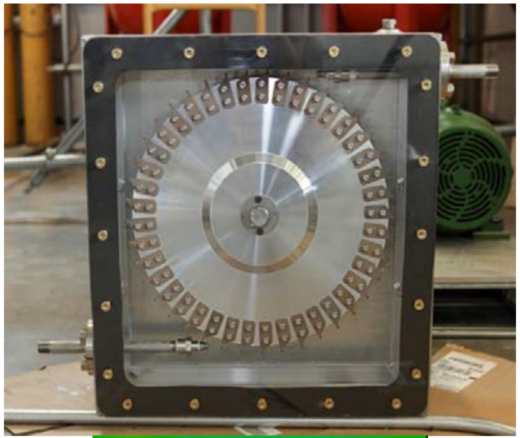
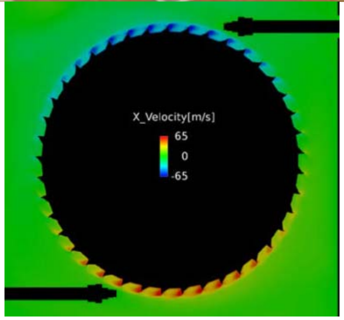
Novel Ground-Level Integrated Diverse Energy Storage (GLIDES) Coupled with Building Air Conditioning

2017 Building Technologies Office Peer Review





U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Ayyoub M. Momen, momena@ornl.gov
Oak Ridge National Laboratory

Project Summary

Timeline:

Start date: 9/1/2016

Planned end date: 8/31/2017

Key Milestones

1. Milestone 1: Identify target performance level necessary for payback ($/kWh, storage time, RTE)-12/31/2016
2. Milestone 2:Develop a subscale benchtop prototype and meet 80% of RTE and ED identified in the above milestone-9/30/2017

Budget:

Total Project $ to Date:

- DOE: $227K
- Cost Share: $11%

Total Project $:

- DOE: $500K
- Cost Share: $63.8 (11.5%)

Key Partners:

Blue Mountain Energy, Inc.
Georgia Tech (GaTech)

Project Outcome:

The outcome of this project is to demonstrate:

- Value proposition of on-demand dispatchable electricity generation based on GLIDES energy storage.
- The efficiency improvement potential of the air conditioning system (demonstrated through modeling).
- Improvement in GLIDES Round Trip Efficiency (RTE) and Energy Density (ED), compared to the existing baseline GLIDES system, upon integration to the waste heat from AC condenser.

Purpose and Objectives

Problem Statement: The technology aims to introduce a solution to the following main problems in the buildings: a) waste heat recovery, b) energy storage, and c) peak demand reduction and/or load shifting applications.

Target Market and Audience:

- Residential and Commercial buildings
- The improvement in air conditioning performance could potentially save up to 1,341 TBtu/year.

Impact of Project:

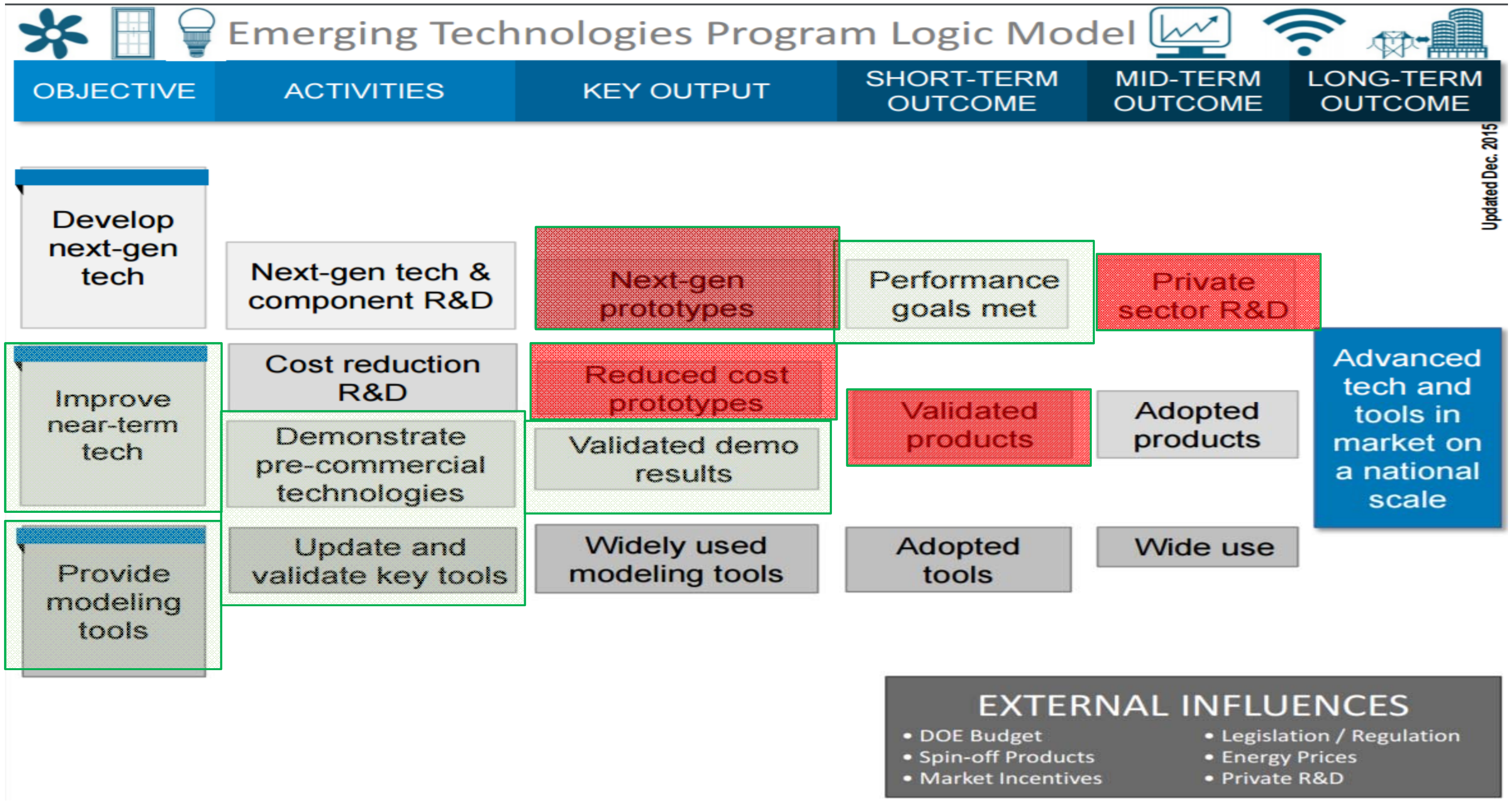
The proposed technology could provide energy storage for buildings at 75% roundtrip efficiency, while improving HVAC COP by up to 35%. The project's final products will be a prototype demonstrating the feasibility and the value proposition of the technology.

