Technology Performance Report

SustainX Smart Grid Program

Contract ID: DE-OE0000231

Project Type: Demonstration of Promising Energy Storage Technologies

Company Name: SustainX

Revised: July 30, 2014

Recipient: SustainX, Inc.

Principal Investigators: Benjamin Bollinger, PhD

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

Acknowledgements. This work was funded in part by the U.S. Department of Energy's National Energy Technology Laboratory (U.S. DOE-NETL) under the American Recovery and Reinvestment Act (ARRA) under award number DE-OE0000231.

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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 1kW 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 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 consists 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 consists of eight tasks, completion of each of which constitutes a milestone. Six 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	2/4/10	2/19/10
40 kW prototype manufacture	9/24/10	9/10/10
40 kW prototype test	1/14/11	Prelim. results, 1/14/11. Testing completed, 5/6/11.
MW-scale system preliminary design	12/31/11	12/27/11
Phase 2		
2.1 Crank Shaft System Analysis & Layout	12/19/11	4/17/2012
2.2 Spray System Modeling & Testing	2/3/12	11/16/12
2.3 MW-scale Detail Design	9/11/12	2/22/13
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	-
2.8 Submit Final Technical Report	1/2/2015	-

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. We currently employ 44 people.

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

208 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 Turbo-Diesel 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.

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[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 Prototype has been operational for both compressions (charge) and expansions (discharge) since September 30, 2013.

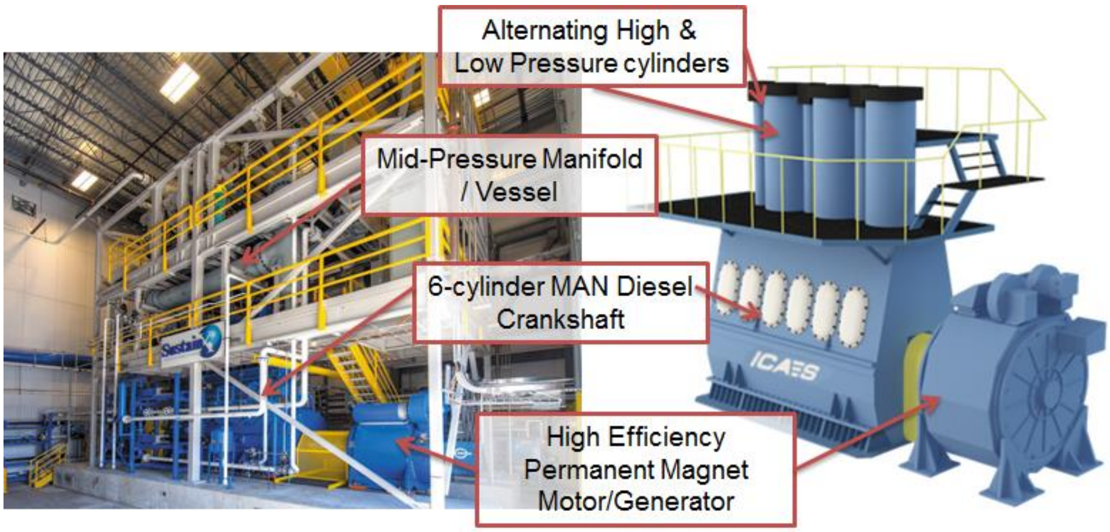

Figure 3: *Left*: Completed SustainX Megawatt-scale ICAES system located at Seabrook, NH, October 2013. *Right*: Rendering of ICAES power unit showing cylinder arrangement.

The 1.5 MW 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 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

3 PERFORMANCE ESTIMATION METHODOLOGIES AND ALGORITHMS

3.1 Physical Performance Estimation Methodologies

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 mentioned in the section above have been evaluated in different manners, as appropriate for each. 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 energy consumption, both during run-time and during standby.

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

3.2 Financial Performance Estimation Methodologies

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.

Details of the SustainX LCOE model, as well as our analysis of the markets and applications for energy storage, will be given in the final report.

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 4) to examine sprays over a range of orifice designs and operating conditions.

