviations

AC	alternating current
ARRA	American Recovery and Reinvestment Act
CAES	Compressed Air Energy Storage
CFD	computational fluid dynamics
DC	direct current
DOE	Department of Energy
g	gram
GE	General Electric
GEFS	General Electric Financial Services
HPLIA	high-pressure liquid in air
HPU	hydraulic power unit
HXTST	Heat Transfer Test Stand
I&CS	Interoperability and Cyber Security Plan
ICAES	Isothermal Compressed Air Energy Storage (SustainX trademark)
in	inch
IP	intellectual property
JDA	joint development agreement
kW	kilowatt
L	liter
LCOE	levelized cost of energy
LRC	lined-rock cavern
MAN	MAN Diesel & Turbo
m	meter
min	minute
mm	millimeter
ms	milliseconds
MW	megawatt
NETL	National Energy Technology Laboratory
NH	New Hampshire
PMG	permanent magnet motor/generator
PMP	Project Management Plan
psi	pounds per square inch
psia	pounds per square inch, atmosphere
psid	pounds per square inch, differential
psig	pounds per square inch, gauge
RPM	revolutions per minute
sec	second
µm	micrometer

1 PROJECT OVERVIEW

1.1 Project Objectives

This project develops and demonstrates a megawatt (MW)-scale Energy Storage System that employs compressed air as the storage medium. An isothermal compressed air energy storage (ICAES™) system rated for 1 MW or more will be demonstrated in a full-scale prototype unit. Breakthrough cost-effectiveness will be achieved through the use of proprietary methods for isothermal gas cycling and staged gas expansion implemented using industrially mature, readily-available components.

The ICAES approach uses an electrically driven mechanical system to raise air to high pressure for storage in low-cost pressure vessels, pipeline, or lined-rock cavern (LRC). This air is later expanded through the same mechanical system to drive the electric motor as a generator. The approach incorporates two key efficiency-enhancing innovations: (1) isothermal (constant temperature) gas cycling, which is achieved by mixing liquid with air (via spray or foam) to exchange heat with air undergoing compression or expansion; and (2) a novel, staged gas-expansion scheme that allows the drivetrain to operate at constant power while still allowing the stored gas to work over its entire pressure range. The ICAES system will be scalable, non-toxic, and cost-effective, making it suitable for firming renewables and for other grid applications.

1.2 System Designs

The SustainX ICAES system stores potential energy in the form of compressed air. An electrically-driven mechanical system is used to compress air to high pressure (up to 3,000 psi) for storage. This air is later expanded through the same mechanical system to drive the electric motor as a generator. The technology uses isothermal gas cycling coupled with staged pneumatic compression and expansion to deliver an efficient, cost-effective energy storage solution. SustainX technology relies largely on off-the-shelf components, contains no toxic materials other than commonplace industrial hydraulic fluids, and emits no air pollution or effluents. It will have an extremely high cycle lifetime and achieve high round-trip efficiency. Breakthrough cost savings and high efficiency are made possible by exploiting basic thermodynamic principles to compress and expand air in a highly efficient manner.

Our rapid, well-targeted technology development process to date has proceeded through three major stages:

1) Alpha System. In early 2009, prior to the DOE demonstration project award, we effectively demonstrated a 1 kW round-trip energy storage system utilizing air compression and expansion at high isothermal efficiency. The fundamental isothermal concept was shown to be sound and practicable.

2) 40 kW Pilot System. As part of the DOE award, in September 2010 we successfully commissioned a 40 kW round-trip ICAES system. This system incorporated and successfully demonstrated key enabling technologies for isothermal CAES of this scale, including novel spray-based heat transfer for isothermal cycling and an optimized hydraulic drivetrain. These technologies are discussed in detail in later sections. Learnings from the 40kW Pilot system were instrumental in developing system layouts and new technologies required for a commercial-scale system.

3) 1.5 MW Commercial-Scale Prototype. As a continuation and primary focus of the DOE award, SustainX has developed our latest ICAES technology generation, the 1.5 MW Commercial-Scale Prototype. This system incorporates numerous crucial lessons learned from our earlier, smaller systems as well as new, enabling technologies developed for this implementation. These include the newly developed techniques and approaches for using foam to effect rapid heat transfer and high isothermal efficiencies at faster speeds; new valve technology for low flow and actuation losses; and a new crankshaft-based drivetrain platform that allows for reduced system cost, higher efficiency, and greater future scalability. These technologies are discussed in detail in later sections. The 1.5 MW Commercial Prototype has been operational since September 30, 2013; early data has already begun to inform future design enhancements.

1.3 Schedules and Milestones

This project consisted of two major phases (Table 1):

Phase 1: ICAES research, design, and optimization (40 kW ICAES system)

Phase 2: MW-scale ICAES system design, build, and testing

The goal of Phase 1 was to research, design, and optimize all aspects of our energy storage system, including the construction and testing of a 40-kW ICAES system, which would contain all refinements necessary for the MW-scale system. In Phase 2, a MW-scale system was to be designed, built, and tested. This MW-scale system, **now in operation,** will serve as a system building block, allowing for power installations sized to any multiple of this base power to be installed.

Phase 1 consisted of 11 tasks, which were completed by the end of 2011:

Task 1.1: Update Project Management Plan (PMP)
Task 1.2: Develop Interoperability and Cyber Security (I&CS) Plan
Task 1.3: Develop Metrics and Benefits Reporting Plan
Task 1.4: Heat Transfer Optimization
Task 1.5: Hydraulic Drivetrain Optimization
Task 1.6: Control System Development
Task 1.7: Grid Interconnection System
Task 1.8: Compressed Gas Storage
Task 1.9: 40 kW Design
Task 1.10: 40 kW Manufacture and Test
Task 1.11: Mega-watt Scale Preliminary Design

Phase 2 consisted of eight tasks, completion of each of which constituted a milestone. Each of these tasks/milestones have been completed as of the submission date of this report (see also Table 1).

Task 2.1: Crankshaft System Analysis & Layout
Task 2.2: Spray System Modeling & Testing
Task 2.3: MW-scale Detail Design
Task 2.4: Crankshaft Installation
Task 2.5: Engine spinning with no valve actuation
Task 2.6: Start-up Testing
Task 2.7: MW-Scale Pilot Test Completion
Task 2.8: Submit Final Technical Report

Table 1. Major project milestones.

Milestone	Target Date	Completed Date
Phase 1		
40 kW prototype ("the Pilot") design	2/4/2010	2/19/2010
40 kW prototype manufacture	9/24/2010	9/10/2010
40 kW prototype test	1/14/2011	Prelim. results, 1/14/11. Testing completed, 5/6/11.
MW-scale system preliminary design	12/31/2011	12/27/2011
Phase 2		
2.1 Crank Shaft System Analysis & Layout	12/19/2011	4/17/2012
2.2 Spray System Modeling & Testing	2/3/2012	11/16/2012
2.3 MW-scale Detail Design	9/11/2012	2/22/2013
2.4 Crankshaft Installation	3/1/2013	3/1/2013
2.5 Engine spinning with no valve actuation	8/1/2013	9/11/2013
2.6 Start-up Testing	11/1/2013	10/27/2013
2.7 MW-Scale Pilot Test Completion	10/1/2014	9/15/2014
2.8 Submit Final Technical Report	1/2/2015	1/6/2015

1.4 Interactions with Project Stakeholders

1.4.1 Technology Collaborators

SustainX has worked with multiple collaborators throughout the execution of this project as a means to draw in external expertise and reduce project risk. A few of the technical collaborators are described below.

SustainX. SustainX is the lead on the DOE Demonstration Award Project and is the developer of the core ICAES technology. The company was founded in 2007 by engineers from the Thayer School of Engineering at Dartmouth. In 2011, SustainX relocated from its Lebanon, NH facility to a larger, 42,000 square foot building at 72 Stard Road, Seabrook, NH (Figure 1). The new facility houses offices, research labs, and assembly space, and is equipped with ceiling cranes and other resources required to handle the construction and testing of megawatt-scale ICAES units.

Figure 1: SustainX facility in Seabrook, New Hampshire

Creare. Creare is a premiere engineering R&D firm located at 16 Great Hollow Road, Hanover, NH, 03755. Creare provided invaluable collaborative work on thermal modeling, heat transfer, and fluid dynamics throughout the early development of SustainX's patented heat transfer processes, working closely with SustainX engineers to define needs, approaches, and deliverables. During 2009 to 2011, Creare and SustainX held frequent face-to-face meetings aided by their proximity. Creare's facility covers 43,000 square feet, one-third of which is laboratory and machine-shop space. The balance comprises offices, a technical library, and computing facilities. The laboratories have been developed to meet a broad range of requirements for component fabrication and experiments in cryogenics, single- and two-phase flow, heat transfer, and biomedical engineering. They are fully equipped and are staffed by highly skilled and experienced personnel, i.e., mechanical, electronic, and laboratory technicians; machinists; and computer numerical controlled (CNC) programmers and prototypers.

MTechnology. A consulting engineering firm located at 2 Central Street, Saxonville, MA, 01701, MTechnology offers integrated design, analysis and fabrication services for implementation of power system hardware. It specializes in the design of robust, highly reliable electrical systems and operates a laboratory where it tests and designs power supply equipment. Capabilities include power supply design and control, failure analysis, and finite element structural and thermal analyses. MTechnology provided expertise on grid connection electronics and load-bank design for both the 40 kW and 1.5 MW ICAES systems.

MAN Diesel & Turbo. MAN is a world leader in large diesel and gas-fired internal combustion engines for marine and power-generation applications. It has partnered with SustainX to adapt its crankshaft technology to our ICAES unit under a joint development agreement (JDA) with SustainX. Close collaboration of MAN and SustainX engineers has enabled detailed modeling of bearing loads and vibrations, enabling design, construction, and installation of a 1.5 MW ICAES system employing a MAN crankshaft.

1.4.2 Financial Stakeholders

SustainX has received equity funding from a number of top-tier venture and private equity investors, as outlined in Table 2.

Table 2. Roles of project partners.

Project Partner	Partner Role
POLARIS VENTURE PARTNERS	Polaris Venture Partners is a venture capital firm with 90 current investments and over $3 Billion under management. The firm seeks to build lasting companies through an active and long-term approach to helping management teams.
ROCKPORT CAPITAL PARTNERS	RockPort Capital Partners is a cleantech-focused venture capital firm with deep expertise in the energy industry. It has invested in a variety of clean energy technologies, and currently has over 30 current investments in its cleantech portfolio.
CADENT ENERGY PARTNERS	Cadent Energy Partners is a private equity firm that invests in small to medium-sized companies in the energy industry. Cadent provides expansion capital to firms that want to accelerate growth and build exceptional shareholder value in partnership with an experienced energy investor. Cadent's principals have invested >$890M in privately negotiated transactions over a range of energy sub-sectors.
GE ecomagination	GE Energy Financial Services invests globally across the capital spectrum in essential, long-lived and capital-intensive energy assets that meet the world's energy needs. GEFS offers GE's technical know-how, technology innovation, financial strength and rigorous risk management. It holds equity investments in power projects that can produce 23 GW. SustainX was selected to be a partner of the GE Ecomagination "Powering the Grid" project in late 2010.
General Catalyst Partners	General Catalyst Partners is a private equity firm focused on venture capital investments in early stage technology-based companies including software, infrastructure software and applied technology businesses. The firm has raised approximately $1.6 billion since inception across five funds including a $600 million venture capital fund raised in 2007.

2 DESCRIPTION OF TECHNOLOGIES AND SYSTEMS

The ICAES approach uses an electrically driven mechanical system to raise air to high pressure for storage in low-cost pressure vessels, pipeline, or lined-rock cavern (LRC). This air is later expanded through the same mechanical system to drive the electric motor as a generator.

Key technologies have been developed that have allowed the successful implementation of full isothermal compressed air energy storage systems, first at moderate scale and later at full grid scale. This section describes the new technologies and the technical evolution that has led to SustainX's MW-scale commercial prototype system.

2.1 Technology: Spray-based Heat Transfer for Isothermal Cycling

Gas being compressed will increase in temperature if heat is not removed. Gas being expanded will decrease in temperature if heat is not added. This is the fundamental challenge to using air compression as a means of storing energy.

If gas is both compressed and expanded *adiabatically* (with no heat removal or addition), a theoretical maximum thermal efficiency of 100% can be achieved. However, such a process is extremely difficult to implement in practice due to the large temperature extremes – a compressed air energy storage system compressing air adiabatically from 1 atmosphere to 200 atmospheres would increase air temperature by over 1000^{o}C. Such temperatures are extremely difficult to deal with, both from a materials and equipment perspective as well as a heat and efficiency loss perspective.

Alternatively, gas can be both compressed and expanded *isothermally* (at constant temperature), and again a theoretical maximum thermal efficiency of 100% can be achieved. This process, by definition, eliminates temperature extremes and the associated challenges. This is the approach used in SustainX's ICAES systems.

The challenge for an isothermal process is the heat transfer – an isothermal compression or expansion requires continuous heat exchange between the gas and some other substance to remove heat as the gas is compressed or to add heat as the gas is expanded. Although perfectly isothermal compression or expansion is not practicable, a gas can be expanded or compressed near-isothermally if heat exchange occurs quickly enough relative to density change. Faster heat exchange is more desirable because it enables an isothermal compressor/expander system of a given size to process more gas in a given time without impacting thermal efficiency.

In 2008, SustainX began development of a water spray-based heat transfer approach to effect rapid heat transfer for near-isothermal air compression and expansion. Water is an ideal medium with which to exchange heat due to its high heat capacity. Spraying water into the low-pressure stage and high-pressure stage cylinders allowed for continuous heat transfer during both compression and expansion processes. Furthermore, the large number and small size of the droplets allowed for large amounts of heat to be transferred at a low air-to-water temperature difference, resulting in high thermal efficiency.

There were two key challenges to creating a successful spray system for isothermal compressed air energy storage. First, generation of the spray needed to consume a very low amount of energy since the energy needed to spray the water directly reduces system efficiency. This equates to the need for a low pressure drop across the spray nozzles (on the order of 3.5 bar, or 50 psid). This is especially difficult to achieve in the high-pressure cylinder stage, where cylinder pressures range up to 207 bar gauge (3000 psia). SustainX's high-inlet pressure pumps and closed-loop water spray circuit addressed this challenge.

Second, since spray is continuous during the compression and expansion processes, the spray nozzles must be able to create very fine droplets at all cylinder pressures – a 200:1 pressure range – all while still meeting the low pressure drop criterion for energy consumption.

Along with our technology collaborator Creare, SustainX performed extensive analysis, design, and experimentation to develop both the nozzles and the spray support systems necessary to overcome these challenges and to create a low energy consumption spray system that would result in high isothermal air compression and expansion efficiency. Details of the system, as well as the test stands used to validate the technology, are described in section 4.1.

2.2 Technology: Staged Hydraulic Drivetrain for ICAES

For the 40 kW Pilot, the results of the spray-based heat transfer experimentation dictated a 3 second compression or expansion per stage, resulting in cylinder stroke durations of 3 sec. With two strokes per cycle, this equates to a 10 revolution per minute (RPM) equivalent speed. A hydraulic drivetrain offered low cost at low operational speeds (<20 RPM) and could be fabricated relatively quickly from off-the-shelf components at moderate power levels.

Reasonable hydraulic drivetrain efficiency is possible for systems with near-constant pressure and flow rate. However, efficiency can fall dramatically for systems with highly variable conditions. Several innovative technologies were patented and adopted at SustainX to

1. Increase hydraulic drivetrain efficiency by maintaining high hydraulic pump pressures despite large variations in cylinder air pressure during compression and expansion.
2. Allow for hydraulic power smoothing.

Several iterations of the hydraulic drivetrain were implemented, as described in the results section 4.2, but ultimately the design goals of the hydraulic drivetrain – low cost, high efficiency, long life, and hydraulic power smoothing – were not all simultaneously achievable. This, in part, led to the development of the crankshaft-based drivetrain platform for commercial ICAES, as will be described in section 2.5.

2.3 System: 40kW Pilot

The 40 kW Pilot, which became operational in September 2010, incorporated the two enabling technologies discussed above – a continuous spray-based isothermal heat transfer process and a staged hydraulic drivetrain – as well as other key system design aspects to create a fully functional, round-trip electricity in/ electricity out energy storage system.

The system featured two pneumatic stages, a low-pressure and a high-pressure, with two cylinders per stage. Each stage had a pressure ratio of 14.4:1, for a total capability to compress to and expand from

207 bar gauge (3000 psig). Each of the pneumatic stages featured a closed-loop water spray system, as described above. The pneumatic cylinders were coupled via a common mechanical connection to two hydraulic cylinders, which formed part of the staged hydraulic drivetrain. The hydraulic drivetrain, well-suited for the relatively slow, 10 RPM operation, was used to convert reciprocal motion to rotary motion and then electrical power. The system also incorporated all of the necessary support systems, including among others a reversible motor drive and local grid connection, water holding reservoir and treatment systems, water makeup systems, and hydraulic fluid filtering systems.

