SustainX
SMARTER ENERGY STORAGE

ICAES

DOE Final Briefing

Webex	https://mmancusa.webex.com/mmancusa/j.php?MTID=maadb3130caf8c1cb165527c1e073d819	Meeting Number: 744 541 035 Meeting Password: 151143Aa!
By phone	1-888-677-0837	PC-11053

Presentation and Discussion Topics

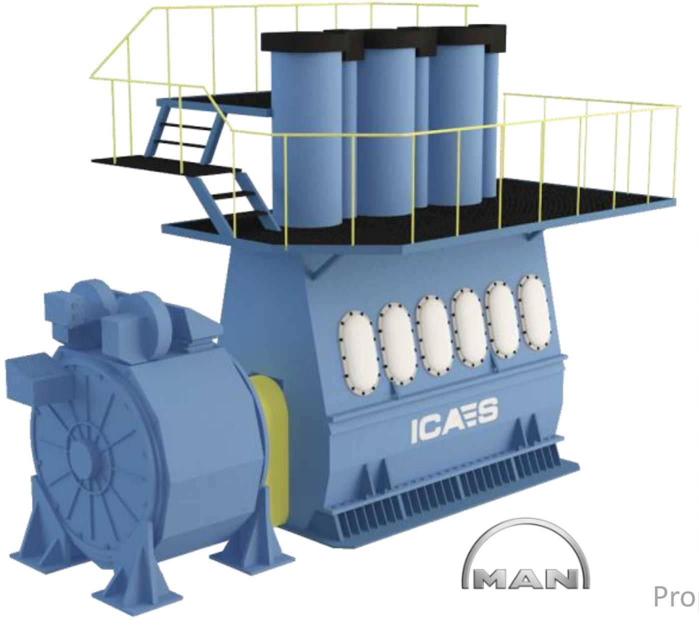
- General Overview and History
- Supporting Technology Development
  - Spray-based Heat Transfer ◦ Staged Hydraulic Drivetrain ◦ 40 kW Pilot System
  - Foam-based Heat Transfer ◦ Crankshaft-based Drivetrain ◦ High Performance Valves
- 1.5 MW Commercial Prototype
  - Data Acquisition and Controls ◦ System Testing and Performance
- Lined Rock Cavern—Brief Overview
- Cost Analysis
- Market and Market Applications Analysis
- Business Model
- Current Company Status and Direction

General Overview and History

Isothermal Compressed Air Energy Storage (ICAES™)

Disruptive mechanical grid-scale energy storage solution

- Fuel-free mechanical system using compressed air
- None of the cost, life, and safety issues of batteries
- Enables site-flexible and scalable bulk storage
- Lowest levelized cost of energy



Strong Technical & Financial Foundation

Technology

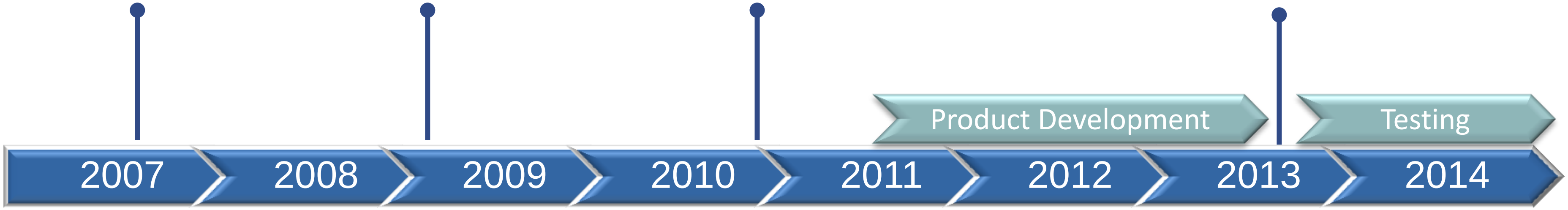
DARTMOUTH 1769

**SustainX Founded
(Dartmouth spin-out)**

**1kW – 5kWh
Alpha System**

40kW Pilot

1.5 MW Full-Scale Prototype



Seed Round $500k

POLARIS VENTURE PARTNERS
ANGELI PARVI

SBIR $150K

Series A-1 $4M

POLARIS VENTURE PARTNERS
ROCKPORT CAPITAL

SBIR $1M

SGDP award $5.4M

Series A-2 $20M

POLARIS VENTURE PARTNERS
ROCKPORT CAPITAL
CADENT ENERGY PARTNERS
General Catalyst Partners
ecomagination

***New Fundraise
in Progress***

Financing

Commercial Performance Validated on 1.5 MW ICAES System

- ✓ System Power
- ✓ AC Roundtrip Efficiency
- ✓ Foam Heat Transfer
- ✓ Valve Performance
- ✓ Valve Reliability (1M+ cycles)
- ✓ Storage Pressure
- ✓ Mature Driveline

Commercial Performance Validated on 1.5 MW ICAES System

Permanent Magnet Motor/Generator

- ✓ Borrowed Directly from Wind Industry
- ✓ Grid Connected through Full Power Converters
- ✓ Established Manufacturing & Proven Reliability

THE SWITCH

Commercial Performance Validated on 1.5 MW ICAES System

SustainX
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Crankshaft

- ✓ Borrowed Directly from Diesel Industry
- ✓ Drives Reciprocating Pneumatic Process
- ✓ Established Manufacturing & Proven Reliability

Commercial Performance Validated on 1.5 MW ICAES System

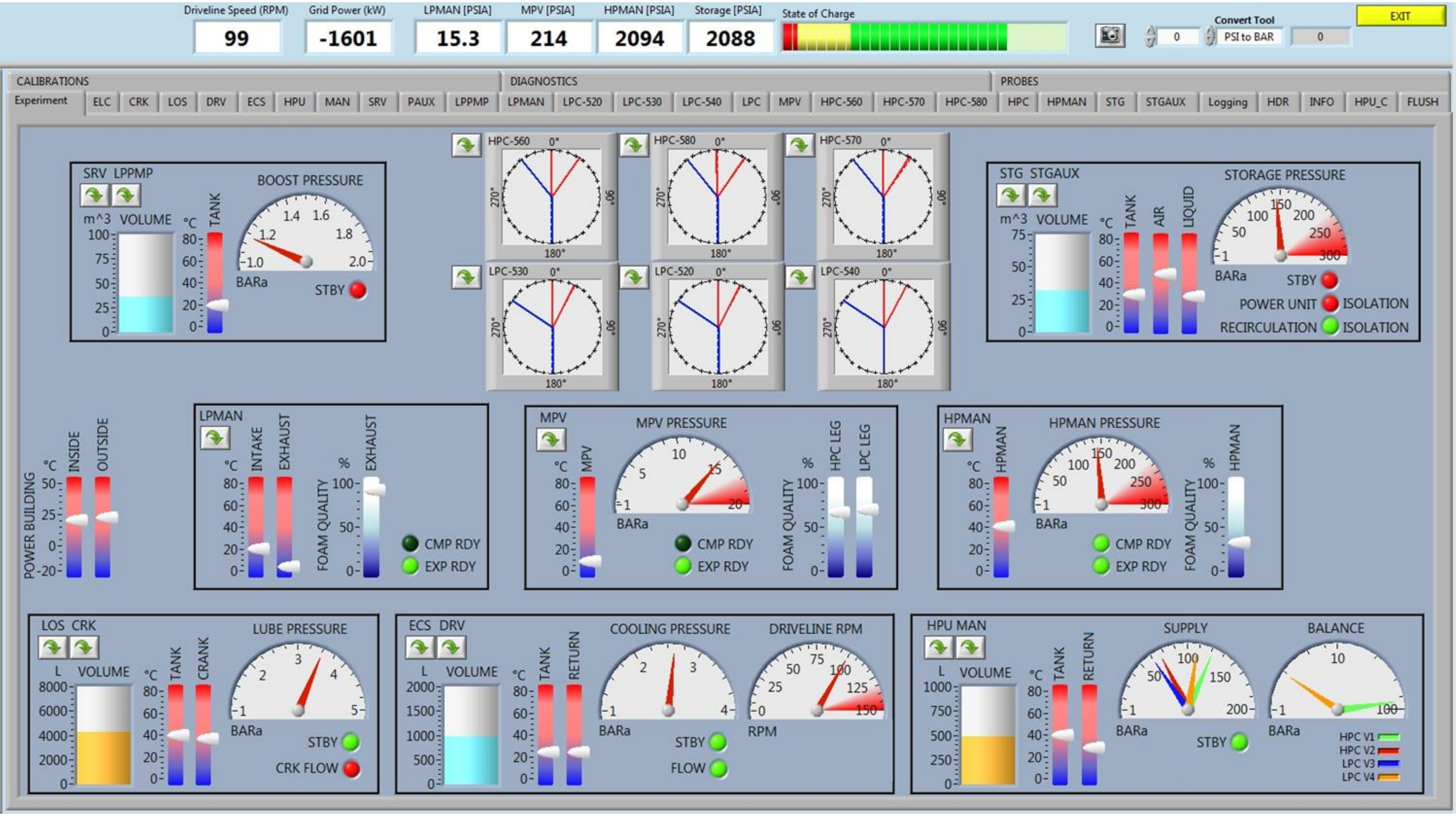
SustainX
SMARTER ENERGY STORAGE

Heat Transfer Technology

- ✓ SustainX Patented Foam-Based Isothermal Process
- ✓ >200 Bar Δ ↔ <50 °C Δ
- ✓ Mature Industrial Components and Principles

Commercial Performance Validated on 1.5 MW ICAES System

SustainX
SMARTER ENERGY STORAGE

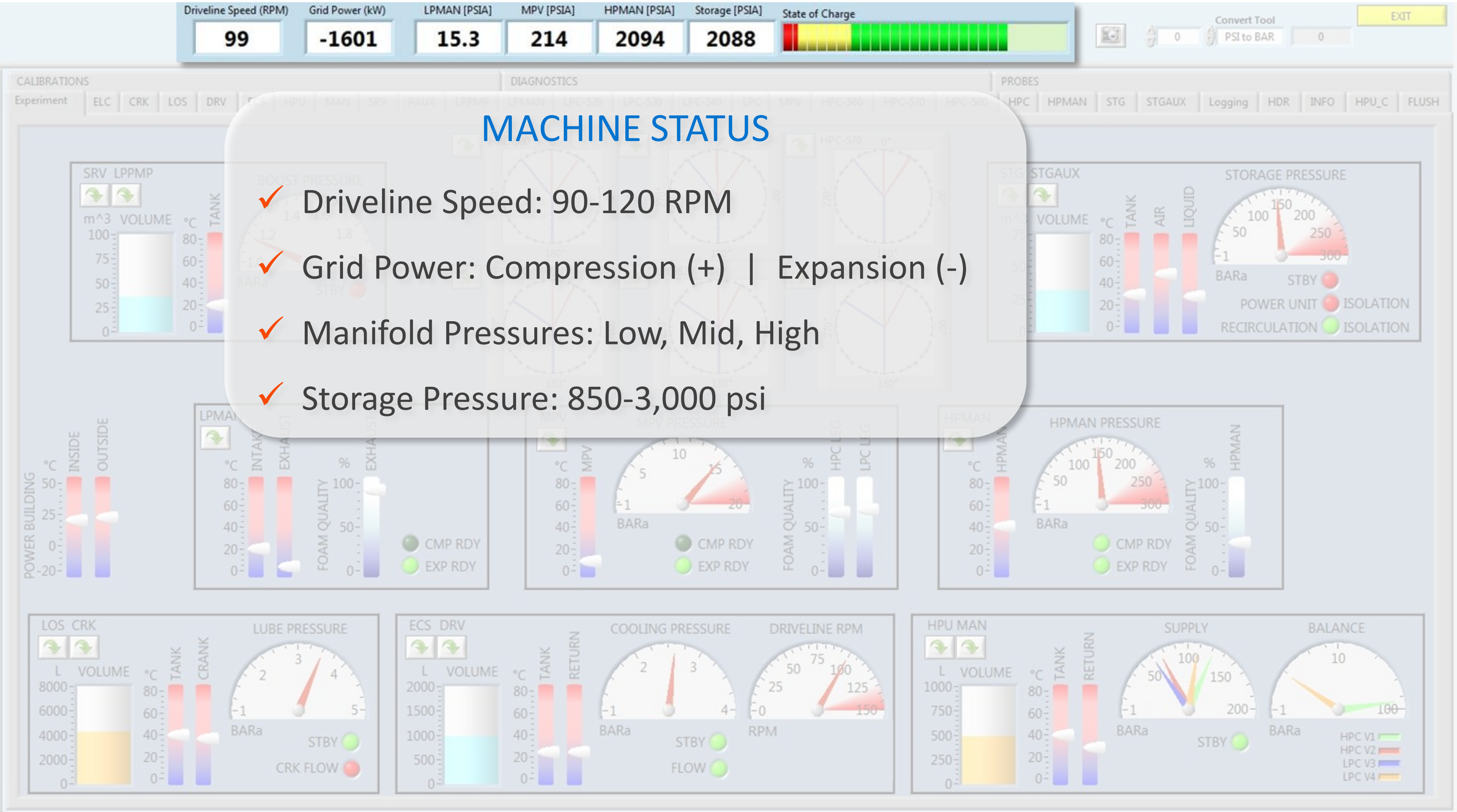


Driveline Speed (RPM)	Grid Power (kW)	LPMAN [PSIA]	MPV [PSIA]	HPMAN [PSIA]	Storage [PSIA]
99	-1601	15.3	214	2094	2088

State of Charge

Convert Tool: 0 PSI to BAR 0

Commercial Performance Validated on 1.5 MW ICAES System

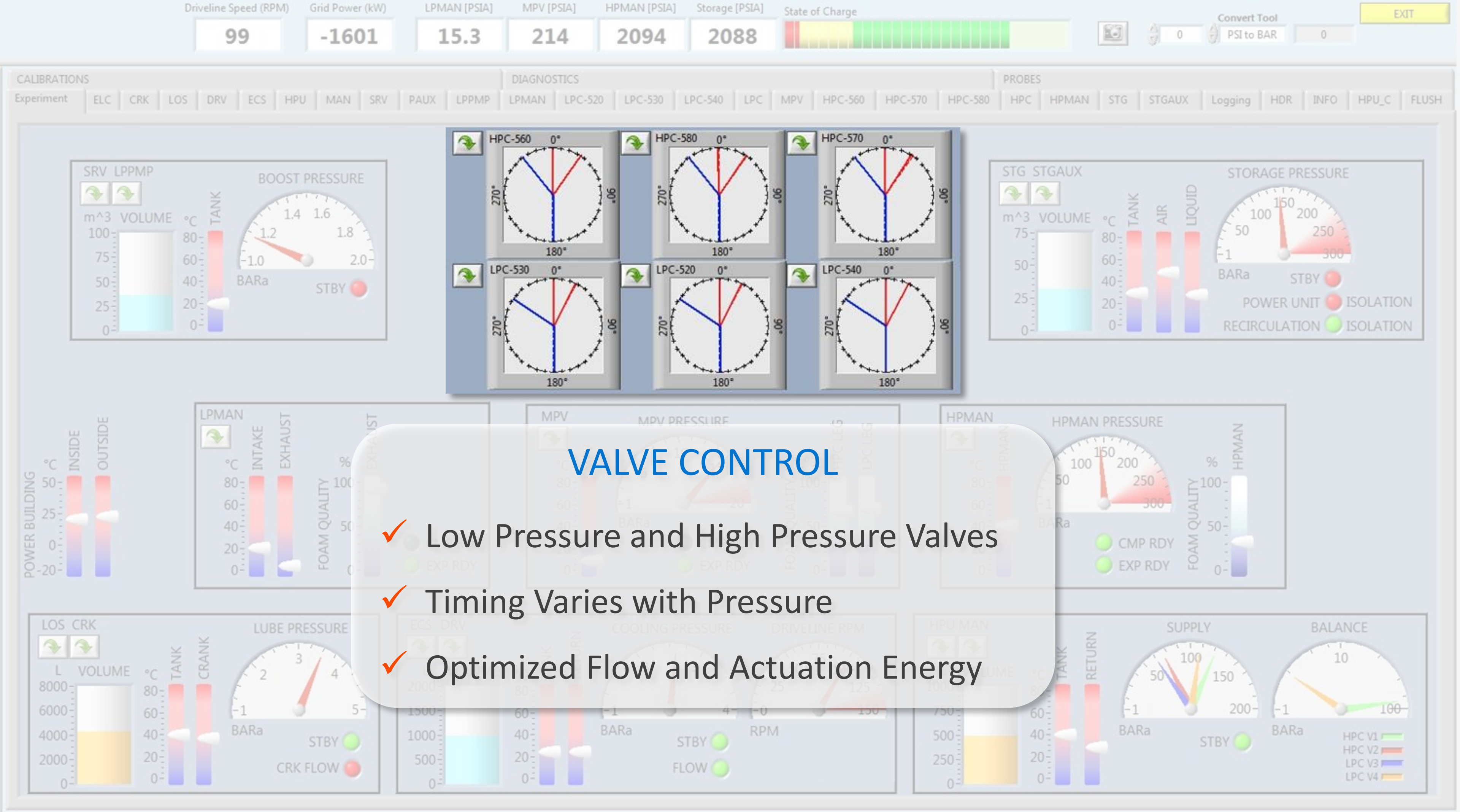


Driveline Speed (RPM)	Grid Power (kW)	LPMAN [PSIA]	MPV [PSIA]	HPMAN [PSIA]	Storage [PSIA]
99	-1601	15.3	214	2094	2088

MACHINE STATUS

- ✓ Driveline Speed: 90-120 RPM
- ✓ Grid Power: Compression (+) | Expansion (-)
- ✓ Manifold Pressures: Low, Mid, High
- ✓ Storage Pressure: 850-3,000 psi

Commercial Performance Validated on 1.5 MW ICAES System

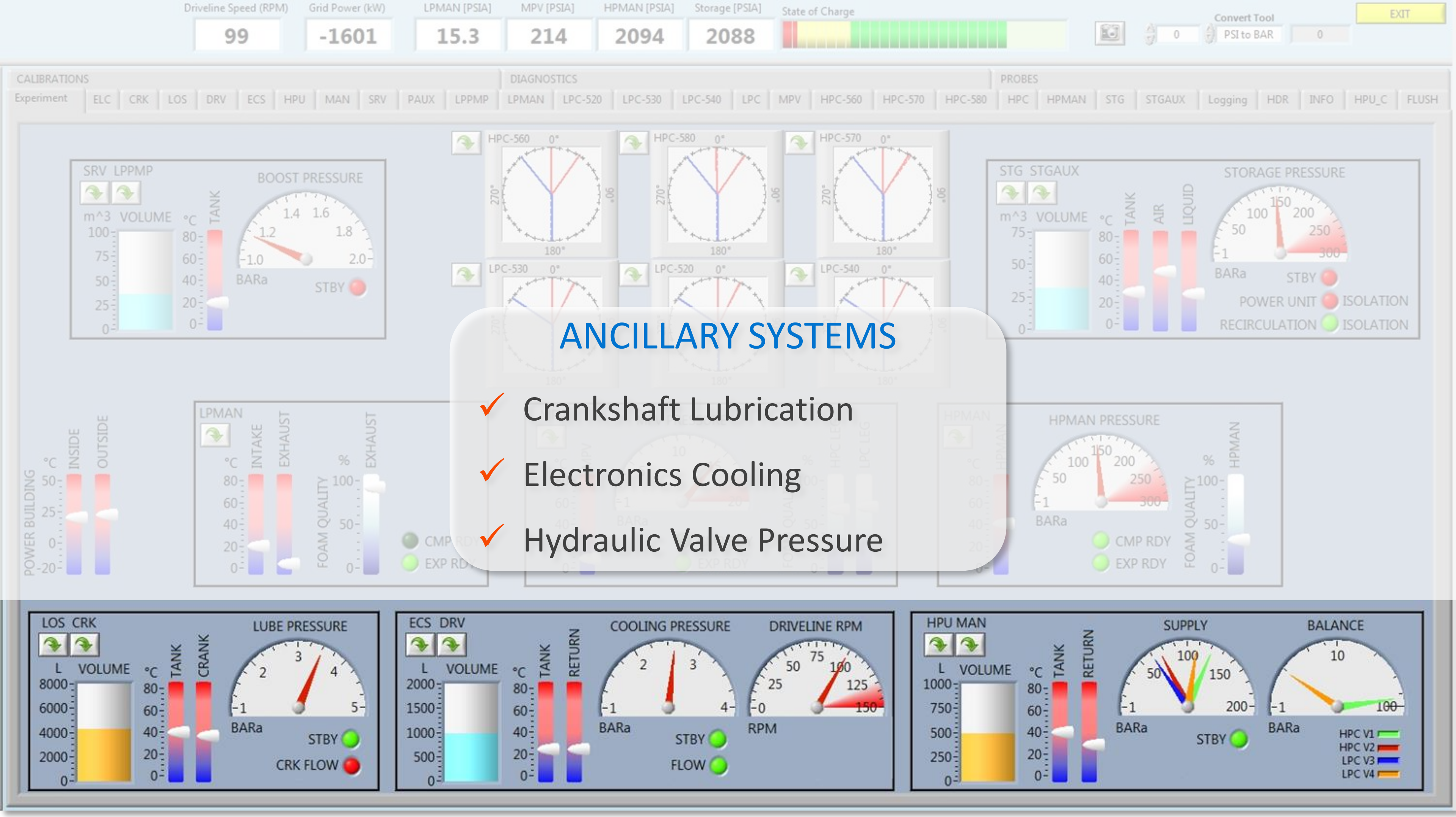


Driveline Speed (RPM): 99
Grid Power (kW): -1601
LPMAN [PSIA]: 15.3
MPV [PSIA]: 214
HPMAN [PSIA]: 2094
Storage [PSIA]: 2088

VALVE CONTROL

- ✓ Low Pressure and High Pressure Valves
- ✓ Timing Varies with Pressure
- ✓ Optimized Flow and Actuation Energy

Commercial Performance Validated on 1.5 MW ICAES System



Driveline Speed (RPM)	Grid Power (kW)	LPMAN [PSIA]	MPV [PSIA]	HPMAN [PSIA]	Storage [PSIA]
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ANCILLARY SYSTEMS

- ✓ Crankshaft Lubrication
- ✓ Electronics Cooling
- ✓ Hydraulic Valve Pressure

How Does ICAES Work?

Air Compression Process (1 of 2)

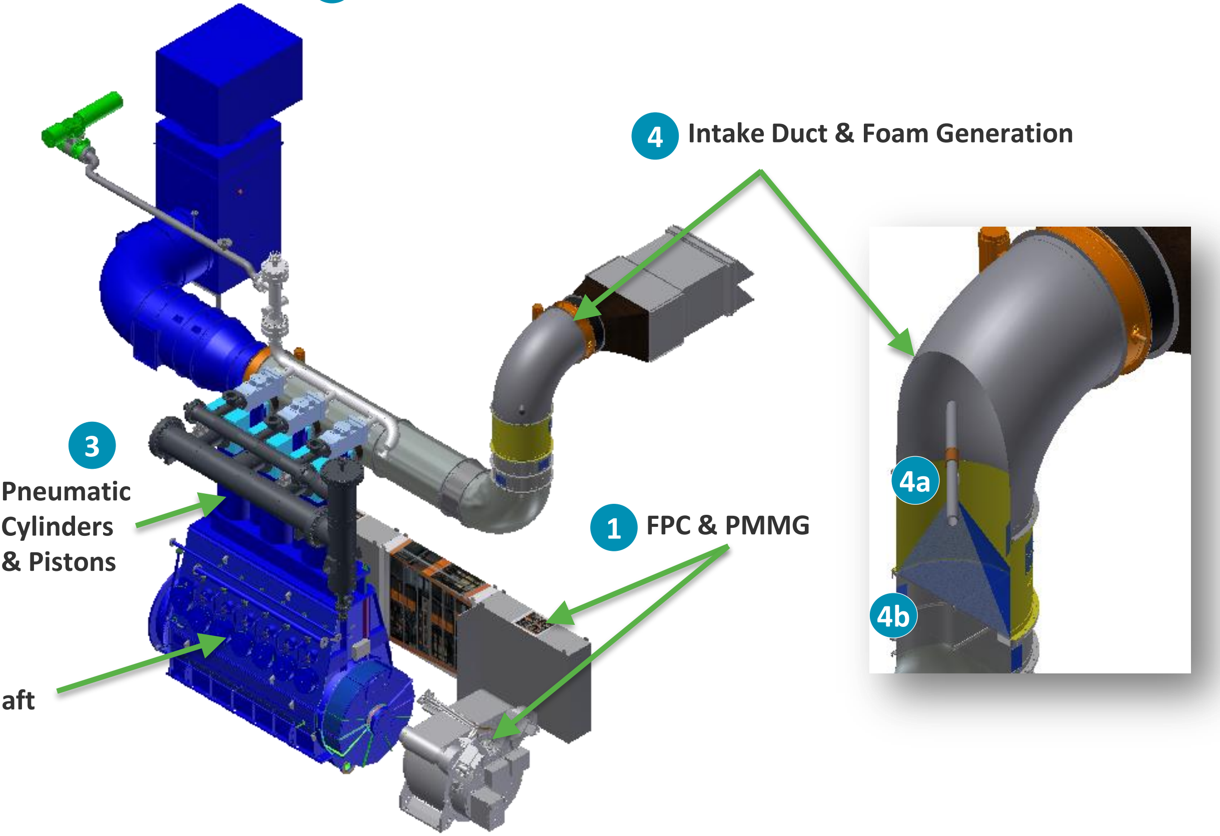
① Electricity from any source powers Permanent Magnet Motor/Generator (PMMG) via Full Power Converters (FPC)

② The PMMG motors a crankshaft via a direct mechanical coupling

③ The crankshaft in turn drives a series of reciprocating pneumatic pistons

④ Meanwhile, within the intake duct, ambient air is mixed with a measured mass of process water to generate a foam

- The foam is generated by spraying (4a) process water onto a screen (4b) where it mixes with ambient air
- Foam is then drawn into and fills the low pressure cylinders ③ for the first stage of compression



④ **Intake Duct & Foam Generation**

③ **Pneumatic Cylinders & Pistons**

① **FPC & PMMG**

② **Crankshaft**

How Does ICAES Work?