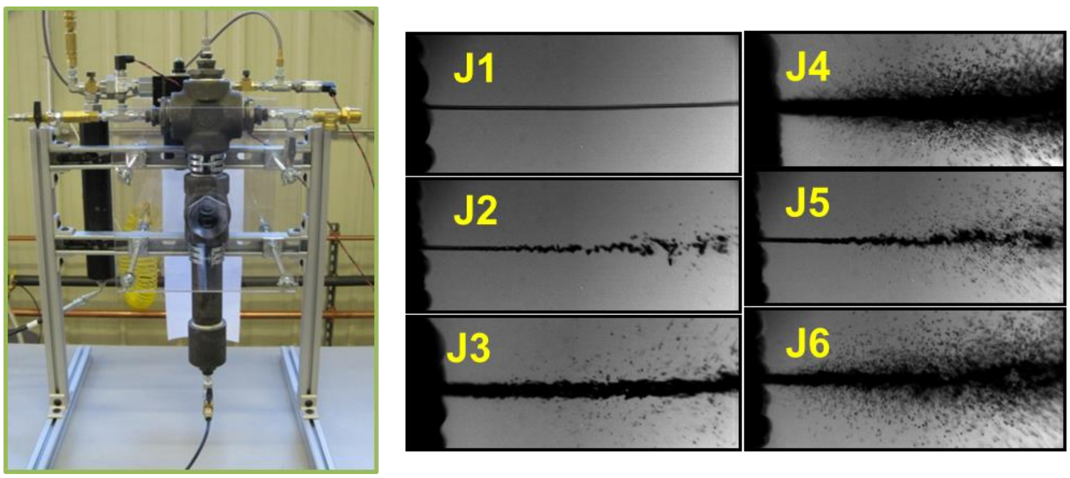

Figure 4: Spray characterization experiments. *Left*: HPLIA test unit. *Right*: jet breakup experiments using different nozzles, classified by J type per Bachalo et al.

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 4). 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.

[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.

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 5, 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.

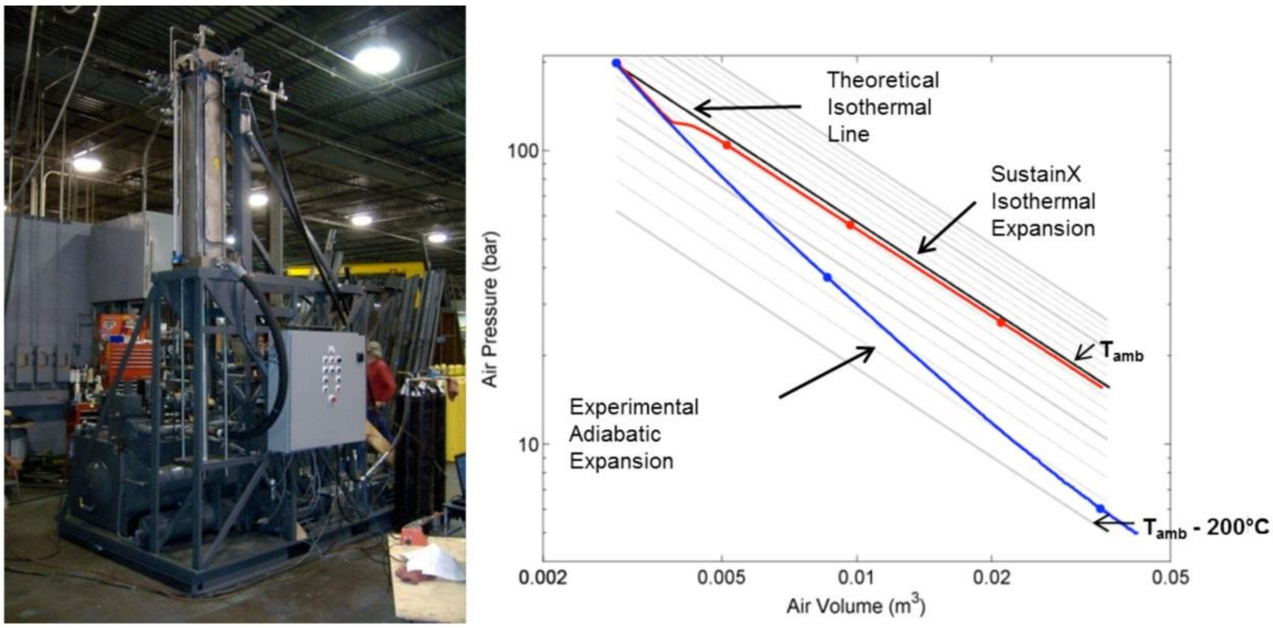

Figure 5: *Left*: Heat-transfer test stand, a.k.a. HXTST. *Right*: Experimental results for an isothermal expansion (red) vs. adiabatic expansion (blue) vs ideal expansion (black) for the same mass of air. Dots are marked at 1 second intervals for reference. Grey lines are lines of constant temperature 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. The hydraulic chamber empties as air pushes the piston downward. Power level and spray technique are determined as above.