  a. Near-term outcomes will a be fully evaluated demo prototype
  b. Intermediate outcomes will be to overcome the main challenges identified
  c. Commercialization/pilot plant size demo

Approach

Short term approach under this project

5 year approach under follow up projects



Emerging Technologies Program Logic Model

OBJECTIVE	ACTIVITIES	KEY OUTPUT	SHORT-TERM OUTCOME	MID-TERM OUTCOME	LONG-TERM OUTCOME
Develop next-gen tech	Next-gen tech & component R&D	Next-gen prototypes	Performance goals met	Private sector R&D	Advanced tech and tools in market on a national scale
Improve near-term tech	Cost reduction R&D Demonstrate pre-commercial technologies	Reduced cost prototypes Validated demo results	Validated products	Adopted products	
Provide modeling tools	Update and validate key tools	Widely used modeling tools	Adopted tools	Wide use	

Updated Dec. 2015

EXTERNAL INFLUENCES
- DOE Budget
- Spin-off Products
- Market Incentives
- Legislation / Regulation
- Energy Prices
- Private R&D

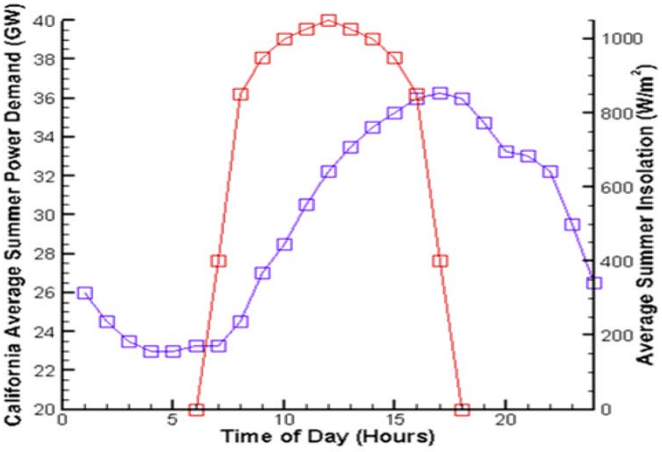
Key Issues: GLIDES is a brand new technology which requires improvement and validation to encourage private sector investment.

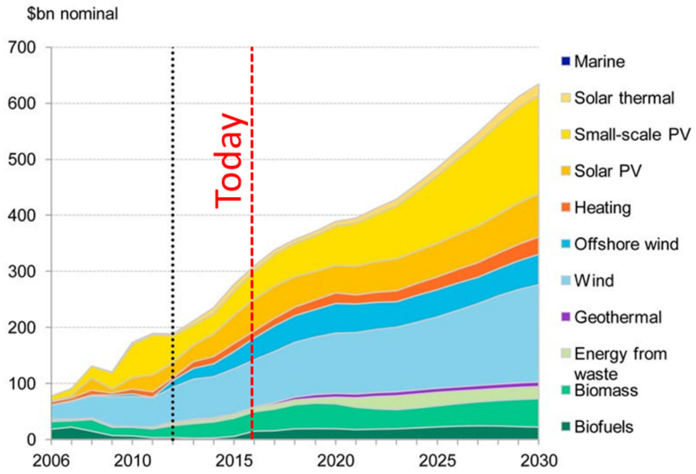
Distinctive Characteristics: Developing a reliable cost model, performance data, and identifying real world application challenges (i.e. compliance with building codes).

Technical Approach

- Renewable energy sources are naturally intermittent.
- Electricity demand charge is on the rise.
- Low-cost, high- Round-Trip Efficiency (RTE) energy storage can address the above challenges.