Air Compression Process (2 of 2)

① The foam passes through a series of hydraulically-actuated valves to enter the Low Pressure (LP) cylinders

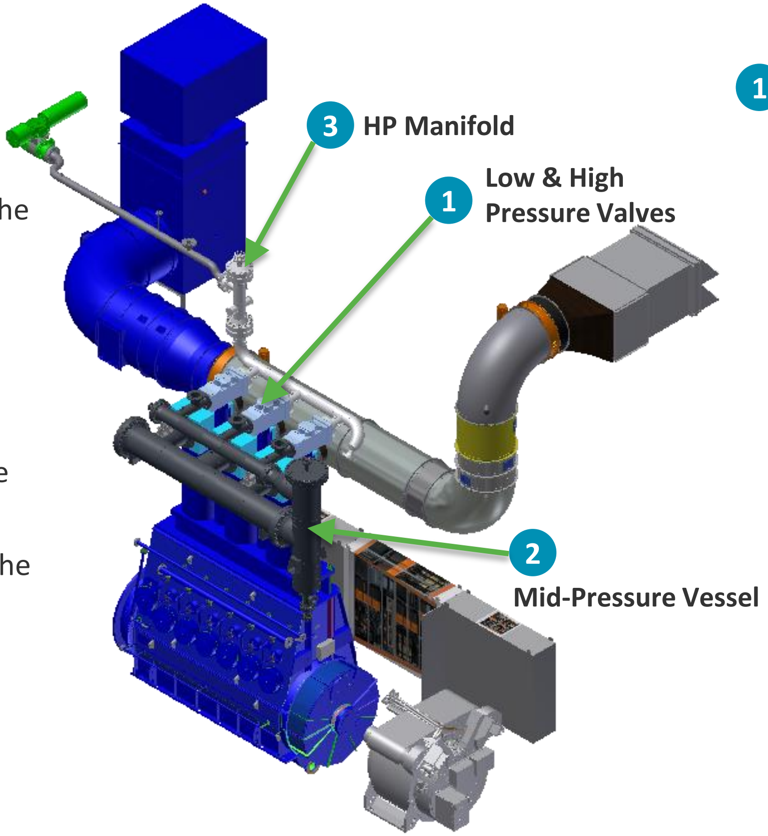
- As the air is compressed in the LP cylinders, the foam enables rapid heat transfer from the air to the water

② The partially compressed foam flows from the LP stage through a 2^{nd} set of valves into the Mid-Pressure Vessel (MPV)

- The MPV connects the three LP cylinders to the three High Pressure (HP) cylinders
- The foam (air and water) is then drawn into the HP stage where it is compressed until it reaches storage pressure

③ As with the LP cylinders, flows into and out of the HP cylinders are controlled by a set of valves

- Foam exiting the HP cylinders flows into the HP manifold
  - Within the HP manifold, the foam is separated into distinct water and air streams
  - The water is motored down to atmospheric pressure and stored in the thermal pond
  - The air, still at high pressure, flows to the high pressure storage volume



How Does ICAES Work?

Air Expansion Process

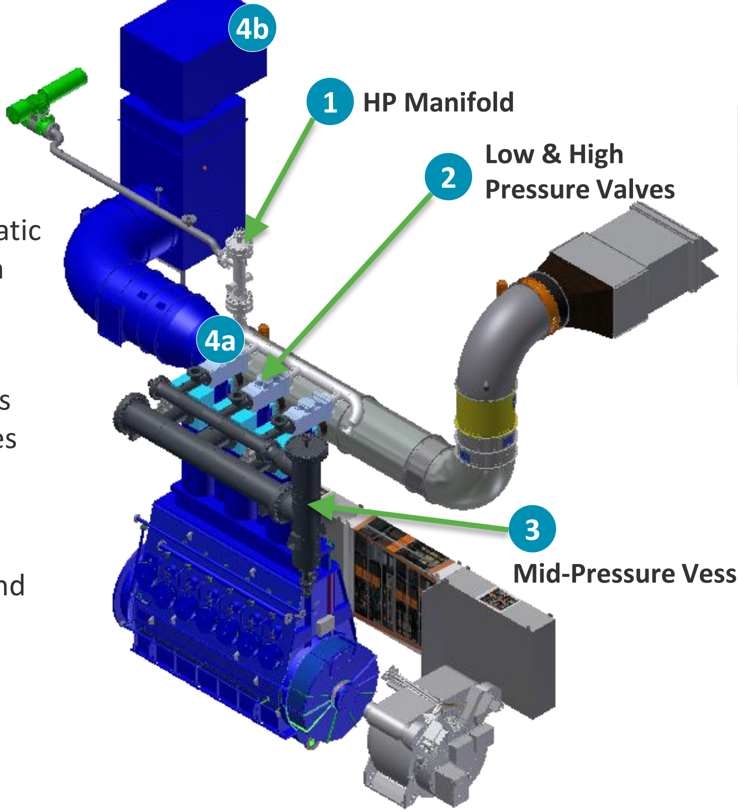
① Within the High-Pressure (HP) manifold, air from storage is mixed with process water to generate a foam

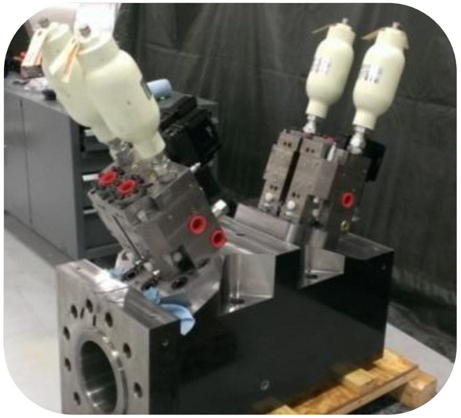
- The water is drawn from the thermal pond and pumped to high pressure before being mixed with the air

Once the foam enters the pneumatic cylinders, the expansion process is simply the reverse of the compression process

- The valves ② again control the flow of foam into and out of the cylinders.
- Air expanded in the HP cylinders passes through the mid-pressure vessel ③ and into the LP cylinders.
- As the air expands through both stages, the foam enables rapid heat transfer from the water to the air, preventing the air from drastically cooling.

- The expansion of the air within the pneumatic cylinders turns the crankshaft which in turn drives the PMMG, acting as a generator, to deliver electricity to the grid
- Meanwhile, the fully expanded foam passes through a foam breaker 4a which separates the air and water
  - Air flows out an exhaust duct 4b
  - The water flows back to the thermal pond



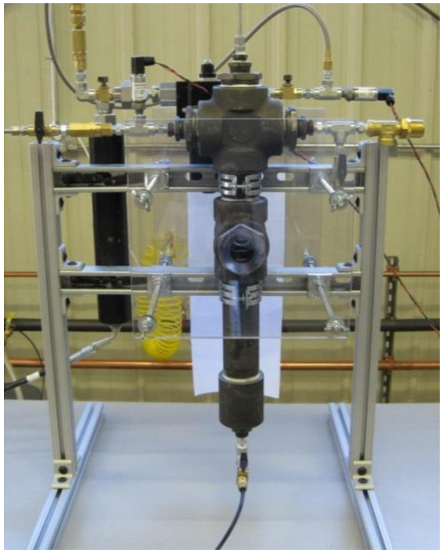


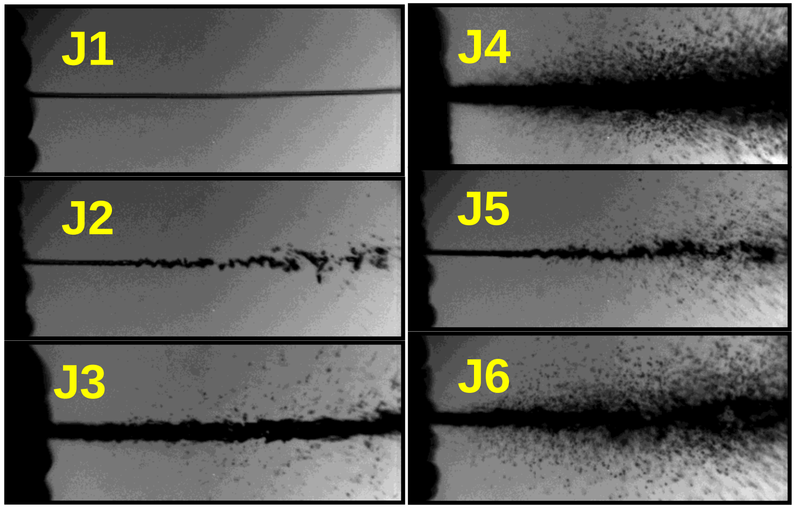
Supporting Technology Development

Spray-based Heat Transfer

SustainX's patented technology expedites heat transfer, allowing for greater thermal efficiency and power output

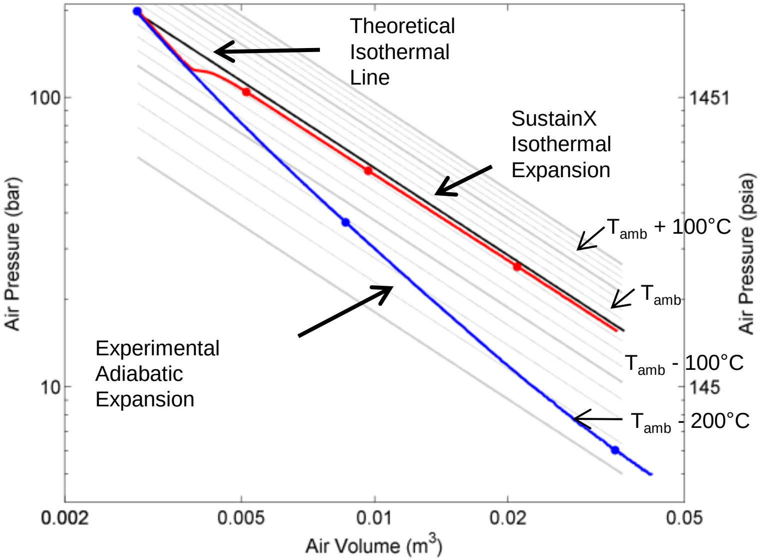
Optimized Spray Injection





SustainX has done extensive optimization of the spray injection which makes high power density and efficiency feasible

Scaled Heat Transfer (December 2009)



95% isothermal efficiency is compared with 54% efficiency of an experimental adiabatic expansion over the same pressure range.

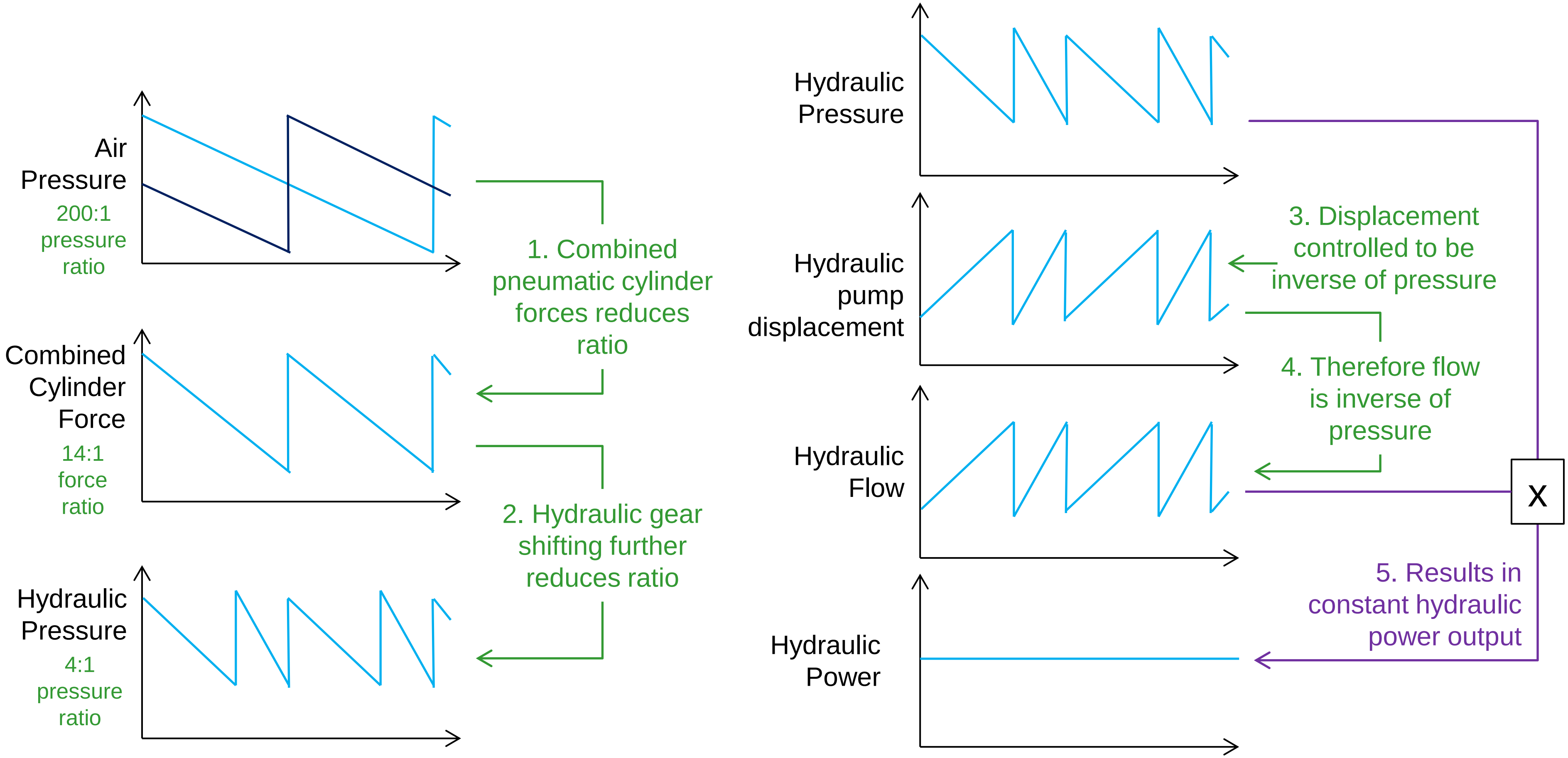
Supporting Technology Development

Staged Hydraulic Drivetrain

Staged Hydraulic Drivetrain

- Two air stages along with hydraulic gear shifting reduces the 200:1 air pressure ratio first to a 14:1 force ration and then to a 4:1 hydraulic pressure ratio experienced by the pump, increasing pump efficiency

- Variable displacement pump is used to shift displacement inversely with pressure, resulting in constant power output



1. Combined pneumatic cylinder forces reduces ratio

2. Hydraulic gear shifting further reduces ratio

3. Displacement controlled to be inverse of pressure

4. Therefore flow is inverse of pressure

5. Results in constant hydraulic power output

Supporting Technology Development

40 kW Pilot System

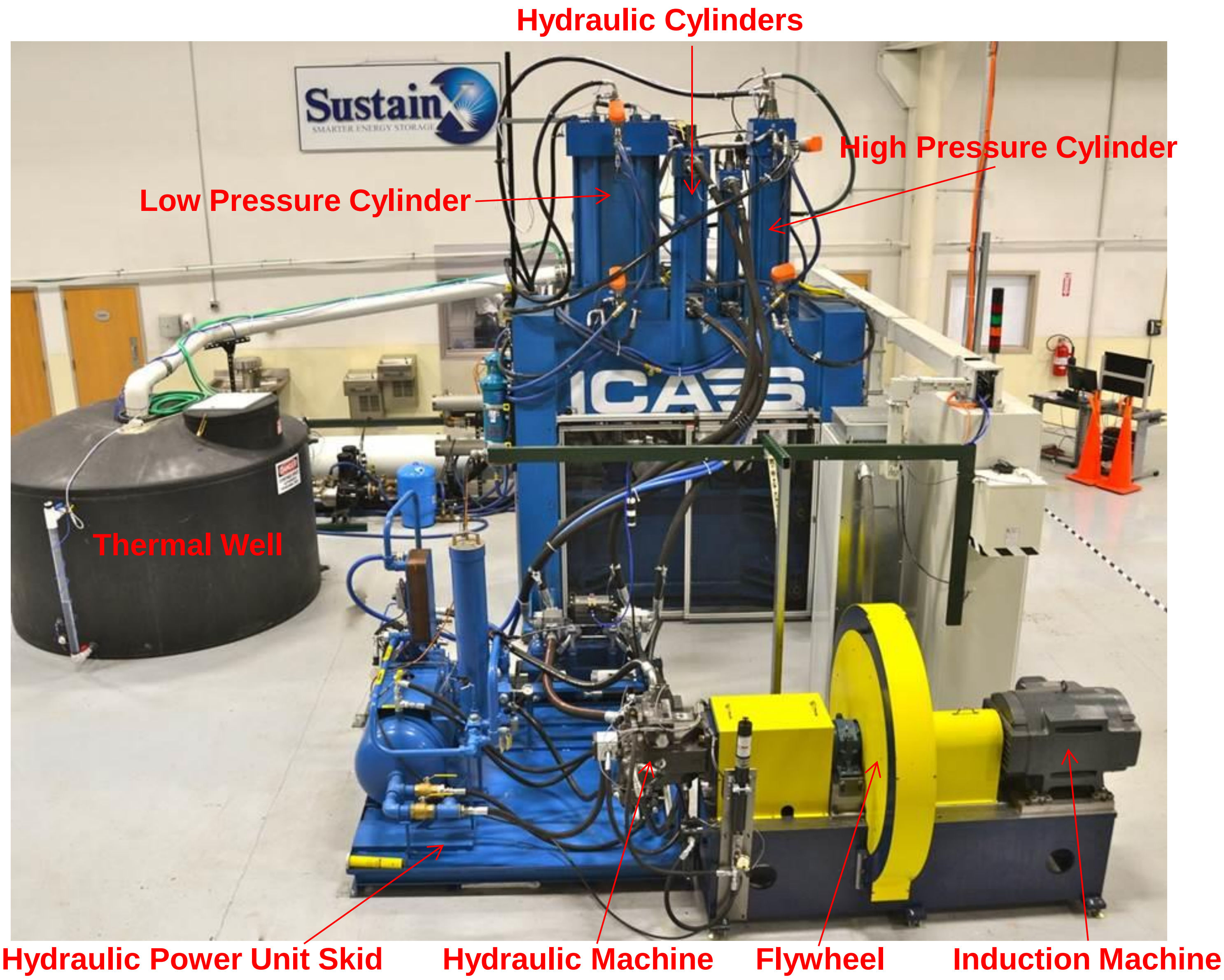
Pilot 40 kW ICAES system

Full Pilot System
(September 2010)

The goal of the Pilot system was to establish proof of concept and enable core IP not to maximum machine efficiency

- Continuous isothermal heat transfer process including thermal well
- Mechanical staging of pneumatic & hydraulic cylinders
- 14:1 pressure ratio per pneumatic stage, two stages
- 3 second stroke per stage
- Closed-loop water pump and spray heat transfer per compression/expansion chamber
- The Pilot platform IP translates to Demo design concepts
  - Allows an efficiency and cost reduction roadmap to be implemented

Pilot 40 kW ICAES system



Pilot System Learning – Hydraulic

- **Hydraulic Machine:** The majority of initially hydraulic system losses were due to "cylinder to tank shock pressure drop," which is caused by air dead volume in the system. Conversion to a closed loop pump eliminates end of stroke shock and allows for recovery of the energy used to compress the air dead volume. This also eliminated controllability issues on expansion.

- **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 to reduce pressure ratio at the pump does improve pump efficiency, but only for smaller pressure ratios (i.e. also using hydraulic valving). For larger pressure ratios, 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.

Pilot System Learning – Pneumatic

- **Single-acting vs. double-acting pneumatic cylinders:** Double acting cylinders with ports only at the cylinder heads do not appreciably decrease the cost compared to two single acting cylinders due to increased complexity. Furthermore, the lower chamber of a double acting cylinder introduces dead volume issues that cannot be resolved due to the inability to add standing water on top of the water drain.

- **Water management:** 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 and collapse in efficiency and ability to compress to desired pressure. Management results in 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 LPC water management from the HPC water management

Pilot System Learning – Pneumatic, cont.

- **Water circulation drain submergence:** For closed loop heat transfer systems with a drain and supply to each cylinder compression/expansion chamber, the submergence of the water drain (distance below the free water-air surface) is critical. Insufficient submergence leads to air bubbles being drawn into the water circulation loop, drastically increasing air dead volume, which increases losses and prevents the system from reaching full pressure.

- **Stroke time:** The original stroke time of 3s resulted in some amount of air bubbles being pulled into the water circulation loop and increased air dead volume. Attempts increase the system speed to 1s strokes (to increase power and reduce cost) resulted in collapse of the water circulation heat transfer and operability of the system.

- **Internal obstructions:** Nozzles or other protrusions from the top of cylinder into 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 the valve port, exacerbating air dead volume and water management concerns

Supporting Technology Development

Foam-based Heat Transfer

Isothermal Heat Transfer Approach

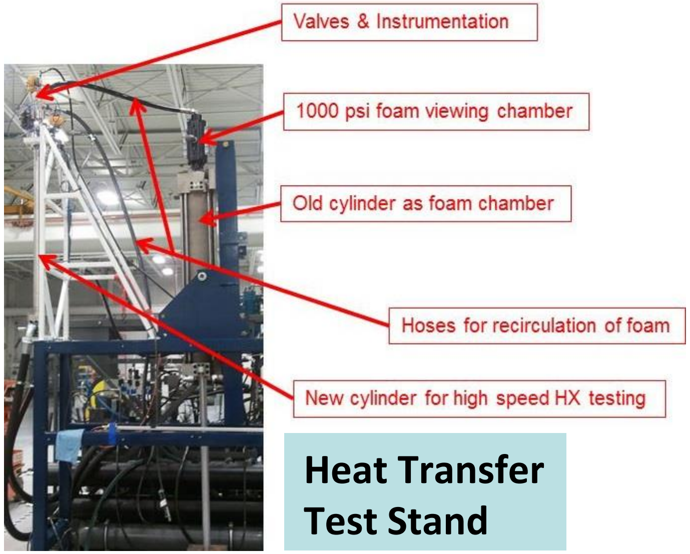
- The 2nd generation heat transfer technology distributes the water with the air as a fine-textured, homogeneous foam matrix

- Foam provides greater surface area between the air and water than droplets, and because the foam is semi-solid, exposure of the air to the entire mass of water is maintained throughout the compression stroke, resulting in high thermal efficiency.

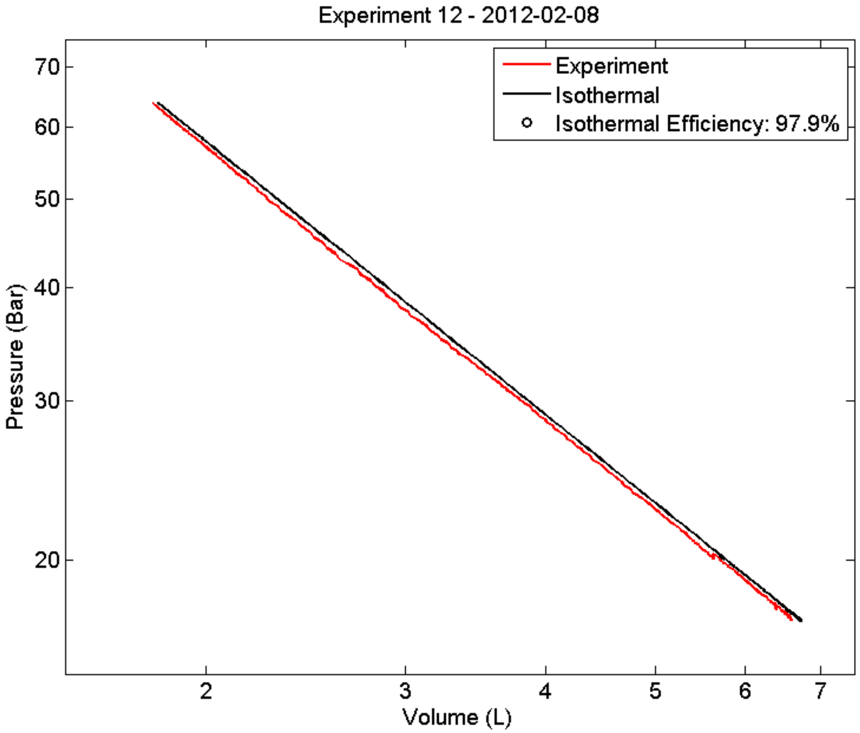
Foam enables mid-speed ICAES

- Improved heat transfer experiments in 2012 demonstrated that foam could achieve comparable thermal efficiencies at a 12x increase in speed

This experimental plot demonstrates >95% isothermal efficiency using foam at speeds equivalent to 120 RPM.

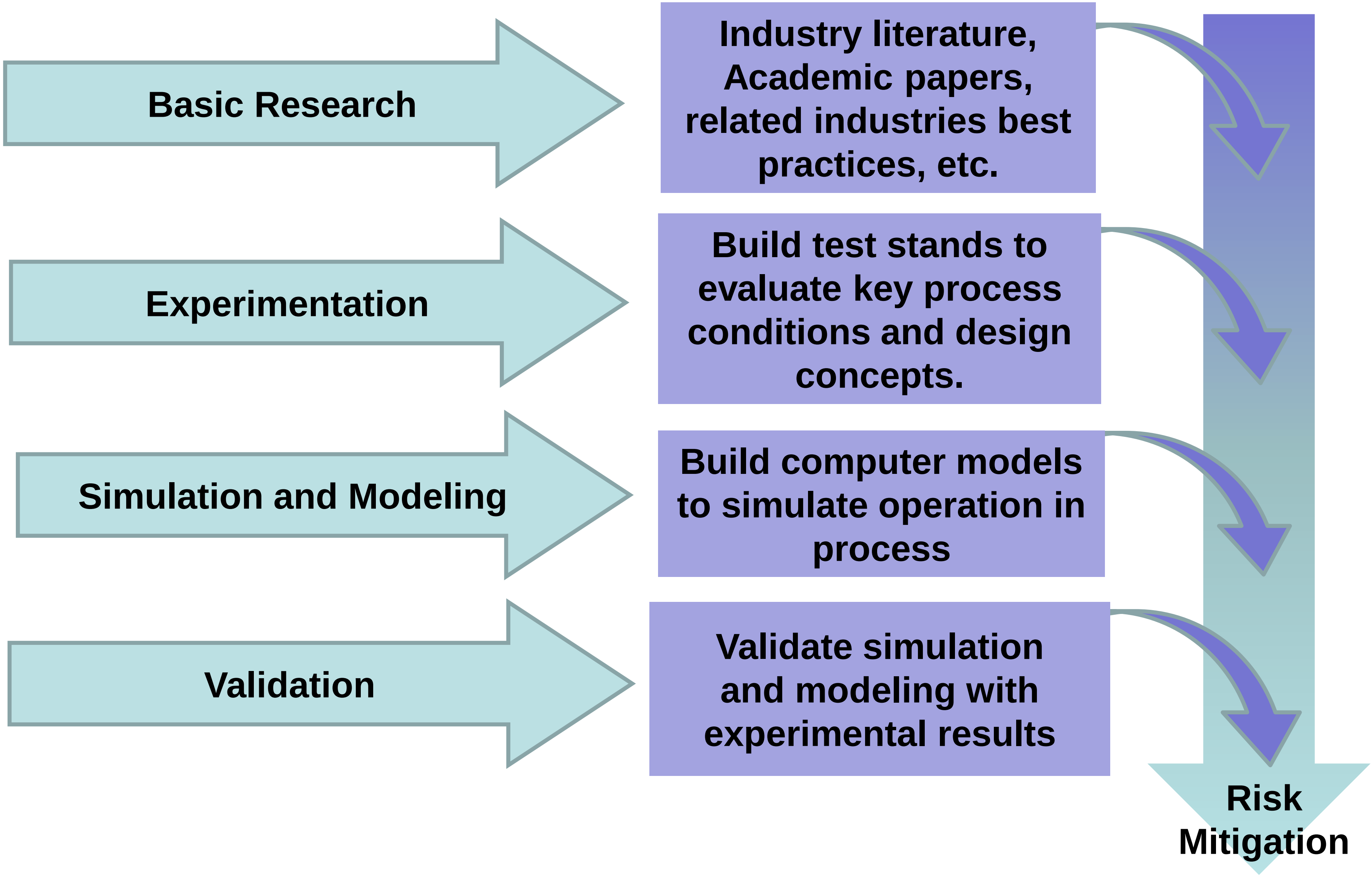


Heat Transfer Test Stand



- The increased speed allowed by the foam heat transfer enables the use of a mid-speed crankshaft platform, increasing power density and decreasing cost

Development Approach



Basic Research

Industry literature, Academic papers, related industries best practices, etc.