Results from this system are described in section 4.3. Experimental data and operational experience with the 40 kW Pilot allowed an efficiency-improvement and cost-reduction roadmap to be designed and implemented in our next design round.

2.4 Technology: Foam-based Heat Transfer for Isothermal Cycling

Following successful demonstration of the spray-based heat transfer in the 40kW Pilot System, SustainX continued efforts to further improve the speed of heat transfer between air and water undergoing compression or expansion. Decreasing cylinder stroke times (increasing RPM) results in higher power density and lower cost but in turn requires higher rates of heat transfer to maintain high thermal efficiency.

At higher speeds (and especially with water additives for anti-corrosion, lubricity, and other purposes), foaming becomes more prevalent. Somewhat by accident, it was discovered in ongoing experimentation that air and water suspended together as foam could result in higher thermal efficiencies (or similar thermal efficiencies at higher speeds). This began the effort to better understand the ability of foam to allow for rapid heat transfer and higher speed isothermal compression and expansion.

A mixture of air and water as a homogeneous foam has several advantages over water suspended in air as droplets. Foam

- increases the surface area between air and water, as compared to the same volume of water suspended in air as droplets;
- maintains contact between air and water during an entire compression or expansion stroke due to the fact that foam is semi-solid, increasing heat transfer as compared to droplets, which tend to fall out or collect on the piston as the piston strokes; and,
- in some cases, increases the effective heat transfer coefficient (fine-textured foams only) by decreasing the heat transfer length scale (distance between any one small volume element of air and the nearest water).

While it is relatively easy to mix water and air together as foam, it is in practice quite challenging to create a foam that performs well for heat transfer and can also hold up well to the demands of a real, physical system. The key challenges include generation of high-quality foam, transport of the foam through pipes and valves and into cylinders without foam destruction, and breakdown of foam into its air and water constituents at the appropriate part of the process (after it has been used for heat transfer purposes). SustainX's development efforts have addressed each of these challenges and have allowed for the successful use of foam to enable higher speed, isothermal compression and expansion. Results of these efforts are presented in section 4.4.

The increased system speed (from 10 RPM to 120 RPM) that was allowed for by the improved heat transfer with foam resulted in two major side effects.

1. The increased speed allowed for the adoption of a crankshaft-based drivetrain platform for ICAES as opposed to the original hydraulic drivetrain platform. This technology improvement is described in section 2.5.
2. The increased speed resulted in an order of magnitude increase in the flow rates through the pneumatic valves. This, along with the stiffness of the crankshaft platform and the need to pass foam through the valves, placed a host of significant additional design requirements and constraints on the cylinder valves. The resulting technology is described in section 2.6.

2.5 Technology: Crankshaft-based Drivetrain for ICAES

Improvements in SustainX's heat transfer technology allowed for faster, quarter-second strokes, thus enabling higher speed operation and the use of a mechanical crankshaft. The crankshaft represents a major improvement in efficiency and reliability over our previous, hydraulics drivetrain used in the 40 kW system. A hydraulic drivetrain converts rotary mechanical energy to fluid power energy and then to reciprocal (linear) mechanical energy. These two energy conversions are replaced by a single energy conversion when using a crankshaft, which directly converts rotary mechanical energy to reciprocal mechanical energy, improving drivetrain efficiency.

Even at the faster 120 RPM speed allowed for by the improved heat transfer, the speed is still slow by piston engine standards, which typically run in the thousands of RPM range. Furthermore, for a MW-scale ICAES system, the pneumatic cylinders are quite large, with a 1.55 m (61 in) stroke and diameters of 750 mm (29.5 in) and 220 mm (8.7 in) respectively for the low-pressure and high-pressure cylinders. The cylinder dimensions and speed match very well with the size and speed of two-stroke marine diesel engines. Photographs of the crankshaft and the cylinders during installation are shown in Figure 2.

SustainX uses the lower half of a small MAN Diesel and Turbo engine as the crankshaft for the ICAES system. The MAN machine is a standard industrial product, as is the 150 max RPM wind-industry direct-drive permanent-magnet motor/generator (PMG) to which it is paired. SustainX worked with both the crankshaft and the PMG suppliers to adapt these technologies as necessary and ensure their suitability for the ICAES application. This work is summarized in the results section 4.5.

Figure 2: ***Left:*** **Test-fit of a SustainX HP cylinder on top of the lower-half of a MAN engine (crankshaft). A PMG can be seen to the right of the crankshaft.** ***Right:*** **Installation of a LP piston into a LP cylinder.**

2.6 Technology: High-Performance Valves for ICAES

The increase in system speed (to 120 RPM) allowed for by the improved heat transfer placed significant additional requirements and constraints on the cylinder valve design. Commercial off the shelf valves no longer were able to meet all of the design requirements.

SustainX has developed new valve technology to specifically meet the requirements of high-efficiency isothermal CAES. Tests on earlier units had made clear that valving for precise control of air intake and exhaust is crucial to the success of our system: variable, precision valve timing is critical because of bi-directional machine operation (compression and expansion), two-phase fluid flow, the range of process RPM, and the range of operating pressures encountered as gas storage is progressively filled or emptied.

We designed semi-active control valves for bi-directional compressor/expander flow that are highly efficient (i.e., with low flow losses and low actuation energy consumption); packaged into cylinder heads to maximize flow area and minimize dead volume[1]; operable with mixed flow (air + water) at pressures up to 3,000 psi; fast-operating (5–10 ms actuation time) with built-in passive cushioning; capable of variable timing up to 120 RPM; and protected against cylinder over pressure by a passive, failsafe design.

[1] When a cylinder's piston is at top-dead center, the remaining volume within the cylinder is termed its clearance volume. The term dead volume refers to the portion of the clearance volume that is occupied by air. The air mass in the dead volume is compressed and expanded each cycle. Excessive dead volume can result in lower efficiency, lower system power, and, in extreme cases, the inability to compress to max storage pressure.

Two high-pressure valves and two low-pressure valves meeting the above criteria were designed and constructed. A discussion of the design and test results is given in section 4.6.

2.7 System: 1.5 MW Commercial-Scale Prototype

Our latest ICAES technology generation is the 1.5 MW Commercial-Scale Prototype system, shown in Figure 3. The system incorporates numerous crucial lessons learned from our earlier, smaller systems, as well as the newly developed enabling technologies described in the previous sections. The 1.5 MW Commercial Prototype has been operational for both compressions (charge) and expansions (discharge) since September 30, 2013.

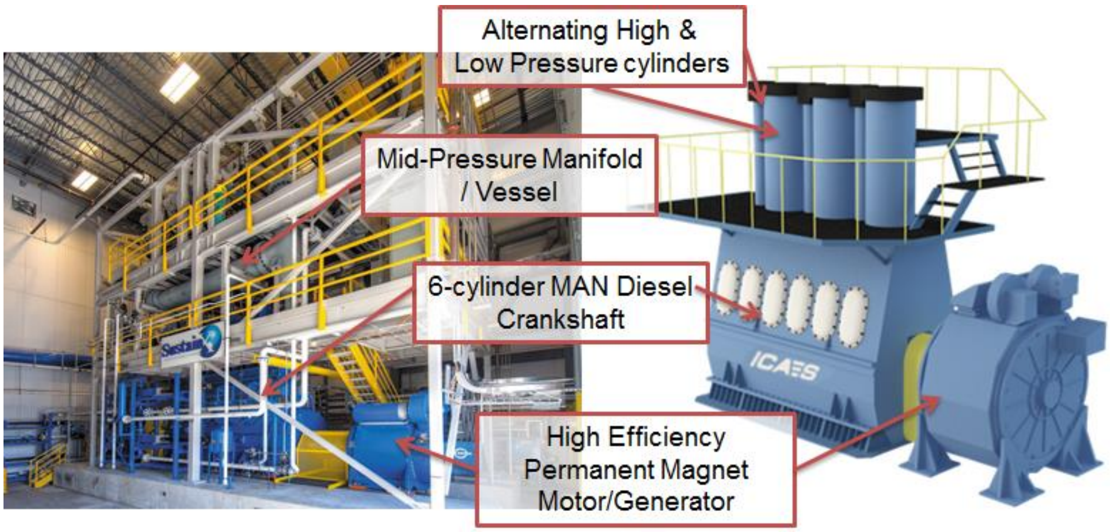


Figure 3: *Left*: Completed SustainX Megawatt-scale ICAES system located at Seabrook, NH, October 2013. *Right*: Rendering of ICAES power unit showing cylinder arrangement.

The 1.5 MW Commercial Prototype comprises six compression/expansion cylinders (three low-pressure paired with three high-pressure) coupled to a crankshaft for converting the pistons' reciprocating motion into rotary motion suitable for a standard industrial electrical motor/generator. Each cylinder pair consists of a large diameter low-pressure cylinder (0 to 180 psig in compression mode) and a smaller diameter high-pressure cylinder (180 to 3,000 psig). To achieve isothermal compressions and expansions, a two-phase liquid-air mixture is used in the cylinders. The permanent magnet electric motor/generators (PMGs) are controlled by full (AC-DC-AC) power converters (FPCs) which allow the speed of the PMGs to vary as the air storage pressure varies. The FPCs are connected to load banks and to the grid via the switchgear. Per the current interconnection agreement with the local utility, the load banks and an intertie protection relay in the switchgear are used to prevent back-feeding of energy onto the grid during SustainX's initial testing period.

From standby, the 1.5 MW Commercial Prototype system can reach full power (charge or discharge) in less than 60 seconds. Charge-to-discharge turnaround time is under 1 second. The ratio of charge time to discharge time is 1.3:1.

The 1.5 MW Commercial Prototype is heavily instrumented, with a total of 840 inputs/outputs (I/O). Of these, 121 are inputs received over the communication bus from sub-controllers, motor drives, or bus-coupled sensors (e.g. encoders) and 512 are external analog or digital inputs (e.g. pressure transducers, limits switches). External inputs are received by standard industrial analog and digital input modules (e.g. B&R X20 AI 4622). In addition to real-time monitoring of system parameters, including a full suite of diagnostics, all I/O are logged by the by the system main controller or valve controller at the controller speeds, 100 Hz and 1250 Hz respectively. The data is pulled off by an FTP server and stored on-site for later post-processing and analysis.

3 PERFORMANCE ESTIMATION METHODOLOGIES AND ALGORITHMS

3.1 Analysis Objectives

The SustainX development process has been methodical and deliberate, moving first from calculation to experimentation and physical demonstration of each of the technologies described above. We have used a series of simulations, test stands, and full-system builds to evaluate, test, and prove out key ICEAS technologies and systems. Each of the technologies and systems mentioned in the section above has been evaluated in different manners, as appropriate for each. For each of the technologies, the analysis objective was to evaluate performance of the developed technology and assess its ability to enable success of the larger round-trip energy storage system into which it will be implemented. For the systems, the objective of the analysis was to evaluate the high-level performance of the overall system, specifically the key system parameters such as power and efficiency.

3.2 Methodologies for Determining Technical Performance

While methodologies for evaluating performance differed for each technology and system developed, a few generalizations can be made. The methodology included simulation and analysis, and where possible, experimentation. Simulations include finite element analysis (ANSYS), computational fluid dynamics (ANSYS Fluent), and physical domain systems modeling (Mathworks Simulink/SimScape). In some cases, multiple test stands were built to validate a particular technology.

For the full round-trip systems, evaluations have followed a set of principles and guidelines. Rated power is the power during discharge at the point of grid-connect. Efficiency is evaluated on an AC-to-AC basis, all-in, including full-power converters and parasitic electric energy consumption during both run-time and standby.

Details of the evaluations for each technology and system, including simulations, test stands, and experimental methods where appropriate, are included in the results sections.

3.3 Methodologies for Determining Grid Impacts and Benefits

Financial performance estimates have been a key input to the SustainX technology design process. SustainX was one of the early proponents of the use of levelized cost of energy (LCOE) for energy storage applications. The SustainX LCOE model was developed in 2010 and used the California Energy

Commission LCOE model as its basis. Use of LCOE has helped guide design decisions that require a tradeoff on capital cost, efficiency, and lifetime.

Figure 4 compares the LCOE for SustainX's ICAES technology to other energy storage technologies. The size of the bar segments in the LCOE chart can be used to demonstrate the impact of cost, efficiency, and lifetime for energy applications. The size of the blue column represents the initial capital cost. Advanced battery solutions have the highest initials costs, while a mature gas turbine has the lowest. For high energy applications, the limited cycle life of a li-ion battery leads to replacements within the 20-year life of the modeled project. The cost of these replacements is shown by the yellow bar. The combined height of the yellow and blue bars represents the total capital cost for a 20-year project. ICAES does not require replacements and thus has no yellow bar. The red segment at the top of each bar represents the impact of efficiency. Li-ion batteries have the highest efficiency and thus the smallest red bar. ICAES has a relatively lower efficiency, but the advantages of lower capital cost and longer life far outweigh the relatively larger red segment.

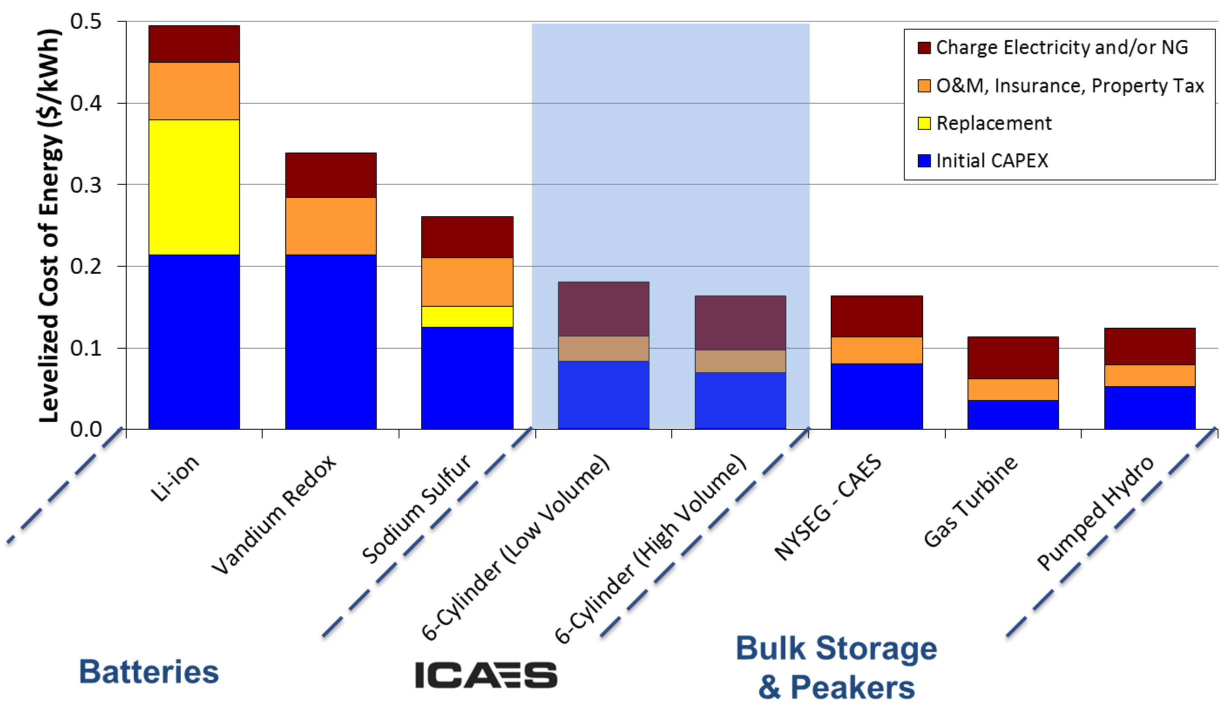


Figure 4: LCOE Comparison of ICAES vs other storage technologies. Assumes: 6-hour daily discharge, 20-year project, US off-peak charge electricity ($30/MWh), US gas pricing ($4/mmBtu), POU finance.

To further guide our cost, performance, and market strategy a wide array of grid applications were modeled in detail for different geographic and regulatory regimes. Results will be described in Section 5 but two key examples are shown below. Storage was modeled as a both a "generation asset" in applications such as firm wind and also as a "T&D asset" for applications such as T&D substitution.