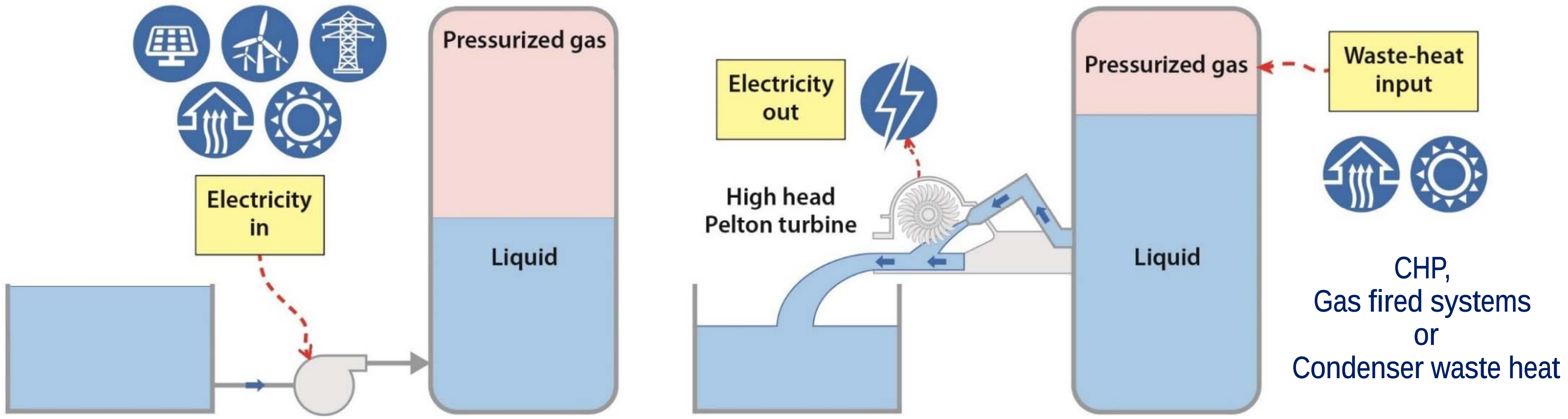
- **Off-grid buildings:**
  - Store energy from renewable sources for use during production down-times
- **On-grid buildings:**
  - Reduce peak demand
  - Reduce energy bills
  - Improve grid reliability
- **Grid support:**
  - Grid-scale energy storage/peak-load time shifting
  - Enable temporal mismatch between generation and use
  - Facilitate ‘building-to-grid’ interaction





The GLIDES Concept

Objective: Develop a unique, low-cost, high RTE storage technology for, a) small scale building applications, and b) large scale modular pump hydro storage.

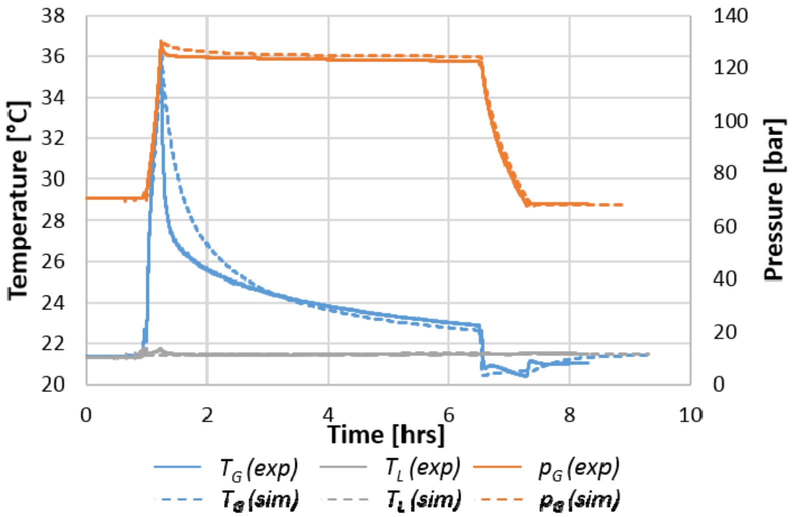


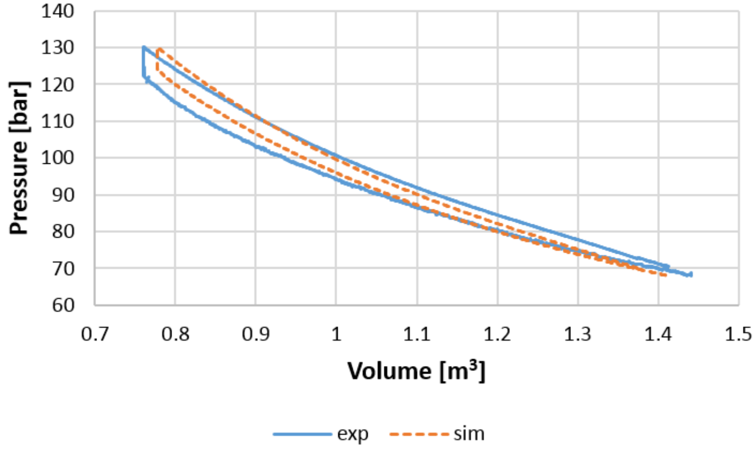
CHP,
Gas fired systems
or
Condenser waste heat

Key advantages	
Simple, low cost (expected to be at lower cost than batteries)	Dispatchable, scalable
Accepts heat and/or electricity as inputs	Decouples power/energy storage capacity
Round-trip efficiency>70%	Terrain independent

A.M. Momen, K. J. Gluesenkamp, O. A. Abdelaziz, E. A. Vineyard, A. Abu-Heiba, A. O. Odukomaiya., "Near isothermal combined compressed gas/pumped-hydro electricity storage with waste heat recovery capabilities," US Provisional Patent Application filed 09-01-2016; serial number 15/254,137.