Experimentation

Build test stands to evaluate key process conditions and design concepts.

Simulation and Modeling

Build computer models to simulate operation in process

Validation

Validate simulation and modeling with experimental results

Risk Mitigation

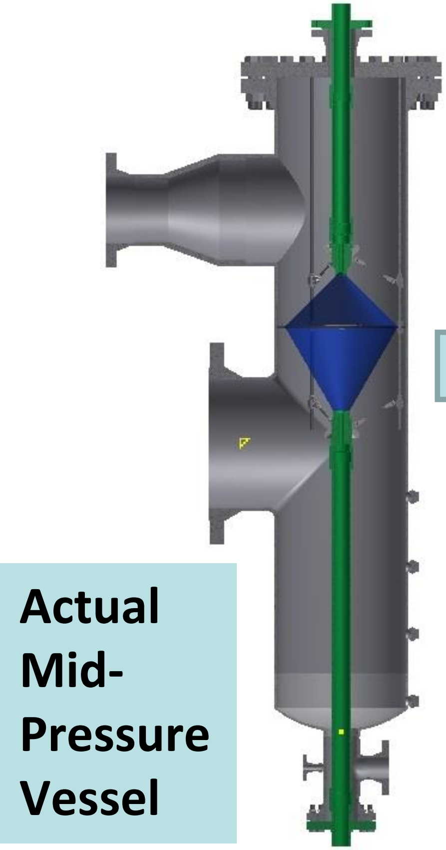
Bench Top Foam Testing

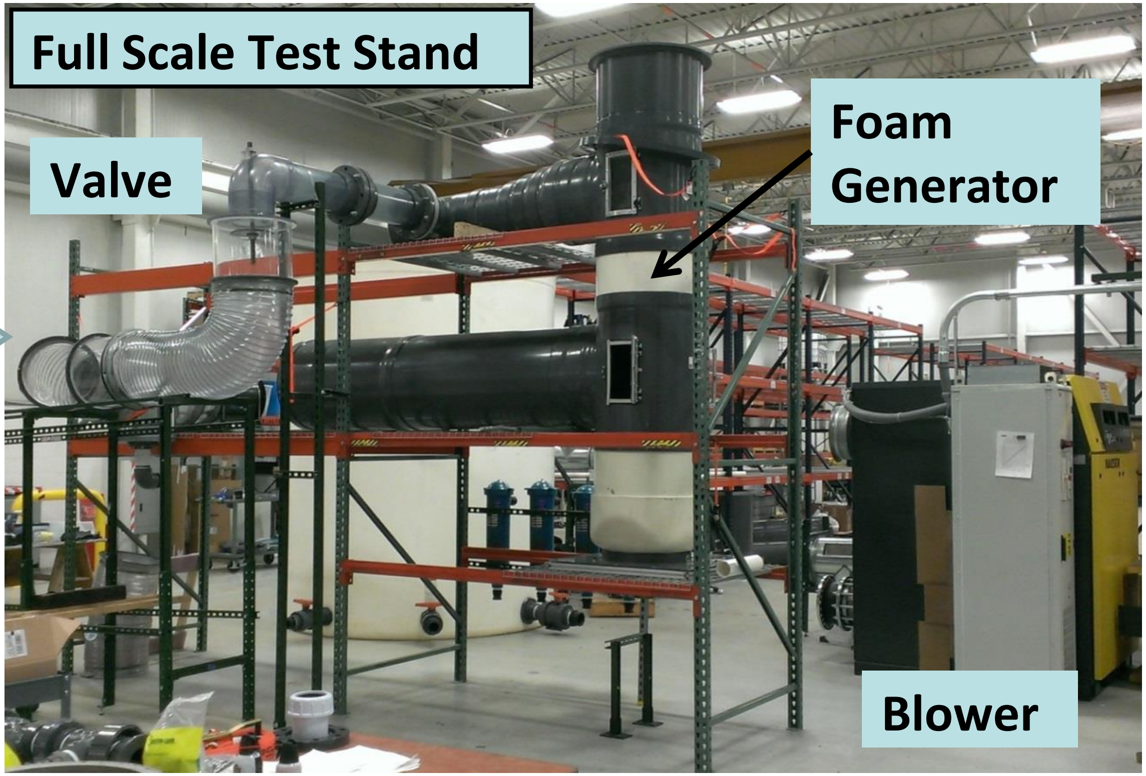
- Used to determine best approach for foam generation at small scale
- Small low-pressure parts allow for quick changes and many iteration cycles
- Techniques evaluated:
  - Screens and stacked screen assemblies
  - Metal & Polymer foams (with and without added screens)
  - Packed bed (various size spheres packed in tube)
  - Flow focusing
  - Different nozzle(s) and configurations
  - Horizontal and vertical orientation
  - Air setup as co-flow and counter-flow to spray
- Primary Path is a stacked screen assembly with vertical, co-flow air direction.
- Results in a simple, yet reliable generator over a wide range of process conditions

Full-Scale, Mid-Pressure Testing

Mid-Pressure *(Race Track Gen 2)* Test Stand

- Full scale, low-pressure, mockup of mid pressure vessel
- 3D shape and dimensions are full scale. Air flow rate at process scale.
- Replica of actual foam generation cartridge





Supporting Technology Development

Crankshaft-based Drivetrain

Power Density, Capital Cost, and Efficiency

- Selection of a medium-speed crankshaft platform for the commercial system allows for reduced capital cost through increased power density without reductions in efficiency

Slow Speed

10 RPM

- Low speed requires hydraulic drivetrain, resulting in higher drivetrain losses
- Low speed results in lower power density for the same quantity of steel, driving up cost

Medium Speed

120 RPM

- Efficiency and CAPEX risk addressed with new mid-speed (foam) heat transfer approach and reduction of flow losses through proprietary valves

High Speed

1,200 RPM

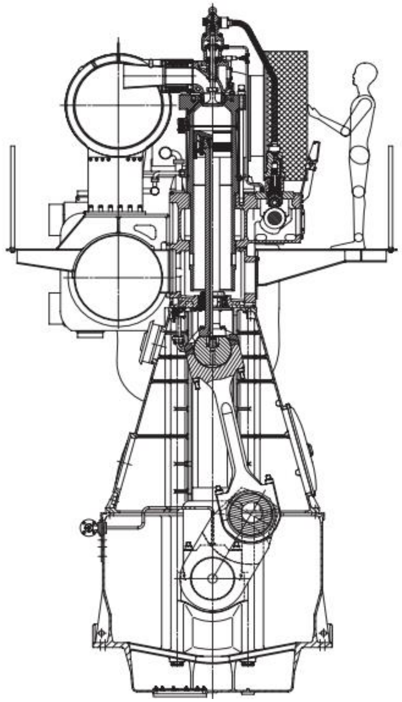
- Mass of water required for isothermal compression results in extremely high flow losses at high speed
- Large clearance volumes not appropriate for isothermal cycling

Crankshaft selection for ICAES

- SustainX evaluated existing crankshaft technologies for use as the base for the ICAES system

Marine Diesel Engine	Large Recip. Compressor
Crosshead style crankshaft	Crosshead style crankshaft
Hydrodynamic bearings	Hydrodynamic bearings
Large cylinder bore	Large cylinder bore
Long stroke	Short stroke
High compression ratio	Low to moderate compression ratio
Vertical cylinder orientation	Horizontal cylinder orientation
100 – 160 rpm	800 – 1800 rpm
Optimized for lower speed direct-drive ship propulsion	Optimized for higher speed adiabatic air compression

- SustainX has selected the lower half (crankshaft portion only) of a marine diesel engine to couple the electric motor/generators to the pneumatic compression/expansion cylinders
  - Long stroke, low speed, and high compression ratio closely matched the SustainX isothermal air compression and expansion cylinders
  - Vertical orientation is advantageous for heat transfer & valve design
  - Speeds exceeding ~150 rpm prove difficult for efficient heat transfer



MAN B&W S35MC cross section

http://www.mandiesel.com/files/news/filesof8009/5510-0025-00ppr.pdf

MAN crankshaft bearing analysis

MAN crosshead and crankpin FEA models

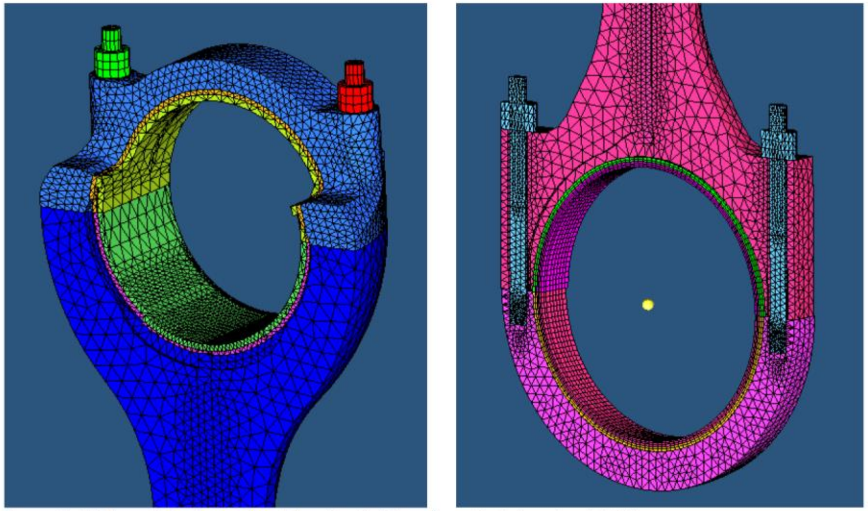


Figure 1: FEM-models of crosshead bearing (left) and crank pin bearing (right).

Piston force profiles supplied by SustainX

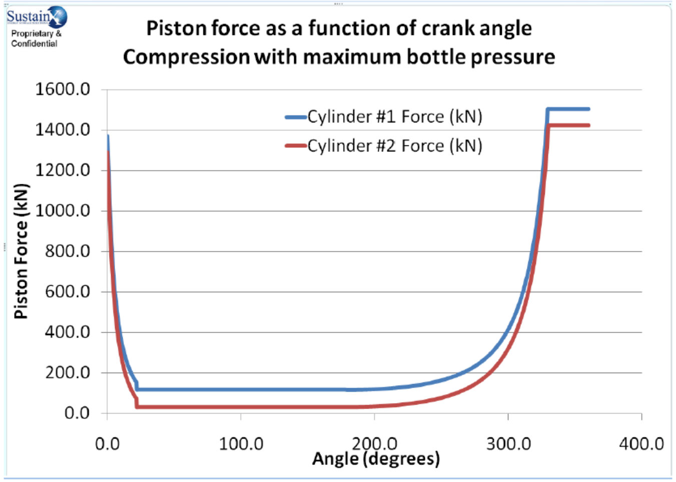
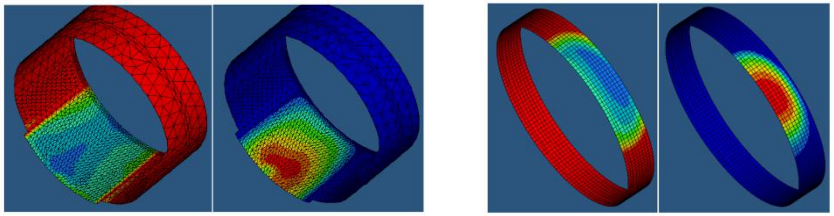
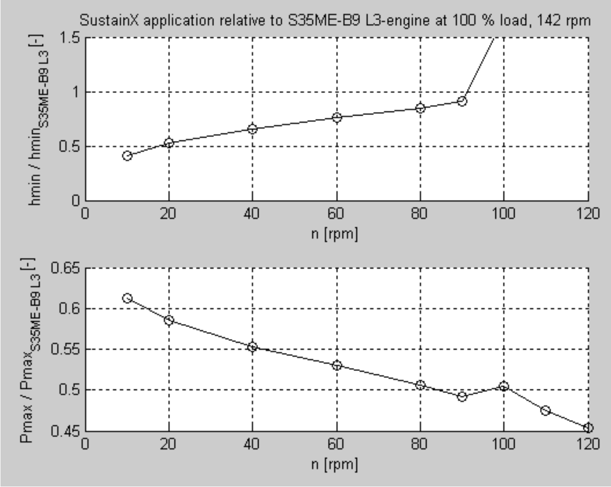


Figure 2: Cylinder forces used in calculations.

Oil film thickness and pressures checked vs speed

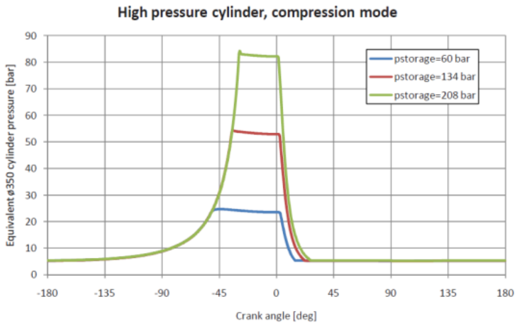


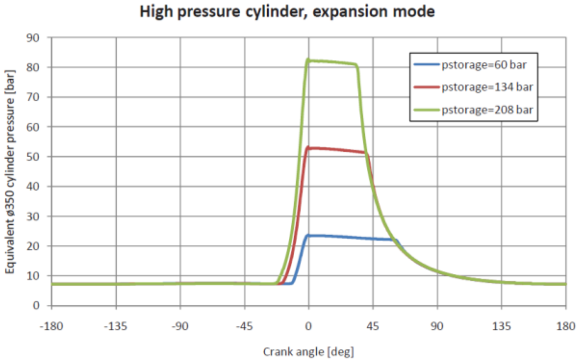
90 rpm: "roughly the same as in a standard engine"

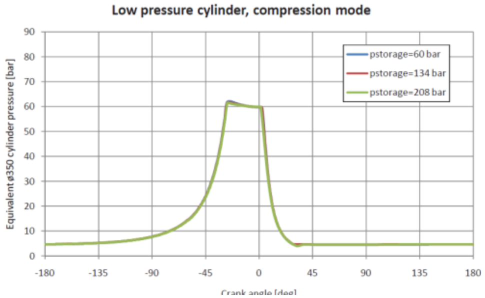


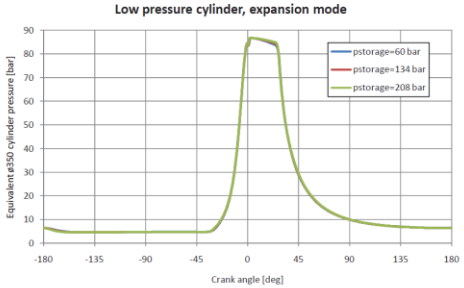
MAN driveline dynamic analysis

Cylinder pressure profiles supplied by SustainX

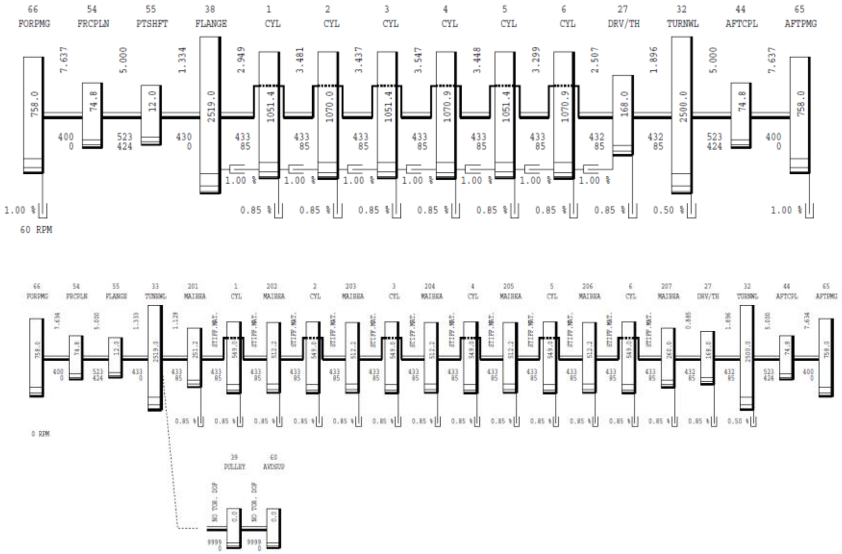




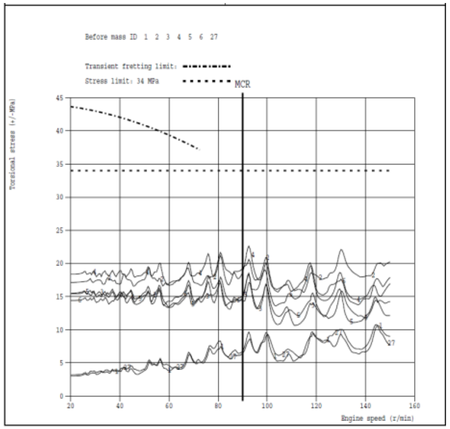


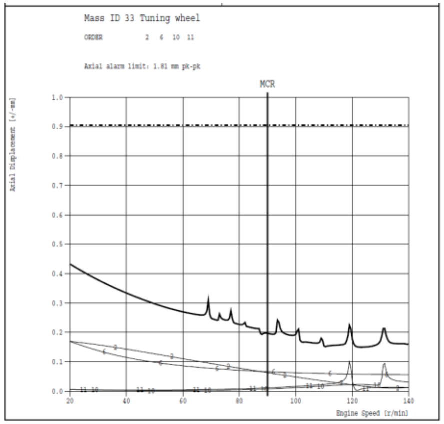


Torsional and tor-axial models developed by MAN



Typical torsional and axial response spectra and limits





PMMG & FPC

- Commercially proven Permanent Magnet Motor/Generators
  - Developed for high efficiency, low-speed wind turbine applications
  - Direct drive eliminates need for gearbox, avoids torsional resonance issues
  - Minor revisions for foot mounting vs flange and shaft coupling
  - Factory tested prior to delivery

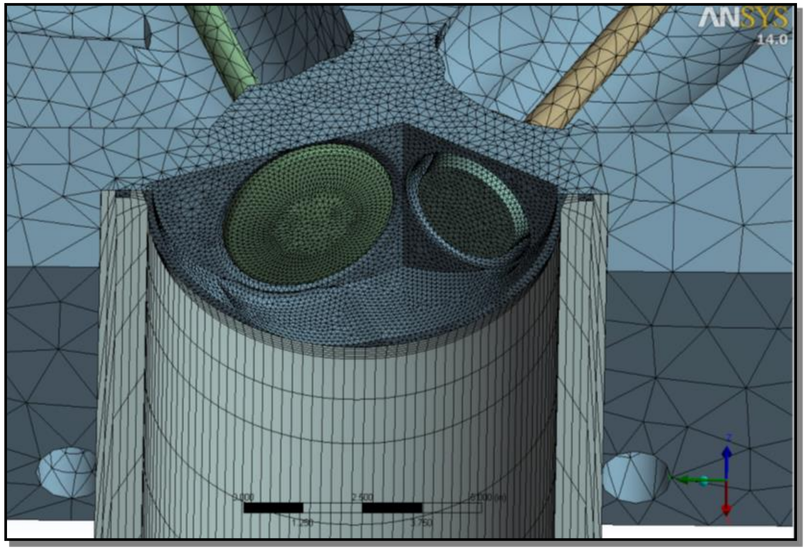
SustainX units undergoing back-to-back test

Supporting Technology Development

High Performance Valves

Why are valves so important to ICAES?

- Just like in an automotive engine, valves must precisely control the air intake and exhaust timing
- Unlike a typical car engine valve, the SustainX valve-train must allow complete variable valve timing
- Variable valve timing is critical because of the bi-directional machine operation *(compression & expansion)*, range of process RPMs and operating pressures.
- Valves are a major contributor to the overall machine efficiency and system capacity



Valve Development

- The move to 120rpm required significant improvement to valve and cylinder head design in order to meet efficiency targets.

Challenge → **Result**

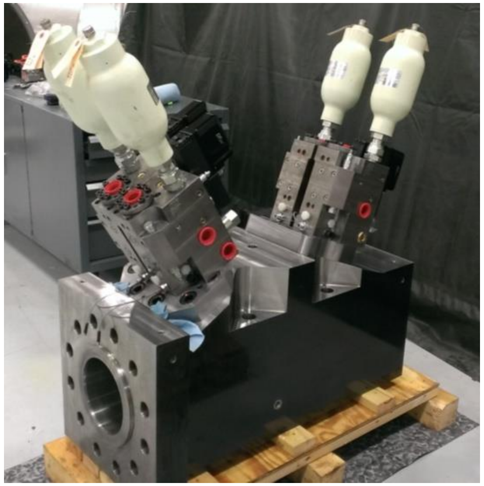
Challenge

- Design (4) fully active control valves for bi-directional compressor/expander flow
- Highly efficient (low flow losses and low actuation energy consumption)
- Efficient packaging into custom cylinder heads to maximize flow area and minimize dead volume
- Ability to operate with mixed flow (air + water) at pressures up 3000 psi
- Fast operation (5-10 ms) operation with built in passive cushioning
- Variable valve timing up to 120 RPM
- Protection from cylinder over pressure with passive failsafe design

Result

- (4) Engine Style Poppet valves (75-200mm in Size), 2 cylinder heads, validated with CFD analysis
- Custom designed Electro-hydraulic valve actuator, validated with simulation and physical prototype testing

LP Head Assy

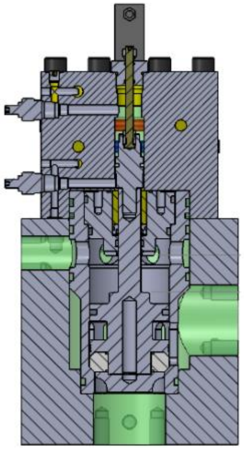


HP Head Assy

Valve Development Path

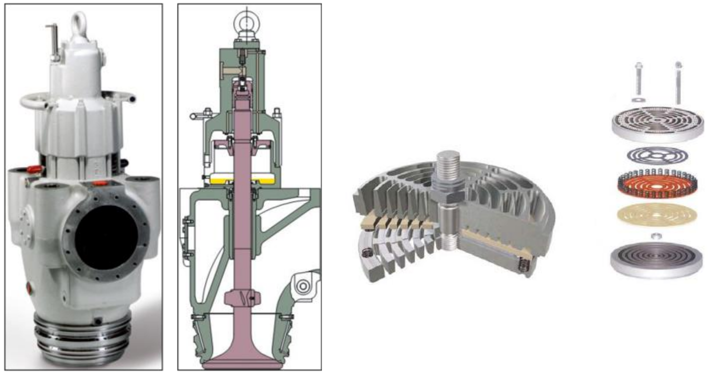
SustainX
SMARTER ENERGY STORAGE

- Determination of key design/process requirements
- Exhaustive industry review of valves *(Compressor, Engine, Hydraulic/Pneumatic & Process)* and determined:
  - Requirements are unique – did **not** exist in market
  - Critical to success of overall machine operation



- Development path selection

  (internal, outsource or collaboration?)
  - develop valves internally due to critical importance, core competency, required schedule and in-house expertise



- Overall design and fundamentals validated by respected industry leaders:

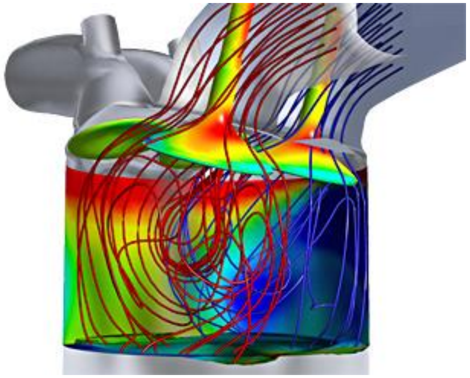
RICARDO

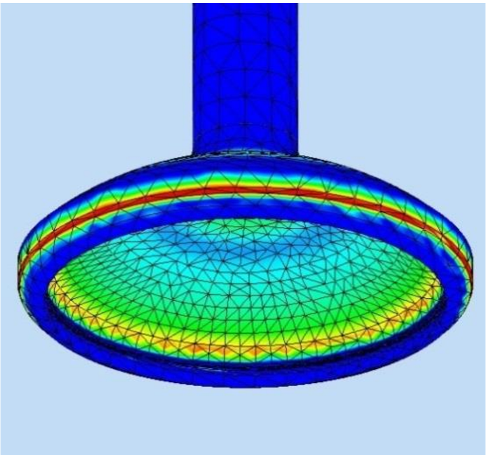
SOUTHWEST RESEARCH INSTITUTE®

… AND consultants who designed an isothermal air compressor (ISO-Engine)

Valve Team and Expertise

- Team consists of up to 12 engineers/PHDs operating over 16 months
- Estimated >10,000 hours of engineering design
- SustainX in-house expertise in:
  - Hydraulic system and component design
  - CFD (Computational Fluid Dynamics)
  - Simscape (Simulation modeling)
  - CAD and FEA (Finite Element Analysis)
  - Engine valves, injectors and hydraulic actuators
  - Industrial gas compressor design
  - Pressure vessel design



