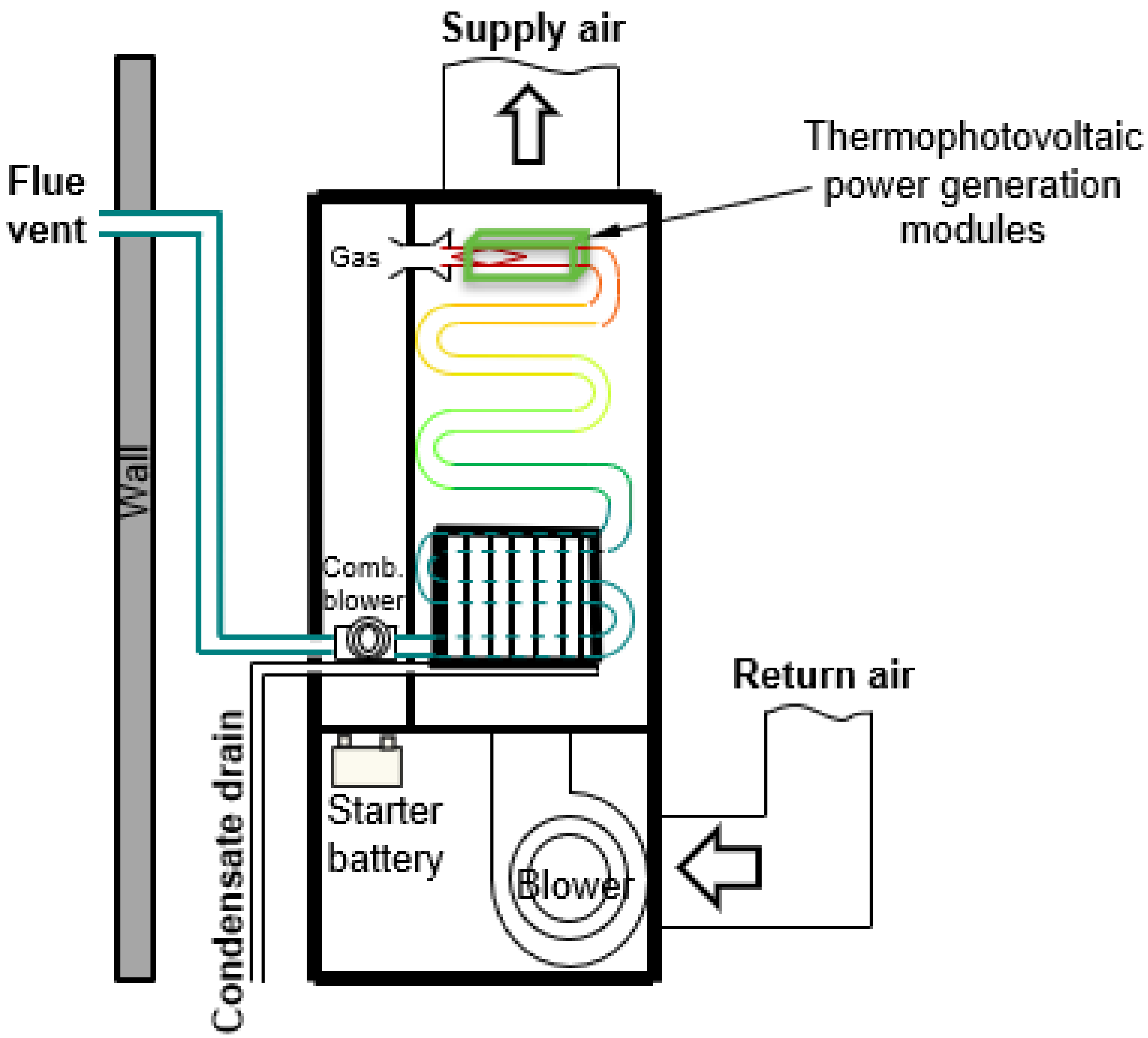
Self-Powered Furnace



Oak Ridge National Laboratory
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Project Summary