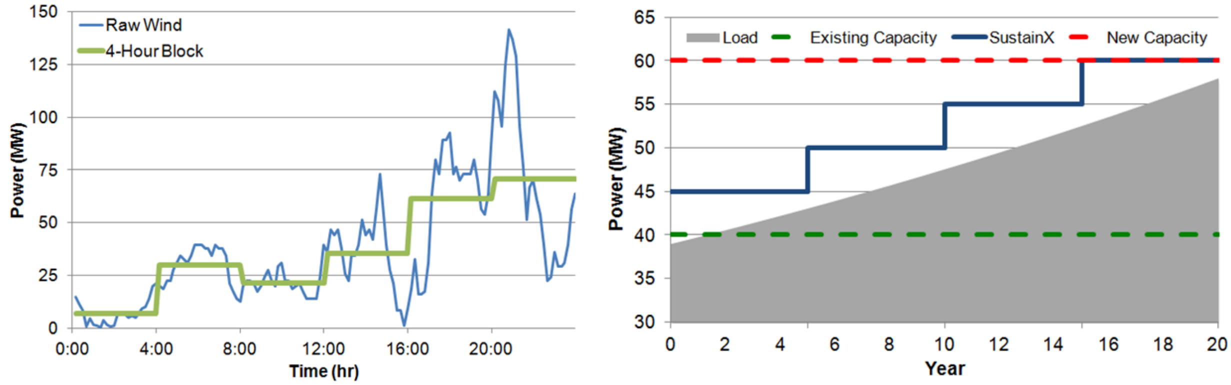


Figure 5: Left: Multi-hour "firm" wind. Right: Storage as a T&D substitute.

4 PERFORMANCE RESULTS OF TECHNOLOGIES AND SYSTEMS

We have used a series of simulations, test stands, and full-system builds to evaluate, test, and prove out key ICEAS technologies and systems. The sections below describe the technologies that have been developed, the simulation and experimentation used to validate them, and the round-trip energy storage systems that they have enabled.

4.1 Technology: Spray-based Heat Transfer for Isothermal Cycling

SustainX utilizes continuous heat transfer between liquid and air during compression and expansion processes to avoid temperature extremes and achieve high efficiency. A primary goal of Phase 1 of SustainX's DOE Demonstration project was to increase the efficiency of heat transfer between liquid and air during compression and expansion. Energetically efficient and effective heat transfer between liquid and air during compression or expansion requires three key features: (1) minimal distance between liquid and air during compression/expansion (i.e., complete coverage of a compression/expansion cylinder volume with liquid—ideally, uniform distribution), (2) maximal contact surface area between liquid and air during compression/expansion, and (3) minimal energy usage for generation of the liquid/air mixture.

Much is known about spray creation at atmospheric pressure. Substantially less is known about the droplet sizes, distributions, and general character of sprays created at higher chamber pressures (as is needed for spray-based heat transfer for ICAES).To better understand sprays at higher pressures, SustainX built a high-pressure, liquid-in-air (HPLIA) test setup (Figure 6) to examine sprays over a range of orifice designs and operating conditions.

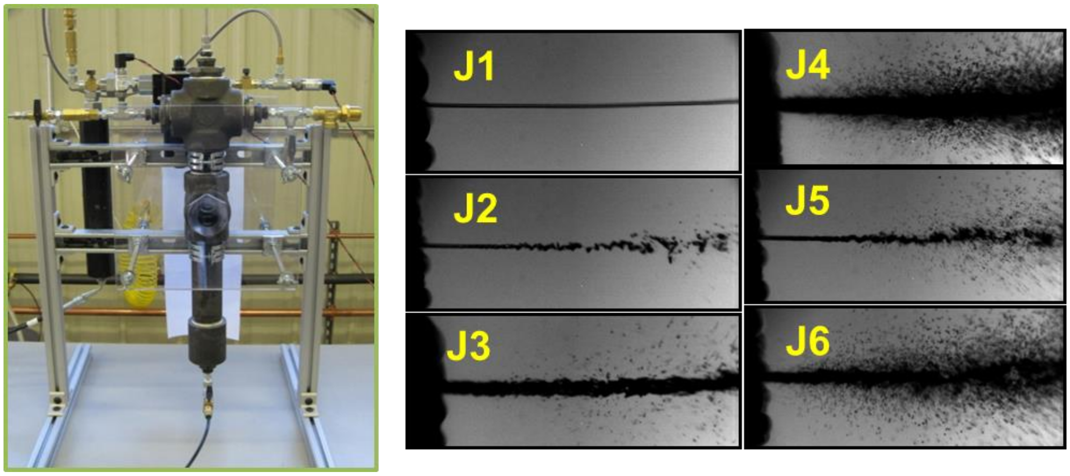


Figure 6: Spray characterization experiments. *Left*: HPLIA test unit. *Right*: jet breakup experiments using different nozzles, classified by J type per Bachalo et al.

Our calculations indicated that droplets of 100 µm–900 µm would be needed for optimal heat transfer (given injection velocities, cylinder air density, stroke-time, dwell-time, and other constraints); accordingly, 23 spray heads were manufactured having 1–7 nozzles each and with orifice diameter and taper varying from head to head. These were tested with air pressures of 1–69 bar (15–1000 psia) and differential injection pressures of 0.35–3.45 bar (5–50 psid). Qualitative classification of injection breakup was based on Bachalo et al[2] (see Figure 6). Heads were ranked based on power required to achieve acceptable flow breakup at a given pressure. For the best nozzle size and geometry, injection at 2 bar differential pressure was found to produce J6 spray breakup in air above 60 bar and J4/J5 spray breakup above 20 bar. These results were used to select the primary target nozzles for further experimentation.

In order to prove the ability of liquid spray in air to achieve high isothermal efficiency, a test stand was needed that could quantitatively measure the isothermal efficiency of rapidly compressing or expanding air. To this end, SustainX designed and built its Heat Transfer Test Stand (HXTST) to study the effects (e.g., isothermal efficiency) of sprays in actual air cycling.

The HXTST is comprised of a vertical, 37.9 liter, 207 bar-rated pneumatic/hydraulic piston cylinder (i.e., pneumatic above the piston and hydraulic below), a 7.6 liter water-injection cylinder, a 132.5 L, 345 bar-rated bank of accumulators, and a 5 kW hydraulic pump, control and instrumentation, and other support equipment (see Figure 7, left). The pneumatic portion of the cylinder operates between 17.2 bar and 207 bar (between 250 psia and 3000 psia). A spray head is affixed to the upper interior surface of the pneumatic chamber and allows water to be sprayed during air compression or expansion.

[2] Bachalo W, Chigier N, Reitz R (2000) Spray Technology Short Course Notes. Norman Chigier, Carnegie Mellon University, Pittsburgh, PA, pp. 1-22–2-10.

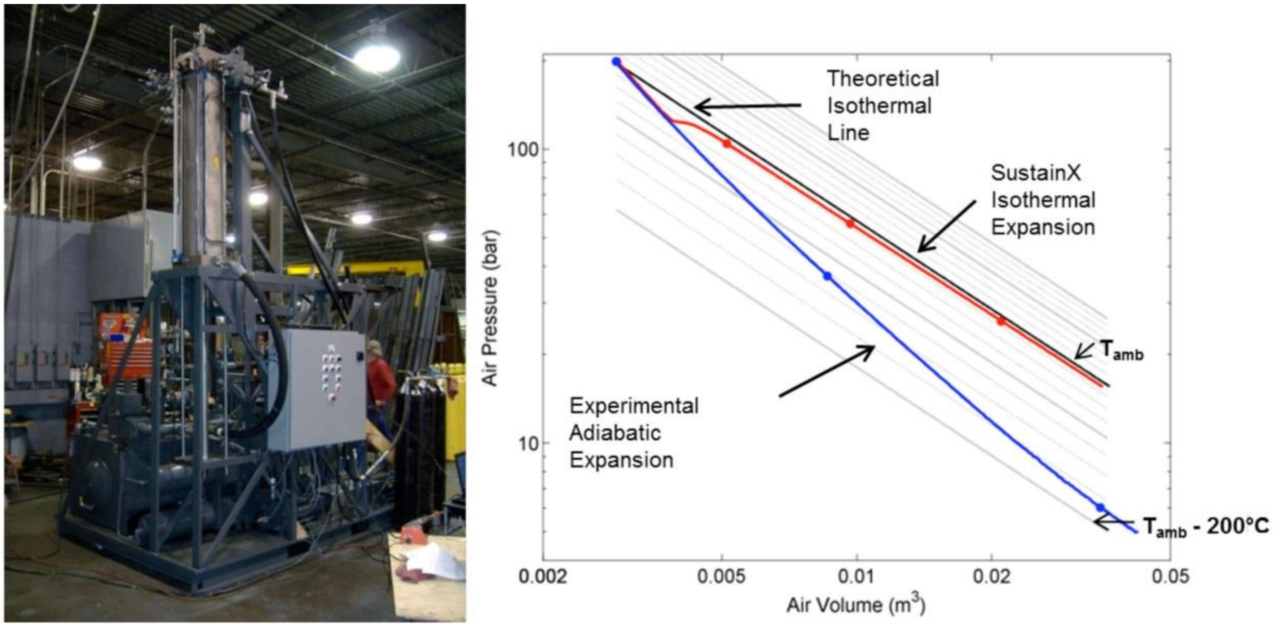


Figure 7: *Left*: Heat-transfer test stand, a.k.a. HXTST. *Right*: Experimental results for an isothermal expansion (red) vs. adiabatic expansion (blue) vs ideal expansion (black) for the same mass of air. Dots are marked at 1 second intervals for reference. Grey lines are lines of constant temperature at 25°C increments from ambient temperature.

The test stand allows a calibrated mass of air to be rapidly expanded or compressed with any desired spray volume or profile. The known mass of air and experimental start and end pressures provide the theoretical isothermal work that can be achieved for a given stroke. The known hydraulic fluid pressure and flow rate over the expansion or compression stroke provide the actual work achieved (for expansion) or needed (for compression). This allows for an accurate calculation of isothermal efficiency.

When starting a *compression* stroke, the HXTST piston is at the bottom of the cylinder and the air pressure in the upper (pneumatic) chamber is 17.2 bar. Hydraulic fluid in the lower chamber pushes the piston upward while spray is generated in the pneumatic chamber. A power level (i.e., rate of work performed by the piston on the air) between 25 kW and 75 kW is specified and the water-pump speed is set so that a specific volume of water (up to 7.6 liters) is spray-injected during the stroke.

When starting an *expansion* stroke, the piston is near the top of the cylinder and the starting air pressure is 207 bar (3000 psig). The hydraulic chamber empties as air pushes the piston downward. Power level and spray technique are determined as above.

The results in Figure 7, from 2010, show experimental data for two expansions of the same mass of air. When the air was expanded without the water spray, it expanded near adiabatically – the expansion lasted ~2.3 seconds and ended over 175°C colder than the ambient start temperature, an isothermal efficiency of 54%. When the same mass of air was expanded again, this time with the water spray, the temperature curved back up towards the theoretical once the spray started (at approximately 0.5 seconds into the expansion) and maintained a 15°C difference with ambient for the remainder of the stroke, achieving a 95% isothermal efficiency. This run maintained the same constant power for 3.8

seconds, 65% longer than for the run without spray, due to the heat from the water being able to maintain higher air pressures throughout the expansion.

These experiments demonstrated the key uncertainty in the ICAES process – the ability to achieve isothermal expansion and compression at decent speeds – and laid the foundation for the 40 kW system design based on 3-second strokes per stage and able to achieve >95% isothermal efficiency with a water spray consuming <2% of system power.

4.2 Technology: Staged Hydraulic Drivetrain for ICAES

The demonstrated heat transfer from the spray experimentation required relatively slow operation of the compression/expansion cylinders: three second strokes, or 10 RPM. An efficient drivetrain to convert energy in the form of this low speed linear (reciprocating) motion to electrical energy is technically challenging to develop.

A crankshaft is a natural choice for converting reciprocating to rotary motion. However, at 10 RPM the speed is too slow for standard hydrodynamic bearings (low cost, low friction, long life) and would instead require roller-element bearings (higher cost, higher friction, lower life). Furthermore, the gearbox needed to convert the low speed to the much higher speeds (e.g. 1800 RPM) for standard electric motor/generators would be costly and inefficient.

Hydraulic systems, on the other hand, are well suited for converting the high speed (1800 RPM) rotary motion best suited for electric motor/generators to the low speed (10 RPM) linear motion required by the pneumatic cylinders. Furthermore, a hydraulic drivetrain offered low cost at low operation speeds (<20 RPM) and could be fabricated relatively quickly from off-the-shelf components at moderate power levels. The challenge with hydraulics is to do the energy conversion in a sufficiently efficient manner to support a round-trip energy storage system.

For the 40 kW system, high-efficiency commercial hydraulic pump/motors were used as the primary driver. The pumps were used to drive two double-acting hydraulic cylinders that were coupled to the double-acting low and high pressure pneumatic cylinders via a common mechanical connection.

The key challenge with the hydraulic drivetrain was pressure. As the air pressure increased or decreased over the course of a 3 second stroke, the hydraulic pressure increased or decreased accordingly. SustainX initially developed a staged hydraulic drivetrain that integrated hydraulic valves between the hydraulic pump/motor and the hydraulic cylinders. This allowed the effect of the 200:1 pneumatic pressure ratio (air compression from atmospheric to 3000 psi) to be reduced to a 4:1 pressure ratio experienced by the hydraulic pump/motor. The result was a sufficiently high hydraulic pump/motor efficiency to support the target ICAES system efficiency.

However, the hydraulic valves proved to have an unexpectedly negative impact on overall hydraulic drivetrain efficiency due to the large flow losses during the valve transition events. This prompted the removal of the valves, thus removing a portion of the hydraulic staging. The result was an increase to a 14:1 pressure ratio experienced by the hydraulic pump/motor, reducing the pump/motor efficiency.

To improve performance of the 40 kW system's hydraulic drivetrain, all major hydraulic pump/motor manufacturers were approached. Each produced a pump/motor with peak efficiencies exceeding 90% at full displacement. All hydraulic pumps, however, loose efficiency as pressure or displacement decrease or as speed moves off of nominal. Manufacturers' efficiency data over a range of operating pressures, pump displacements, and speeds were used to simulate operation for the actual pressure profiles of the 40 kW system. Simulated efficiencies were as high as 87%, but *achieved* efficiencies for pump/motors that were tested were 10 percentage points lower.

Ultimately, four different pump/motors and hydraulic system configurations (one with and the rest without the hydraulic valve staging for minimizing operating pressure range) were tested in the 40 kW system, with none achieving efficiencies over 80% under real operating conditions. With refined and validated simulations, simulated efficiencies for all existing hydraulic pump/motors operating with actual pressure profiles were under 80%. Additional hydraulic losses in piping and valves, and leakage through spools and valves, further reduced drivetrain efficiency.

Overall, the hydraulic drivetrain was a quick and effective means of using commercial off-the-shelf components to drive the 40 kW test ICAES system at slow speeds (e.g. 10 RPM). While several innovative technologies were patented and adopted at SustainX to increase efficiency of the hydraulic drivetrain (as well as provide power smoothing – which was successful – and other benefits), ultimately, after exhaustive study, hydraulics were deemed too inefficient for use in a commercial system at reasonable power levels. Improved heat transfer using foam, as will be discussed in section 4.4, enabled higher speed operation and allowed for the use of a crankshaft platform for subsequent systems.

4.3 System: 40kW Pilot

The goal of the 40 kW Pilot System was to enable continuous testing of our isothermal compression and expansion processes with approximately 3-second stroke speeds and implement into a full round-trip energy storage system, establishing proof of concept and enabling core IP. As noted above, the hydraulic drivetrain was effective in reciprocating the system at the appropriate 10 RPM setup and was highly flexible in varying stroke distance, speed, and profile over a range of low RPM, but did not meet the efficiency requirements of a round-trip energy storage system.