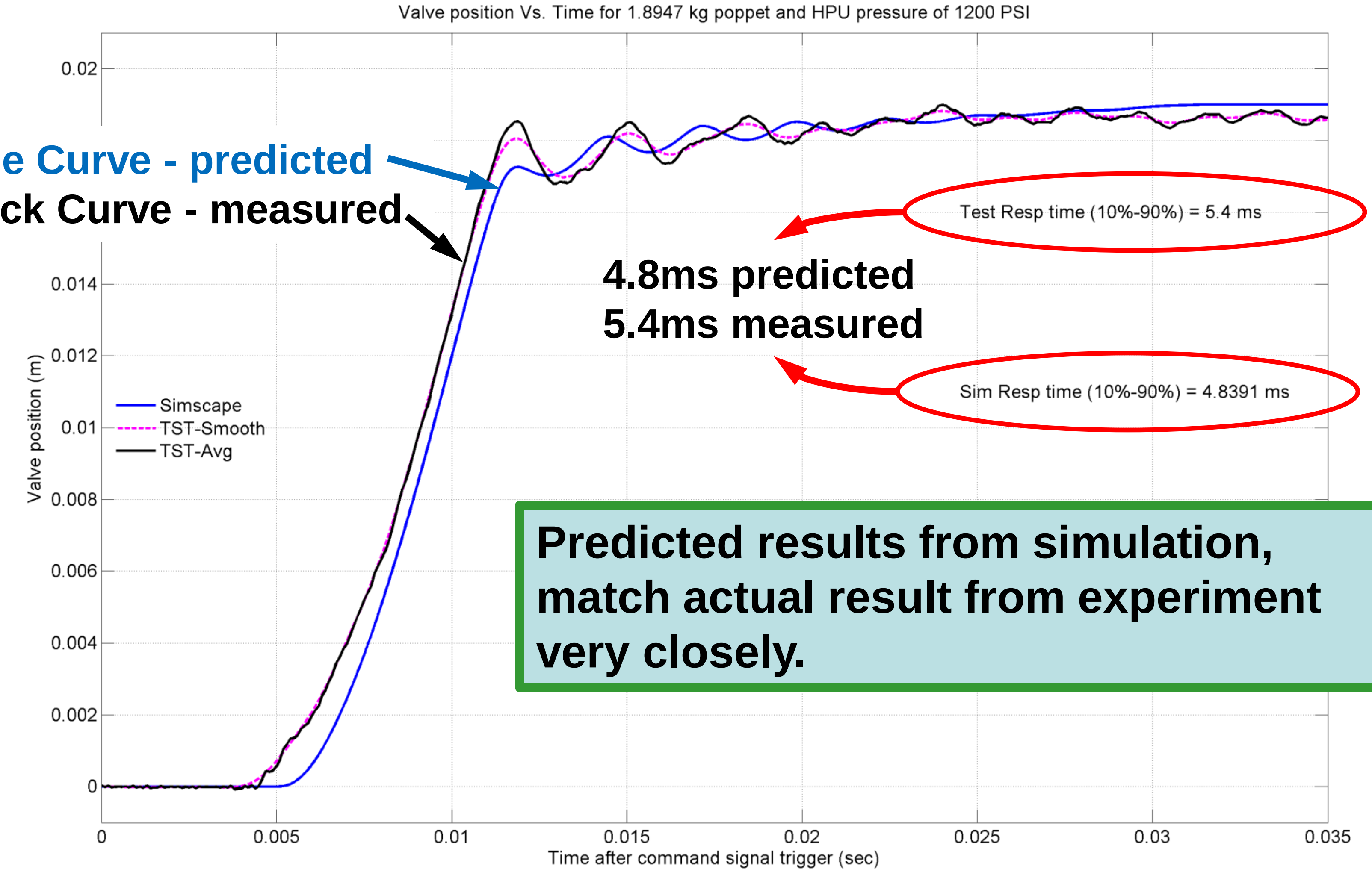


MathWorks

Autodesk Inventor

ANSYS

Simulation vs. Experimental



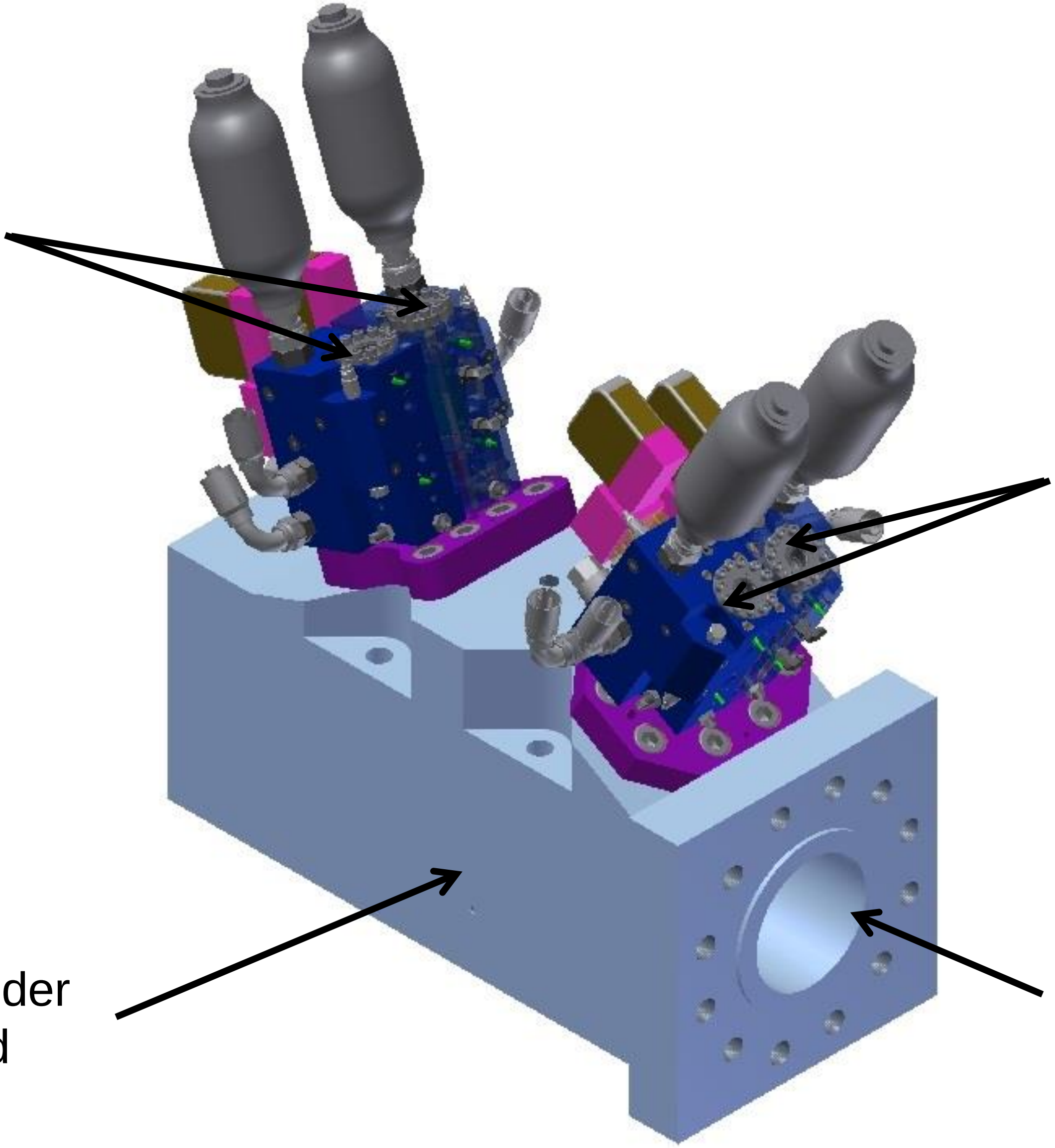
Blue Curve - predicted

Black Curve - measured

4.8ms predicted
5.4ms measured

Predicted results from simulation, match actual result from experiment very closely.

High Pressure Valve Assembly



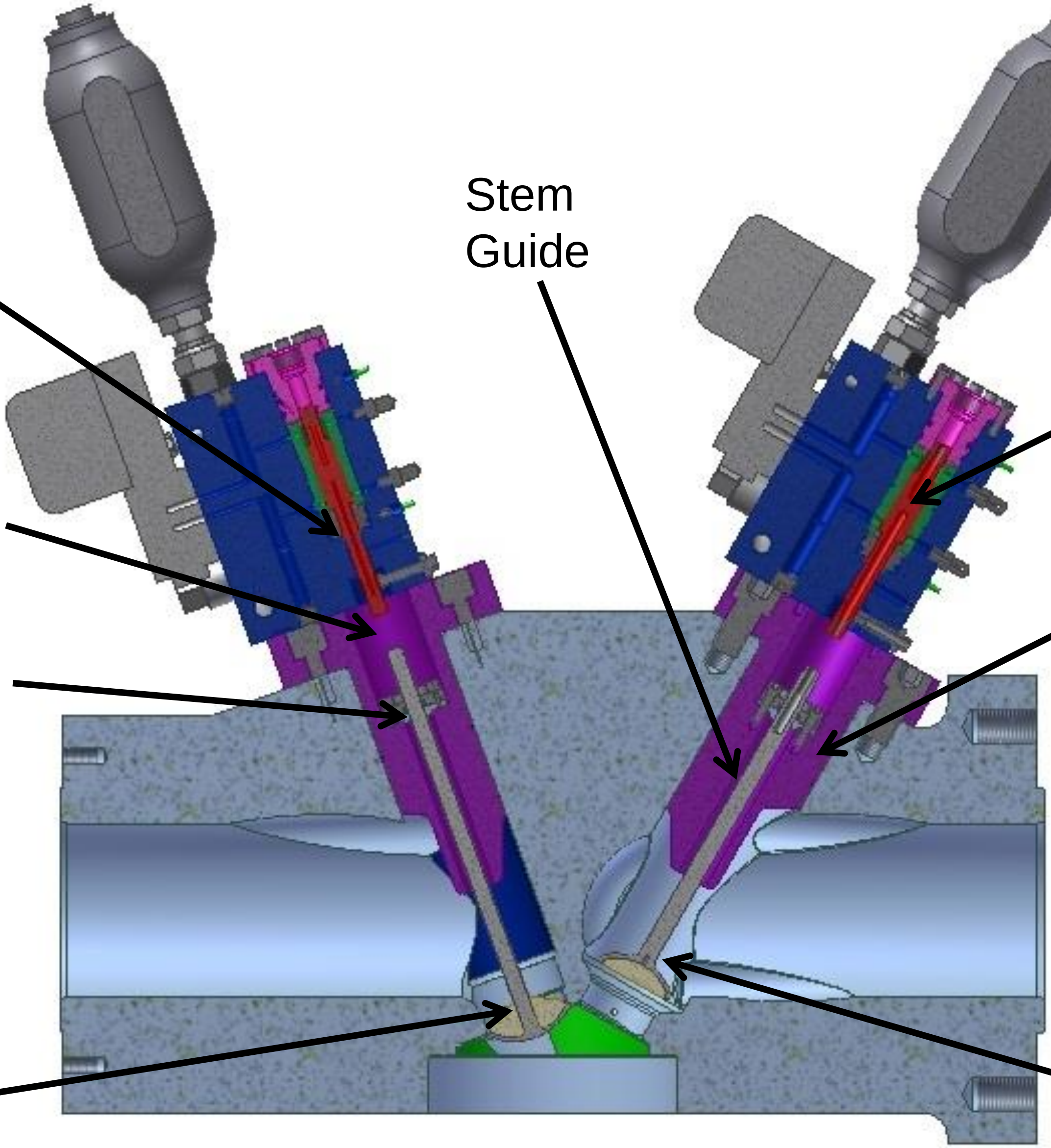
V2 Electro-Hydraulic valve actuator assemblies

V1 Electro-Hydraulic valve actuator assemblies

Cylinder Head

Discharge Port to high pressure storage

High Pressure Valve Head – Cross Section



Oil Side Seal Cartridge

Stem Guide

Actuator Piston

Vent Chamber

Stem Guide Block

Pneumatic Side Seal Cartridge

Poppet

Poppet

Valve Actuator Operation

- All valve poppets are controlled via individual valve actuators
- Actuator consists of a two-stage hydraulic control piston
- Command signal to servo valve initiates valve actuation
- High response of servo valve yields very fast poppet opening or closing, but…
- High impact velocity would damage the poppet, therefore a passive hydraulic “cushion” acts to slow the poppet before impact.
- Actuator must also allow passive operation of main poppet in the event of failure of the actuator or controls. In this case, valve poppet can “check” open to prevent machine damage or unsafe over-pressure condition.

1.5 MW Commercial Prototype

Data Acquisition and Controls

Control Systems Architecture

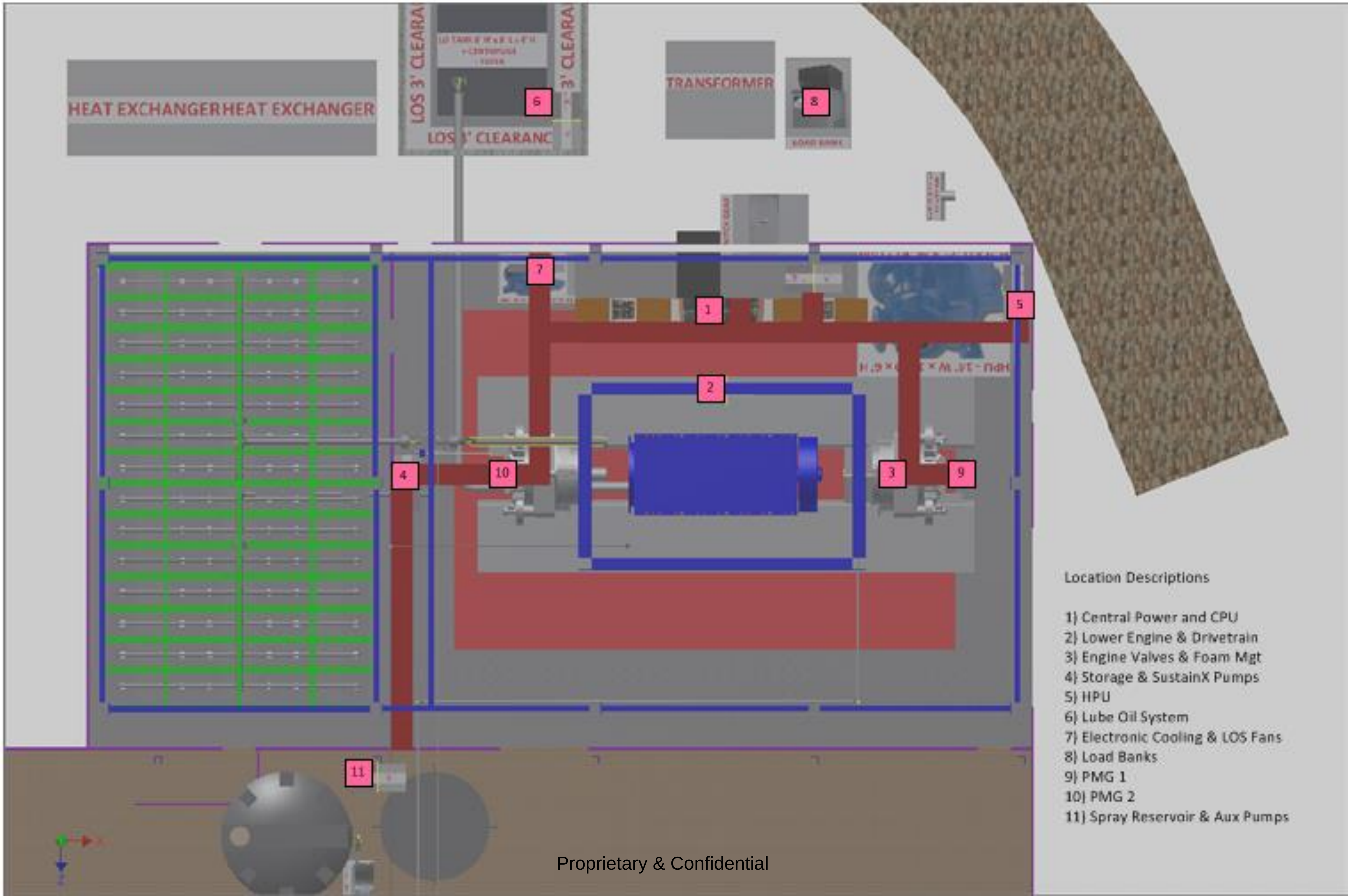
- Distributed data acquisition
  - Cabinets placed local to sub-systems provide I/O

- Distributed control
  - Where necessary, cabinets provide local control authority
    - E.g. valve control – CAB#3

- Star formation and fiber optic interconnectivity increases noise immunity
  - Ground loop circulation ~eliminated

- Modular design and configuration supports multiple-source purchasing moving forward

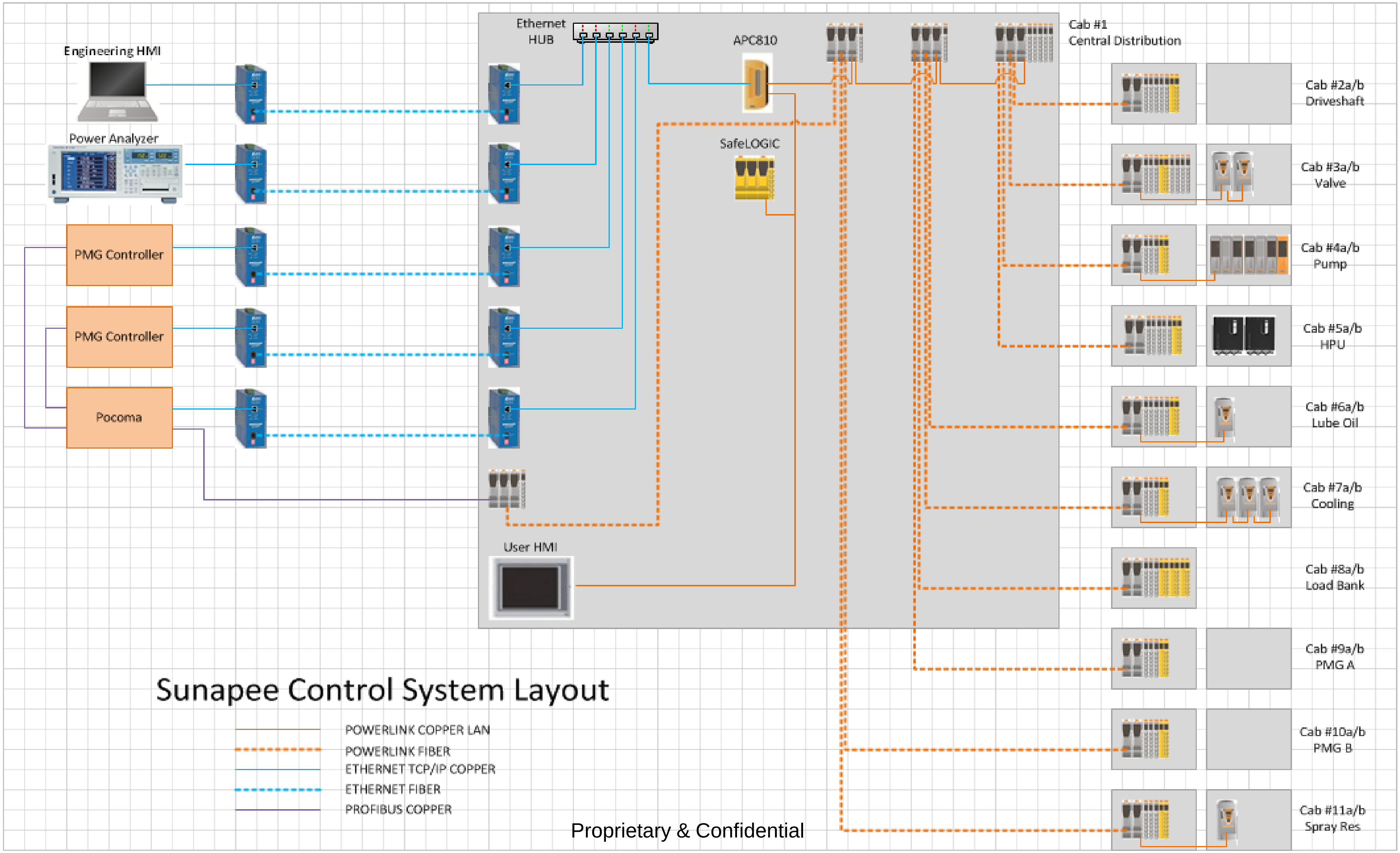
Control Systems Architecture



Location Descriptions

1) Central Power and CPU
2) Lower Engine & Drivetrain
3) Engine Valves & Foam Mgt
4) Storage & SustainX Pumps
5) HPU
6) Lube Oil System
7) Electronic Cooling & LOS Fans
8) Load Banks
9) PMG 1
10) PMG 2
11) Spray Reservoir & Aux Pumps

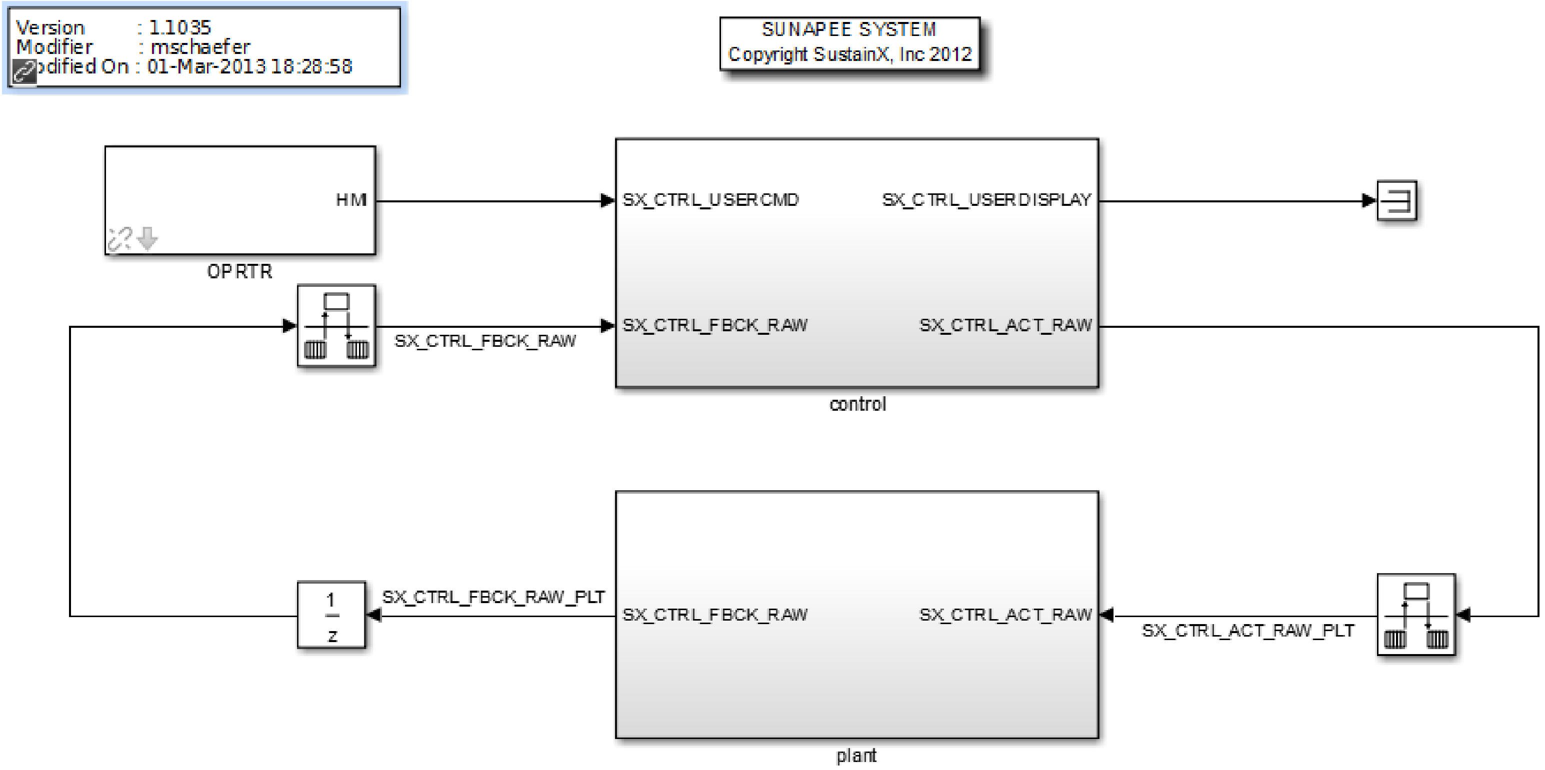
Control Systems Architecture



Sunapee Control System Layout

Model Based Design

- Graphical representation of:
  - Control strategy, complex non-linear dynamics
- Common "language" for multiple disciplines
  - Mechanical / Fluid Power / Electrical / Controls / Software
- Traceable to system piping and instrumentation diagram's (P&ID's)

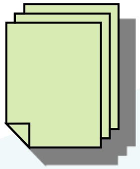


Version : 1.1035
Modifier : mschaefer
odified On : 01-Mar-2013 18:28:58

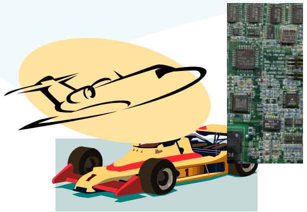
SUNAPEE SYSTEM
Copyright SustainX, Inc 2012

Advantages of Model-Based Design

Requirements and Specs

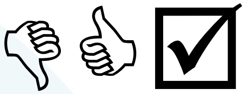


Design



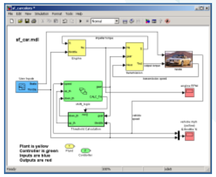
Implementation

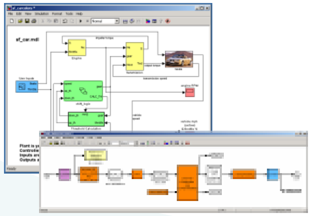
Test and Verification

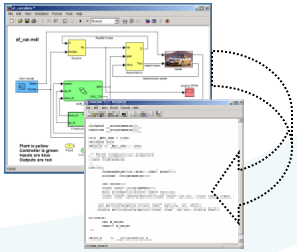


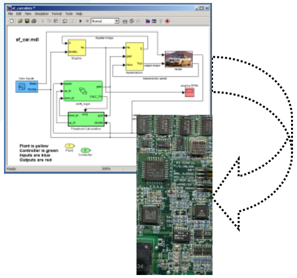
Model elaboration

Continuous verification









Executable models
-unambiguous
-only "one truth"