Timeline:

Start date: 10/1/2018

Planned end date: 9/30/2021

Key Milestones

1. Design combustion system (9/20/2020)
2. TPV cells and emitter integrated in lab (3/31/2021)

Budget:

Total Project $ to Date:

- DOE: $785k
- Cost Share: $0

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Key Partners and Contacts:

MTPV Power Corporation (thermophotovoltaic systems manufacturer)
Southern California Gas
Antora Energy
Gas Technology Institute

Project Outcome:

Demonstrate **resilient**, self-powered furnace with **higher energy efficiency** than conventional condensing furnaces. Demonstrate the concept to provide energy security and lower operating cost without the installation, maintenance, and fueling requirements of backup gensets.

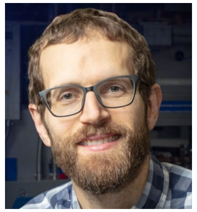
The new furnace will generate all electric power required for its operation and air distribution via an internal power cycle.

- A new, **readily retrofittable**, replacement furnace
- High level of **consumer resilience** in power outages due to single utility connection
- Eliminates grid power consumption from the furnace, thus improving **grid resilience**

The new technology will elevate fleet efficiency of space heating, with a technical potential of **190 TBtu/yr**.

Team

- **Team expertise**
  - Furnace design and evaluation
  - Thermophotovoltaic systems design and manufacturing
  - Natural gas engines, power cycles and combined heat and power systems
- **Resources**
  - State-of-the-art facilities for heat transfer R&D, including extensive heat transfer and thermodynamic measurement capabilities
  - Dedicated furnace evaluation chamber
  - Natural gas calorimeter



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Challenge

38% of US households use gas furnaces for space heating.

These furnaces consume both electricity and natural gas, with implications for:

- **Consumer safety and resilience:** power outage = no heat
  - Consumers experience significant expenses resulting from power outages (frozen pipes, hotel stays, backup generators, food spoilage)
- **Efficiency:** grid efficiency impacts the total primary energy utilization efficiency
  - PER: primary energy ratio. Heating energy delivered per unit total primary energy consumed.
  - GUE: gas utilization efficiency. Fraction of gas energy turned into useful heat. (AFUE)

Conventional furnace technology	GUE	PER
Non-condensing	82%	0.768
Condensing	92%	0.859

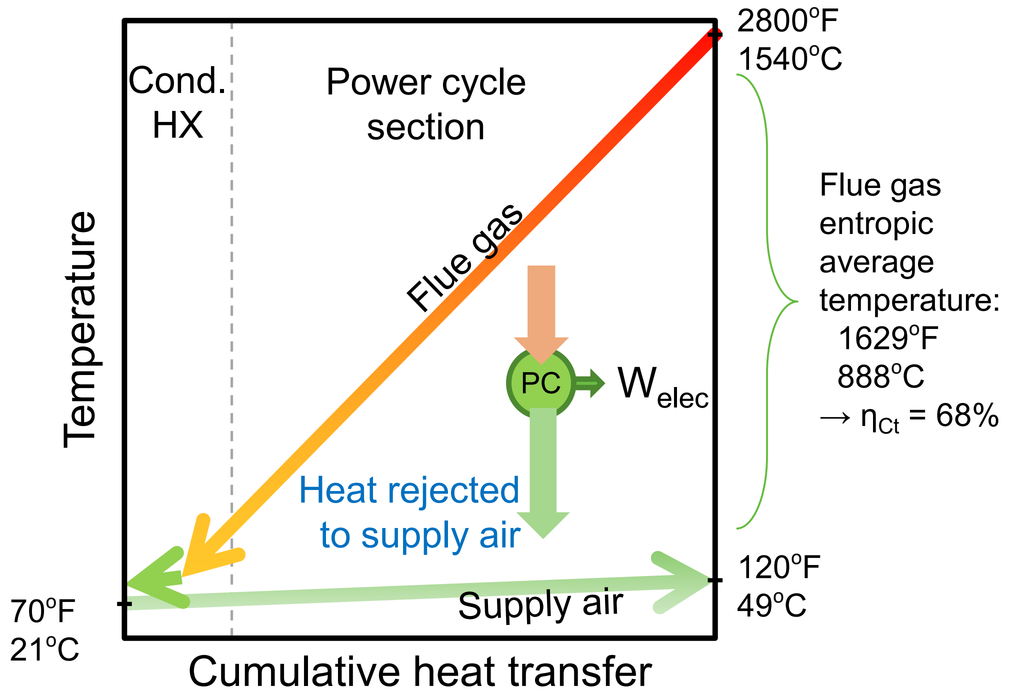
Primary energy ratio for today's furnaces is 5 to 6% lower than nameplate efficiency