Figure 8: 40 kW Pilot unit at the original Lebanon, NH location, showing cylinders and air storage vessels (back right)

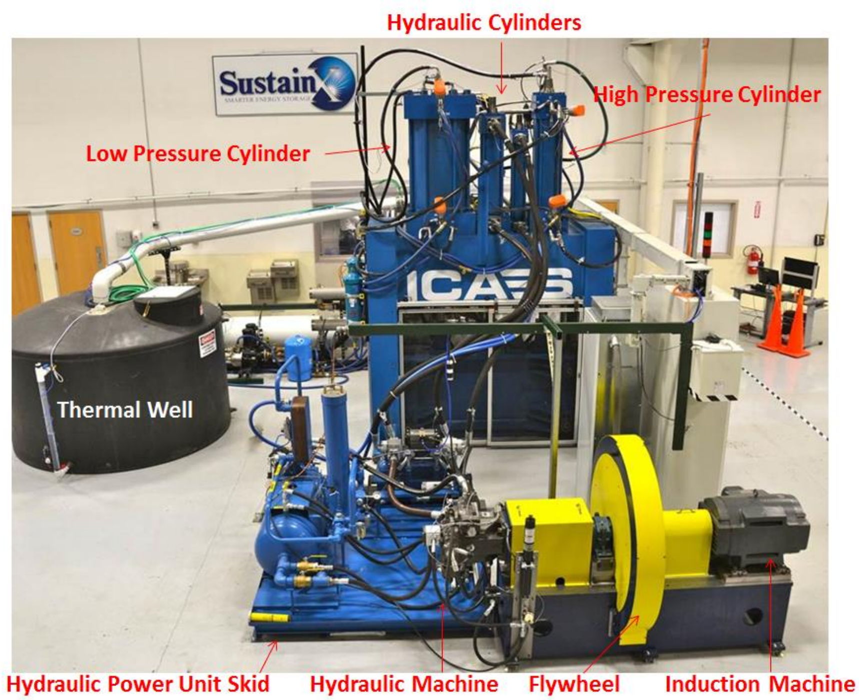


Figure 9: 40 kW Pilot unit, with major components identified, after the move to Seabrook, NH

The 40 kW Pilot, shown in Figure 8 and Figure 9, produced a large body of experimental knowledge to inform the design of our MW-scale Commercial ICAES prototype. Several of the key lessons from the 40 kW Pilot system are described below.

- **Hydraulic valving.** Hydraulic valves, along with a second hydraulic cylinder, were used to create an effective hydraulic transmission. However, flow losses through valves during valve transition events resulted in either significant energy losses or significant and damaging hydraulic shock. Energy losses and hydraulic shock cannot be simultaneously addressed without eliminating the hydraulic valves, which increases the size and cost of the hydraulics.
- **Hydraulic power smoothing.** Using displacement inversely proportional to hydraulic pressure can successfully smooth power output hydraulically with negligible efficiency impact, but only for smaller pressure ratios (i.e. when also using hydraulic valving). For larger pressure ratios at the pump, there is a net efficiency loss due to poor volumetric efficiency at very low displacements. Much larger equipment (cost) is also required to maintain stroke times and power.
- **Water management.** From a systems perspective, water gain/loss is near zero. A small amount of water is gained during compression as water vapor from the intake air is condensed. Similarly on expansion, some water will evaporate and exit the system with the exhaust air (all liquid phase water settles out in the exhaust system and is retained). Even in dry climates, the required makeup water is only 100 g/kWh. While very little water is actually lost from the system, there is movement of water between components within the system as air is compressed and expanded. Control at all times of the water content within each component, particularly the cylinders, constitutes the water management challenge. Some amount of water will be pushed out of the cylinders (and on to the next stage) at the end of each stroke. This process must be managed to prevent growth of air dead volume within the cylinder and its closed loop water spray system, which could collapse efficiency and ability to compress to desired pressure. Water management results in a net flow of water with the air into storage on compression and out of storage on expansion.
- **Coupled water management.** Directly compressing from the low-pressure cylinder into the high-pressure cylinder couples the use of water to manage dead volume within the cylinders and often results in over-pressurization of the low-pressure cylinder. Incorporation of mid pressure vessel de-couples the low-pressure cylinder water management from the high-pressure cylinder water management.
- **Stroke time.** The original stroke time of 3 sec resulted in some amount of air bubbles being pulled into the water circulation loop and increased air dead volume. Attempts to increase the system speed to 1 sec strokes (to increase power and reduce cost) resulted in significantly increased air dead volume and the associated increased losses and inability to reach full pressure.
- **Internal obstructions.** Nozzles or other protrusions from the top of cylinder into the cylinder volume restrict air flow from the back of the cylinder to the exit at the valve. The restriction results in a pressure gradient sufficient enough to depress water levels at the back of the cylinder and force water out of the valve port, exacerbating air dead volume and water management concerns.

The 40 kW platform was an essential and successful phase of our technology development process, underlying an efficiency and cost reduction roadmap and allowing key learnings and intellectual property to translate to the MW-scale design.

4.4 Technology: Foam-based Heat Transfer for Isothermal Cycling

Following successful testing of the 40 kW system (3 sec stroke, >95% isothermal efficiency), additional heat transfer research was conducted at increased cycle speeds. The goal of this research was to increase the rate of heat transfer from air to water (or vice versa) within the cylinders to allow for faster system speed at comparably high isothermal efficiencies, therefore increasing power density and reducing system cost.

To test faster cycle speeds, the Heat Transfer Test Stand (HXTST, Figure 7) was upgraded in October of 2011 to increase the maximum capable speed and decrease the stroke (1.5 m) time from 3 sec to 0.25 sec. Early results from the upgraded HXTST demonstrated the potential for foam to achieve high thermal efficiency at faster speeds than had previously been demonstrated. Figure 10 shows experimental data for high-pressure foam expanded within the HXTST cylinder at a 0.25 sec stroke time. These early results prompted a broader investigation on the use of foam for heat transfer, ultimately leading to the development of multiple additional foam study and validation test stands and the generation of a large body of in-house knowledge relating to the challenges and solutions to high-quality foam generation, transport, and destruction for ICAES.

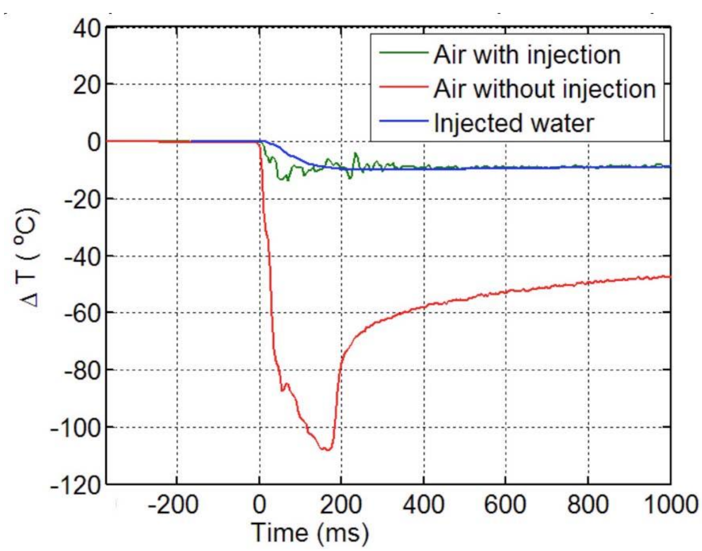


Figure 10: Comparison of non-isothermal to approximately isothermal air expansion with foam in the HXTST test cylinder: quarter-second piston stroke (0–250 ms), pressure change from ~200 bar to ~20 bar. Air temperature change (ΔT) is shown without heat exchange (red) and with foam heat exchange (green). Liquid temperature (blue) decreases slightly as heat is transferred from liquid to air; liquid and air quickly achieve thermal equilibrium (i.e., approach a common temperature). Without foam, maximum temperature drop is 108°C; with foam, only 12°C.

In the effort of achieving high rates of heat transfer (and therefore high thermal efficiencies) at low energy cost of doing so, a mixture of air and water as a homogeneous foam has several advantages over water suspended in air as droplets.

1. Two-phase contact area for a given liquid mass can be made larger for a foam at low energy cost, as compared to spray. Since the rate of heat exchange between a gas and a liquid is proportional to the area of contact between the two phases, the greater the contact area, the faster the heat flow. Achieving rapid heat exchange between a gas and a liquid therefore means, in practice, maintaining a large contact area (relative to mass) between a gas and a liquid. For spray, contact area can in general only be increased by decreasing droplet size and increasing droplet number, which is energetically expensive. Figure 11 shows comparative data from the HXTST for foam and sprayed droplet thermal efficiency vs. energy consumed to create the foam or spray.

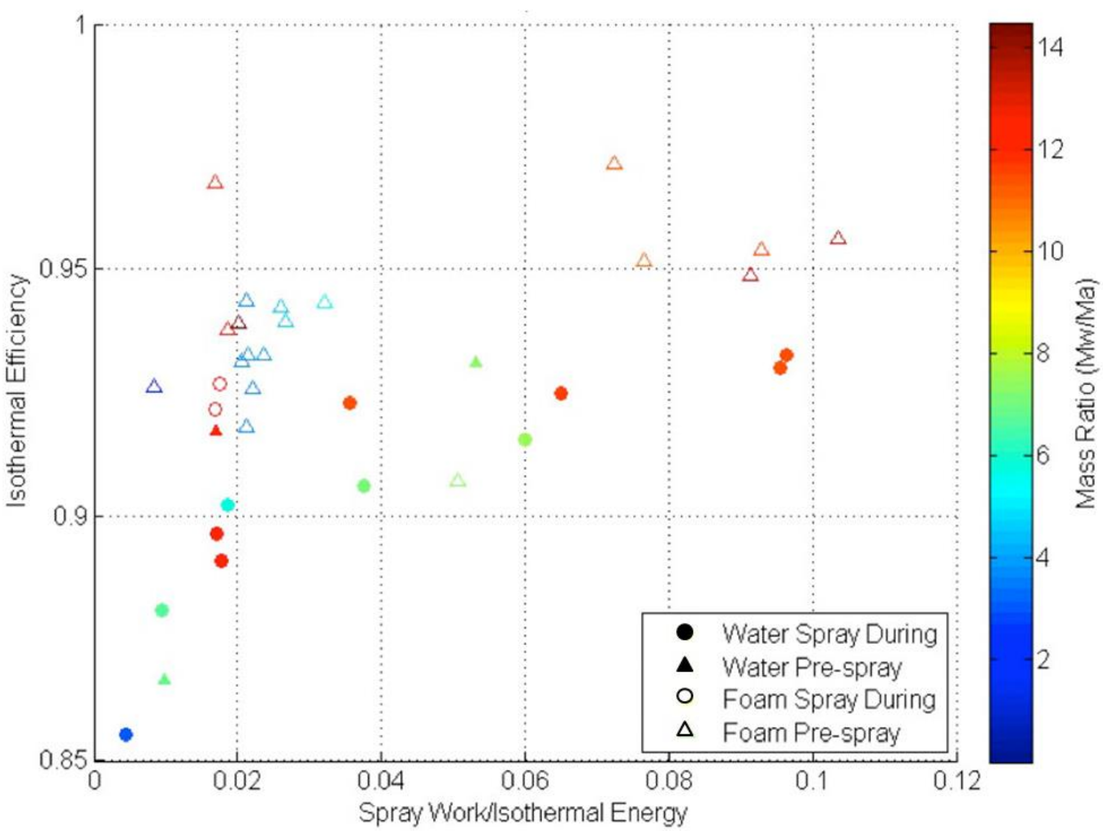


Figure 11: Data on spray and foam heat transfer from air expansions at the same power levels in a SustainX heat-transfer test stand. Foam generated before expansion ("foam pre-spray"—open triangles) achieved substantially higher efficiency at lower spray- energy (work) input levels than direct spray injection of droplets (closed circles)

2. Since foam behaves as a semi-solid, it maintains contact between air and water during an entire compression or expansion stroke, increasing heat transfer as compared to droplets. Droplets can dwell only temporarily in a volume of non-turbulent gas: when they strike a sidewall, rain to

the bottom of the chamber, or are struck as the piston strokes, two-phase surface area decreases and heat exchange slows.

3. A spray cannot be readily carried in a flow of gas (e.g., through pipes or valves) without striking sidewalls and falling out of the stream. To be effective, droplets must be injected directly into the gas as it is expanded or compressed within a cylinder. Foam, which can retain its integrity (cell size and air/water surface area) while flowing, can be generated outside a cylinder and admitted during a filling stroke, the procedure SustainX terms "port injection." With port injection, foam generation and conditioning mechanisms can be separated from the cylinder, easing design constraints.
4. Droplet distribution within a cylinder tends to be fairly non-uniform, with the droplet concentrations a strong function of the intake air flow and the spray nozzle locations. Foam, on the other hand, can be generated as a homogeneous mixture of air and water, increasing the effective heat transfer coefficient by decreasing the heat transfer length scale.

Tests from the HXTST have shown that air with water as a homogeneous foam can be expanded or compressed rapidly with high isothermal efficiency. However, creating this situation of uniform foam within the compression/expansion cylinders, and thus enabling high thermal efficiency within a real system, presents additional challenges.

Several challenges exist when using foam for heat transfer within an ICAES system: generation, transport, and destruction. These challenges are influenced by system geometry, pressure, water chemistry, and other factors.

1. Foam generation. In order for foam to be used for heat transfer within an ICAES system, it first must be generated at the appropriate ratio of water to air. Creation of coarse-textured and poly-disperse foams is relatively straightforward. However, such foams are not robust. Particular equipment (nozzles and screens) and flow conditions must be met in order to create the robust foams with fine, homogeneous textures that hold up well to real conditions. This is especially true for the "dry" foams needed in the low-pressure range.
2. Foam transport. Once a mixture of air and water as foam is generated at the correct ratio, the foam must be transported through pipes and valves and into the cylinders for compression or expansion. The speed of transfer of foams into cylinders can be limited by the shear forces generated during passage; sufficiently high shear can break down foam and reduce its effectiveness for heat transfer.
3. Foam destruction. The robustness of foam is a balancing act. Foam must be robust enough to survive transport through the system, but must be weak enough to allow for air/water separation prior to air exhaust during the expansion (discharge) process.

Much work has been done with foams[3] that can be leveraged to bound the challenges above and how they apply within an ICAES system. However, to reduce risk, effective solutions to these challenges must

[3] Stevenson, Paul. *Foam Engineering, Fundamentals and Applications*. Wiley-Blackwell, 2012
Weaire, Denis, Stefan Hutzler. *Physics of Foams*. Oxford University Press, 1999

be demonstrated experimentally before implementation in a full-scale ICAES system. Therefore, In addition to the HXTST, SustainX has built and run multiple foam-related test stands in the past two years in order to better understand the challenges outlined above and to develop solutions and approaches for the MW-scale system. The foamability test setup allows rapid iteration through different water chemistries, allowing the effects of water additives on foam cell size and texture to be examined. The benchtop foam test stand allows the foam created by different foam generation setups to be evaluated at small scale (but at actual system velocities) and allows the foam robustness to be quantified. This testing is a precursor to testing on the final setup, which is a full-scale multi-purpose test stand. The simulated mid-pressure foam generation and transport test stand (Figure 12) is a closed-loop system that includes a full-scale replica (in plastic) of the mid-pressure vessel designed for the 1.5 MW Commercial Prototype. This system allows full-scale foam generation, transport, and breakdown to be studied.

Learnings from these test stands provided the basis for the design of the foam equipment and techniques used in the 1.5 MW Commercial Prototype system, and have allowed these systems to be optimized. Efficient capture and re-use of the system process water has been achieved through the use of foams that are long-lived relative to the heat-exchange cycle time (e.g., less than a second), yet short-lived relative to the air storage time. Foam generation setups have been optimized to use large-orifice nozzles (reducing energy usage and maintenance requirements) and robust multi-layer screens that generate foam of the right texture and expansion ratio over a large operating range, assuring foam integrity at pressure and during flow.

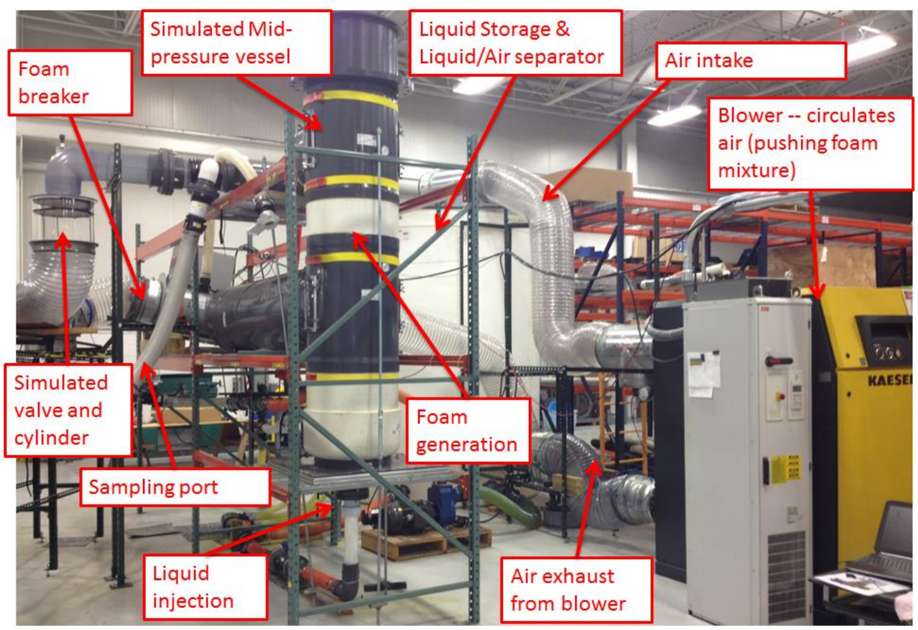


Figure 12: Foam generation and transport test stand, which mimics the mid-pressure vessel in our 1.5 MW ICAES system

SustainX's two-phase heat-transfer processes enable near-isothermal gas expansion and compression. Rapid heat exchange between liquid and air has allowed development of a megawatt-scale compressor/expander with >95% isothermal efficiency across the full operating range of the system.