Simulation
-reduces "real" prototypes
-systematic "what-if" analysis

Automatic code generation
-minimizes coding errors

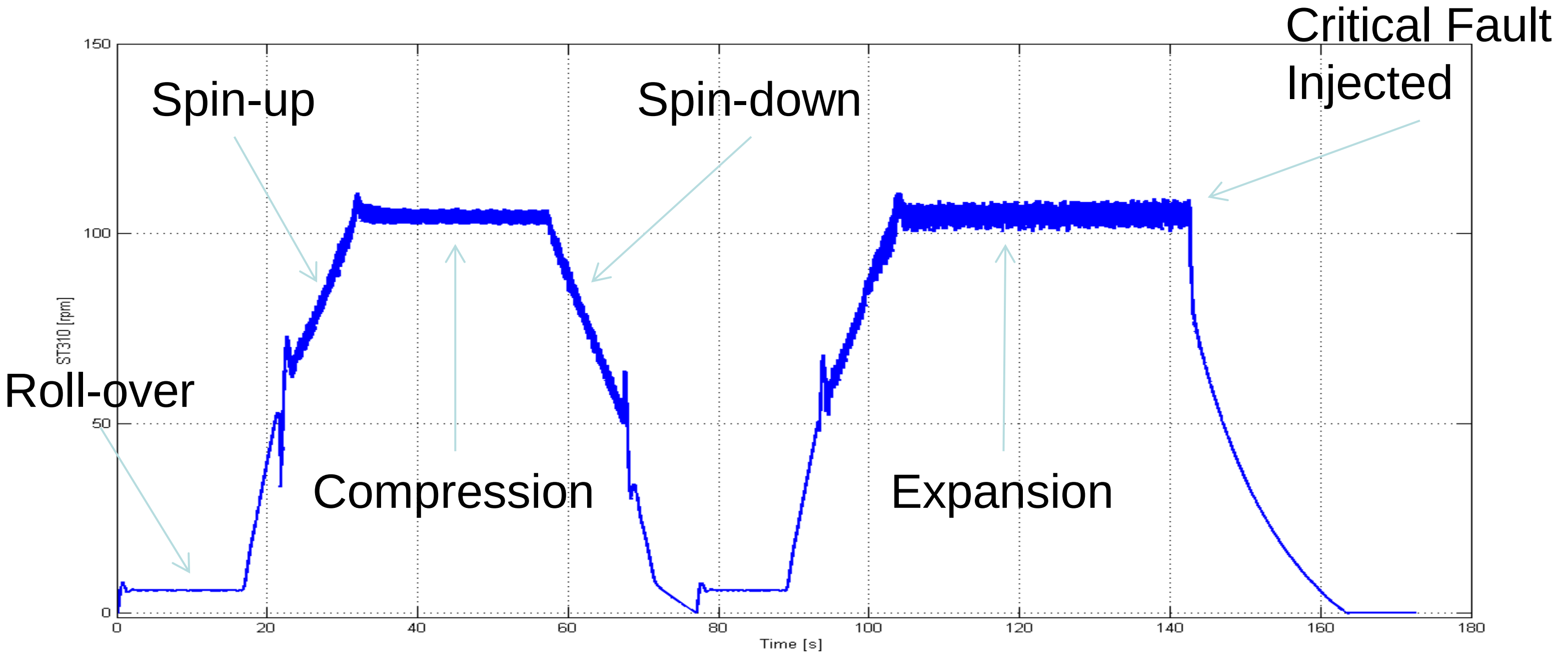
Test with Design
- detects errors earlier

Model Based Design

- Use elements and fundamentals of machine design cycle
  - FMEA output drives diagnostic algorithms
  - P&ID defines interface to/from algorithms
- Automate repeatable tasks
  - P&ID → model interfaces
    - Scripts developed internally ensure / automate cohesion between P&ID and models
  - Code automatically generated from models
    - COTS tool chain w/proven track record
      - Aero / Defense → Boeing / GEAE
      - Auto → Toyota / Ford / GM
      - Marine → ZF
      - etc…
  - Regression testing
    - Ever-growing set of regression tests applied to system
- Maintain independent processes as necessary
  - Per DOD-178A/B development processes
    - "no steps in a verification / validation process can be skipped when auto-code tools are used"
  - e.g. unit / integration / system testing of SW

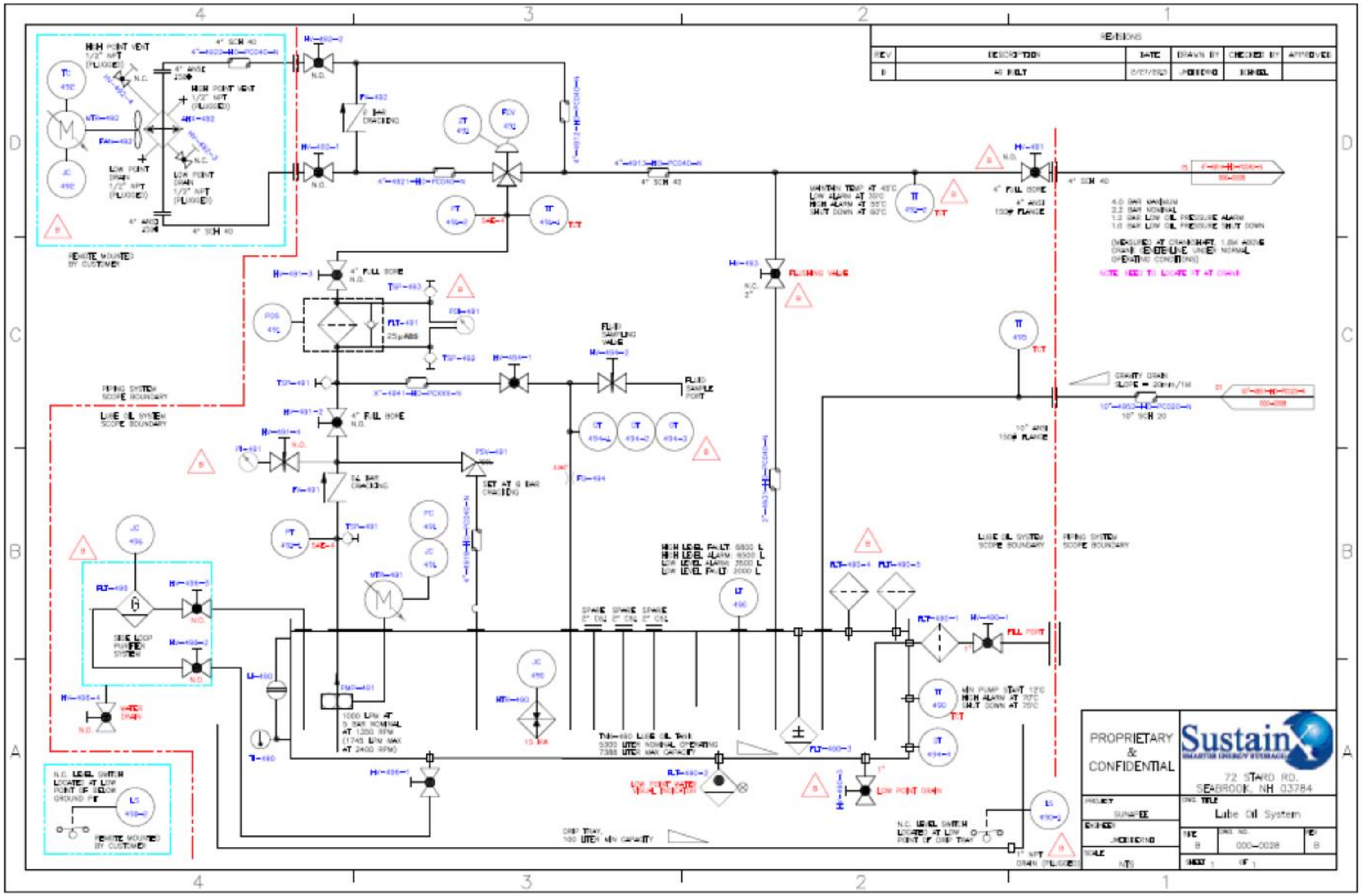
Model Based Design

- **Regression test(s) used to demonstrate:**
  - **State / mode / diagnostics coverage**
  - **Boundary value conditions**
  - **Requirements**
    - **Functional**
    - **Performance**
    - **Business**



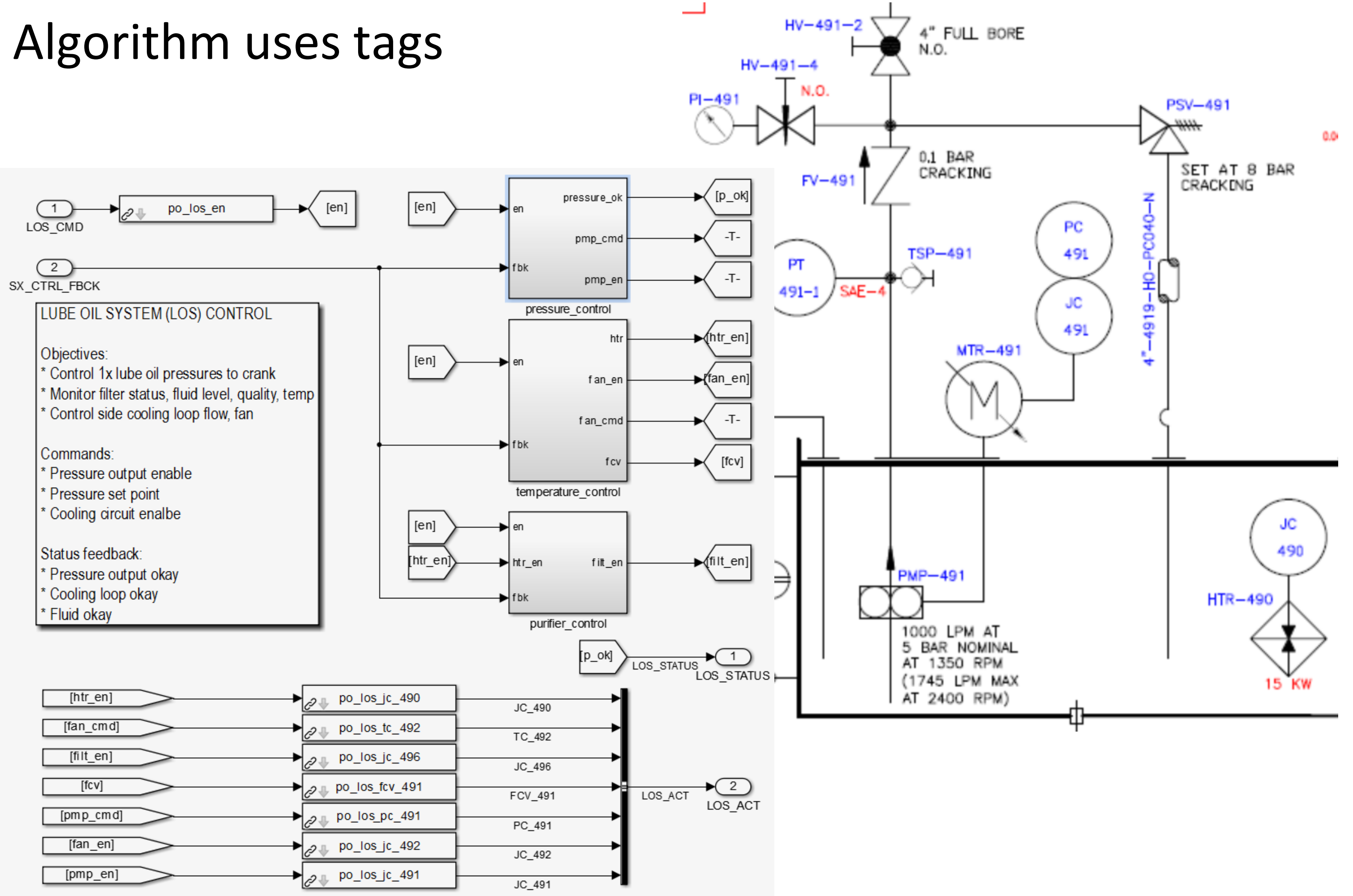
Model Based Design

- Traceable to P&IDs



P&ID Traceability

- Algorithm uses tags



LUBE OIL SYSTEM (LOS) CONTROL

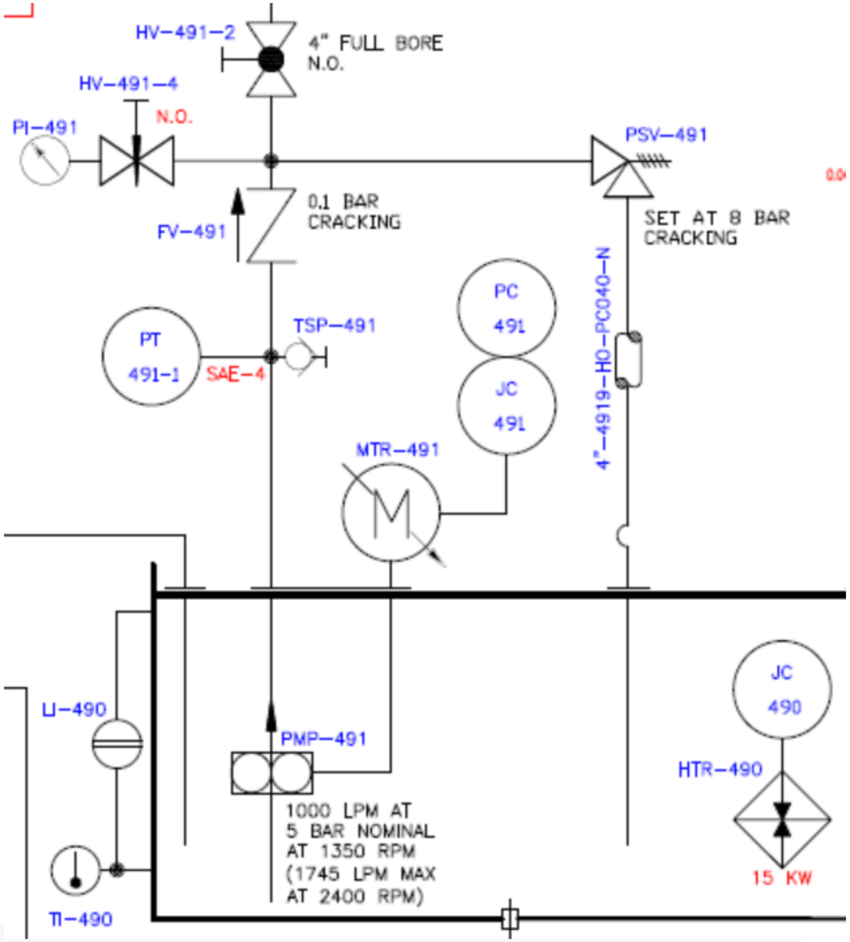
Objectives:
* Control 1x lube oil pressures to crank
* Monitor filter status, fluid level, quality, temp
* Control side cooling loop flow, fan

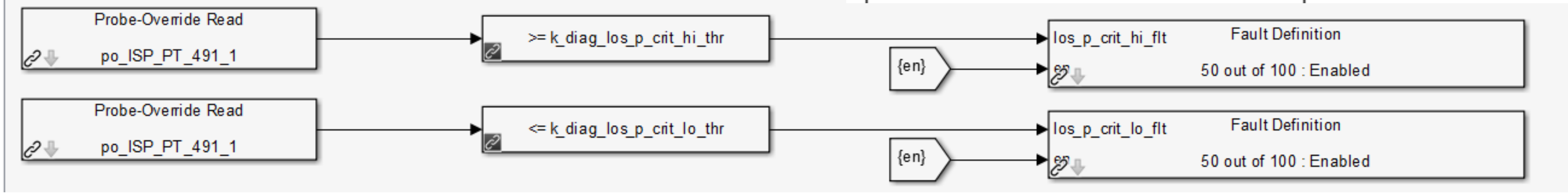
Commands:
* Pressure output enable
* Pressure set point
* Cooling circuit enalbe

Status feedback:
* Pressure output okay
* Cooling loop okay
* Fluid okay

P&ID traceability

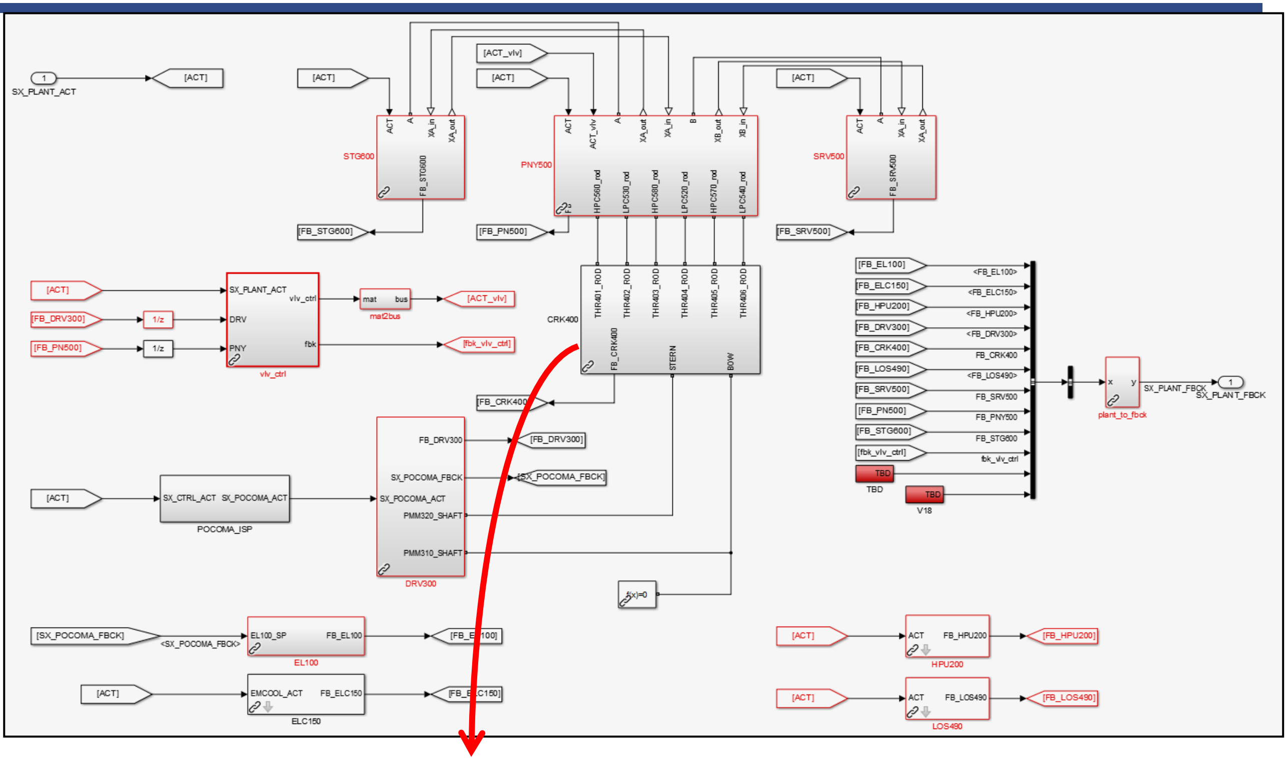
- Diagnostics uses tags

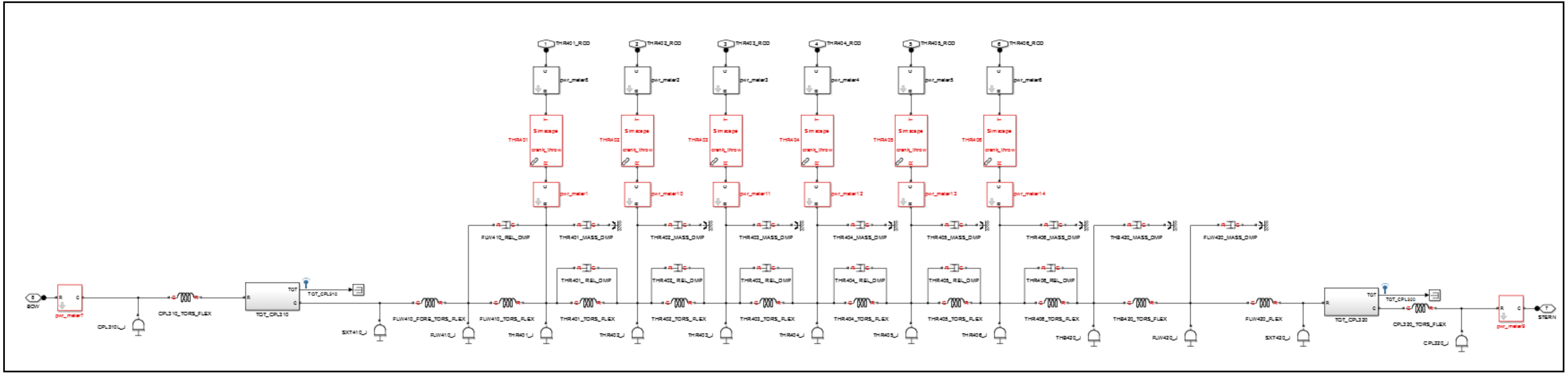




Advanced Control Systems Strategy

- Nonlinear Dynamics Represented





Model Based Design

- Developed non-linear dynamic model of power plant
- Developed control / diagnostic strategy to run in closed loop with model of power plant
- Ensure traceability to/from the P&IDs
- Test control strategy in:
  - Model-in-the-loop (non-real-time)
  - Target-in-the-loop (real-time)
- All in advance of machine being built

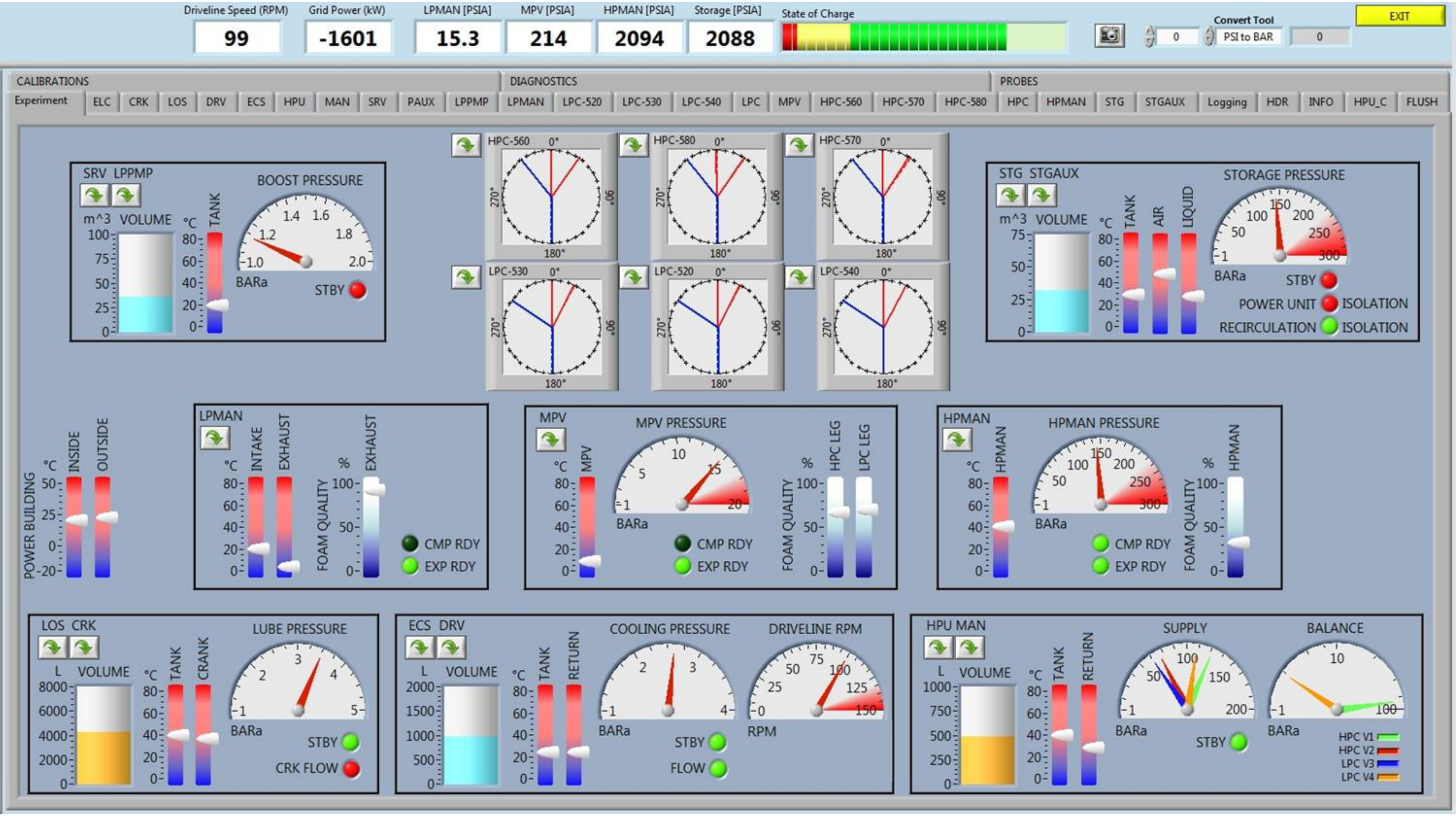
Diagnostics

Comprehensive full sub-system FMEA's feeding directly into control system diagnostics as mitigation method to reduce higher RPN's

SYSTEM	COMPONENT OR FUNCTION		CAUSES AND EFFECTS			SYSTEM IMPACT		FAILURE AND RELIABILITY RISK PRIORITY ASSESSMENT						
	Component or Function	Purpose of Component or Function	Failure Mode/Event	Failure Cause	Effect on Component	Effect on System	Effect on Sunapee Power Module	Severity	Occurrence	Detection Method	Detection	RPN	Action Required	Notes
V1	V1 Open on Command Function	Allows normal HPC operation	Failure to operate	Pilot valve solenoid not energized, no power present	Valve can still passively check open, will slowly close itself as long as pilot pressure present	None	Will impact normal valve cycling pattern	4	2	Currently no feedback to monitor power to valves	10	80		
V1	V1 Open on Command Function	Allows normal HPC operation	Failure to operate	Loss of control signal due to AO card or wiring failure	Pilot valve moves to center position. Poppet can still passively check open, will NOT close itself	None	If valve is checked open, will result in max pressure at max moment arm over-torque on next down stroke	7	2	Currently no measurement to verify output of control signal	10	140		Will happen if only one valve fails. Double check that with one valve open that the pressure in the cylinder will not be low enough that a short circuit can be achieved by opening V2.

Human Machine Interface

Engineering HMI communicates with system controller over OPC, a standard protocol for SCADA systems.