Initial Experimental Results (system size ~ 3kWh)





	T_G [°C]	T_L [°C]	p_G [bar]
RMSE[%]	0.1	1.03	1.9

Transient Model Formulation

Gas (air) energy equation:

$$m_G c_{v,G}\frac{dT_G}{dt} = -h_{G,L}A_{G,L}(T_G - T_L) - UA_G(T_G - T_{amb}) - p_G\frac{dV_G}{dt}$$

Liquid (water) energy equation:

$$m_L c_L\frac{dT_L}{dt} = h_{G,L}A_{G,L}(T_G - T_L) - UA_L(T_L - T_{amb}) + \dot{m}_L c_L(T_{amb} - T_L)$$

Tank walls energy equations:

$$m_{T,G}c_T\frac{dT_{T,G}}{dt} = h_{i,G}A_{i,G}\left(T_G - T_{T,G}\right) - h_o A_{o,G}\left(T_{T,G} - T_{amb}\right)$$

$$m_{T,L}c_T\frac{dT_{T,L}}{dt} = h_{i,L}A_{i,L}\left(T_L - T_{T,L}\right) - h_o A_{o,L}\left(T_{T,L} - T_{amb}\right)$$

Gas (air) continuity equation: $\dfrac{dV_G}{dt} = -\dfrac{\dot{m}_L}{\rho_L}$

Liquid (water) continuity equation: $\dfrac{dm_L}{dt} = \dot{m}_L$

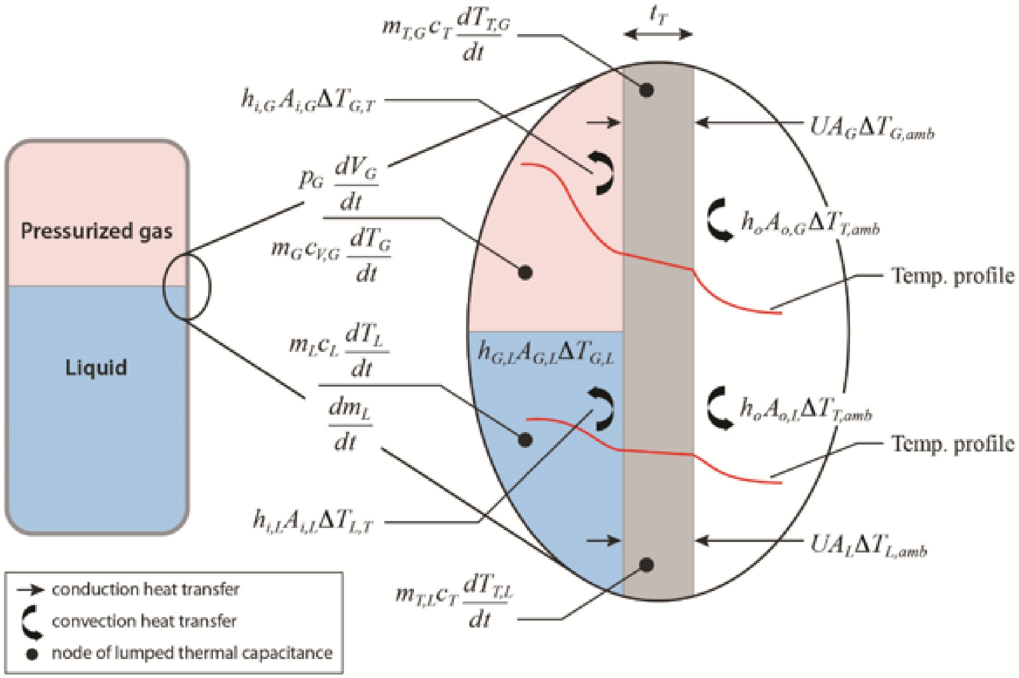
Tank wall overall conductance:

$$UA_G = \frac{1}{\left(\frac{1}{h_{i,G}A_{i,G}}\right) + \left(\frac{t_T}{k_T A_{ave,G}}\right) + \left(\frac{1}{h_o A_{o,G}}\right)}$$

$$UA_L = \frac{1}{\left(\frac{1}{h_{i,L}A_{i,L}}\right) + \left(\frac{t_T}{k_T A_{ave,L}}\right) + \left(\frac{1}{h_o A_{o,L}}\right)}$$

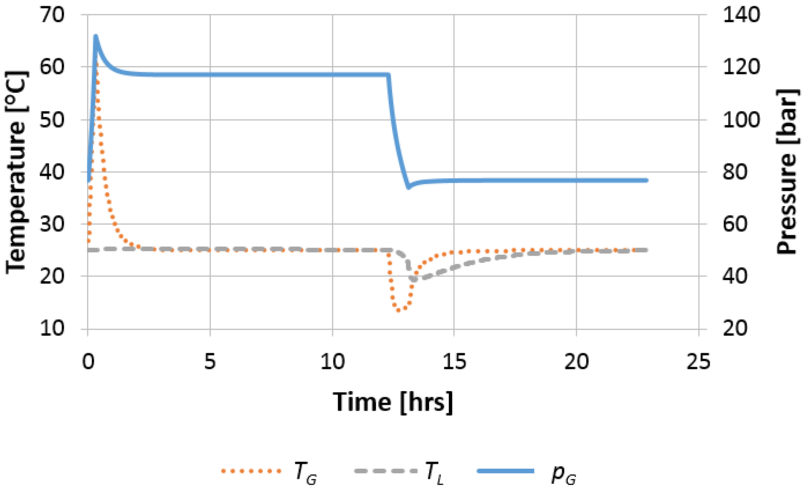
Modeling assumptions:

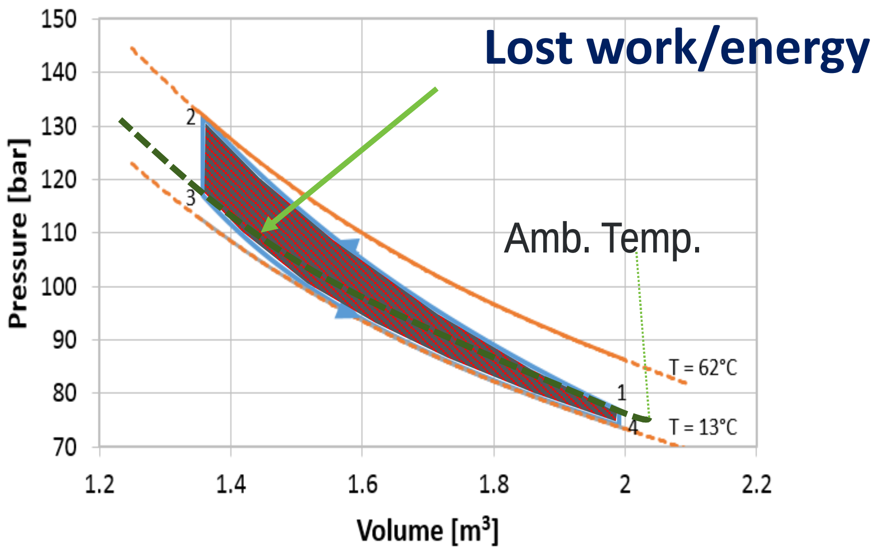
- No spatial temperature gradients
- Constant ambient temperature
- Constant thermophysical properties for tank wall
- Air behaves as a Redlich-Kwong ideal gas
- Negligible heat transfer between Tank1 and Tank2 masses
- Quasisteady processes