4.5 Technology: Crankshaft-based Drivetrain for ICAES

As mentioned in previous sections, improved heat transfer with foam allowed for faster operating speeds, allowing the transition from the previous hydraulics-based drivetrain platform to a crankshaft-based drivetrain platform. Benefits of this transition include

- the elimination of an energy conversion stage since crankshafts directly convert linear mechanical energy to rotary mechanical energy without the intermediary fluid power stage; and
- improved power density with higher speed, unlike hydraulics which scale linearly with speed in both size and cost.

Two key challenges to a crankshaft drivetrain platform for ICAES needed to be evaluated and overcome.

1. Bearings. A system speed of 120 rpm is still slow for most crankshaft-based engines and systems. One notable exception is the two-stroke marine diesel engine industry, which strives for ever slower speeds in order to allow for improved propulsion efficiencies for direct-propeller drive ships.
2. Torsional vibration. The torque profiles produced by ICAES pneumatic cylinders vary considerably more than do standard engine combustion cylinders. ICAES cylinder torques are different for low- and high-pressure cylinders, change as a function of storage pressure, and flip signs when switching between compression and expansion modes.

SustainX uses the lower half of a small MAN Diesel and Turbo engine as the crankshaft for the ICAES system due to the good match between cylinder size and system speed. SustainX has partnered with MAN Diesel & Turbo (the world leader in two-stroke marine diesel engines), to perform the necessary simulations and evaluations of the suitability of using a commercial MAN crankshaft for ICAES applications.

Studies with MAN indicated that the SustainX pneumatic cylinder force profiles would result in sufficient oil film thickness for each of the bearings over the full 360° of rotation. Figure 13 shows the output of one of the dynamic elasto-hydrodynamic simulations performed by MAN indicating sufficient oil film thickness and oil film pressure. Bearing suitability has been confirmed experimentally after successful operation of the MW-scale prototype. MAN performed a full-bearing inspection after 2 months of operation of the 1.5 MW Commercial Prototype to assess the bearing performance because the system has been a new use-case for the MAN crankshaft. No wear on the bearings or other adverse conditions were evident.

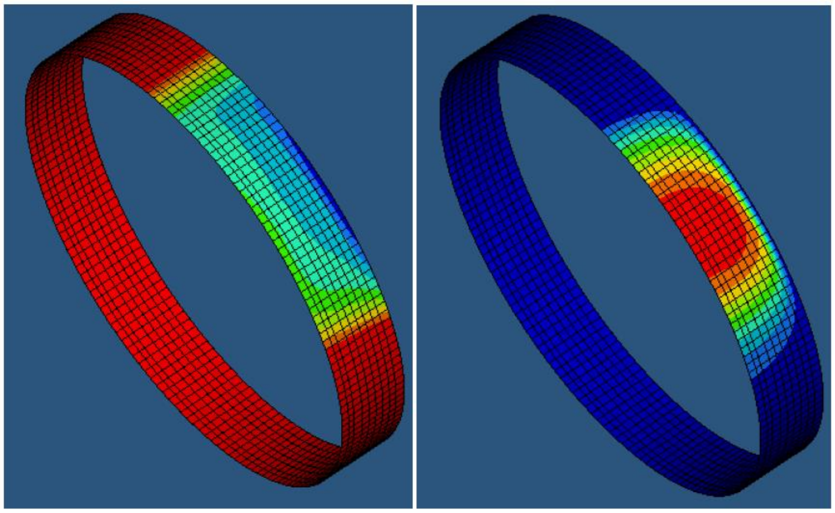


Figure 13: Dynamic elasto-hydrodynamic simulation results from MAN for the crank-pin bearing of the high-pressure cylinder at top dead center. *Left*: oil film thickness. *Right*: oil film pressure.

Torsional vibration analyses were performed by both MAN and SustainX. The rapid SustainX simulations allowed the cylinder piston mass and PMG coupling designs to be rapidly iterated, while the MAN simulation provided verification of design suitability. This iterative process allowed the piston masses, coupling stiffness, and crankshaft moment of inertia to be tuned to eliminate low order harmonics and reduce torsional vibration. Standard torsional vibration sensors on the crankshaft of the 1.5 MW Commercial Prototype have not indicated excessive torsional vibration during the system operation to date, validating original calculations and design.

Successful operation of the MW-scale Prototype has validated the use of a crankshaft-based drivetrain in SustainX's ICAES systems.

4.6 Technology: High-Performance Valves for ICAES

The increase in system speed (to 120 RPM) allowed for by the improved heat transfer placed significant additional requirements and constraints on the cylinder valve design. Requirements were driven heavily by the energy loss limits as well as by fail-safe considerations. Low full-open valve flow losses required large valve cross sectional area. However, the requirement for low clearance volume restricted valve poppet area to the top surface of the cylinder. Low transient flow losses required quick valve actuation on the order of 5–10 ms. Parasitic loss requirements, however, necessitated low valve actuation energy. Valves needed to be actuated in order to perform the variable valve timing required to accommodate varying air storage pressures and to be functional for both compression and expansion. However, valves also needed to be able to operate passively in order to provide a safeguard against hydrolocking and cylinder overpressure.

SustainX approached multiple third parties with this development effort, but ultimately decided to hire a team with the appropriate skills and relevant experience and bring the development in-house.

The valves developed by SustainX to meet these requirements can be viewed in two portions: the valve poppets (including how they fit within and interface with the cylinder heads) and the valve actuators, both of which were designed by SustainX in-house. Additionally, four different valve designs were required: a high-pressure side and a low-pressure side valve for each of the high-pressure and low-pressure cylinders. This resulted in a total of four poppet designs, four actuator designs, and two cylinder head designs. Commonality was applied throughout the designs wherever possible.

Modified engine-style poppet valves (with a distinct valve body and valve stem) were chosen for the poppets. This style valve maximizes the valve cross-sectional flow area while allowing the valve seat to be as close to the interior cylinder wall as possible, minimizing cylinder clearance volume. Although the valve poppets are fully-custom SustainX designs, standard practices and valve design features from other industries were incorporated to reduce design risk.

Simulation was used extensively throughout all aspects of the valve design. Computational fluid dynamic (CFD) simulations (using ANSYS Fluent) were performed during the design of the poppets and cylinder heads to evaluate valve Cv, a measure of the valve pressure drop for a given flow rate and a key metric for valve flow loss. Dozens of valve poppet and cylinder head geometries and configurations were analyzed before a final selection was made. CFD was also used during the later stages of the design to tune geometrical features to maximize flow and flow distribution. Figure 14 shows the velocity field for the flow through a low-pressure cylinder's intake valves prior to and following tuning of valve geometry. Small geometry changes can effect Cv by as much as 30%.

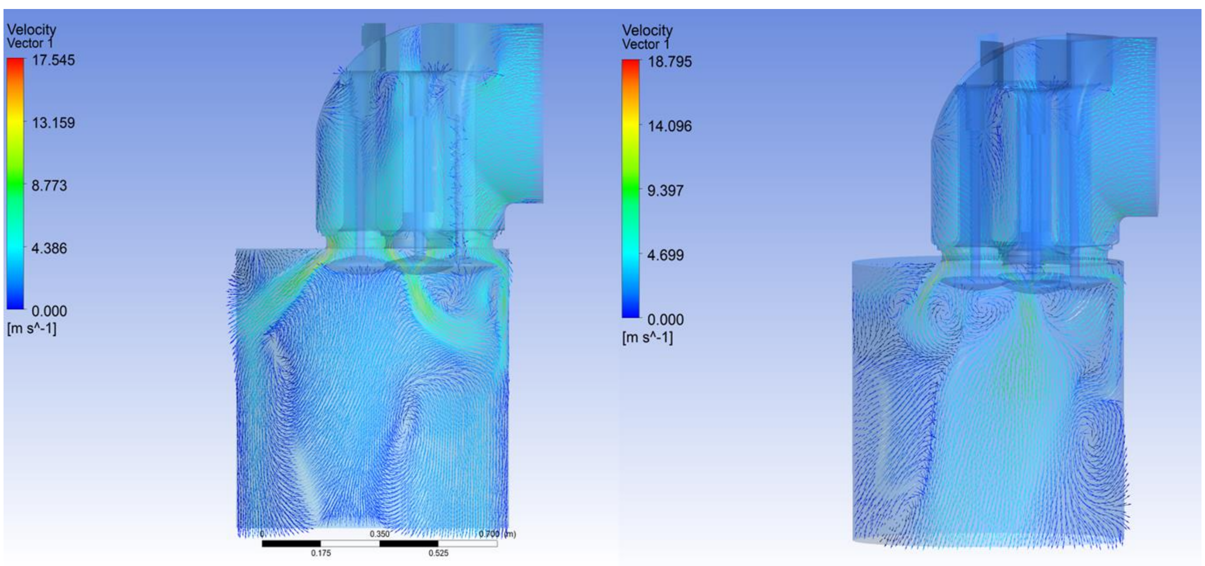


Figure 14: CFD simulation of air flow in through the low-pressure cylinder intake/exhaust valves. *Left*: prior to flow guide optimization, intake air forms jets that impact cylinder walls. *Right*: after flow guide optimization, intake flow is more uniformly distributed within cylinder.

Electrohydraulic actuation was chosen for the valve actuators. This allows for infinitely variable valve timing, low actuation energy, and passive valve cushioning to reduce valve impact velocities and extend valve life.

A multi-domain physical system simulation tool (The Mathworks Simulink/SimScape) was used to model the valve poppet and actuator dynamics from a systems perspective. The effects of the hydraulic actuator circuit design (from the oil supply control valve to the hydraulic cushion chamber) were captured and modeled within the hydraulics domain, the effect of the valve poppet mass and friction were captured within the linear mechanical domain, and the effects of cylinder pressure, manifold pressure, and poppet pressure drop were captured using a custom-built two-phase mixed flow (air and water) domain.

Results from the dynamic poppet and actuator model allowed the geometries and valve actuator circuit design to be virtually tested and modified until the design met the stringent valve actuation time, impact velocity, and cushion pressure requirements.

To validate valve performance (and affirm results from the dynamic simulations), a valve actuator test stand (Figure 15) was designed and constructed to test valve actuator performance and valve response time under a variety of scenarios (simulated external poppet forces). Actual test results have matched predicted results from simulation very closely; see, for example, Figure 16. Any deviations between model and actual valve behavior have been used to update our valve dynamic models as well as our valve responses within the full system dynamic model.

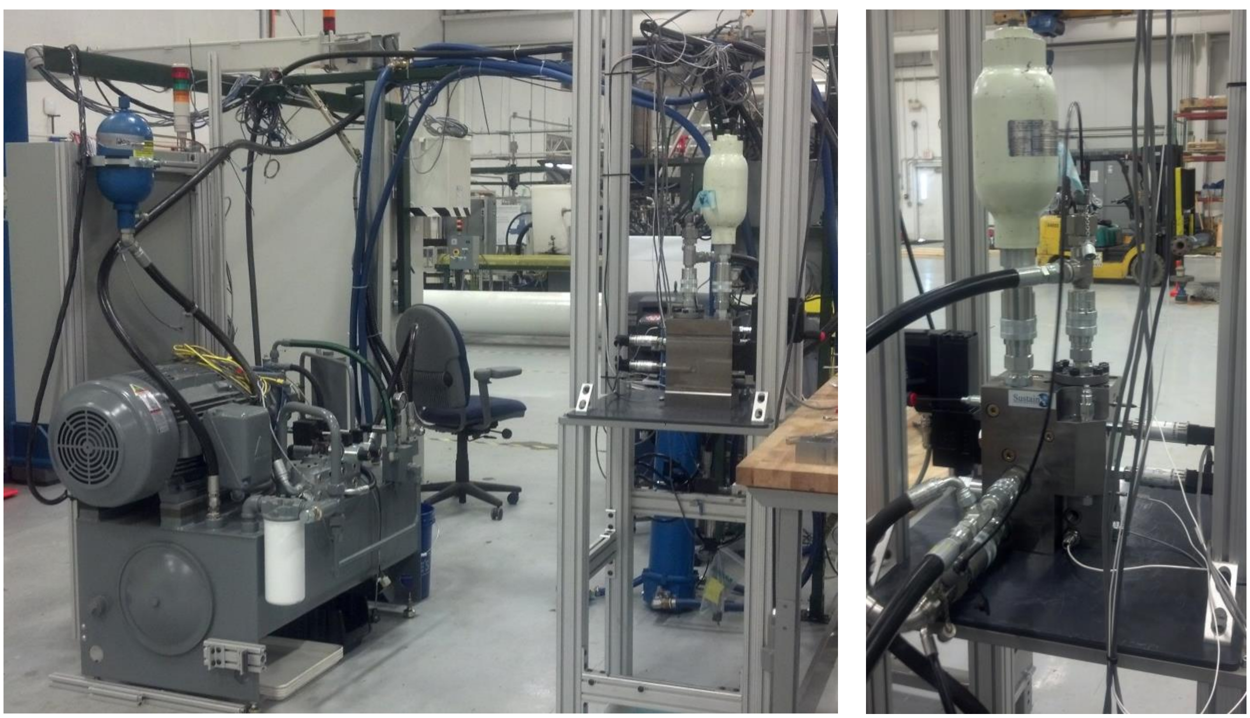


Figure 15: Valve actuator test stand. *Left*: Full test stand showing hydraulic power unit and control cabinet at left and test table at right. *Right*: close-up of valve actuator on test table

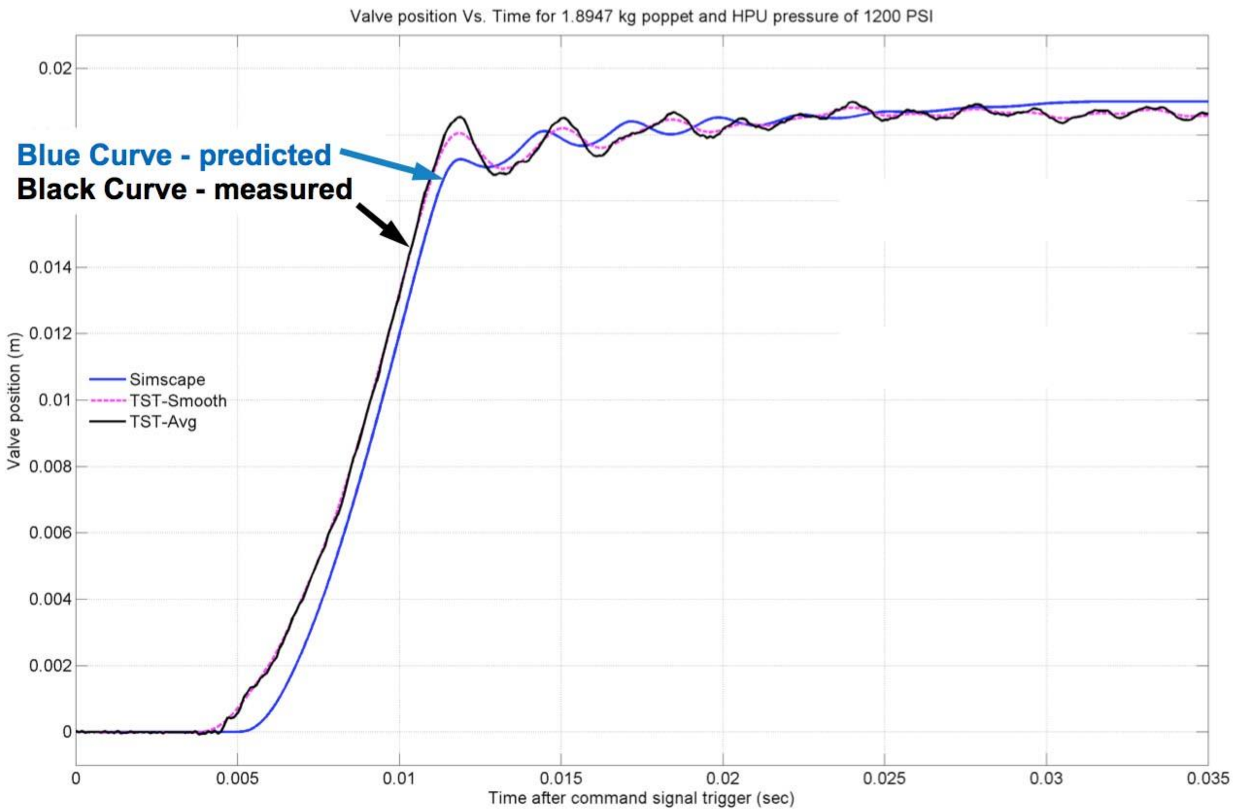


Figure 16: Measured vs. simulated valve position vs. time for valve closing event, affirming model simulations and confirming valve response time (<10 ms) and cushion performance.