Driveline Speed (RPM): 99
Grid Power (kW): -1601
LPMAN [PSIA]: 15.3
MPV [PSIA]: 214
HPMAN [PSIA]: 2094
Storage [PSIA]: 2088
Convert Tool: PSI to BAR 0

1.5 MW Commercial Prototype

System Testing and Performance

Pilot System

Designed

Aug. 2011 to May 2013

Construction

Jan. to Aug. 2013

Commissioned

Aug. to Sept. 2013

Initial Operations

Sept. 2013 to present

Key Technology Metrics

The Seabrook Prototype has met the projected performance metrics

Specifications	Seabrook Prototype Original Projections	Seabrook Prototype As Tested
Charge power	2.2 MW	2.2 MW
Discharge power	1.5 MW	1.5 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	< 5 minute
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	-20ºC to 40ºC	-20°C to +40°C

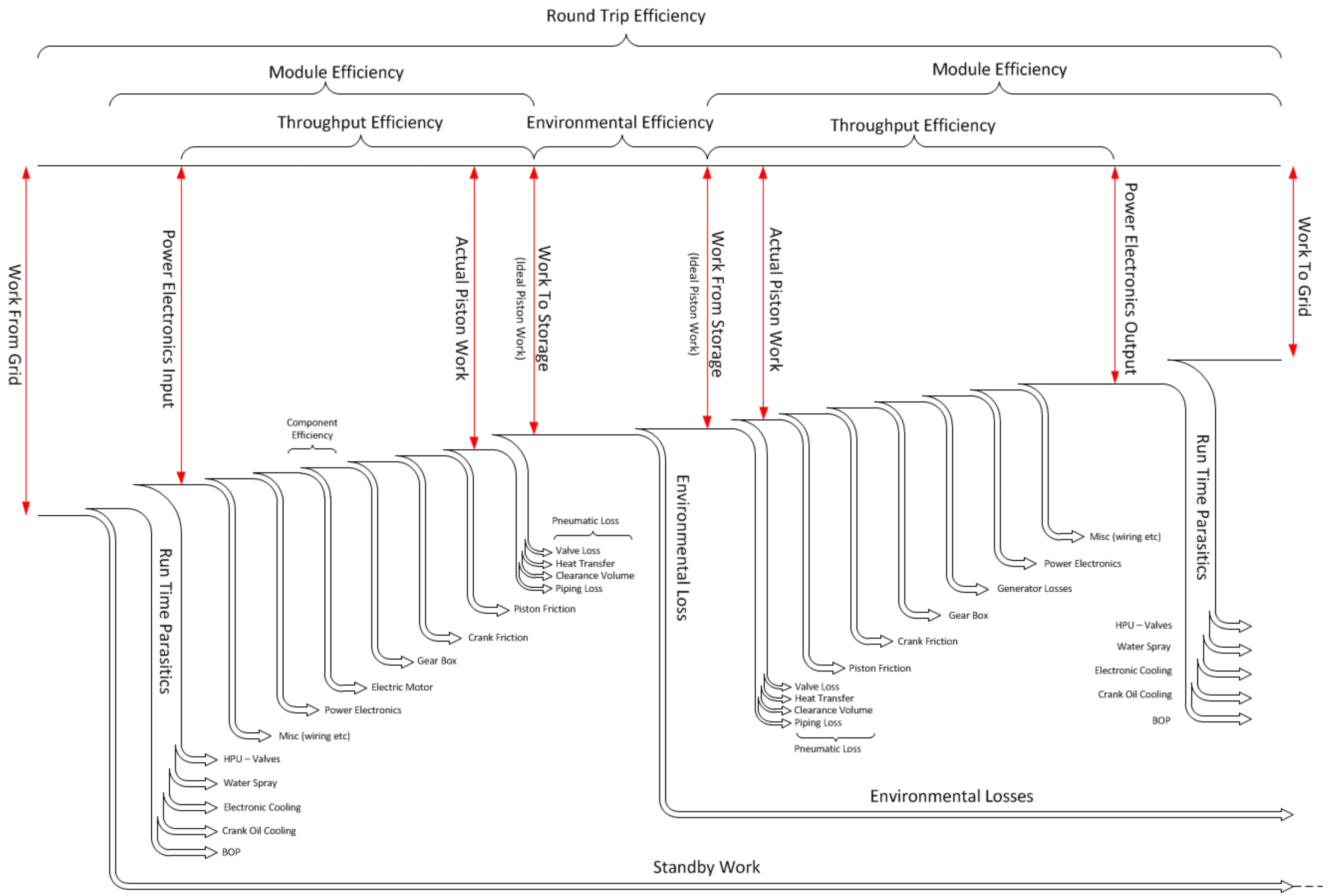
Power module technology risk has been eliminated

Testing Summary

- 433 runs total, 241 of which are cycle runs
- Cumulative run time
  - 36.5 hrs of total spinning time
  - 19.0 hrs of compression
  - 6.5 hours of expansion
- Component cycles
  - 225,000 revolutions of the driveline
  - 155,000 *in-situ* valve cycles

Efficiency Approach

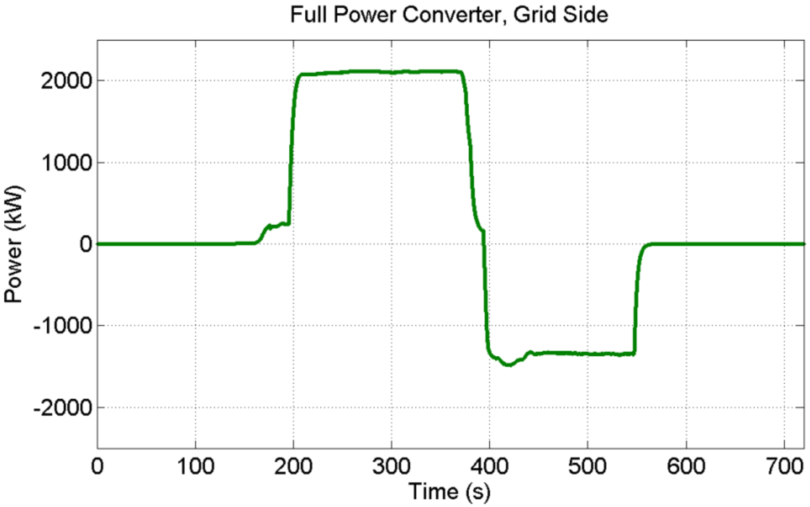
System efficiency is calculated AC-AC from point of grid connection

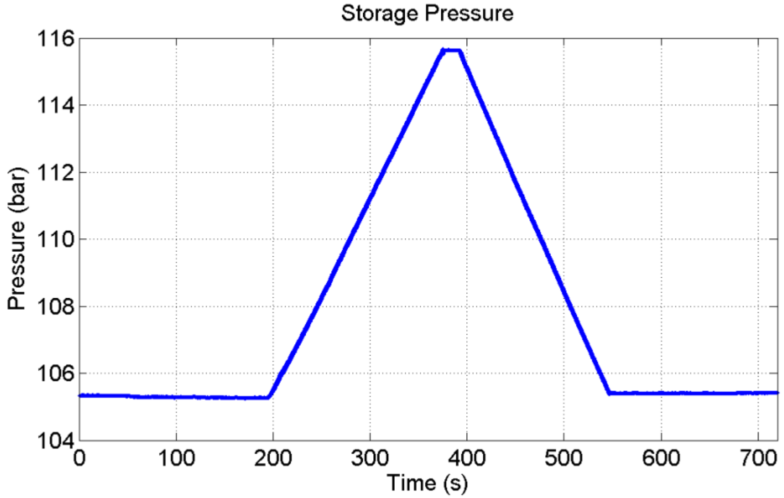


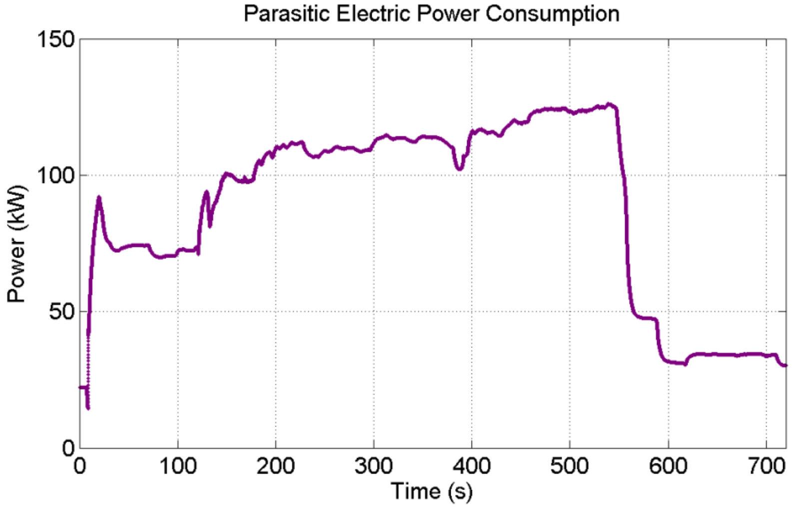
SustainX efficiency data includes electrical full power conversion and all parasitic energy consumption

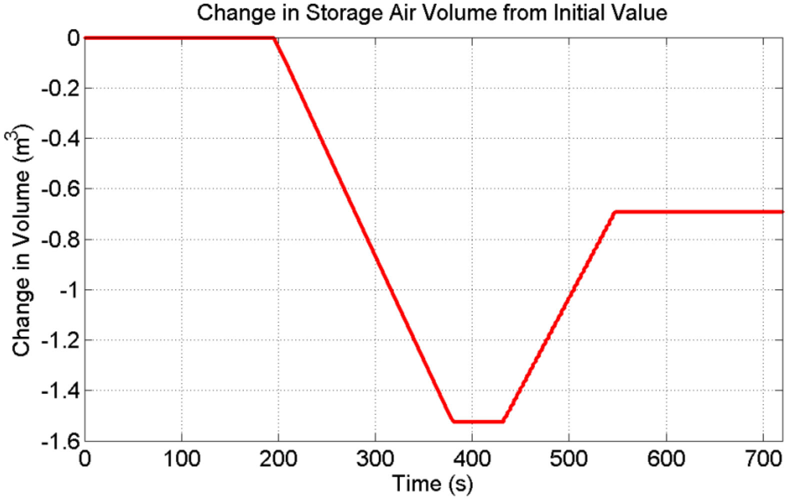
Data traces

Logged data provides required inputs to efficiency calculations


Full Power Converter, Grid Side


Storage Pressure

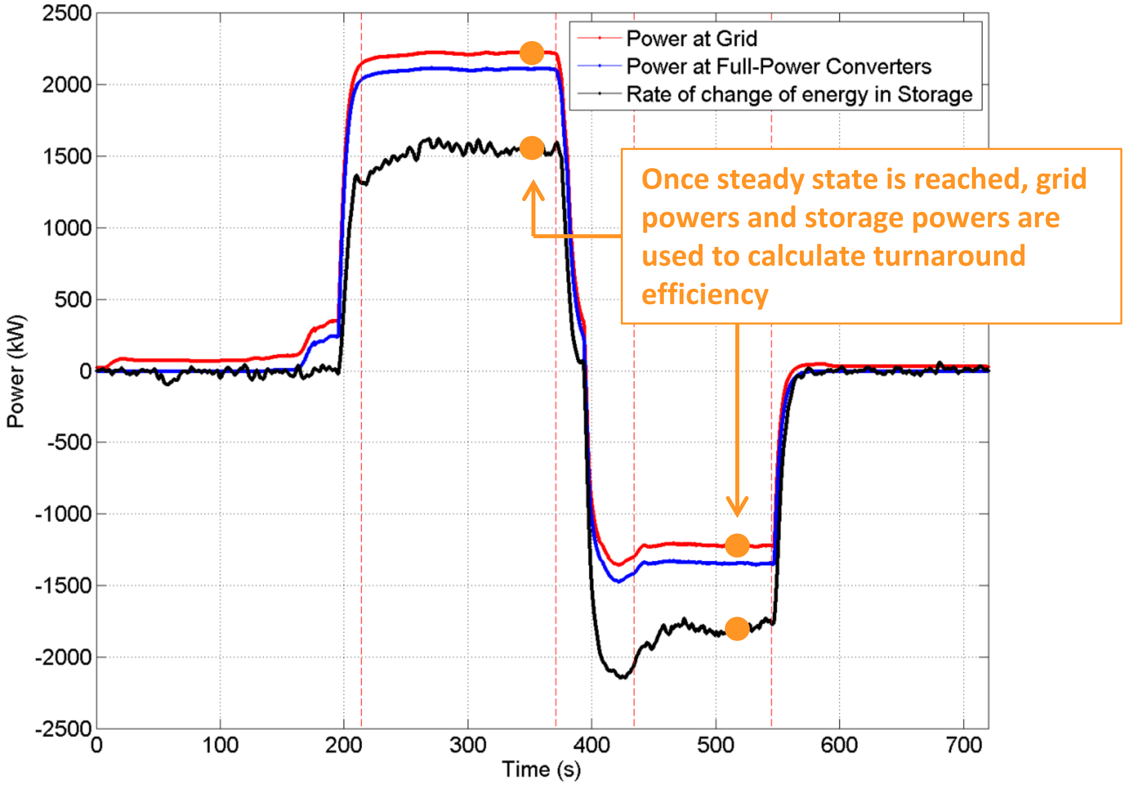

Parasitic Electric Power Consumption


Change in Storage Air Volume from Initial Value

Efficiency Calculation

The round-trip efficiency calculation is straightforward

- Short cycle experiments allow for snapshots of efficiency at a particular operating condition.
- Efficiency calculation using grid and storage powers during both compression and expansion eliminates effects of sensor bias
- Efficiency calculation methods have undergone third party validation by



Once steady state is reached, grid powers and storage powers are used to calculate turnaround efficiency

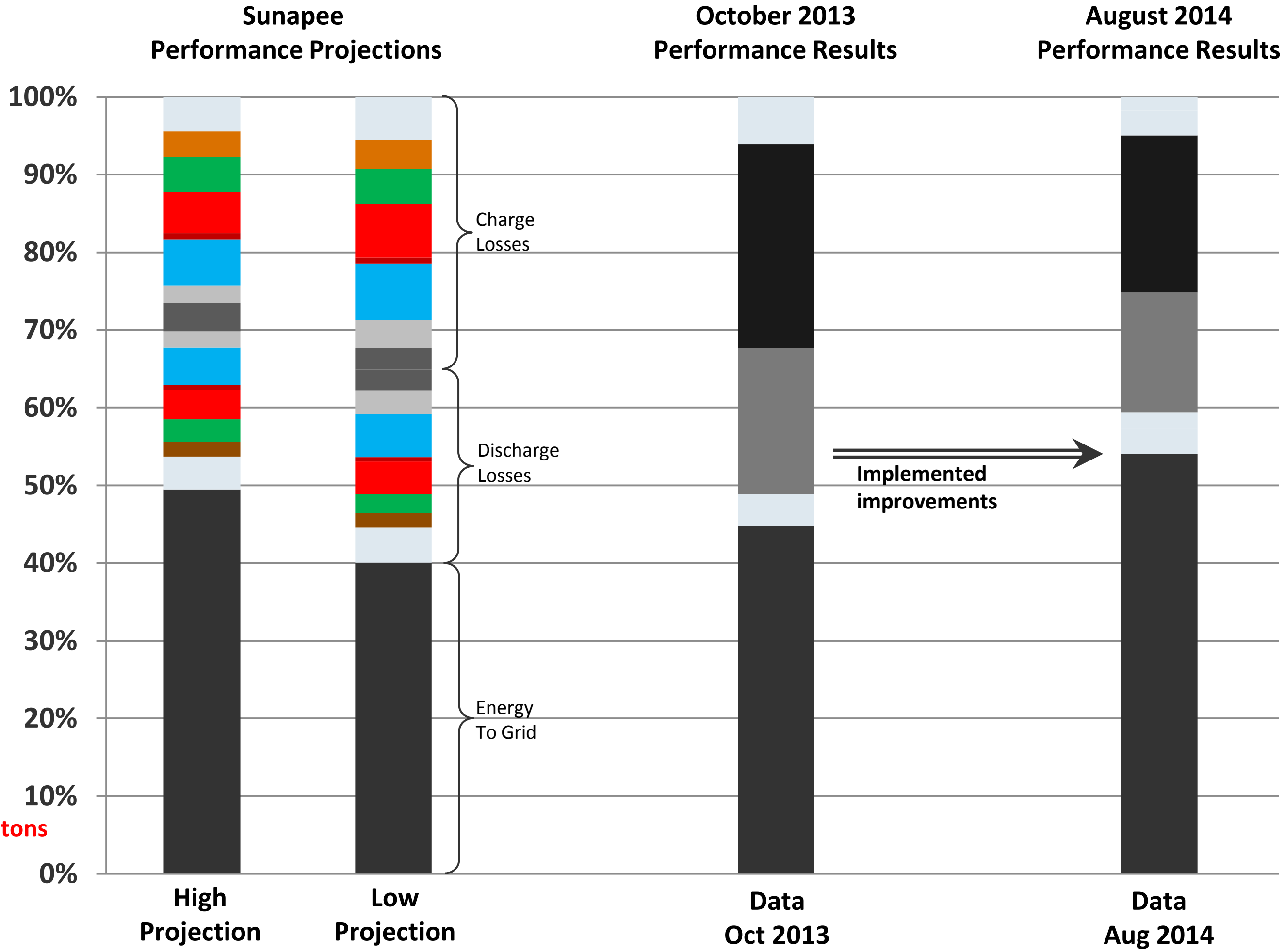
$$\eta_{turnaround} = \frac{\left[\frac{dE_{SV}}{dt}\right]_{cmp}}{PWR_{FPC\ input} + PWR_{rtp,cmp}} \frac{PWR_{FPC\ output} - PWR_{rtp,exp}}{\left[\frac{dE_{SV}}{dt}\right]_{exp}}$$

Round-trip efficiency has been determined experimentally via system testing

Seabrook Prototype round-trip efficiency

Initial testing met efficiency targets and has improved over time

- Improvements include
  - Reductions in compression electrical parasitics
  - Improved LP foam heat transfer
  - Tuning of system parameters



Color Code

Black: electricity to grid

Purple: parasitic electric

Greens: PMG and FPCs

Reds: Crank and pistons

Blues: Pneumatics

Greys: Unallocated

SustainX has demonstrated the ability to meet commercial efficiency targets

Efficiency improvement potential

Path to commercial product efficiency outlined in, and in progress since, November 2013

- Addressable opportunities for efficiency improvements is 14 %-points, with a potential to bring the initially demonstrated 45% round-trip efficiency to 59%

- Efficiency Improvement Opportunities
  - Reduction in crank system losses
    4%-pt potential
  - Improvements to driveline efficiency
    2%-pt potential
  - Reduction in electrical parasitic consumption
    4%-pt potential
  - Pneumatic efficiency improvements due to spray & foam optimization
    4%-pt potential

- Each opportunity is discussed in more detail on the following pages

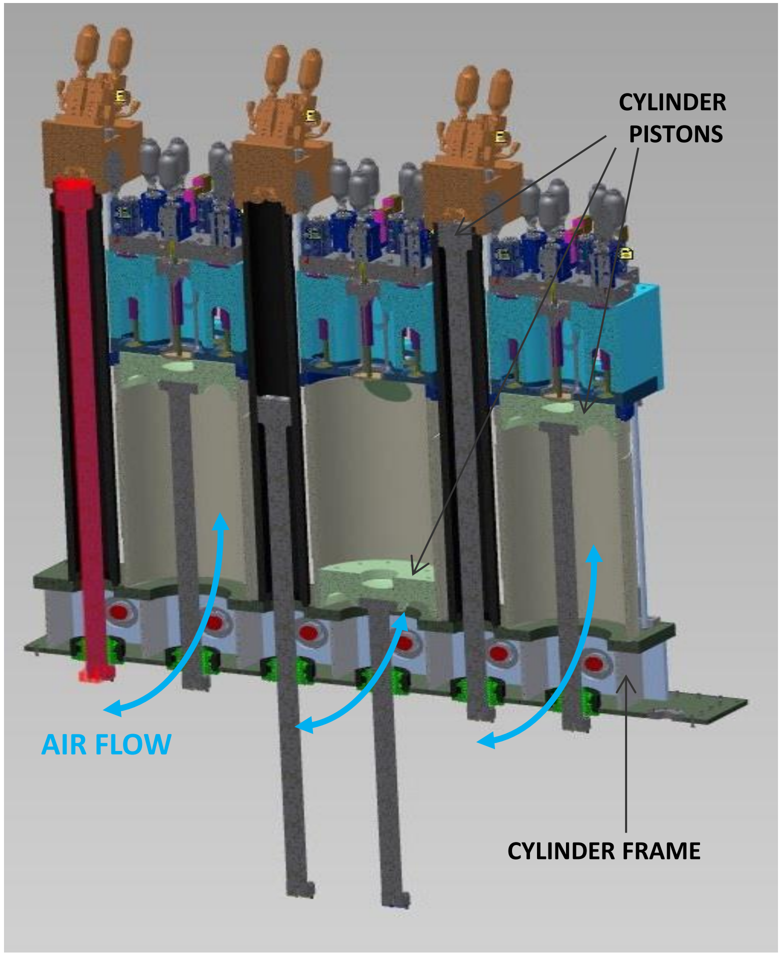
A clear path for efficiency gains was identified and implementation has begun

Efficiency improvement details, 1 of 4

Reduction in crank system losses: 4%-pt potential

- Windage
  - Resistance as air is pulled in and out of the area below the pistons
  - Possible solutions:
    - Seal up the air path and create a vacuum
      (Proven benefit; impacts cylinder cooling)
    - Increase flow area

- Piston friction
  - Current pistons use zero-leak seals
  - Allowing a small leak flow could significantly reduce friction
  - Different seal material can reduce friction



Efficiency improvement details, 2 of 4

Improvements to driveline efficiency: 2%-pt potential

- Changing configuration to a single PMG
  - Eliminates “fighting” between PMGs
  - Reduced bearing losses
    - Fewer bearings
    - One fewer coupling and misalignment
    - More efficient hydrodynamic bearings
  - Short PMG with large diameter is more efficient

- FPC refinements
  - Vector control
  - Silicone instead of ceramic capacitors

- Reduced copper losses

PERMANENT MAGNET GENERATORS

FULL POWER CONVERTERS

Efficiency improvement details, 3 of 4

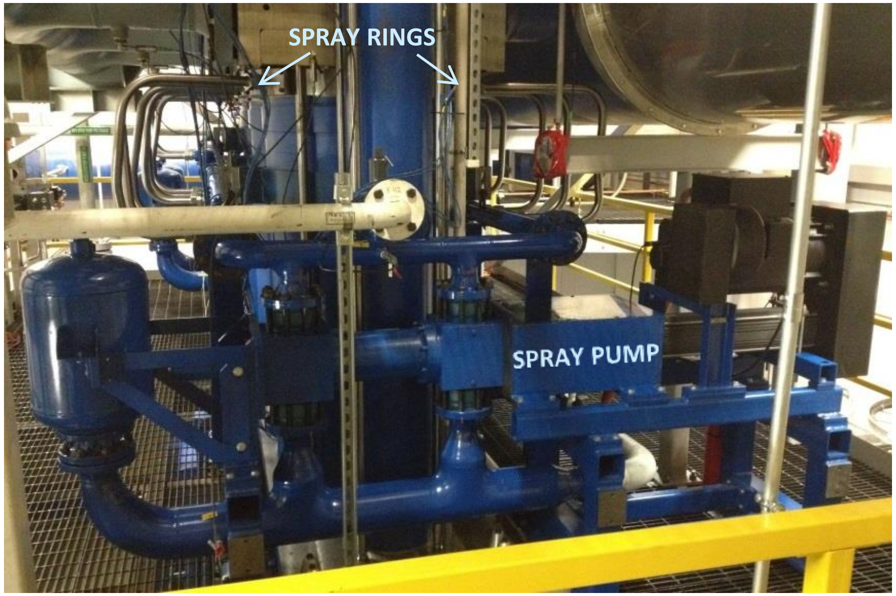
Reduction in electrical parasitic consumption: 4%-pt potential

- Eliminate Spray Pumps (1.5%)
  - Replace LP spray ring system (35 kW draw) with LP foam system (6 kW draw)

  Has been implemented to date

- Re-size ancillary systems for lower power consumption (2.5%)
  - Hydraulic Power Unit (HPU), Lube Oil System (LOS), Electronics Cooling System (ECS), and water "special pumps" were all purposely over-spec'd to allow for flexibility in operation of the prototype
  - Operational data from the Seabrook Prototype will allow each system to be re-sized, allowing the systems' components (e.g. pumps) to operate more efficiently

  Has been partially implemented to date



LP SPRAY RING SYSTEM

Efficiency improvement details, 4 of 4

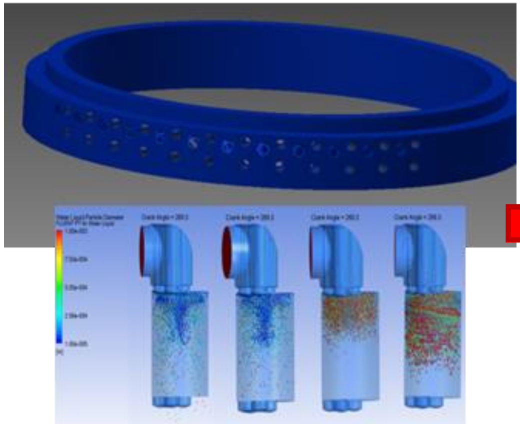
Pneumatic efficiency improvements: 4%-pt potential

- Spray and Foam Optimization
  - Replace LP spray ring system (est. ~92% thermal) with LP foam system (est. 96% thermal)

  Has been implemented to date

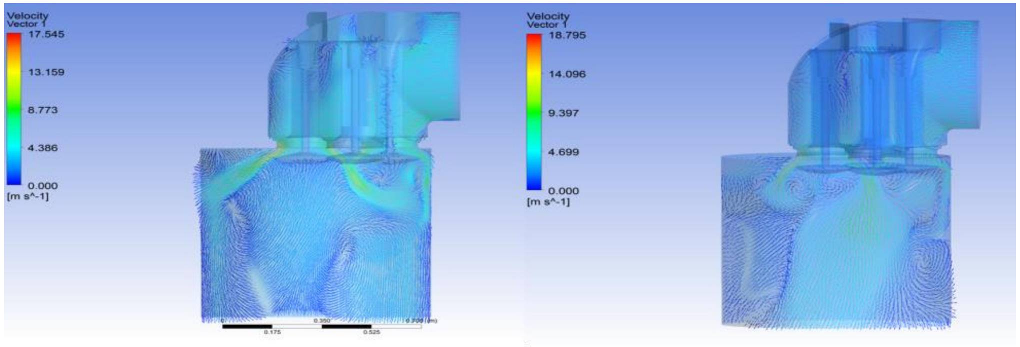
- Valve flow optimization
  - Small geometry changes in valve flowguides and cylinder head can have a large impact