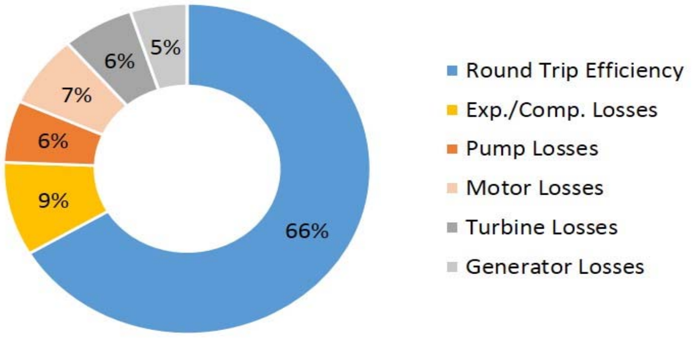


Results\Baseline

Parameter	**Description**	**Value**
$V_{gas,ini}$	Gas initial volume	2 m^3
num_{jets}	Number of Pelton turbine jets	1
T_{amb}	Ambient temperature	25°C
p_{min}	Minimum (initial) gas pressure	77 bar
p_{max}	Maximum (after charging) air pressure	132 bar
$\dot{V}_L$	Liquid pumping flow rate	35 L/min
t_{pause}	Pause time b/w charge/discharge	12 hours
$T_{G,ini}$	Initial gas temperature	25°C
$T_{L,ini}$	Initial liquid temperature	25°C
$T_{T,ini}$	Initial tank wall temperature	25°C

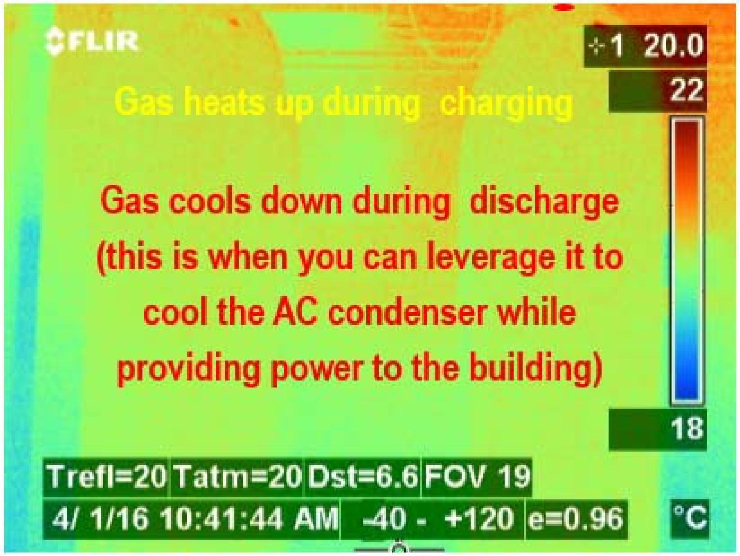






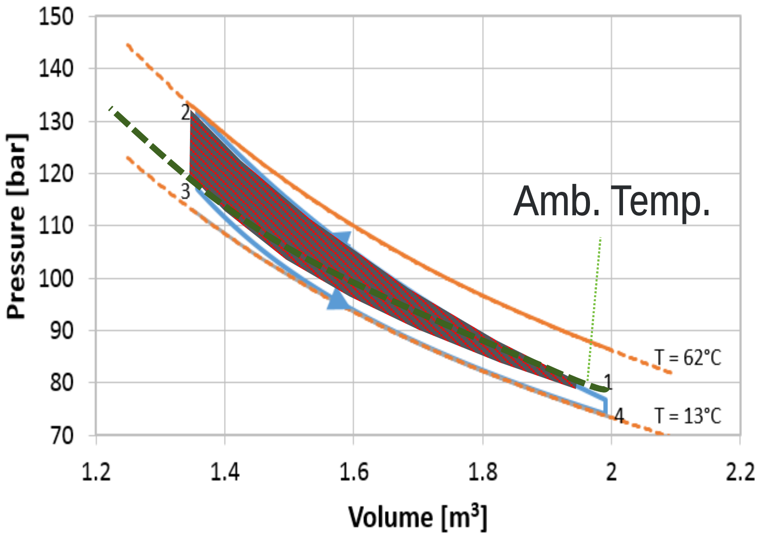
- $W_{ind,in}$ – area under curve (1-2)
- $W_{ind,out}$ – area under curve (3-4)
- $\eta_{ind} = W_{ind,out} / W_{ind,in} = 0.91$
- ED = 2.5 MJ/m^3