The results in Figure 5, 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 6: 40 kW Pilot unit at the original Lebanon, NH location, showing cylinders and air storage vessels (back right)

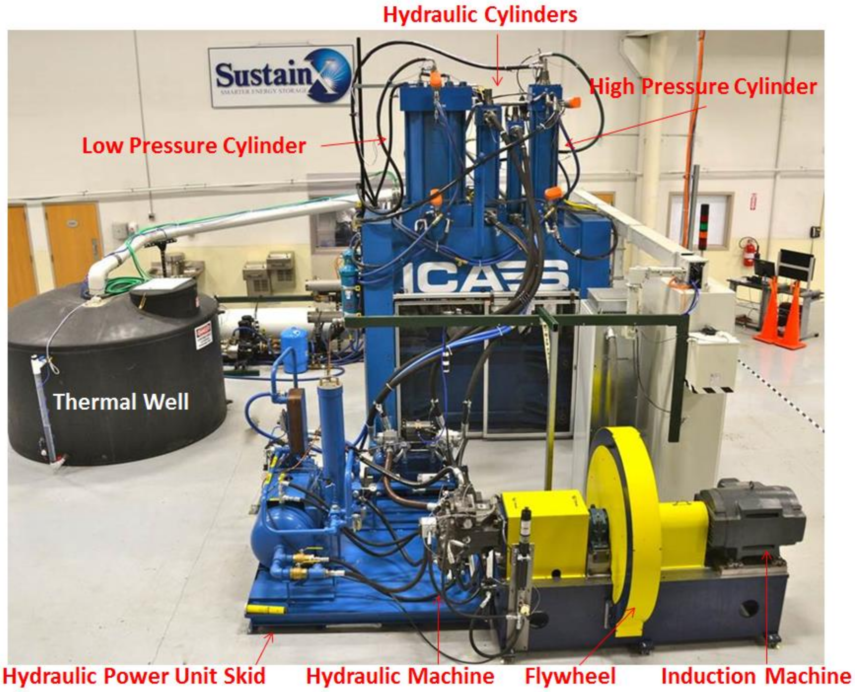

Figure 7: 40 kW Pilot unit, with major components identified, after the move to Seabrook, NH

The 40 kW Pilot, shown in Figure 6 and Figure 7, 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. 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 5) 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 8 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.

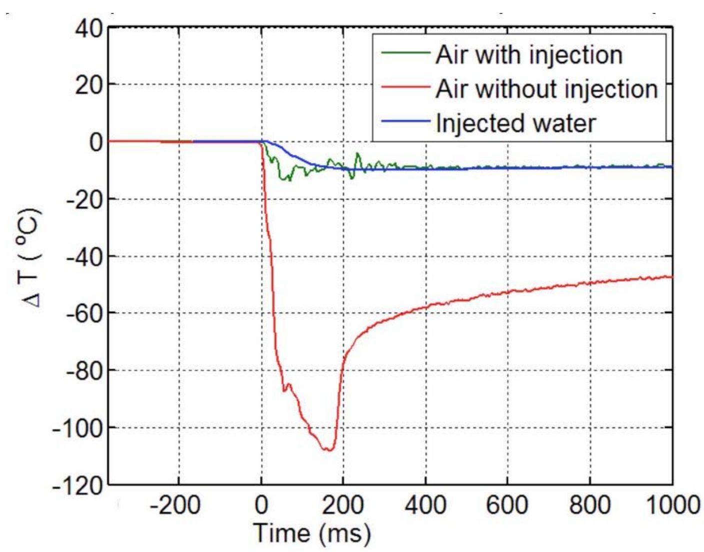

Figure 8: Comparison of non-isothermal to approximately isothermal air expansion with foam in the HXTST test cylinder: quarter-second piston stroke (0–250 ms), pressure change from ~200 bar to ~20 bar. Air temperature change (ΔT) is shown without heat exchange (red) and with foam heat exchange (green). 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 9 shows comparative data from the HXTST for foam and sprayed droplet thermal efficiency vs. energy consumed to create the foam or spray.