- Process Piping Design Optimization



LP SPRAY

LP FOAM

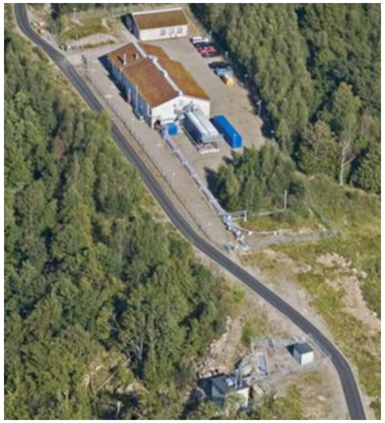


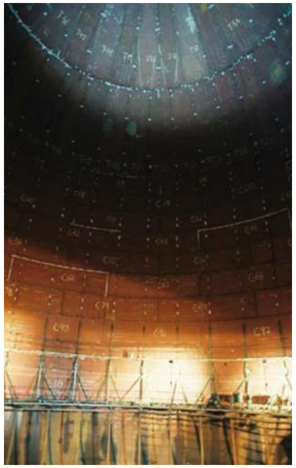
VALVE FLOW OPTIMIZATION

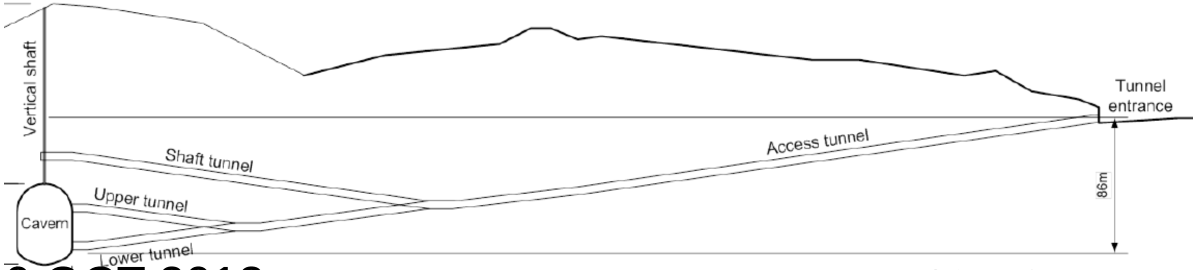
Lined Rock Cavern—Brief Overview

Conventional Lined Rock Cavern

- Engineered pressure vessel in sub-surface rock at shallow depth
  - Access tunnel used to drill, blast, and excavate working volume
  - Thin steel liner provides air tight storage volume
  - Concrete backfill distributes pressure forces directly to surrounding rock
- Capable of high pressure and high cycles
- NG storage for sites lacking salt caverns
  - 200 bar storage at shallow depth
- Demonstrated in Sweden & Japan



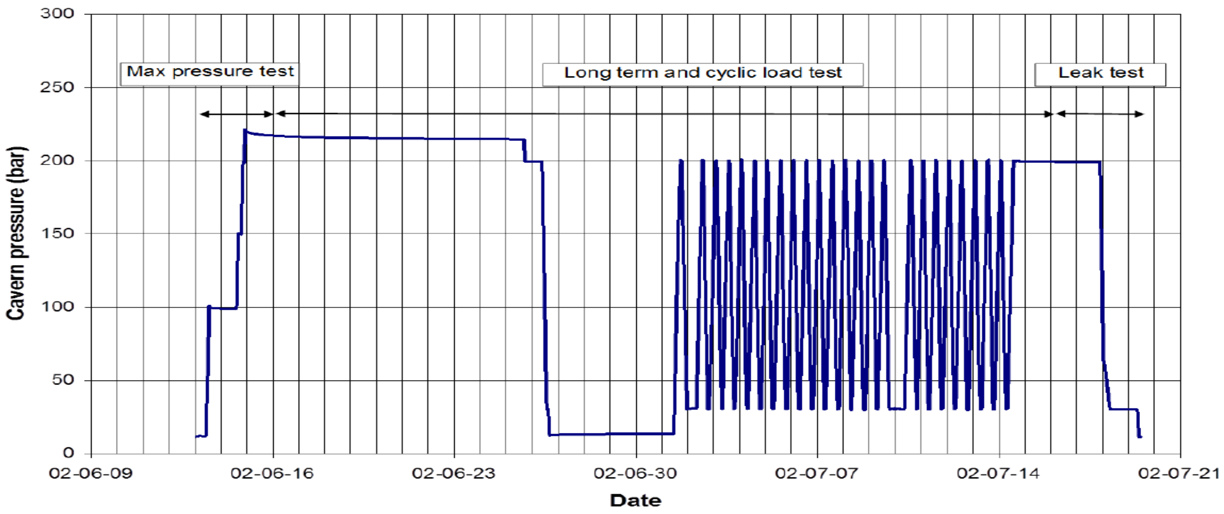




GDF Suez & E.ON Gas Sweden

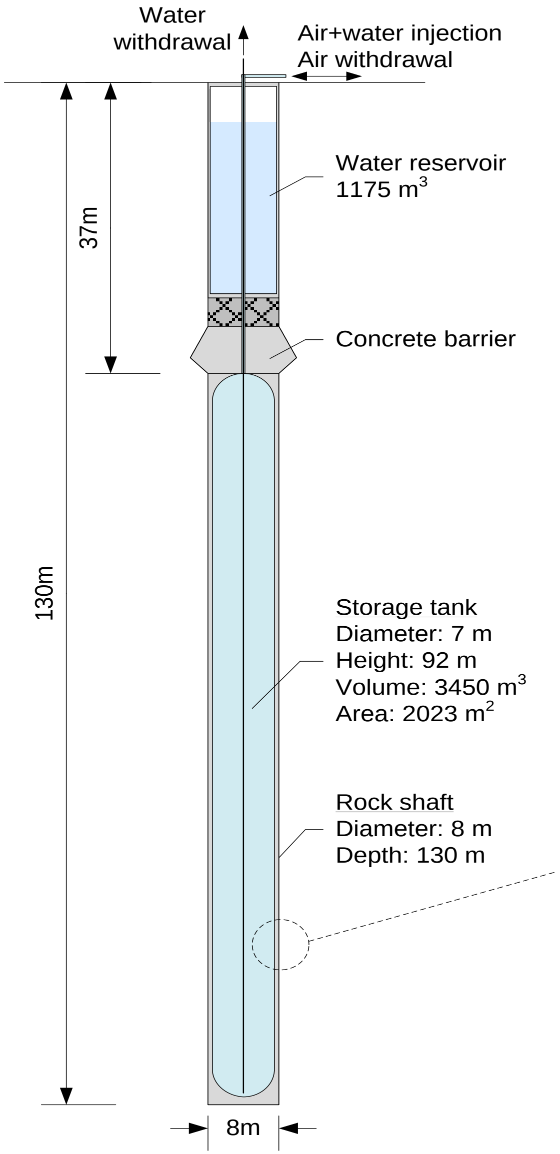
Commercial LRC development

- 120 m^3 pilot caverns built in 1988-1993 to test construction methods and materials
- 40,000 m^3 cavern entered commercial service in 2003
- Validated performance cycling from 200 bar to below 50 bar
- Lead engineer, Jan Johansson, working exclusively with SustainX to adapt technology for ICAES



Vertical Lined Rock Cavern

- Vertical shaft contains working volume
  - Drill and Blast; or Mechanical Excavation
  - Eliminates access tunnels
  - Shaft volume above high pressure storage can house low pressure water reservoir
- Diameter/depth sized for cost & performance
  - Typical diameters of 6-12 meters
  - Typical depths of 100-200 meters
- Design optimizes footprint, thermal performance, and output power
  - Vertical orientation and lack of access tunnel deliver minimal footprint
  - Surface to volume ratio thermally advantageous
  - Shallow depth limits water pumping losses



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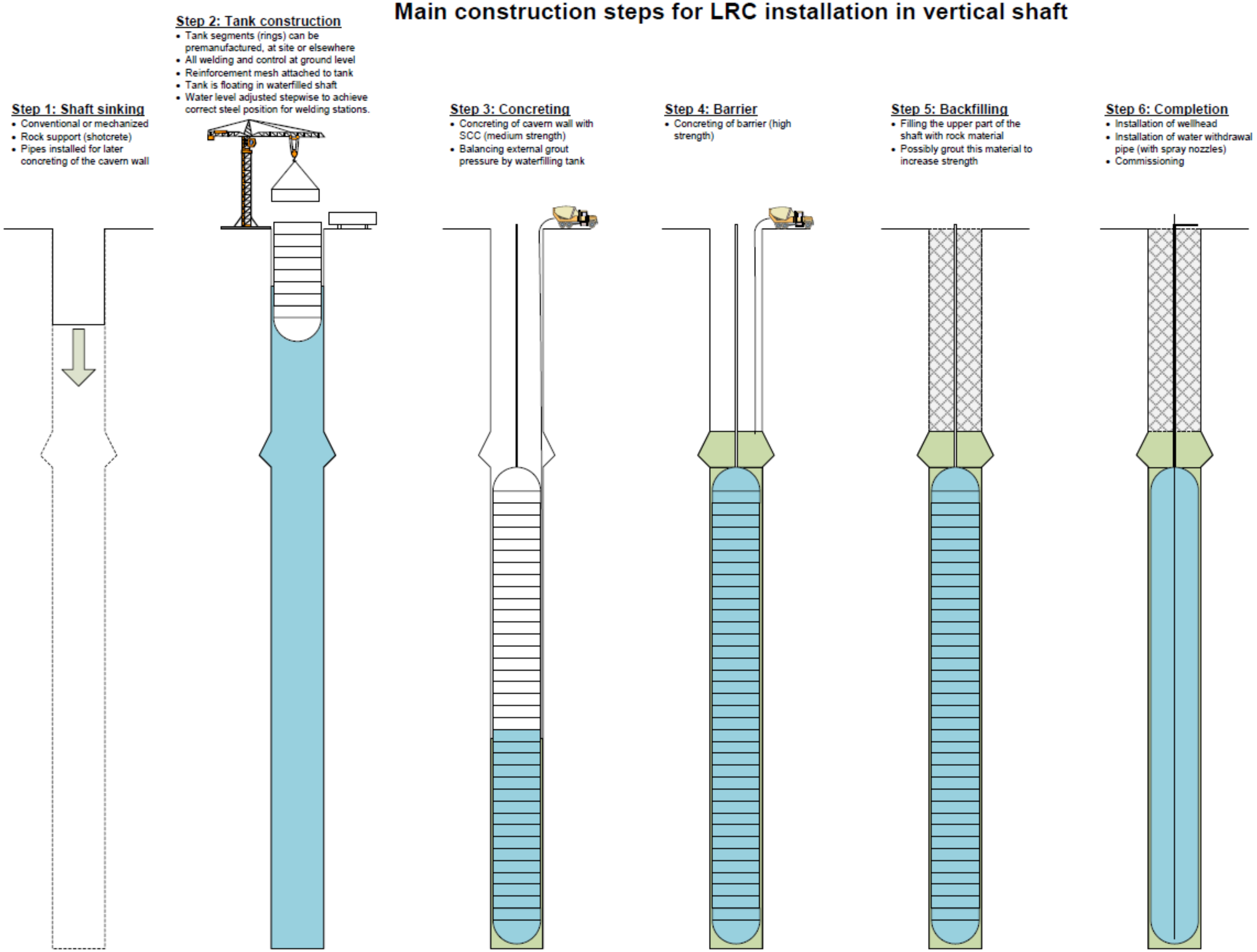
Vertical LRC Construction

Main construction steps for LRC installation in vertical shaft



Step 1: Shaft sinking
- Conventional or mechanized
- Rock support (shotcrete)
- Pipes installed for later concreting of the cavern wall

Step 2: Tank construction
- Tank segments (rings) can be premanufactured, at site or elsewhere
- All welding and control at ground level
- Reinforcement mesh attached to tank
- Tank is floating in waterfilled shaft
- Water level adjusted stepwise to achieve correct steel position for welding stations.

Step 3: Concreting
- Concreting of cavern wall with SCC (medium strength)
- Balancing external grout pressure by waterfilling tank

Step 4: Barrier
- Concreting of barrier (high strength)

Step 5: Backfilling
- Filling the upper part of the shaft with rock material
- Possibly grout this material to increase strength

Step 6: Completion
- Installation of wellhead
- Installation of water withdrawal pipe (with spray nozzles)
- Commissioning

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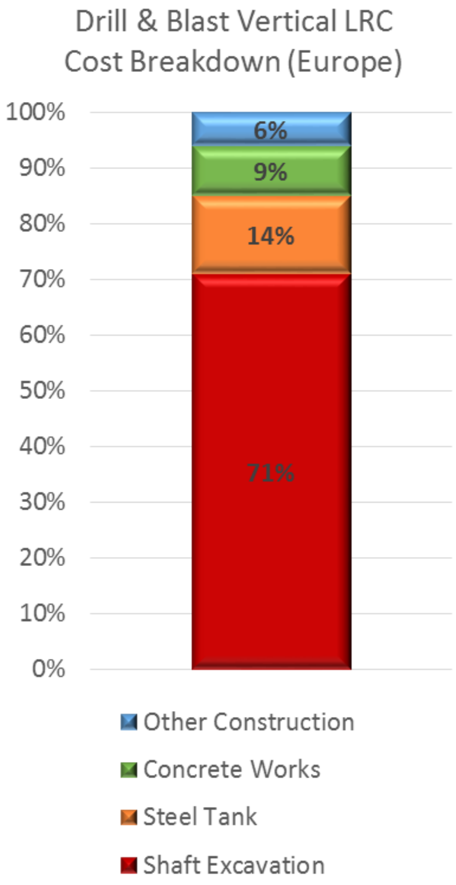
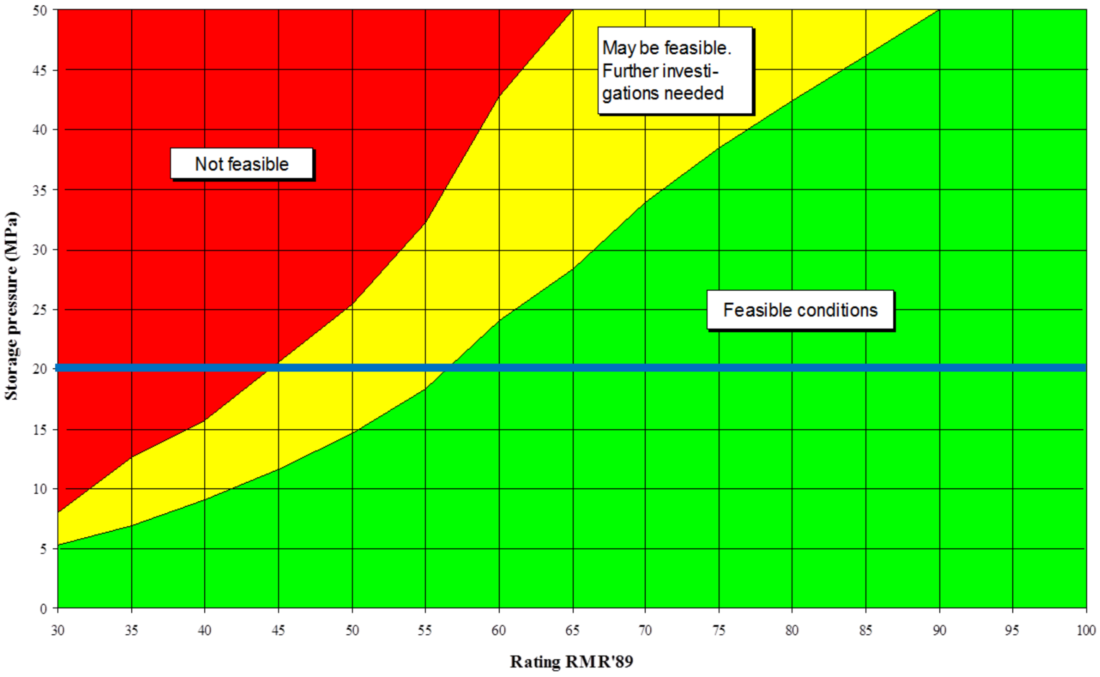
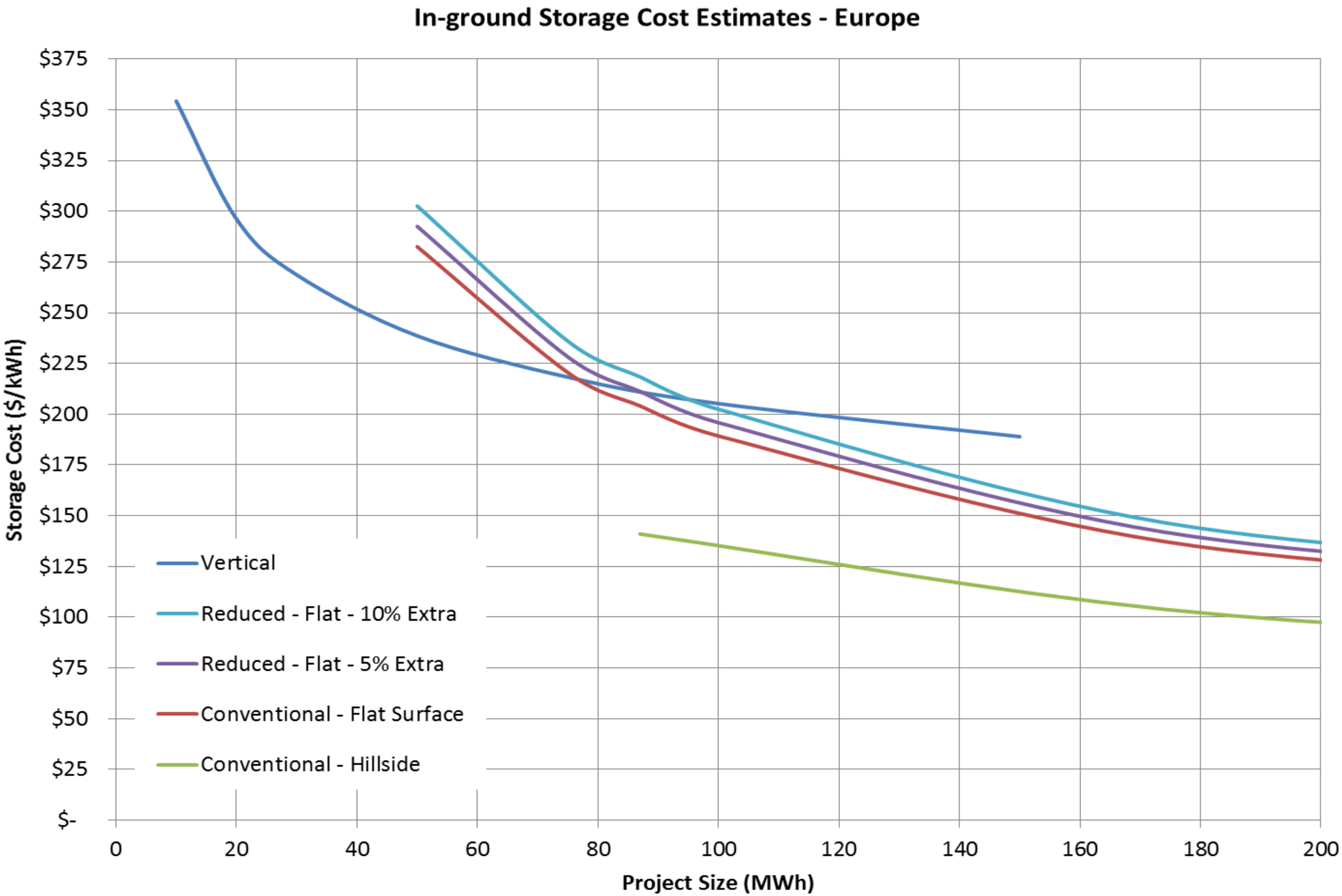
Vertical LRC Costs and Siting

- Shaft excavation is the dominant cost item for drill and blast construction (>70% in EU)
- Mechanical excavation offers faster, cheaper alternative
  - Multiple suppliers engaged
- Minimal soil depth & rock mass rating >55 desirable
  - Preliminary surveys of key regions show high potential





Europe Construction Costs



Cost Analysis

Cost Calculations for 30 MW / 180 MWh Plant

S300 Costs for IPP Licensee

A 30 MW / 180 MWh plant can provide 30 MW of power for 6 hours (if starting with air pressure at 3,000 psi). After that 6 hours, the system would have delivered 180 MWh of electricity to the grid.

Capital Cost for Individual Components

POWER MODULE CAPITAL COST (COMPONENTS, SHIPPING, INTEGRATION)
($1,233/kW) x (30 MW or 30,000 kW) = $36,990,000 cost for power modules

BALANCE OF PLANT CAPITAL COST (FOUNDATION, ENCLOSURE, ETC.)
($163/kW) x (30 MW or 30,000 kW) = $4,890,000 cost for balance of plant

AIR STORAGE CAPITAL COST (COMPONENTS, CONSTRUCTION, INTEGRATION)
($150/kWh) x (180 MWh or 180,000 kWh) = $27,000,000 cost for air storage

---

Capital Cost of Complete System

TOTAL SYSTEM COST = (Power Module Cost) + (Balance of Plant Cost) + (Air Storage Cost)
TOTAL SYSTEM COST = ($36,990,000) + ($4,890,000) + ($27,000,000) = **$68,880,000**
TOTAL SYSTEM COST PER kW = ($68,880,000) / (30 MW or 30,000 kW) = $2,296/kW
TOTAL SYSTEM COST PER kWh = ($68,880,000) / (180 MWh or 180,000 kWh) = $383/kWh

ICAES Cost Targets – 6 Hours LRC Storage

Performance Specifications for All Systems	
AC-AC Rountrip Efficiency:	55%
Standby Losses:	1% per day
Rated Charge Power:	1.5x Discharge Power

6-Cylinder ICAES

Time	**2014 - 2015**				**2016+**			
Annual Systems	1	4	10	50	1	4	10	50
System Power (MW)	1.65	1.65	1.65	1.65	1.8	1.8	1.8	1.8
Power Module Total Cost ($/kw) - unit	$2,463	$2,334	$1,805	$1,331	$2,258	$2,139	$1,655	$1,220
Shipping Cost ($/kW) - unit	$80	$80	$64	$42	$73	$73	$59	$38
Integration Cost ($/kW) - unit	$390	$390	$249	$131	$357	$357	$228	$120
Balance of Plant Cost ($/kW) - unit	$438	$438	$247	$175	$438	$438	$247	$175
Energy CAPEX (Storage Cost)($/kWh) - unit - LRC	$350	$350	$150	$150	$350	$350	$150	$70
Forecasted System Cost ($/kW) - unit	$5,471	$5,341	$3,265	$2,578	$5,226	$5,108	$3,089	$1,973
Forecasted System Cost ($/kWh) - unit	$912	$890	$544	$430	$871	$851	$515	$329

9-Cylinder ICAES

Time	**2014 - 2015**				**2016+**			
Annual Systems	1	4	10	50	1	4	10	50
System Power (MW)	2.8	2.8	2.8	2.8	3	3	3	3
Power Module Total Cost ($/kw) - unit	$1,889	$1,763	$1,358	$994	$1,763	$1,646	$1,268	$928
Shipping Cost ($/kW) - unit	$60	$60	$48	$34	$56	$56	$45	$32
Integration Cost ($/kW) - unit	$294	$294	$188	$107	$275	$275	$175	$100
Balance of Plant Cost ($/kW) - unit	$438	$438	$247	$175	$438	$438	$247	$175
Energy CAPEX (Storage Cost)($/kWh) - unit - LRC	$350	$350	$150	$150	$350	$350	$150	$70
Forecasted System Cost ($/kW) - unit	$4,782	$4,656	$2,741	$2,211	$4,632	$4,515	$2,635	$1,655
Forecasted System Cost ($/kWh) - unit	$797	$776	$457	$369	$772	$752	$439	$276

ICAES Cost Targets – 8 Hours LRC Storage

Performance Specifications for All Systems

AC-AC Rountrip Efficiency:	55%
Standby Losses:	1% per day
Rated Charge Power:	1.5x Discharge Power

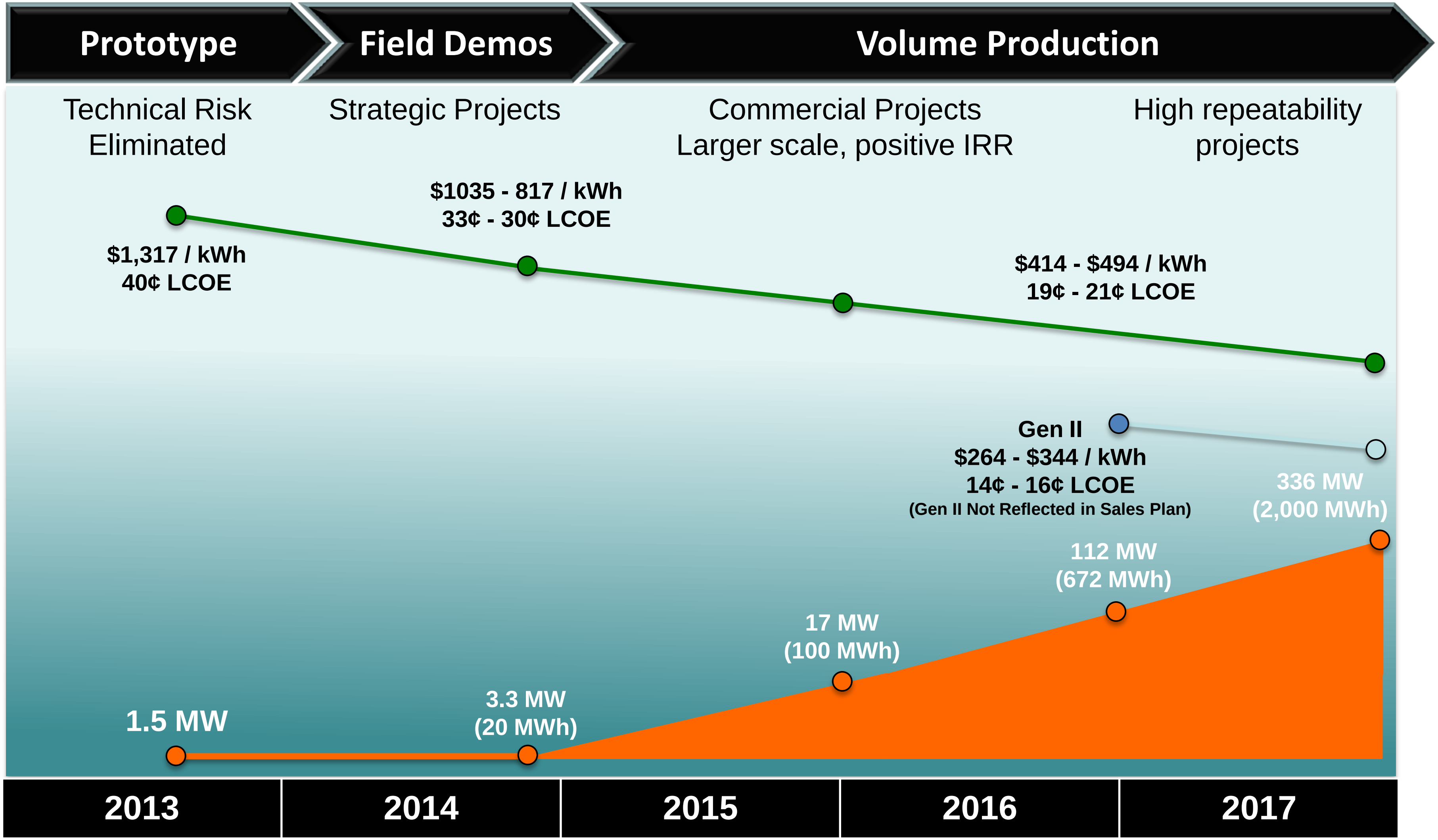
6-Cylinder ICAES

Time		**2014 - 2015**				**2016+**		
Annual Systems	1	4	10	50	1	4	10	50
System Power (MW)	1.65	1.65	1.65	1.65	1.8	1.8	1.8	1.8
Power Module Total Cost ($/kw) - unit	$2,463	$2,334	$1,805	$1,331	$2,258	$2,139	$1,655	$1,220
Shipping Cost ($/kW) - unit	$80	$80	$64	$42	$73	$73	$59	$38
Integration Cost ($/kW) - unit	$390	$390	$249	$131	$357	$357	$228	$120
Balance of Plant Cost ($/kW) - unit	$438	$438	$247	$175	$438	$438	$247	$175
Energy CAPEX (Storage Cost)($/kWh) - unit - LRC	$350	$350	$150	$150	$350	$350	$150	$70
Forecasted System Cost ($/kW) - unit	$6,171	$6,041	$3,565	$2,878	$5,926	$5,808	$3,389	$2,113
Forecasted System Cost ($/kWh) - unit	$771	$755	$446	$360	$741	$726	$424	$264