Videos\Baseline\Least Efficient Operation\RTE 66%



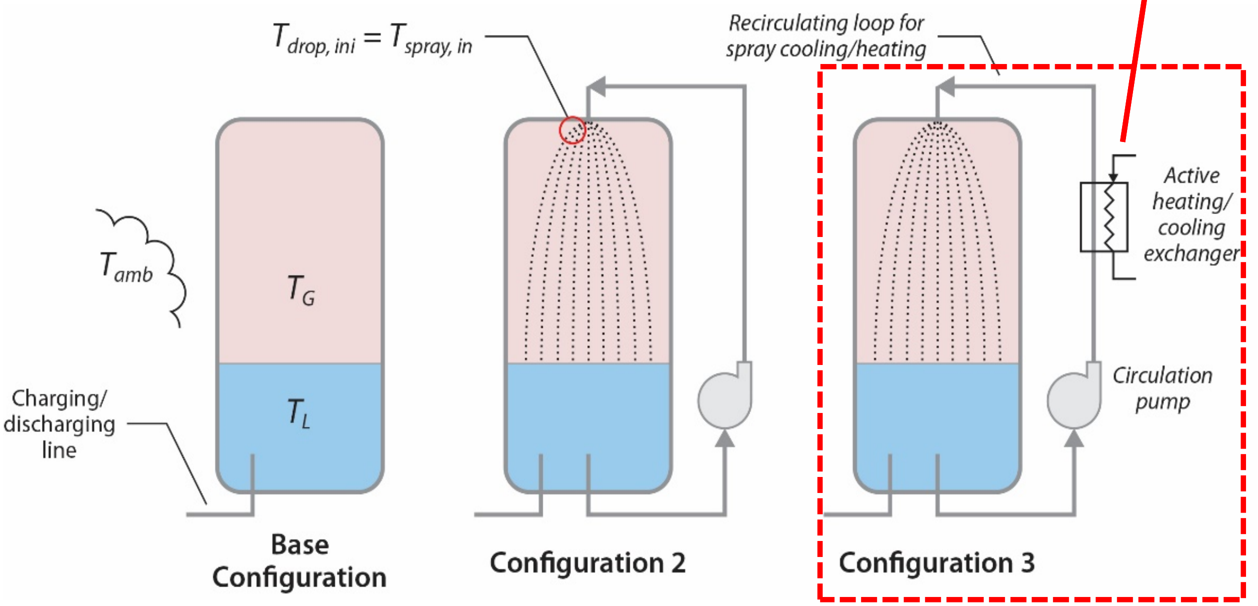
Gas heats up during charging

Gas cools down during discharge (this is when you can leverage it to cool the AC condenser while providing power to the building)



Waste-Heat Integration

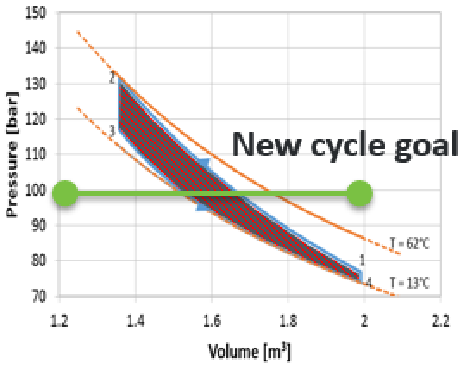
CHP, Gas-fired systems or Condenser waste heat



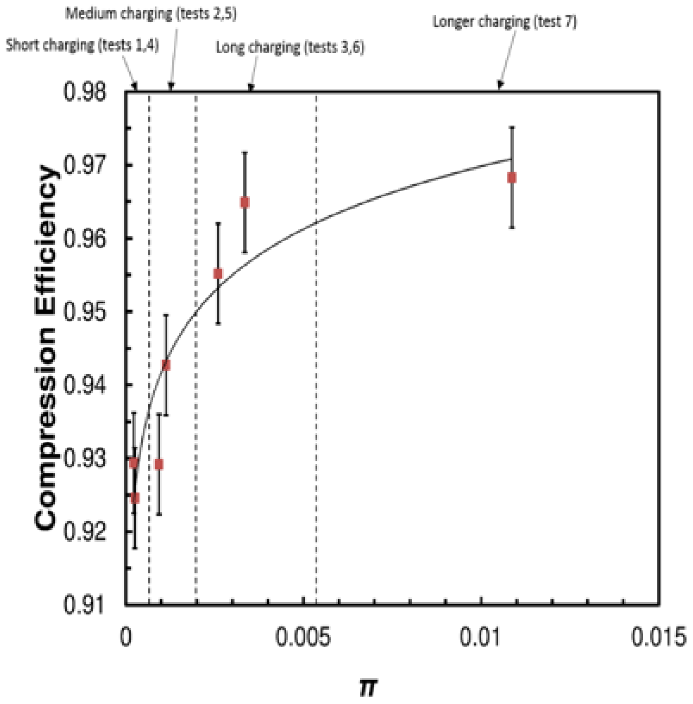
	Base Configuration (Configuration 1)	Configuration 2	Configuration 3		
			$T_{WH} = 50\ ^\circ$ C	$T_{WH} = 70\ ^\circ$ C	$T_{WH} = 90\ ^\circ$ C
η_{elec} [-]	0.66	0.70	0.75	0.78	0.82
η_{ind} [-]	0.91	0.96	1.03	1.07	1.12
ED [MJ/m^3]	2.46	3.08	3.28	3.43	3.59

Subtask 2.1: Isothermal-Isobaric Storage Using Condensable Gas

- Replace air with condensable gas
- Improve ED
- Constant pressure
  - Larger volume displacement
- Tested on small scale using R134a and oil