4.7 System: 1.5 MW Commercial-Scale Prototype

The 1.5 MW Commercial Prototype incorporates the key technologies discussed in sections 4.4 through 4.6 as well as numerous additional components and subsystems. Key design challenges included appropriate sizing of all of the energy converting sub-systems, with respect to each other, for both compression and expansion; tuning the settings of the overall system to minimize variation in operating conditions for all of the sub-systems; and maximizing the performance of each relative to how they operate within the system.

4.7.1 Technical Performance of 1.5 MW Commercial-scale Prototype

Construction of the 1.5 MW Commercial Prototype began in January of 2013, with commissioning complete by the end of August. Initial testing of the system began in September, with system operation at full power for both compression and expansion modes since the end of September. , A key factor in the success and speed of the commissioning and testing process was the use of Model-Based Design (MBD) for the control system. During the system design and build phase, a high-fidelity mathematical model of the full system plant was created using Simulink and SimScape physical system modeling tools (Mathworks, Natick MA). This model was placed in a closed loop with the control system software (Figure 17), allowing the control system to be completely designed and tested prior to the completion of the system build, including diagnostics and fault response for the full range of operating scenarios.

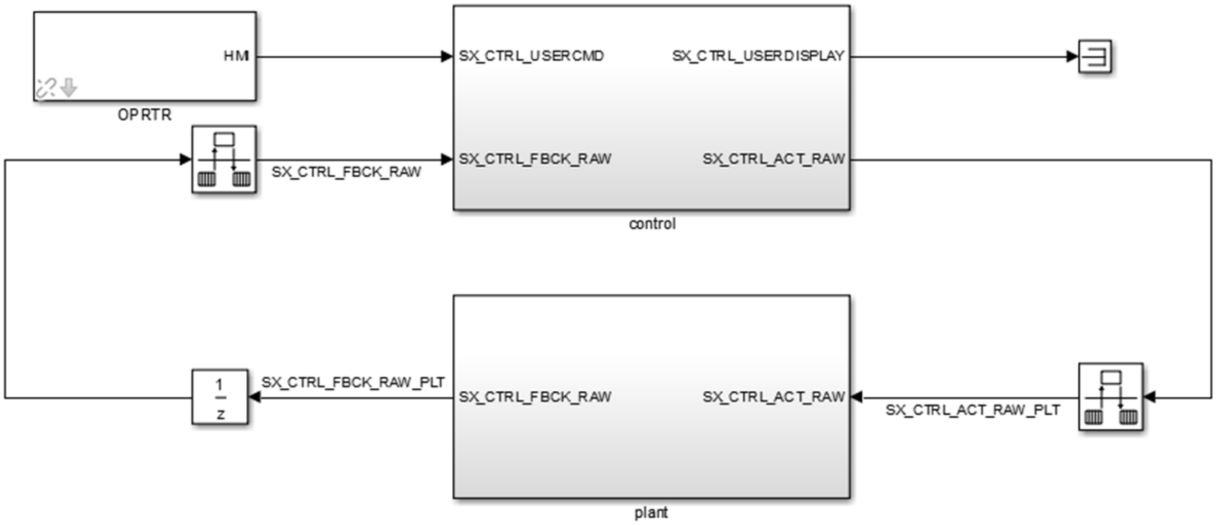


Figure 17: top-level view of the control software integrated into a closed loop with a mathematical model of the plant (full system), allowing for *a priori* testing and validation of the control system

Initial test results from the 1.5 MW Commercial Prototype demonstrated that the overall system performed as expected according to the original projections based on the system models. Table 3 shows both the initial projections for key performance parameters as well as a summary of the performance achieved during testing. All of the original projections have been achieved or exceeded. Over the course of system testing, multiple potential performance improvements were identified and a number of these have been implemented to date. The following subsections describe in more detail the testing and evaluation methodologies, improvements performed, and results achieved.

Table 3: Key Commercial Prototype System Specifications

Key Parameters	Commercial Prototype Original Projections	Commercial Prototype As Tested
Charge power	2.2 MW	2.2 MW
Discharge power	1.5 MW	1.3 MW initial 1.65 MW current
Storage type	ASME Pressure Vessels	ASME Pressure Vessels
Storage capacity on site	1 MWh	1 MWh
Charge time	60 minutes	60 minutes
Discharge time	40 minutes	36 minutes
Standby to full power	< 5 minutes	< 3 minute < 1 minute is possible
Discharge-charge response time	< 60 seconds	< 13 sec < 1 sec is possible
Spinning to full power	< 5 seconds	< 5 sec < 1 sec is possible
Round-trip efficiency	41 – 51 %	45% initial 54% current
Temperature operating range	-20°C to 40°C	-20°C to +40°C

4.7.1.1 Efficiency evaluation

The 1.5 MW Commercial Prototype in Seabrook, NH, is connected to the grid via a switchgear unit containing an intertie protection relay. The switchgear unit is also connected to a 3 MW resistive load bank. Although the prototype system is always grid connected (i.e. during charge, discharge, and standby), the load bank allows the SustainX facility to remain a net energy consumer, a condition ensured by the intertie protection relay per the interconnection agreement with the local utility. The benefit of this setup is that it allows the Prototype system operation and testing schedule to be independent, allowing for easier testing and validation of the system and system improvements.

From the perspective of the Prototype system, it is unaware that generated power is being consumed by the load bank rather than being put on the grid since its typical point of grid connect is on the system side of the switchgear’s intertie protection relay.

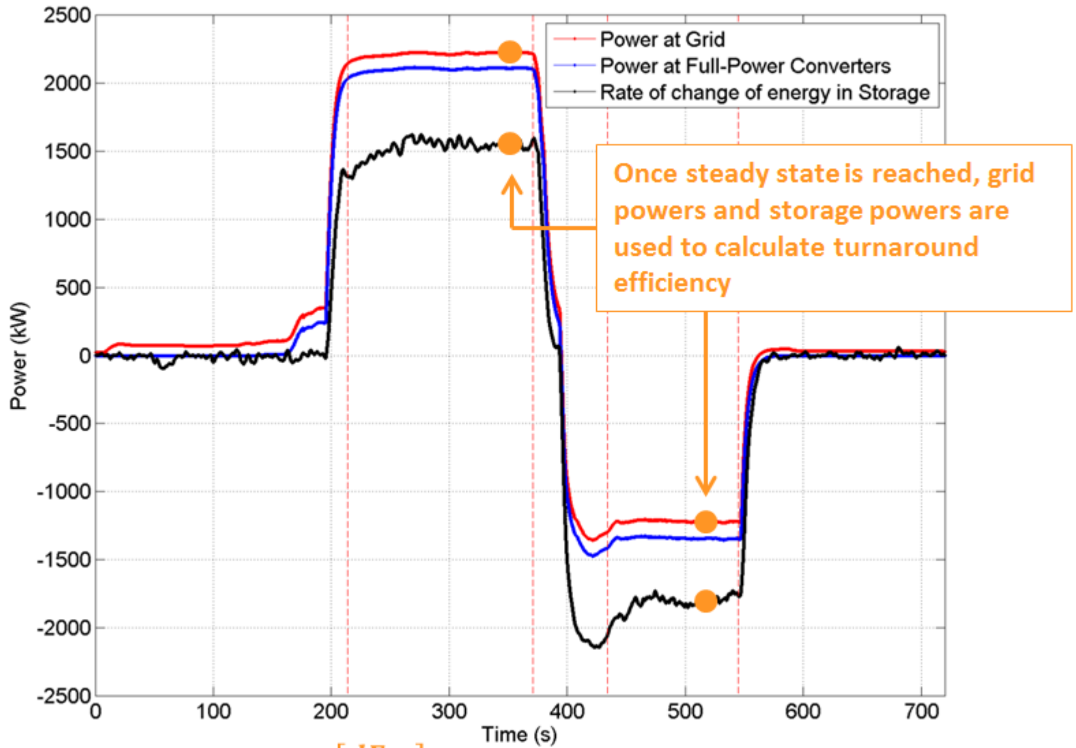
A typical test for the system is a short cycle experiment, involving a few minutes of compression (charge) followed by a few minutes of expansion (discharge) centered at a particular storage state of charge (air storage pressure). This allows the performance of the system to be evaluated at each state of charge and the control systems to be tuned at each state of charge.

Because round-trip system efficiency can be affected by standby losses that vary significantly with environmental and operational scenarios and use cases, SustainX uses the term **turnaround efficiency** to refer to round-trip efficiency exclusive of standby losses, both thermal and electrical. (Etymologically, the term comes from the scenario where a storage system performs a full charge and immediately turns around and performs a full discharge, therefore never being in a standby or idle state.)

The turnaround efficiency of the ICAES system is determined at each state of charge by evaluating the electrical power at the grid (main power draw/supply less the parasitic electrical consumption) as well as the power going into the high-pressure air storage. This “storage power” is the rate of change of energy within the HP air storage, which is proportional to the rate of change of pressure in the storage. Powers are evaluated once steady state is reached in order to eliminate transient effects. This evaluation process is shown in Figure 18, with a description of abbreviations shown in Table 4.

Table 4: List of abbreviations and descriptions for Figure 18

$\eta_{turnaround}$	Turnaround efficiency (round-trip efficiency exclusive of standby losses)
$\left[\frac{dE_{SV}}{dt}\right]_{cmp}$	Rate of change of energy in the HP storage vessels during compression
$\left[\frac{dE_{SV}}{dt}\right]_{exp}$	Rate of change of energy in the HP storage vessels during expansion
$PWR_{FPC\ input}$	Input power to the full power converters. (Grid input power less parasitic electric consumption.)
$PWR_{FPC\ output}$	Output power from the full power converters.
$PWR_{rtp,cmp}$	Run-time parasitic electric consumption during compression
$PWR_{rtp,exp}$	Run-time parasitic electric consumption during expansion



$$\eta_{turnaround} = \frac{\left[\frac{dE_{SV}}{dt}\right]_{cmp}}{PWR_{FPC\ input} + PWR_{rtp,cmp}} \frac{PWR_{FPC\ output} - PWR_{rtp,exp}}{\left[\frac{dE_{SV}}{dt}\right]_{exp}}$$

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Figure 18: Plot of experimentally measured grid power and "storage power", illustrating the calculation of turnaround efficiency. A description of abbreviations is shown in Table 4.

These short cycle experiments are beneficial because they allow for snapshots of performance and efficiency at particular operating conditions. This was also helpful in quickly evaluating impacts of changes to the system operation, from small changes such as tuning water flow rates to large changes such as implementation of LP foam heat transfer for the first compression stage. Figure 19 shows efficiency results from cycle experiments in October 2013 and August 2014, illustrating the efficiency improvements over ten months of system operation. Details on the implemented system improvements are described in the next section.

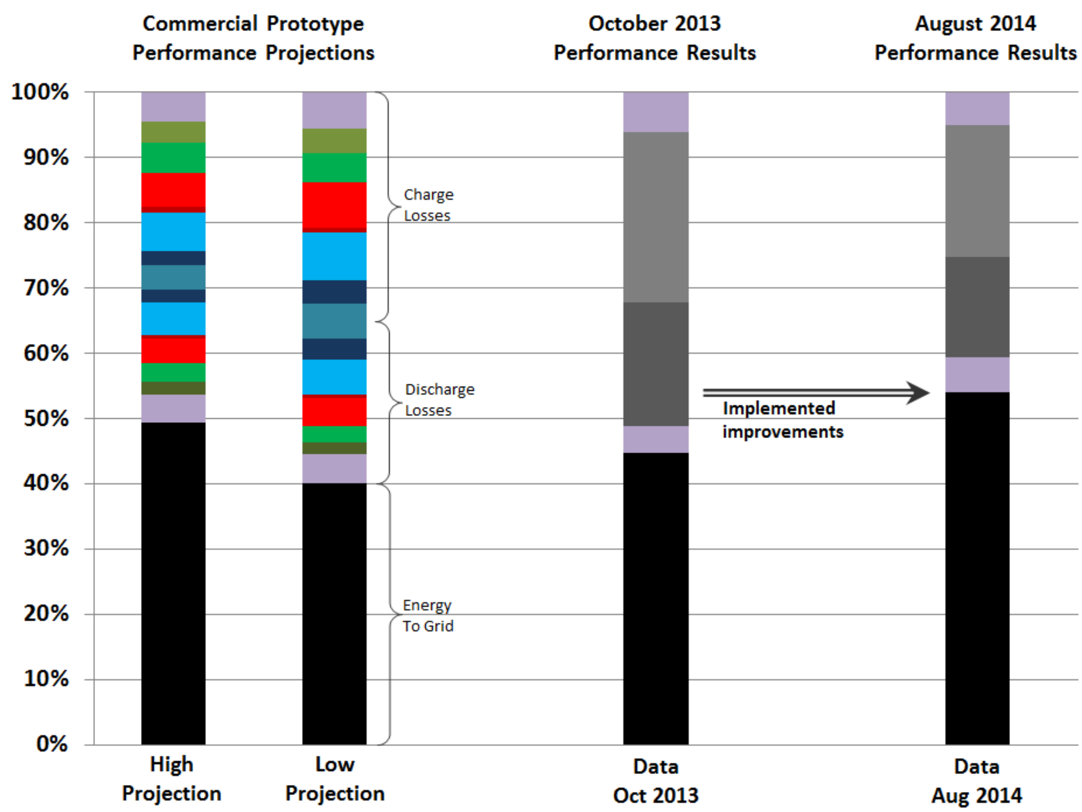

Figure 19: 1.5 MW Commercial Prototype efficiency results compared to initial projections. Color Code: Black: electricity to grid; Purple: parasitic electric; Greens: PMG and FPCs; Reds: Crank and pistons; Blues: Pneumatics; Greys: Unallocated

4.7.1.2 System improvements to power and efficiency

Following initial testing results, several opportunities for performance improvements were identified. Some of these improvements have been implemented and others will be implemented in the next iteration of the system design. The improvements fall into four general categories, with a total potential improvement to turnaround efficiency of 14 percentage points.

Initially identified potential performance improvements were:

1. Reduction in crank system losses – 4 %-pt potential.
   This potential stems from the ability to reduce windage of air flow into and out of the space below the cylinder pistons and the ability to reduce piston seal friction by replacing the current zero-leak hydraulic cylinder style seals with more standard air compressor seals.
2. Improvements to driveline efficiency – 2 %-pt potential.
   This improvement will be realized in the next system iteration by moving from a two PMG setup to a single PMG, reducing bearing losses, improving PMG efficiency (eliminating "fighting" between the two machines and going to a larger diameter), and reducing copper losses.
3. Reduction in electrical parasitic consumption – 4 %-pt potential.
   Each auxiliary system was designed for greater capability than what was expected to be needed in order to allow for flexibility in system operation. The simplification and downsizing of

auxiliaries now that set-points have been tuned has been and will continue to be a significant source of performance improvement.

4. Pneumatic efficiency improvements – 4 %-pt potential.
   The initial implementation of the 1.5 MW Commercial Prototype utilized the higher-performance foam-based heat transfer for three of the four stages: the high-pressure compression stage and the high- and low-pressure expansion stages. However, the low-pressure compression stage was initially implemented with the older spray-based heat transfer due to the state of the foam-based heat transfer development at the time. The pneumatic efficiency improvements come from the improved thermal efficiency of moving that fourth stage from spray-based heat transfer to foam-based heat transfer as well as from further optimizations in valve geometry and pipe routing to reduce pressure drop.

As stated above, multiple improvements have been made to date, and have led to the increase in round-trip (turnaround) efficiency from 45% to 54%. Notable improvements that have been made to the system to date include

1. Implementation of LP foam-based heat transfer.
   During the time period of the 1.5 MW Commercial Prototype system build and initial testing, the ability to generate fine-textured, robust foam was improved to the point where the foam could pass through the high-shear zone of the intake valves without breaking, allowing for implementation of foam-based heat transfer for the LP compression stage. Therefore, in February 2014, a LP foam generator was implemented in the intake duct, replacing the spray systems for the LP compression heat transfer. This change was a rare triple win. Not only is the thermal efficiency better with the foam-based heat transfer, but the LP foam generation equipment is significantly less expensive than the spray equipment and also draws less power, reducing parasitic electrical energy consumption and further improving efficiency.
2. Tuning of auxiliaries
   A reduction in parasitic electrical energy consumption was achieved by tuning the control set points of each of the auxiliary systems for each operating point (e.g. system speed, storage pressure). Tuned auxiliary systems include the hydraulic power unit for the cylinder valves, lube oil system, electronics cooling system, and water pumping systems.
3. Piston alignment
   Adjustments were made to the shims for the crosshead bearings, adjusting the alignment of the piston rod travel with respect to the crankshaft. Run-out measurements and cylinder temperature measurements were used between adjustments to target and minimize cylinder friction.