9-Cylinder ICAES

Time		**2014 - 2015**				**2016+**		
Annual Systems	1	4	10	50	1	4	10	50
System Power (MW)	2.8	2.8	2.8	2.8	3	3	3	3
Power Module Total Cost ($/kw) - unit	$1,889	$1,763	$1,358	$994	$1,763	$1,646	$1,268	$928
Shipping Cost ($/kW) - unit	$60	$60	$48	$34	$56	$56	$45	$32
Integration Cost ($/kW) - unit	$294	$294	$188	$107	$275	$275	$175	$100
Balance of Plant Cost ($/kW) - unit	$438	$438	$247	$175	$438	$438	$247	$175
Energy CAPEX (Storage Cost)($/kWh) - unit - LRC	$350	$350	$150	$150	$350	$350	$150	$70
Forecasted System Cost ($/kW) - unit	$5,482	$5,356	$3,041	$2,511	$5,332	$5,215	$2,935	$1,795
Forecasted System Cost ($/kWh) - unit	$685	$669	$380	$314	$667	$652	$367	$224

Roadmap to Lowest Cost Storage Solution



Prototype | **Field Demos** | **Volume Production**

Technical Risk Eliminated

Strategic Projects

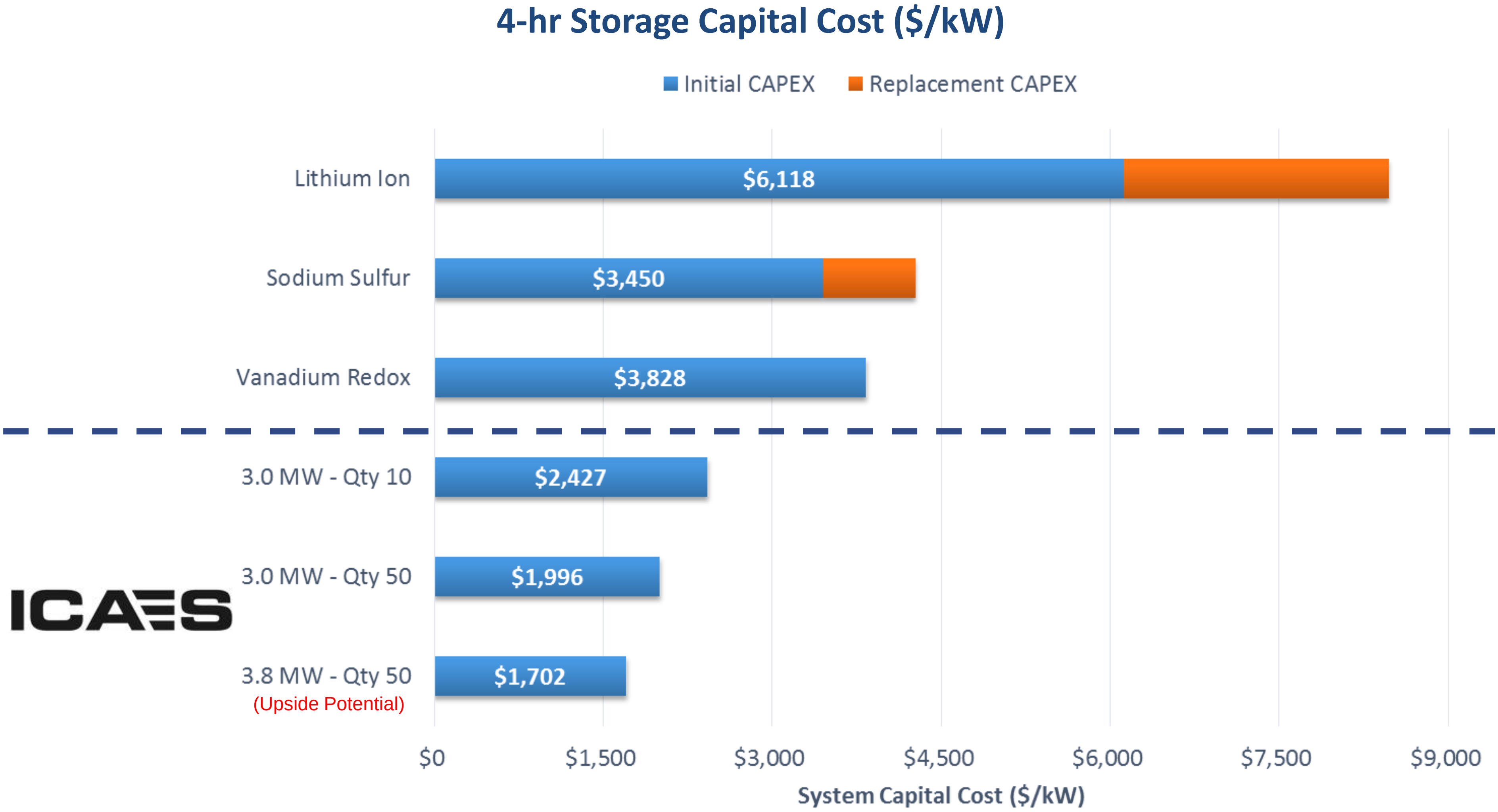
Commercial Projects
Larger scale, positive IRR

High repeatability projects

* Prices representative of project sizes as presented on slide “Rapid Product Enhancement Toward $300/kWh Goal”

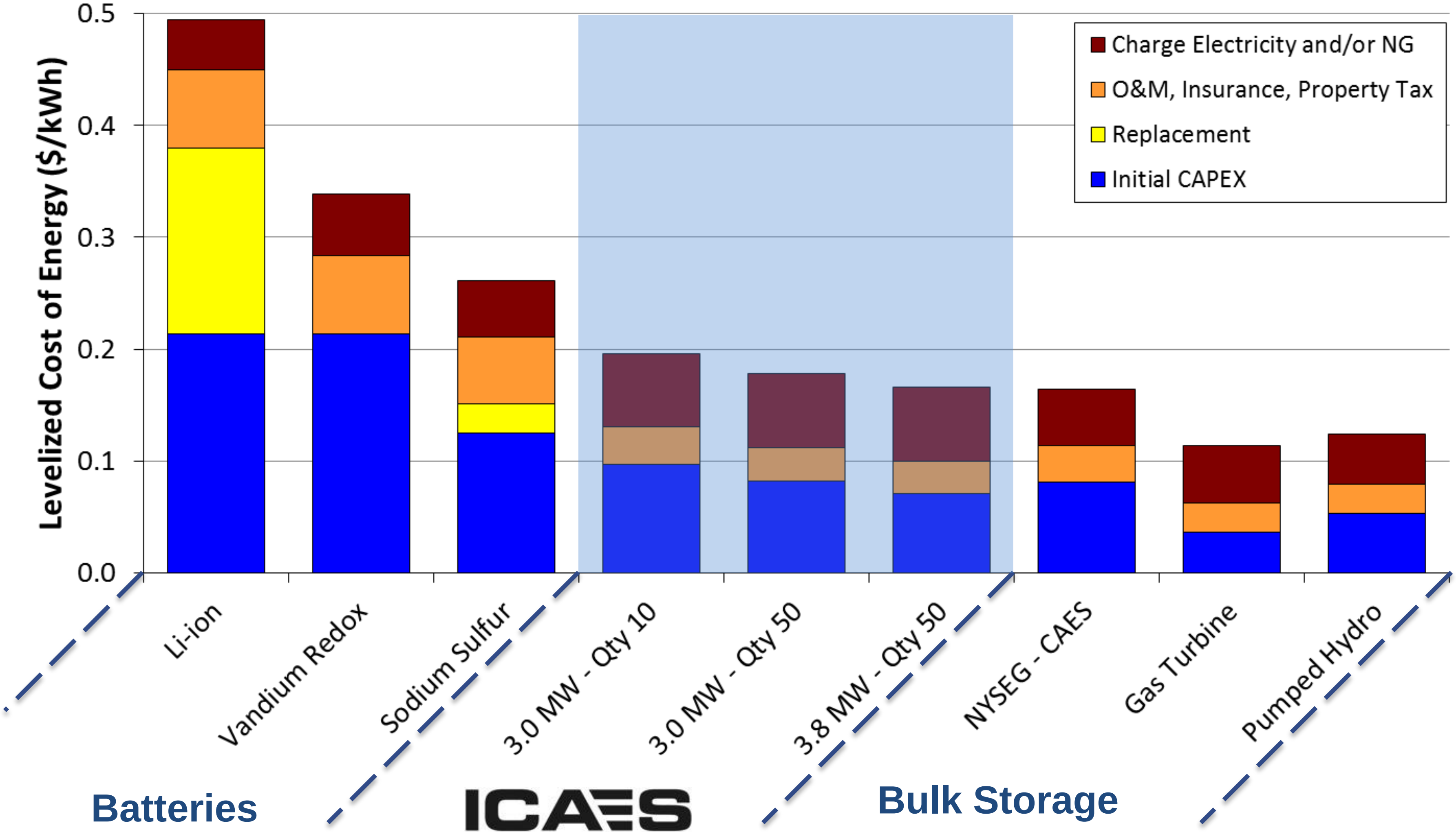
Distributed Storage Offers Superior Grid Solution

ICAES Delivers Disruptive Cost and System Lifetime Advantages



IPP owner/operator of project
Sources: Li-ion & Sodium Sulfur – IHS Research
Vandium Redox – Lux Research

Superior CAPEX and System Lifetime Drive LCOE Advantage



Batteries

ICAES

Bulk Storage & Peakers

Assumptions: 6-hour daily discharge, 20-year project, US off-peak charge electricity ($30/MWh), US gas pricing($4/mmBtu), POU finance

Market and Market Applications Analysis

Commercial Performance Validated on 1.5 MW Full-Scale Prototype

ICAES Commercial Systems

ICAES S165

6-cylinder MAN crankshaft

1.65 MW per machine

ICAES S300/380

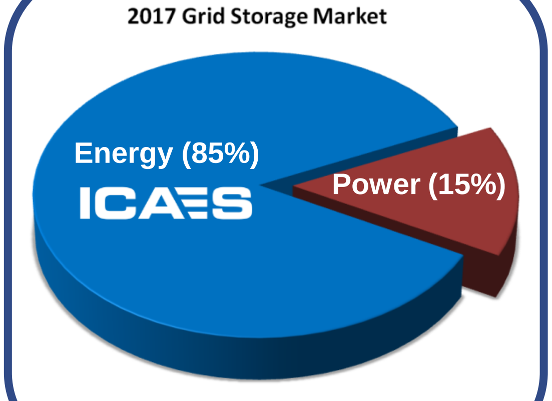
9-cylinder MAN crankshaft

3.0-3.8 MW per machine

SustainX Gen II

Large bore MAN crankshafts	Custom MAN crankshafts
5-16 MW from stock 6-cyl	10-28 MW from 6-cyl

Navigant Research Forecasts CAES Growth to be Double that of Batteries for Utility-Scale Applications



Source: Lux Research

Chart 5.4 CAES New Installed Revenue by Region, World Markets: 2013-2023

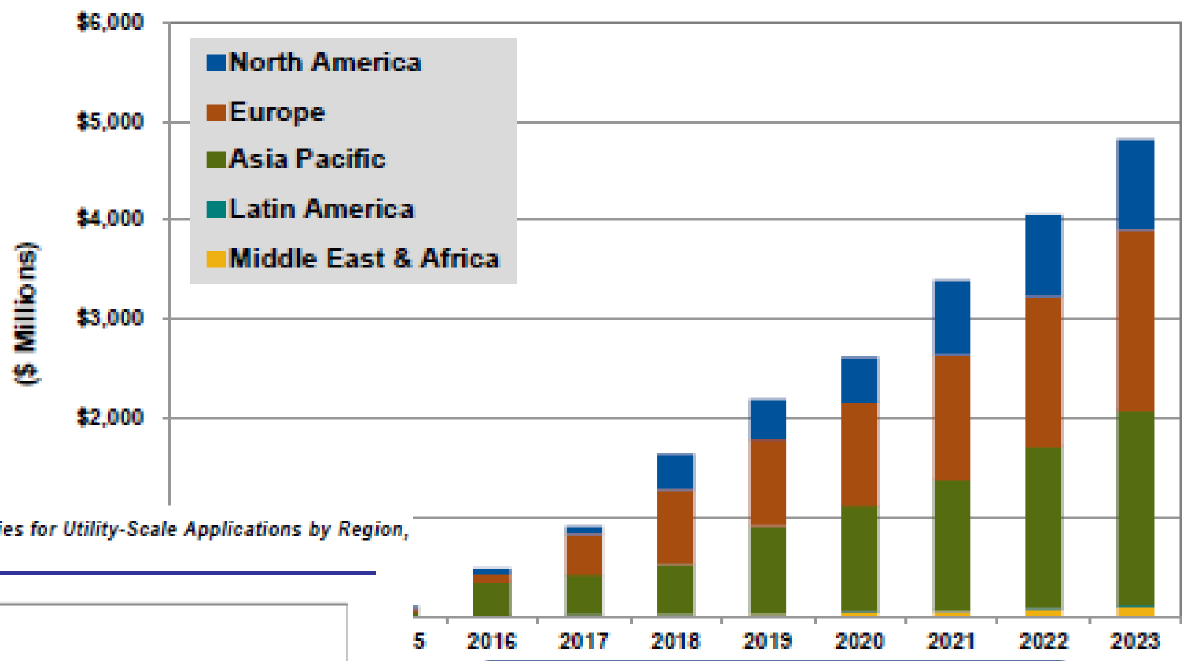
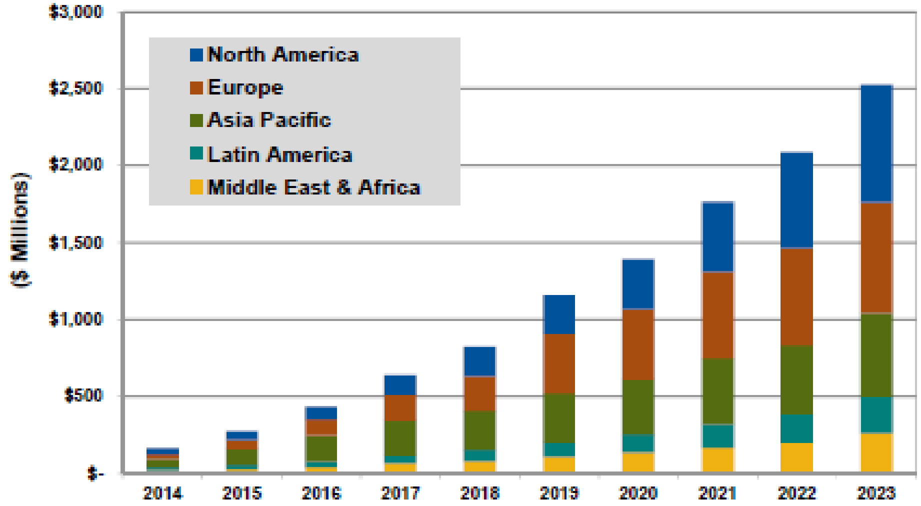


Chart 1.1 Annual Revenue of Cell Sales for Advanced Batteries for Utility-Scale Applications by Region, World Markets: 2014-2023



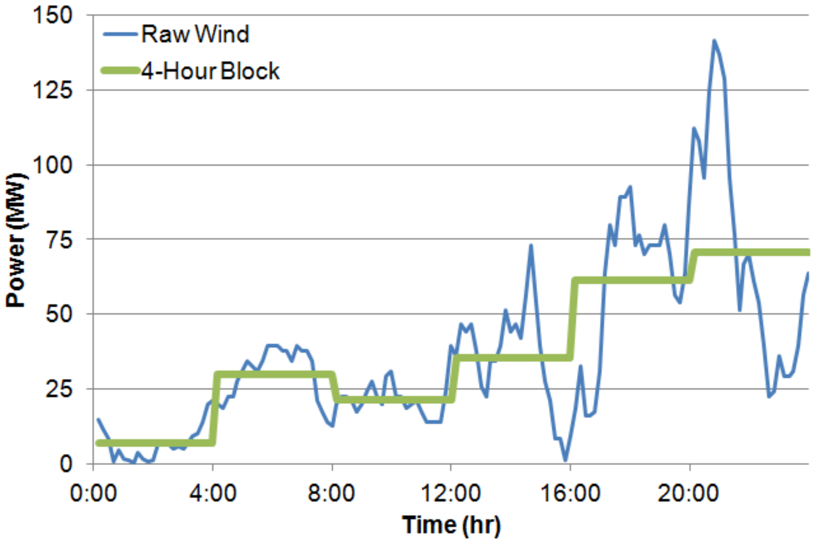
Next-Gen Drives CAES Market
(2013-2023)
53% of Market by Capacity
60% of Market by Revenue

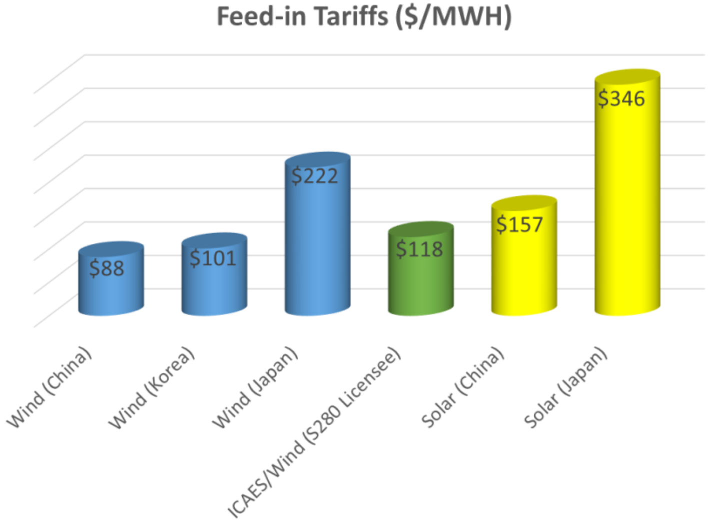
Next-Gen Market Share Increasing
(2023)
67% of Market by Capacity
73% of Market by Revenue

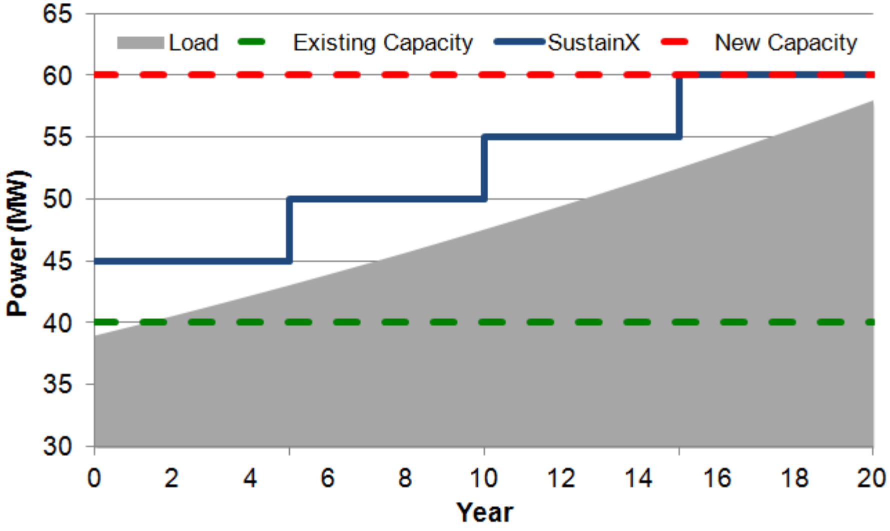
Compressed Air Energy Storage, 2013
Advanced Batteries for Utility-Scale Energy Storage, 2014

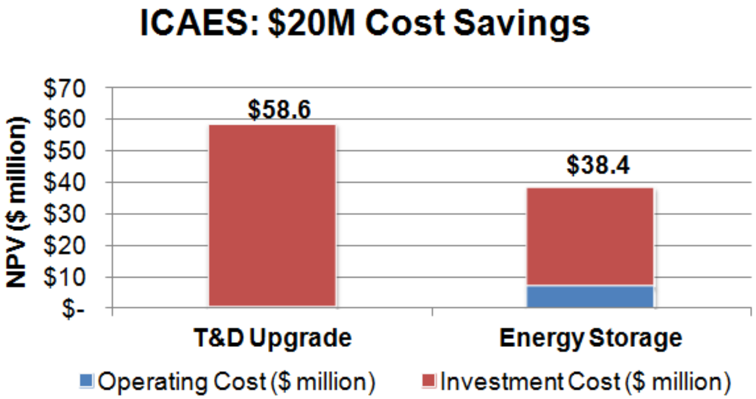
Firming Renewables & Enhancing Grid Flexibility

SustainX
SMARTER ENERGY STORAGE









Analysis by Azure International. Market size from IEA Medium Term Renewables Report 2013

Near-term North America Opportunity

Global Growth Pipeline Established

US - 1.3 GW CA Procurement
- 1st Utility RFO in Dec 2014
- Contracts in Late 2015
- Repeats Every 2 Years

China - Local Partner
- TBEA, $5B Power Equipment Co.
- Pursuing Demo Projects

Korea – Demo Consortium
- Led by Utility KOMIPO
- Govt. Support & LRC Experience

India
- Talking with Major Financial & Industrial Partners

South Africa
- Talking with Major IPP

Japan – Local Partner
- Fuji Electric, $8B Power Equipment Co.
- Marketing, Govt. Funding, Demos

Central Vermont 115 kV System Overload
Traditional Solution: New $157M, 345 kV line

15 MW ICAES: Immediate Solution, Rate-payer Savings, Long Term Flexibility

Background: Elements of 115 kV system in Rutland, VT area fail to meet NERC Reliability Standards during contingency events

VELCO Assessment: System upgrade required, but minimal utilization of new 345 kV line expected

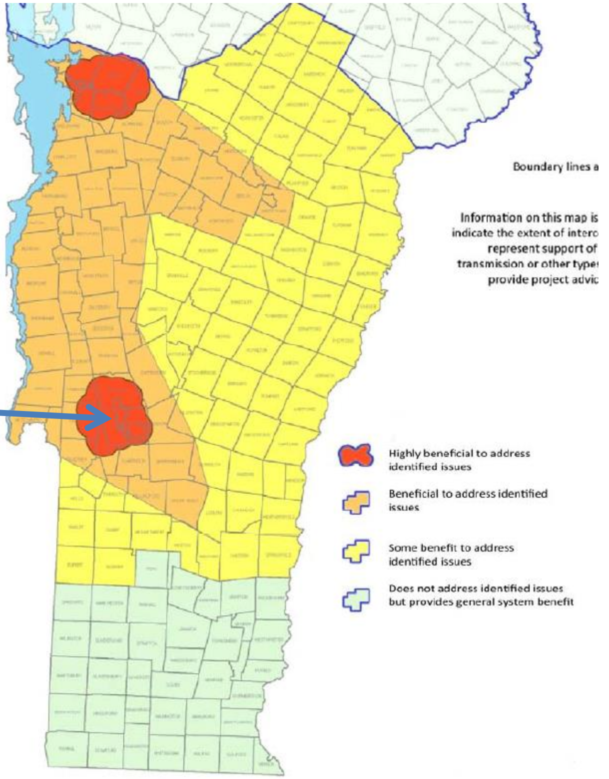
- **Uncertainties:** Vermont Yankee Nuclear Plant, load growth

Non-transmission Alternatives: VELCO looking for alternatives

- **Site-anywhere:** Benefits are location dependent
- **Fuel-free:** No gas pipelines in region
- **Reliable:** Need to cover 6-hour peak, renewables don't help

ICAES provides superior solution

- **Rate-payer Savings:** >$80M during planning period
- **Siteable:** No fuel or geology restrictions
- **Scalable:** ICAES can be added as needs change



Off-grid/Micro-grid Power:

Displace Diesel, Optimize Renewables

Market friendly to storage

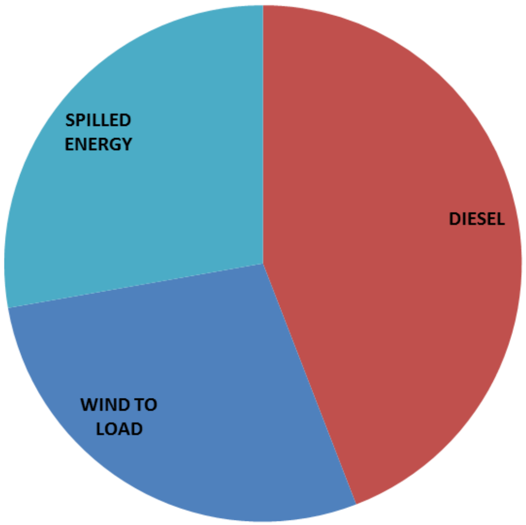
- Diesel power (> $.30/kWh)
- No natural gas
- No grid interconnection/backup

Minimize diesel use

- Displace partial load diesel
- Load balancing and reserve capacity
- Shift curtailed renewable energy

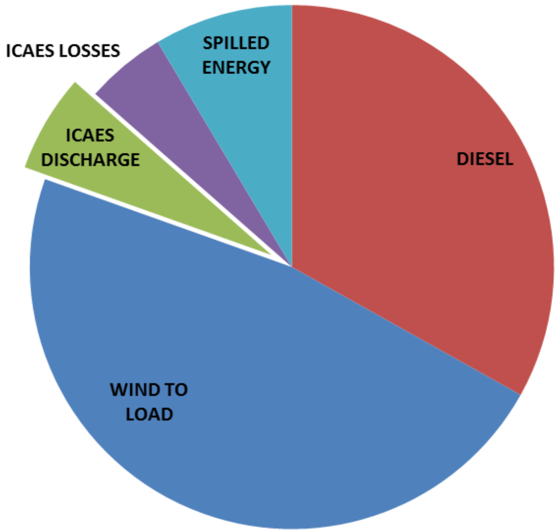
Result: ~ 30% lower diesel use

Grid Without ICAES



61% Diesel Power

Grid With ICAES



33% Diesel Power