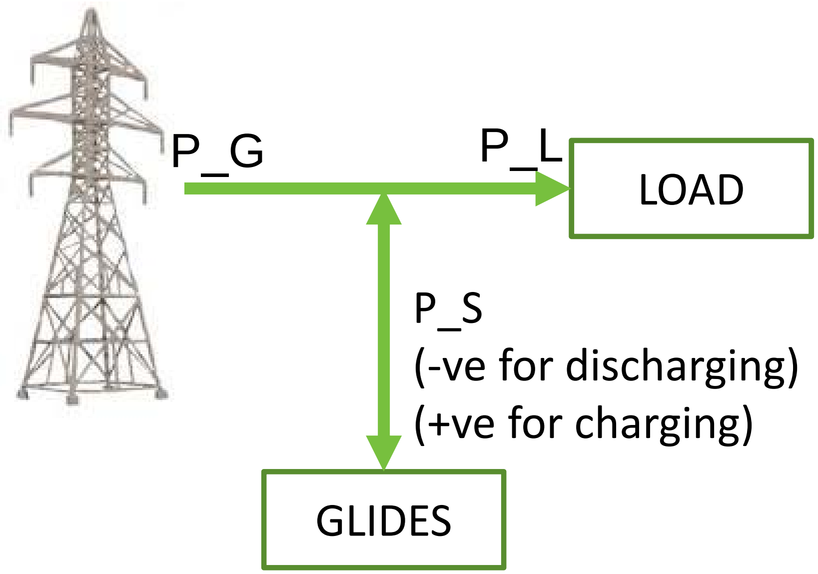
$$\eta_{comp} = \frac{isobaric\ dimensionless\ work\ input}{actual\ dimensionless\ work\ input} = \frac{p_0^*(V_c^* - V_0^*)}{\int_0^c p^* dV^*}$$



$$\frac{dV^*}{dt^*} \approx \frac{UA(T_{sat} - T_{\infty})t_{charge}}{\rho_{sat,v} h_{fg} V_0} = \pi$$

Task 1.3: Outline the Performance Level Necessary for Payback

- P_G(t) = P_S(t) + P_L(t)
- Minimize summation of P_G for the whole year
- At 15 min intervals:
  - 96 steps/hour
  - 96x365 steps/year



P_G

P_L

LOAD

P_S

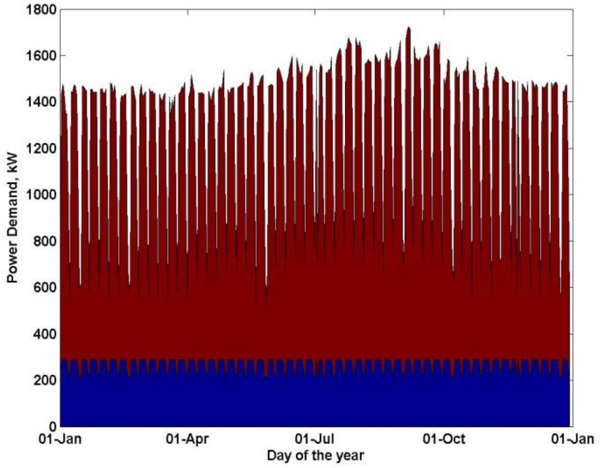
(-ve for discharging)

(+ve for charging)

GLIDES

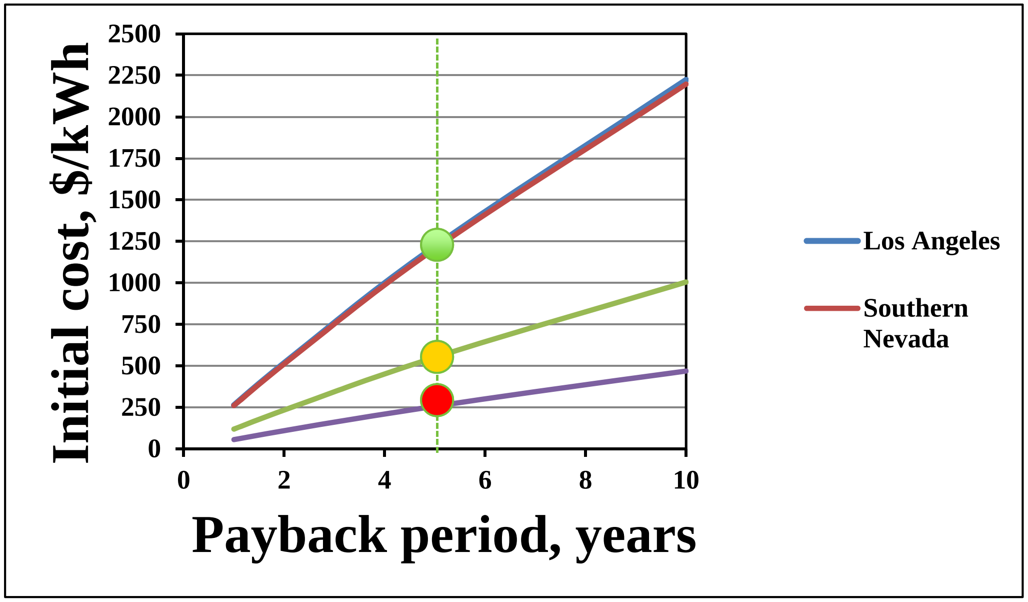
Electricity rate structure in Los Angeles, CA

Monthly charge, $	246.33	Tax	8%
	Time of use	$/kWh	$/kW
From 1/1 to 5/31 and from 10/1 to 12/31	from 0:00 to 8:00	0.01676	7.58
	from 8:01 to 21:00	0.01676	7.58
	from 21:01 to 24:00	0.01676	7.58
From 6/1 to 9/30	from 0:00 to 8:00	0.01676	7.58
	from 8:01 to 12:00	0.01676	8.34
	from 12:01 to 18:00	0.01676	16.42
	from 18:01 to 23:00	0.01676	8.34
	from 23:01 to 24:00	0.01676	7.58
All weekends	from 0:00 to 24:00	0.01676	7.58