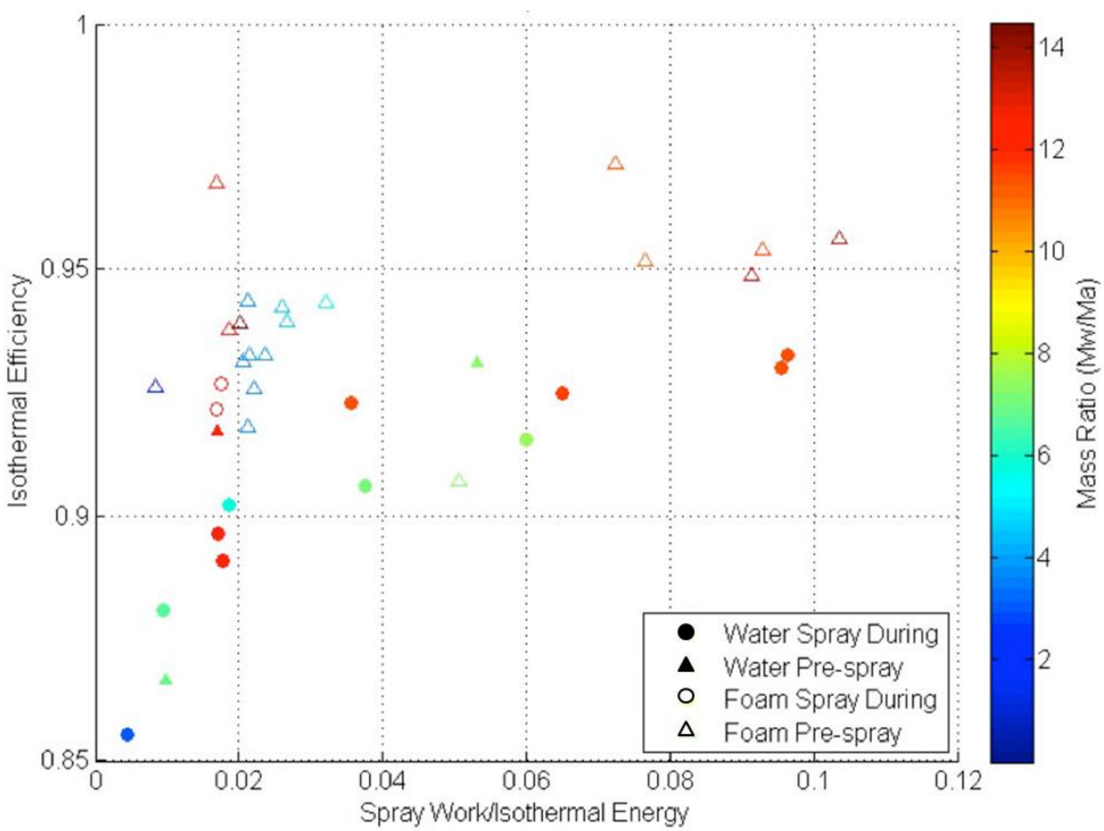

Figure 9: Data on spray and foam heat transfer from air expansions at the same power levels in a SustainX heat-transfer test stand. Foam generated before expansion ("foam pre-spray"—open triangles) achieved substantially higher efficiency at lower spray- energy (work) input levels than direct spray injection 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 10) is a closed-loop system that includes a full-scale replica (in plastic) of the mid-pressure vessel designed for the 1.5 MW 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 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.