4.7.1.3 Response time and ramp rate

The measured response times of the 1.5 MW Commercial Prototype are given in Table 3, as are the possible response times based on physical limitations of the major components. These are illustrated graphically in Figure 20.

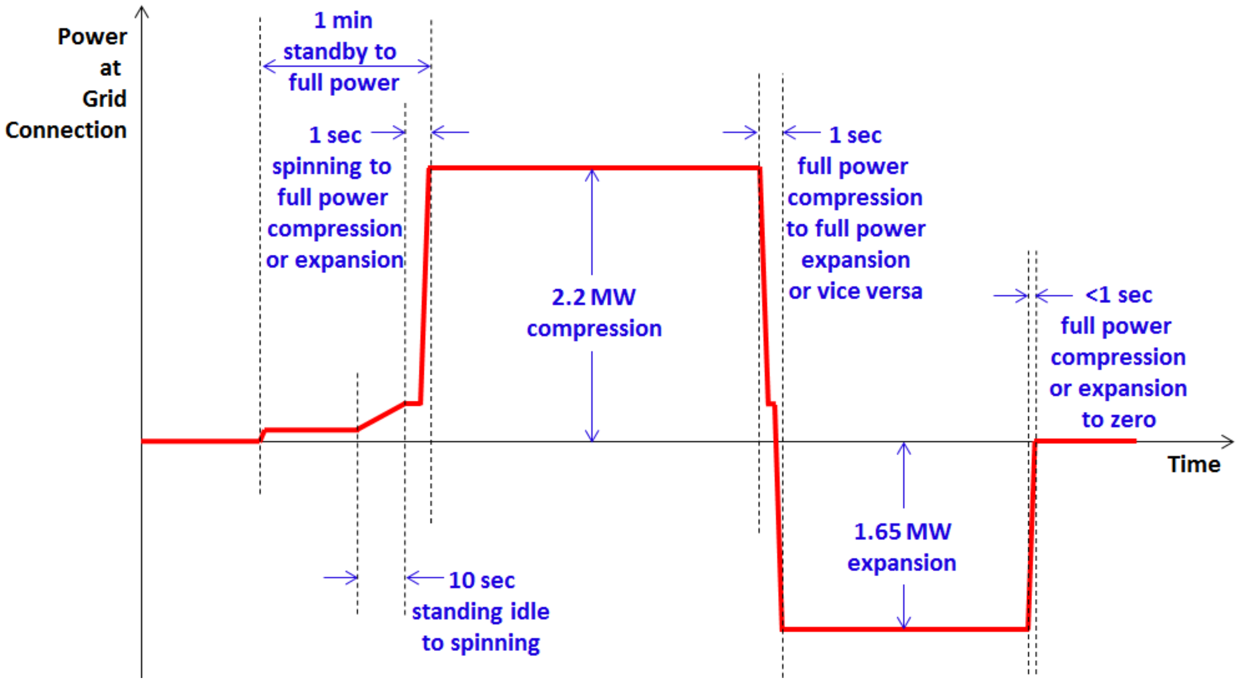

Figure 20: Illustration of system response times

Testing to date of the 1.5 MW Commercial Prototype has not pushed the system to the physical limitations of the major components (e.g. crankshaft, PMG) due to limitations in minor components or auxiliary systems. These are described in more detail below.

- Standby to full power. The major component limitations to the ramp rate from standby to full power in either charge or discharge mode are 1) the spin-up time of the driveline and 2) the response time to full torque of the PMG. The spin-up time of the driveline is limited by the hydrodynamic bearings; because the driveline is relatively small and there is near-zero torque on the pistons during spin-up, the spin-up time is under 10 seconds. The response time to full torque of the PMG is governed by the PMG coil inductance and is roughly a third of one second. Therefore the effective limiter of the time from standby to full power is the auxiliary systems' startup routine. The startup routine for the 1.5 MW Commercial Prototype has been validated experimentally to be less than three minutes, but is more complicated than it would be for the commercial system. Simplification to the startup routine, specifically elimination of an unnecessary crankshaft turnover prior to spin-up, would reduce the startup routine to under one minute.
- Spinning to full power. The spinning to full power (charge or discharge) response time is fundamentally limited by 1) the inductance of the PMGs and 2) changing cylinder valve timing over one revolution of the driveline, both of which can be changed in less than one second. The 1.5 MW Commercial Prototype currently responds from spinning to full power in five seconds, limited by the response time of the intake and exhaust damper valves. Faster actuators (e.g. via higher actuation supply pressure) will eliminate this constraint and allow for the sub one second response time.

- Discharge-charge response time. The charge to discharge response time has the same fundamental limits as the spinning to full power response time (less than one second). For the 1.5 MW Commercial Prototype, this is currently limited by the intake and exhaust damper valve response, as above, as well as by a rise in output pressure of the hydraulic power unit (HPU) at the end of compression. A change in the pressure-compensation control of the HPU will eliminate the pressure rise and eliminate this response time constraint.

Fundamental constraints allow for very rapid ramp rate and response times for the ICAES technology. Small changes from the 1.5 MW Commercial Prototype design will allow these rapid response times to be fully met.

4.7.2 Projected results for commercial system

4.7.2.1 Power and Efficiency

The commercial system will be able to implement the remainder of the improvements identified in Section 4.7.1.2. Those changes, along with a 25% reduction in cylinder clearance volume and a 10% increase in system speed (both within the current design envelope), will allow the commercial system to achieve the target 55% round-trip efficiency at an increased power of 1.8 MW.

4.7.2.2 Air Storage

The ICAES Power Module can be paired with a number of different high-pressure air storage mediums. The prototype system in Seabrook is paired with ASME pressure vessels with a storage capacity of just 1.0 MWh due to space constraints of the Seabrook location. Commercial installations would utilize pipe-type storage or underground Lined-Rock Caverns (LRC) to store the high pressure air. For any configuration or storage type, the installation power is set by the ICAES power module and energy capacity (number of hours of storage) is set by the volume of high-pressure air storage. Therefore, increasing the number of hours of storage represents an incremental cost increase rather than a linear cost increase. This allows the duration of storage (in hours) to be tailored to particular applications. Typical applications would be in the 4-6 hour range.

For long duration (20 to 100+ hour) energy storage, low-cost can be achieved by pairing ICAES Power Modules with salt cavern air storage. In this case, additional equipment is added to remove the heat transfer fluid (water) from high-pressure air prior to storage of the air in the cavern. While this additional equipment reduces system output power by 9% and round-trip efficiency by three percentage points, this is offset by the significantly lower cost of the storage.

4.7.2.3 Economic parameters for commercial systems

Capital costs for commercial systems were based upon multiple inputs. The base cost was taken as the actual capital cost of the 1.5 MW Commercial Prototype system in Seabrook, NH. This cost was then modified by design changes from the commercial prototype to the commercial system, including elimination of un-needed equipment (e.g. for test purposes only), re-sizing of auxiliary systems based on experience from the Commercial Prototype (most Commercial Prototype auxiliary systems were over-sized to provide flexibility in testing), and re-design of components for manufacturability (e.g. cast rather than forged cylinder heads). Vendor quotes, both domestic and international, were received for all new or re-designed components for quantities of 1, 10, and 100. The result was a largely quoted cost model for the commercial system.

Unlike batteries, which require large, custom manufacturing facilities to reach economies of scale, the SustianX power module is largely comprised of components that are non-unique and already manufactured at scale. In addition, new and precision components, such as the cylinder valves and valve actuators, utilize sequences of standard manufacturing and material treatment methods which can be performed by multiple vendors. The result is a supply-chain based manufacturing model which culminates with on-site assembly at a customer's site, eliminating the need for SustainX to build out costly manufacturing facilities.

4.7.3 Analysis of Addressable Energy Storage Applications

Similar to conventional CAES, the ICAES system provides a very long cycle life under high depth-of-discharge (energy) utilization, but the ICAES design also allows for far faster response rates than can be achieved with a conventional CAES system. The long cycle life is achieved by relying on proven mechanical components and processes. The high power ramp rate and rapid charge/discharge turnaround is achieved through a modular system design and the high performance of key components like the cylinder valves. This allows ICAES to provide both high energy and rapid power capabilities, enabling maximal value to the grid.

For renewables applications, especially wind, this dual use capability is essential for managing both the power and energy fluctuations inherent to wind energy. Such a wind firming application is a key design focus for the ICAES system, and we have performed significant economic modeling on the application, see Section 5. Rapid response capabilities also enable the optional value of capturing additional revenue from the currently lucrative, but demanding, "fast-response" frequency regulation market.

The scale and manufacturability of the ICAES system allows application on the T&D network to be addressed. To substitute for a planned transmission upgrade 10's of MW of storage may be required with multiple hours of peak load shifting capabilities. The use of an established global supply chain and a multi-MW building block enables such large projects to be addressed rapidly, repeatedly, and with limited complexity.

5 GRID IMPACTS AND ESTIMATION OF BENEFITS

Navigant Research forecasts a global market for energy storage of nearly 80 GW through 2024. The market opportunity is dominated by "energy" applications like grid asset optimization, spinning reserve, and utility-scale wind integration. "Power" applications like frequency regulation and voltage support represent a much a smaller segment of the market. To understand how ICAES competes in these target applications, SustainX has relied on extensive in-house and external analysis.

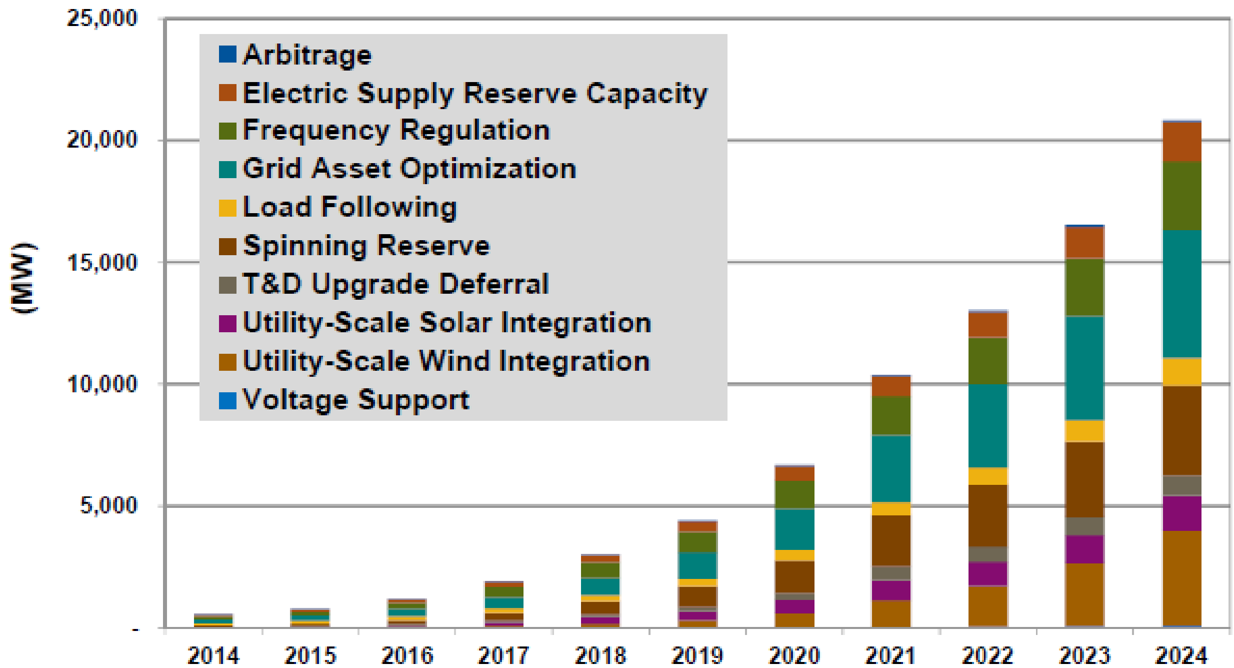

Figure 21: Navigant Research's forecast for global energy storage power capacity through 2024.[4]

In addressing the large market for "energy" applications, the ICAES system can function as a generation asset, a transmission asset, or as a combination of both. SustainX has developed a "utility-scale wind integration" model based on what we term firm or dispatchable wind. Financial analysis of this type of application focuses on the price ($/MWh of electricity) of the "firm energy" that can be delivered. SustainX has also focused on "grid asset optimization" and "T&D upgrade deferral" applications where financial analysis is based on an avoided cost comparison with traditional grid solutions. As the market for storage develops, there is a strong push for regulatory change that would enable storage to perform both generation and T&D functions. As shown below, EPRI has performed detailed analysis of the financial upside if multiple functions can be served by one storage asset.

5.1 Firm Wind

The generally flexible grid of the US, aided by cheap natural gas, has many ways of integrating variable energy from renewables like wind. In the high wind regions of China and many other global grids the generation mix and the local grid conditions present a far more challenging environment for integrating variable generation. Inner Mongolia has exceptional wind resources but also experiences very high curtailment levels of over 20%, see Figure 22. Inner Mongolia's grid is "constrained" due to isolation from major loads, a congested transmission system, a heavy reliance on coal generation, and abundant combined heat and power. SustainX has targeted these "constrained" grids where the attributes of the ICAES system can provide the greatest benefit.

[4] Anissa Dehamna, Sam Jaffe. *Energy Storage for the Grid and Ancillary Services.* Boulder, CO: Navigant Consulting, Inc., 2014

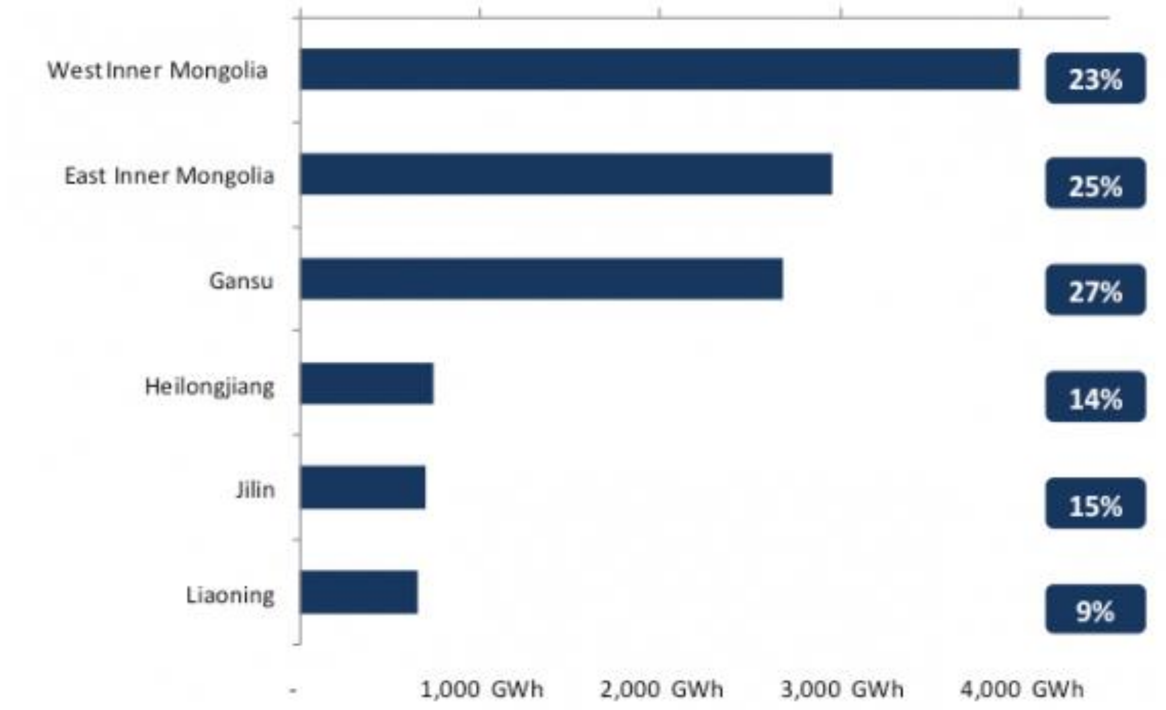

Figure 22: Curtailed wind generation and curtailed percent by province, 2011. Source: China State Electricity Regulatory Commission

SustainX worked with local partners and customers to develop a flexible approach for addressing the challenge of integrating wind on “constrained” grids. As shown in Figure 23, ICAES can be operated together with wind to deliver a flat multi-hour block of energy to the grid. The power and energy independence of the ICAES system allows the profile of this firm power to be tailored for local grid conditions. The ICAES power modules can be scaled in multi-MW blocks to provide 10’s of MW of charge and discharge capability, while the air storage volume can be sized to provide the optimal block duration. ICAES can utilize a variety of air storage media, allowing the firm wind duration to vary from single hours to tens of hours. SustainX developed a firm wind model that analyzes both the energy production and financial outcome, allowing for optimized design of the firm energy product for each grid location.