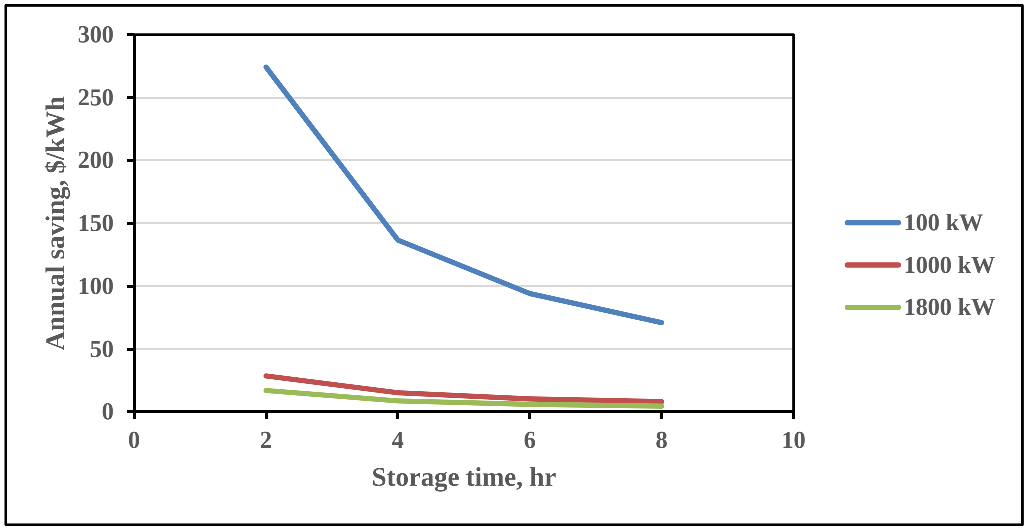


Task 1.3: Outline the Performance Level Necessary for Payback

Maximum economically-viable initial cost at different payback periods for the <u>large office Department of Energy reference building</u>.



Annual savings divided by kWh of GLIDES for different system sizes and capacities in Los Angeles, California.



General trend suggests small storage capacity (i.e. 1 hr.) has much better economical feasibility than the larger capacity storage, so all that is needed is to eliminate intermittent spikes in the demand.

Progress and Accomplishments

Accomplishments:

During the last 4 months, a cost model was developed which helped to identify the metrics needed to be met for the payback in large office buildings.

Preliminary test results collected for alternative design (condensable gas).

Market Impact:

	Lead acid battery	Proposed technology
Energy storage cost $/kWh	$350–600 (replacement needed every 3–5 years)	$180–300 (no replacement needed)
Storage efficiency %	70–85	70–82%
HVAC COP improvement	0%	~35%
2030 national energy savings[9] due to enhanced COP	0	1,341 TBtu

Awards/Recognition:

A. M. Momen, K. J. Gluesenkamp, O. A. Abdelaziz, E. A. Vineyard, A. Abu-Heiba, A. O. Odukomaiya., “Near isothermal combined compressed gas/pumped-hydro electricity storage with waste heat recovery capabilities,” US Provisional Patent Application filed 09-01-2016; serial number 15/254,137.

B. Odukomaiya, Wale O.; Abu-Heiba, Ahmad; Gluesenkamp, Kyle R.; Abdelaziz, Omar; Jackson, Roderick K.; Daniel, Claus; Graham, Samuel; Mehdizadeh Momen, Ayyoub (ORNL) Thermal analysis of near-isothermal compressed gas energy storage system. *Applied Energy*. 179 (October 2016) 948-960.

C. Wale Odukomaiya, Ayyoub M. Momen, Kyle Gluesenkamp, Omar Abdelaziz, Samuel Graham, Transient thermofluids analysis of a Ground-Level Integrated Diverse Energy Storage (GLIDES) System, IMECE2015-50478.

Lessons Learned:

Cost analysis shows that more than 70% of the system cost belongs to the cost of the pressure vessels.

Project Integration and Collaboration

Project Integration:
- Weekly meetings between ORNL team members
- Bi-weekly meetings between ORNL, Blue Mountain Energy and GaTech

Partners, Subcontractors, and Collaborators:
ORNL → ED, RTE improvement, cost model, system design, and prototype testing
Blue Mountain Energy → Prototype development and cost model

Communications:
- Applied Energy Journal
- ASME IMECE
- ASHRAE
- Leadership from congressional staff briefed on the technology

Next Steps and Future Plans

Next Steps:

- Complete cost model
- Alternative design improvement (condensable gas)
- Prototype design
- Prototype development
- Prototype evaluation

Future Plans:

- Demonstrate the prototype in events
- Find interested parties who are willing to invest and take the technology to the next phase

REFERENCE SLIDES

Project Budget

Project Budget: DOE total $500k
Cost share $63.8

Variances: None

Cost to Date: $227k

Additional Funding: None

Budget History					
FY 2016 (past)		FY 2017 (current)		FY 2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
0	0	$500k	10%	0	0

Project Plan and Schedule

Project Schedule												
Project Start: Oct 2016	🟦	Completed Work										
Projected End: Sept 2017	⬛	Active Task (in progress work)										
	♦	Milestone/Deliverable (Originally Planned) use for missed										
	◆	Milestone/Deliverable (Actual) use when met on time										
	FY2013				FY2014				FY2015			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Q1 Milestone: Identify target level for payback	🟦 ◆											
Current/Future Work												
Q2 Milestone: Compile building code warranty compliance	⬛	⬛ ◆										
Q3 Milestone: Develop improved system design to meet targes set in task 1	⬛	⬛	⬛ ◆									
Q4 Milestone: Develop of a subscale prototype and meet 80% RTE and ED in task 1		⬛	⬛	⬛ ◆								