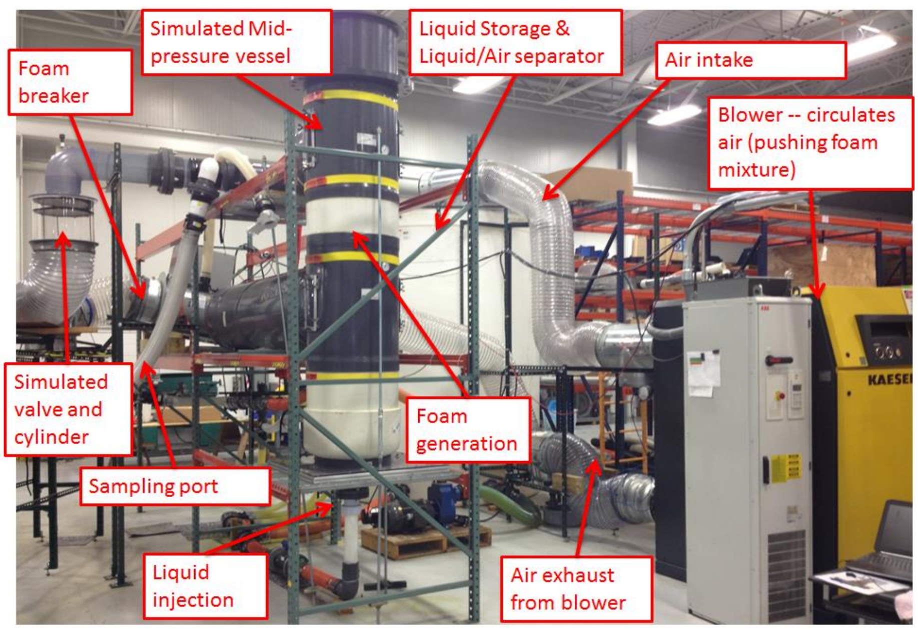

Figure 10: Foam generation and transport test stand, which mimics the mid-pressure vessel in our 1.5 MW ICAES system

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 Turbo-Diesel 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^{o} of rotation. Figure 11 shows the output of one ofthe 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 Prototype to assess the bearing performance because SustainX's 1.5 MW Commercial Prototype ICAES system has been a new use-case for the MAN crankshaft. No wear on the bearings or other adverse conditions were evident.

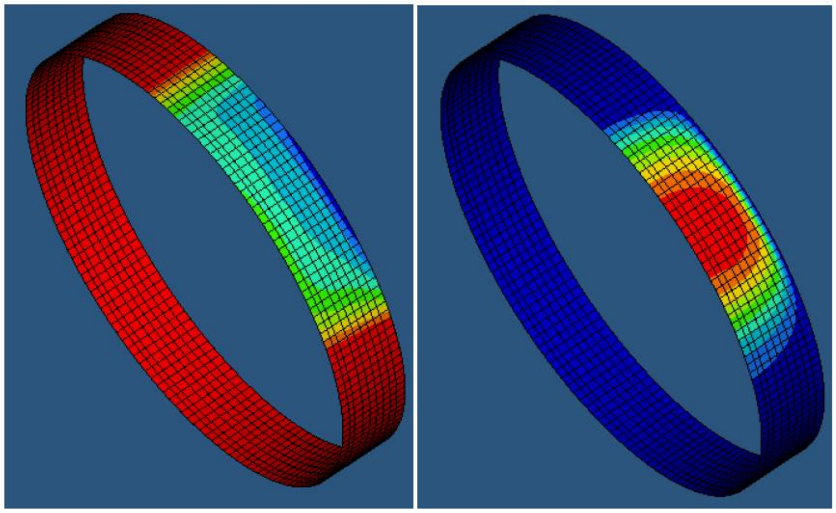

Figure 11: Dynamic elasto-hydrodynamic simulation results from MAN for the crank-pin bearing of the high-pressure cylinder at top dead center. *Left*: oil film thickness. *Right*: oil film pressure.

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 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 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 12 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%.