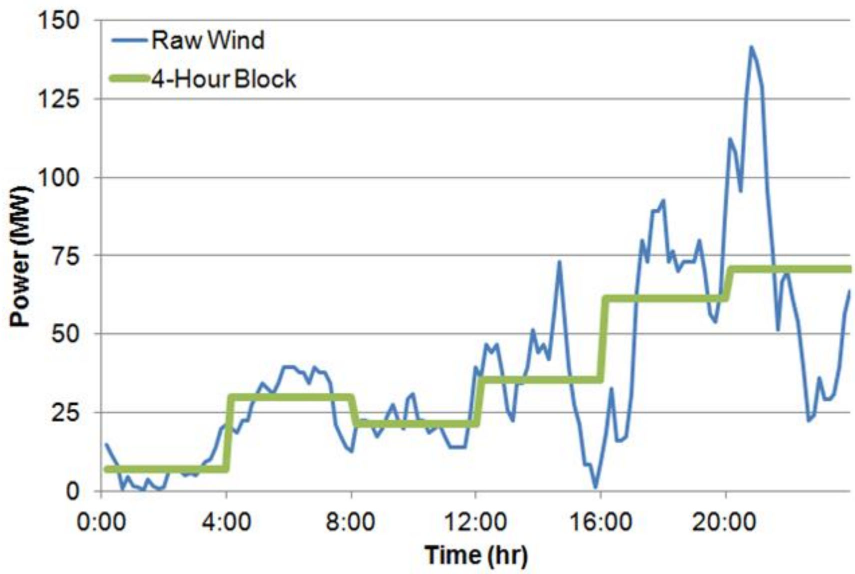

Figure 23: Multi-hour firm wind with ICAES.

Firm wind offers a number of benefits to the regional electric system including:

- Reduced cycling of fossil assets
- Optimized dispatch of fossil assets
- Reduced transmission and distribution congestion
- Reduced wind curtailment

Just as grid conditions are unique for each project, the revenue streams for a firm wind project are unique for each market. China currently has a feed-in-tariff for wind and solar, and a comparable feed-in-tariff can be calculated for a firm wind project. In China, the feed-it-tariff for wind varies by province and wind resource but is approximately $88/MWh. Solar is higher at $157/MWh. Depending on the wind resource and size of the project, firm wind would be financially viable with a feed-in-tariff of approximately $105-118/MWh.

5.2 Transmission and Distribution Substitution

SustainX has developed an analysis tool to model storage as an alternative to traditional grid upgrades. As load and generation profiles change, the existing grid can experience regions of congestion which impact energy prices and reliability. Traditional upgrade options involving higher voltages or new lines are “lumpy”, expensive, and subject to significant right-of-way challenges and delays (i.e., NIMBY or worse). ICAES can provide the power and duration needed to shift large peak loads while allowing utilities a much more efficient use of their capital.

An example scenario is show below. This example is based on what is called a “radial line”. A radial line is a transmission or distribution line that feeds an isolated load, as opposed to a location within the central grid which might have several lines feeding the load. This type of example is far easier to explain, but the same function could be applied in a more complex grid location.

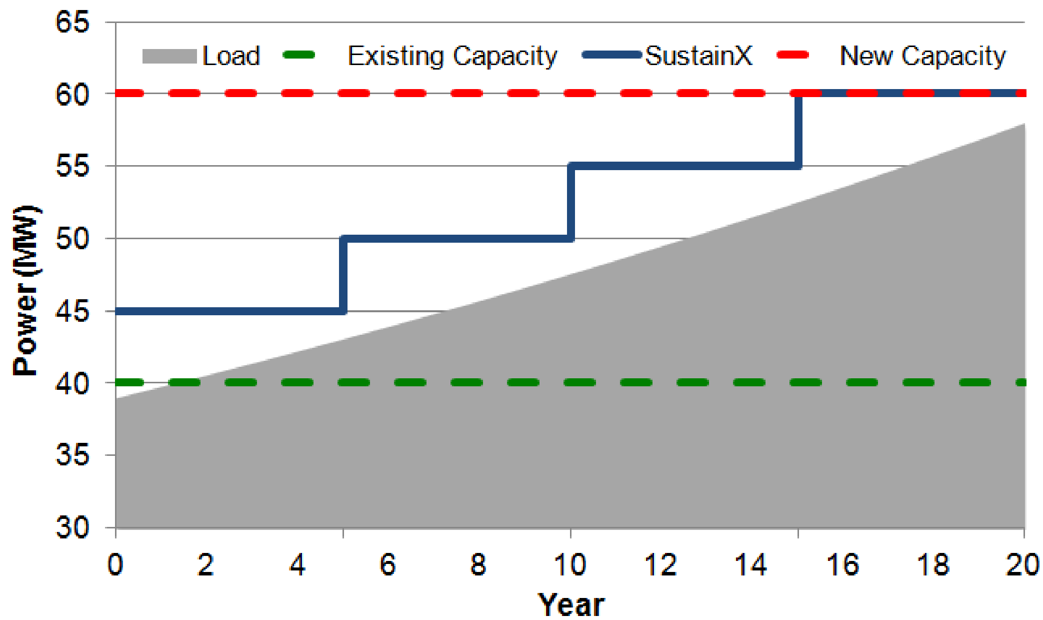

Figure 24: ICAES as a substitute for traditional grid upgrades.

The gray area in the plot represents the peak local electricity demand. The existing transmission line can support 40 MW of load, but load growth in the region is expected to surpass that limit in the immediate future. The utility can upgrade to a higher voltage line which has greater capacity – 60 MW in this example, but that extra 20 MW of capacity might never be needed. Traditional grid upgrades are inherently "lumpy" because there are a fixed number of wire sizes (voltages) to choose from. If the utility does the traditional upgrade, the full cost of that upgrade must be paid for by utility customers starting in Year 1. If the load continues to grow slowly, then that grid upgrade might support the next 20 years of load growth, but if load growth decreases, the full capacity of the upgrade may never be fully utilized.

Storage gives the utility far more flexibility in solving this issue. The utility can install just a few MW of storage to meet the immediate needs. In this example, we show 4 installments of ICAES with each installation being 5 MW with 6 hours of duration. This is based on the rate of peak load growth and the length of the typical peak load period. If the peak load period were longer or shorter the storage duration could be changed accordingly. Similarly, the rate of load growth will determine how many MW of storage are needed. Both of those factors are very location specific.

If load continues to increase during Years 1-5, the utility can choose to install more ICAES, install a traditional line, or do nothing based on the conditions at the time. This efficient utilization of capital directly benefits rate payers. If load growth slows significantly, the financial benefits of ICAES can be even greater. If, for instance, a local factory served by the modeled line closes in Year 10, the utility could choose not to install the 3rd and 4th installments of storage and the customers would see the direct cost savings. Had the utility installed the large line upgrade in Year 1, the upgrade would already be a sunk cost – the customers must pay for it.

This type of application is becoming a key area of focus in the US. California utilities are including storage in their T&D planning process to find locations where it can serve as a cheaper and more effective solution. The analysis for each location is very complicated, but the above example presents the basics of the process. Storage also avoids the significant "right of way" issues associated with running a new T&D line.

5.3 Multi-function Energy Storage

As the market for storage develops, there is a strong push for regulatory change that would enable storage to perform both generation and T&D functions. A recent report[5] performed for the utility Oncor by The Brattle Group concluded that:

> *Given the significant benefits that storage can bring to the system as a whole, enabling cost-effective investments in electricity storage will require a regulatory framework that helps investors capture both the wholesale market and the T&D system values associated with the storage devices.*

EPRI has also performed a detailed analysis of the benefits storage can provide when utilized across multiple market segments, Figure 25. EPRI found that a 20-yr storage solution providing capacity, energy, and ancillary values could justify a capital cost of $2,699/kW. If that same storage asset could also offset a T&D upgrade, the allowable capital cost increases to $4,037/kW.

ICAES offers the scale, lifetime, and combination of high energy and rapid response necessary to perform this wide array of functions.

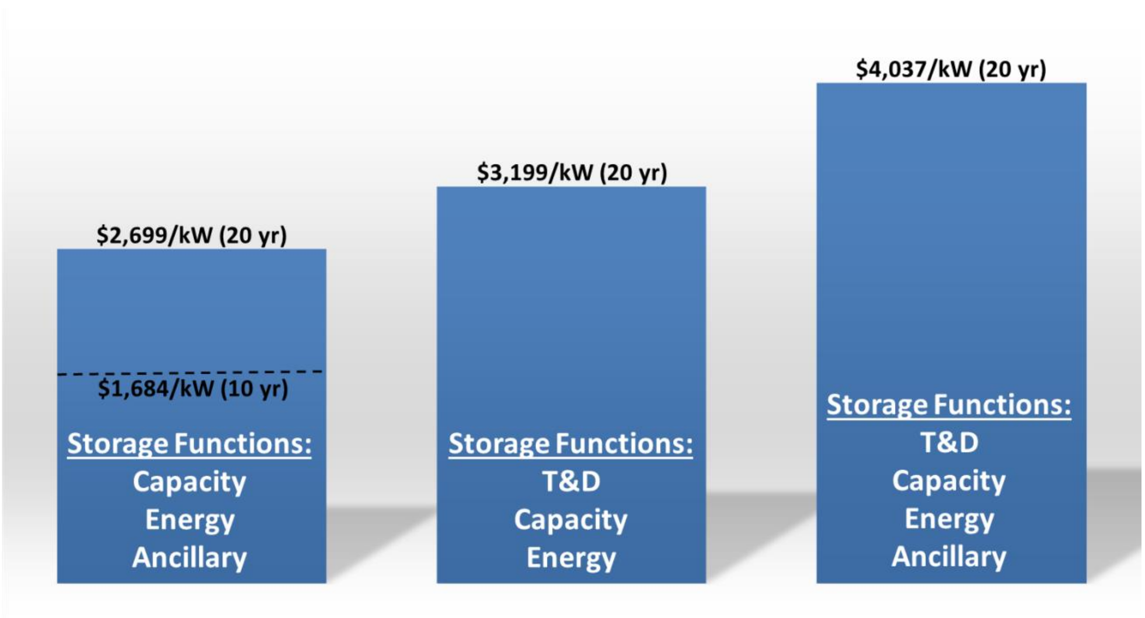

Figure 25: EPRI analysis of energy storage "allowable capital cost" in CA.[6]

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[5] The Brattle Group, *The Value of Distributed Electricity Storage in Texas*, November 2014.

[6] EPRI, *Cost-Effectiveness of Energy Storage in California*, 2013.

6 MAJOR FINDINGS AND CONCLUSIONS

The SustainX ICAES approach has been validated at every step of our R&D process. Upgrading of our technology approaches continues to improve system performance and lower normalized costs. In particular, the replacement of a hydraulic drivetrain with a crankshaft, our innovative use of foam-based heat transfer, and our recognition of the role of highly controllable and efficient valving have led to a many-fold improvement in overall efficiency and power density. Aware that LCOE will be the primary figure of merit for many prospective users of our technology, we have applied classical engineering techniques at every turn to increase efficiency and cut costs, both for the power unit and for bulk compressed-air storage. This disciplined approach has borne fruit in the identification of a development path, now visible in increasing detail, from our 1.5 MW Commercial Prototype to commercialization (see next section).

We conclude that our basic approach—isothermal cycling of compressed air as an energy-storage modality with many advantages, as enabled by our numerous proprietary technology innovations—**has now been proven to be commercially viable**. We have developed a novel energy-storage technology from the ground up with a small, high-caliber staff and on a remarkably short timeline.

7 FUTURE PLANS AND NEXT STEPS

Notably, at every step of R&D, from the earliest days of the company, we have protected our technology advances through an aggressive IP policy, thus **safeguarding the commercial potential of our technology.** We have at least 41 US utility patents granted as of this writing (Table 5), with additional applications pending or provisional, both nationally and internationally. Both core and incidental aspects of our technology innovation have been thoroughly safeguarded.

Table 5. Issued US utility patents on SustainX technology innovations, as of 1/2/15.

Patent Title	Issue Date	Patent #
System and method for rapid isothermal gas expansion and compression for energy	9/28/2010	7,802,426
Systems and methods for energy storage and recovery using compressed gas	11/16/2010	7,832,207
Systems and methods for energy storage and recovery using rapid isothermal gas	1/25/2011	7,874,155
Systems and methods for energy storage and recovery using compressed gas	3/8/2011	7,900,444
Systems and methods for combined thermal and compressed gas energy conversion	6/14/2011	7,958,731
Systems and methods for improving drivetrain efficiency for compressed gas energy	6/21/2011	7,963,110
Energy storage and generation systems and methods using coupled cylinder	10/18/2011	8,037,678
Systems and methods for improving drivetrain efficiency for compressed gas energy	11/01/2011	8,046,990
Increased power in compressed-gas energy storage and recovery	1/31/2012	8,104,274
Energy storage and generation systems and methods using coupled cylinder	2/07/2012	8,109,085
Systems and methods for compressed-gas energy storage using coupled cylinder	2/21/2012	8,117,842
Systems and methods for combined thermal and compressed gas energy conversion	2/28/2012	8,122,718
High-efficiency liquid heat exchange in compressed-gas energy storage systems	5/8/2012	8,171,728

Systems and methods for reducing dead volume in compressed-gas energy storage	6/5/2012	8,191,362
Systems and methods for energy storage and recovery using compressed gas	7/3/2012	8,209,974
Systems and methods for energy storage and recovery using rapid isothermal gas	7/24/2012	8,225,606
Systems and methods for combined thermal and compressed gas energy conversion	8/7/2012	8,234,862
Forming liquid sprays in compressed-gas energy storage systems for effective heat	8/7/2012	8,234,863
Systems and methods for improving drivetrain efficiency for compressed gas energy	8/7/2012	8,234,868
High-efficiency energy-conversion based on fluid expansion and compression	8/14/2012	8,240,140
System and method for rapid isothermal gas expansion and compression for energy	8/14/2012	8,240,146
Improving efficiency of liquid heat exchange in compressed-gas energy storage	8/21/2012	8,245,508
Heat exchange with compressed gas in energy-storage systems	8/28/2012	8,250,863
Systems and methods for efficient pumping of high-pressure fluids for energy storage	1/29/2013	8,359,856
Systems and methods for energy storage and recovery using gas expansion and	5/28/2013	8,448,433
Energy storage and generation systems and methods using coupled cylinder	6/25/2013	8,468,815
Forming liquid sprays in compressed-gas energy storage systems for effective heat	7/2/2013	8,474,255
Increased power in compressed-gas energy storage and recovery	7/9/2013	8,479,502
Systems and methods for reducing dead volume in compressed-gas energy storage	7/9/2013	8,479,505
Energy storage and recovery utilizing low-pressure thermal conditioning for heat	7/30/2013	8,495,872
Systems and methods for efficient two-phase heat transfer in compressed-air energy	9/24/2013	8,539,763
Fluid-flow control in energy storage and recovery systems	11/12/2013	8,578,708
Systems and methods for reducing dead volume in compressed-gas energy storage	11/26/2013	8,590,296
Systems and methods for energy storage and recovery using rapid isothermal gas	1/14/2014	8,627,658
High-efficiency heat exchange in compressed-gas energy storage systems	3/4/2014	8,661,808
Dead-volume management in compressed-gas energy storage and recovery systems	3/11/2014	8,667,792
Systems and methods for energy storage and recovery using compressed gas	5/6/2014	8,713,929
Systems and methods for energy storage and recovery using rapid isothermal gas	5/27/2014	8,733,094
Heat exchange with compressed gas in energy-storage systems	7/1/2014	8.763.390
Systems and methods for efficient two-phase heat transfer in compressed-air energy	8/19/2014	8,806,866

SustainX continues to work with partners in Asia and North America to initialize commercial installations of the ICAES technology.

In addition, SustainX will continue to incorporate test results into design improvements for a MW-scale commercial product that can compete vigorously in the nascent market for utility-scale storage. Design for manufacturability and ramping-up of production volume will reduce costs in a predictable manner, making our product competitive both for its innate features (nontoxicity, siting flexibility, modularity, independent scaling of power and storage, etc.) and its LCOE.