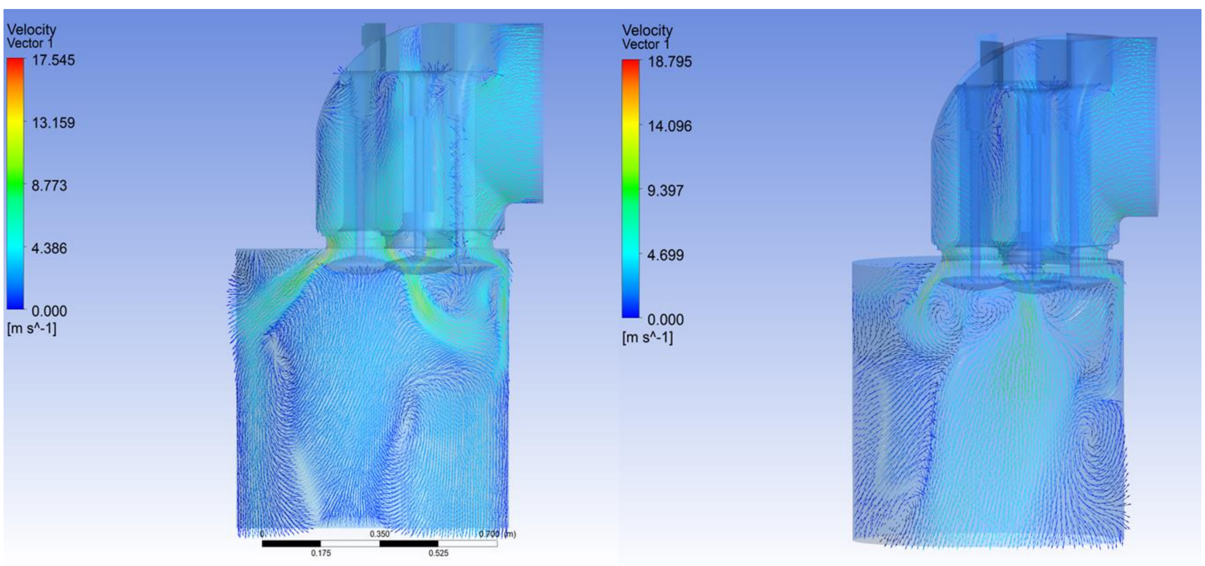

Figure 12: CFD simulation of air flow in through the low-pressure cylinder intake/exhaust valves. *Left*: prior to flow guide optimization, intake air forms jets that impact cylinder walls. *Right*: after flow guide optimization, intake flow is more uniformly distributed within cylinder.

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 13) 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 14. 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.

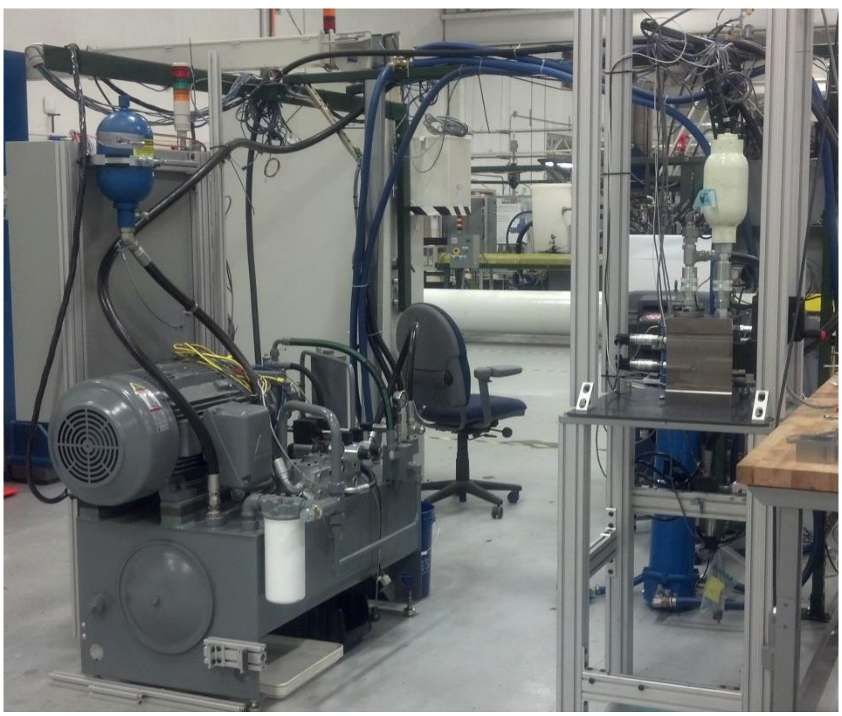

Figure 13: Valve actuator test stand. *Left*: Full test stand showing hydraulic power unit and control cabinet at left and test table at right. *Right*: close-up of valve actuator on test table

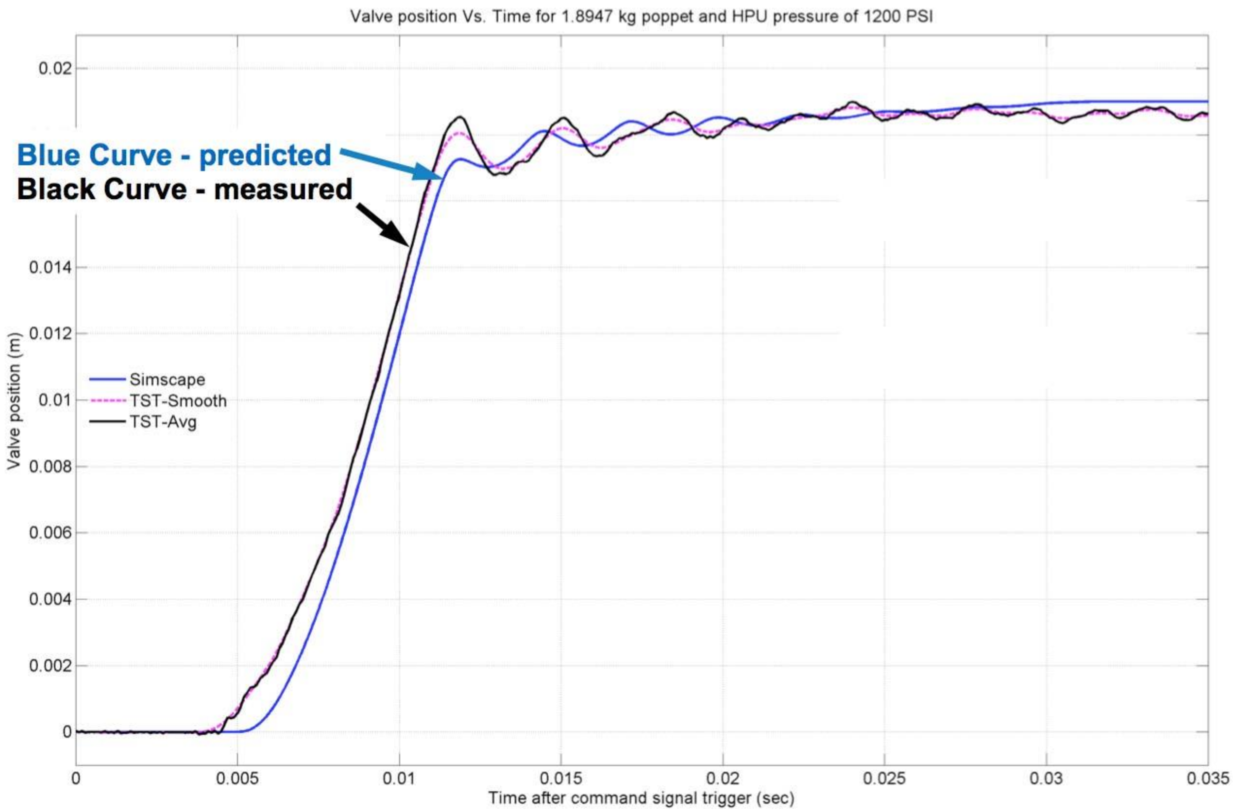

Figure 14: Measured vs. simulated valve position vs. time for valve closing event, affirming model simulations and confirming valve response time (<10 ms) and cushion performance.

4.7 System: 1.5 MW Commercial-Scale Prototype

The 1.5 MW 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.

Construction of the 1.5 MW Prototype began in January of 2013, with commissioning complete by the end of August. Initial testing of the system began in September, with the system operation for both compression and expansion modes since the end of September. Testing of the 1.5 MW Prototype comprises the final phase of the DOE project and is ongoing. Initial testing indicates that the system is performing as expected. Results will be presented in the final report.

5 GRID IMPACTS AND ESTIMATION OF BENEFITS

In 2008, the US Department of Energy stated that revolutionary breakthroughs in electrical energy storage are "perhaps the most crucial need for this nation's secure energy future." However, the

National Renewable Energy Laboratory noted in 2010[4] that simulations of the economic value of storage for the grid are inadequate—challenged, in part, by the sheer diversity of services that storage can offer, and complicated by the complex economics of power from variable generators (especially wind). Grid applications for storage—more than one of which can be fulfilled by a given storage facility – include:

- Renewable energy integration (especially wind)
- Conventional energy load leveling
- Waste heat harvesting (cogeneration)
- T&D upgrade substitution
- Transmission congestion relief
- High-power wind ramping

For large end users (e.g. military bases, large industrial consumers), ICAES offers energy management, electric power reliability and quality (e.g., islanding, outage mitigation), and the potential for cogeneration.

Increasingly sophisticated efforts are being made to quantitatively model the value of storage for real-world grids,[5] but much remains to be done in this field. Nevertheless, there is broad consensus that the benefits storage are potentially immense and grid owners worldwide are eager to avail themselves of them. Also, it is clear that the lower the price of storage, the greater the benefits.

Our ICAES modules—scalable, nontoxic, long-lived, highly-efficient, and built largely from industrially mature, off-the-shelf components—will offer disruptively lower lifetime cost of ownership compared to the competition. According to Lux Research, comparing SustainX to battery-type competitors (May, 2013), ICAES "**is far less expensive than any electrochemical technology at the MW scale**.**"** Potential impacts/applications (Figure 15) include improved grid efficiency and accelerated market penetration by intermittent renewables, especially wind and solar PV, with corresponding benefits including reductions in greenhouse gas emissions. Notably, **wind integration and grid resource optimization** account for the lion's share of CAES impact in the Navigant forecast.

[4] Denholm, Paul, et al. The Role of Energy Storage with Renewable Electricity Generation. Technical Report NREL/TP-6A2-47187, January 2010. At http://www.nrel.gov/docs/fy10osti/47187.pdf (accessed Dec. 6, 2013).
[5] E.g., Denholm, Paul, et al. The Value of Energy Storage for Grid Applications. Technical Report NREL/TP-6A20-58465, May 2013. At http://www.nrel.gov/docs/fy13osti/58465.pdf (accessed Dec. 6, 2013).

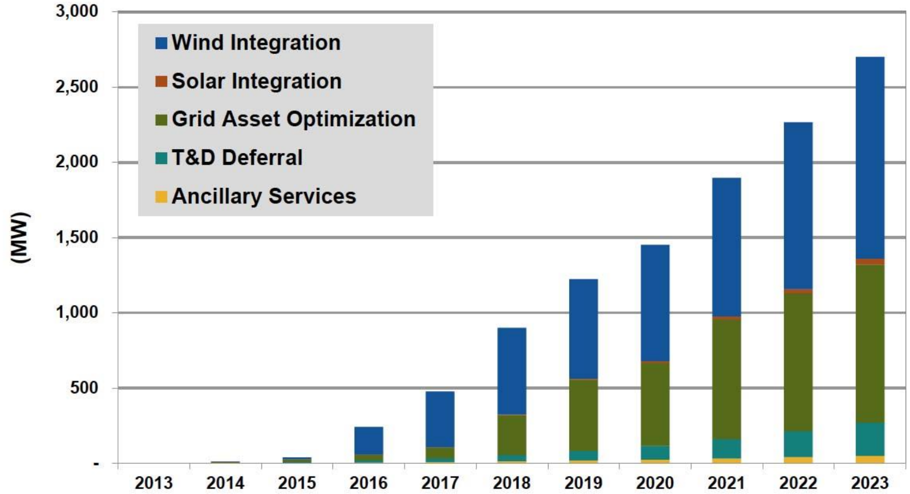

Figure 15: Navigant Research's forecast of global CAES applications by year[6]

The grid impacts and benefits of SustainX's operational 1.5 MW-scale ICAES system will be discussed further in the final report following completion of the MW-scale system testing.

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 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

Our 1.5 MW system is currently undergoing thorough testing and operational optimization: almost every aspect of operation is independently settable, making this unit capable of an extremely wide range of

[6] Warrier, Dilip, Kerry-Ann Adamson, *Compressed Air Energy Storage, Traditional Underground and Next-Generation CAES Technologies: Global Market Analysis and Forecasts*. Boulder, CO: Navigant Consulting, Inc., 2013. p.61

operational states and thus an ideal test-bed for optimization. In particular, in 2014 we will continue operational testing and refinement of the 1.5 MW system, incorporating 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.

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 33 US utility patents granted as of this writing (**Table 3**), 28 pending or provisional, and 10 international pending. Both core and incidental aspects of our technology innovation have been thoroughly safeguarded.

Table 3. Issued US utility patents on SustainX technology innovations, as of 12/12/13.

Patent Title	Issue Date	Patent #
System and method for rapid isothermal gas expansion and compression for	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	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	6/14/2011	7,958,731
Systems and methods for improving drivetrain efficiency for compressed gas	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	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	2/21/2012	8,117,842
Systems and methods for combined thermal and compressed gas energy	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	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	7/24/2012	8,225,606
Systems and methods for combined thermal and compressed gas energy	8/7/2012	8,234,862
Forming liquid sprays in compressed-gas energy storage systems for effective	8/7/2012	8,234,863
Systems and methods for improving drivetrain efficiency for compressed gas	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	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	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	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	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	9/24/2013	8,539,763

Fluid-flow control in energy storage and recovery systems	11/12/2013	8,578,708