- **Peak demand (grid resilience):** Furnace electricity consumption adds to winter peak grid demand.
  - Peak demand in the Southeast shifted from summer to winter during the last two decades.

Approach

Rather than import electricity from the grid to meet the furnace's electric loads (fans, ignitor, and controls), a power generation cycle is integrated into the furnace: a "self-powered furnace."

Furnace technology	GUE	PER
Non-condensing	82%	0.768
Condensing	92%	0.859
Condensing, self-powered	92%	0.920



For a furnace, the minimum required power cycle efficiency is only 1 to 4%.

Approach – Plan

Design

- Identify most suitable power cycle for the application
- Conceptual design and thermal analysis of the integration

Prototyping

- Engineering design of the self-powered furnace
- Demonstrate working prototype and evaluate its performance in the laboratory

Commercialization

- Ongoing throughout the project
- Engage stakeholders for technology development, maturation and commercialization
- Opportunity for both component OEMs and furnace OEMs

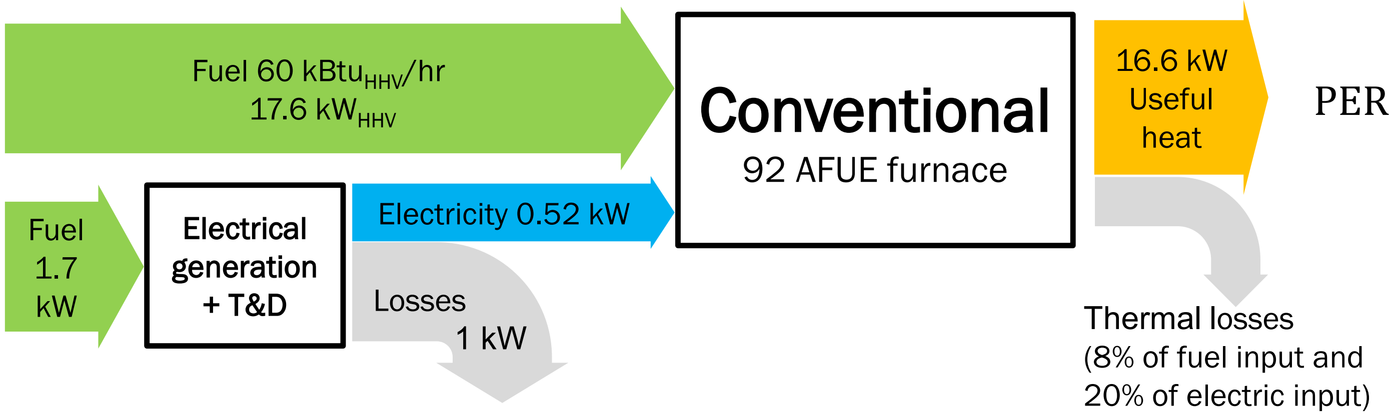
Impact – Highest Performing Furnace System

Best resilience and lowest utility cost

System type	Performance		
	Duration of heating during power outage	Energy (utilities) cost	Maintenance requirements
Baseline furnace	None	High	None
Baseline with backup generator	Unlimited	Highest	High
Baseline with backup battery	Limited	High	Moderate
Self-powered furnace	Unlimited	Lowest	None (goal)

Impact – Energy Benefits

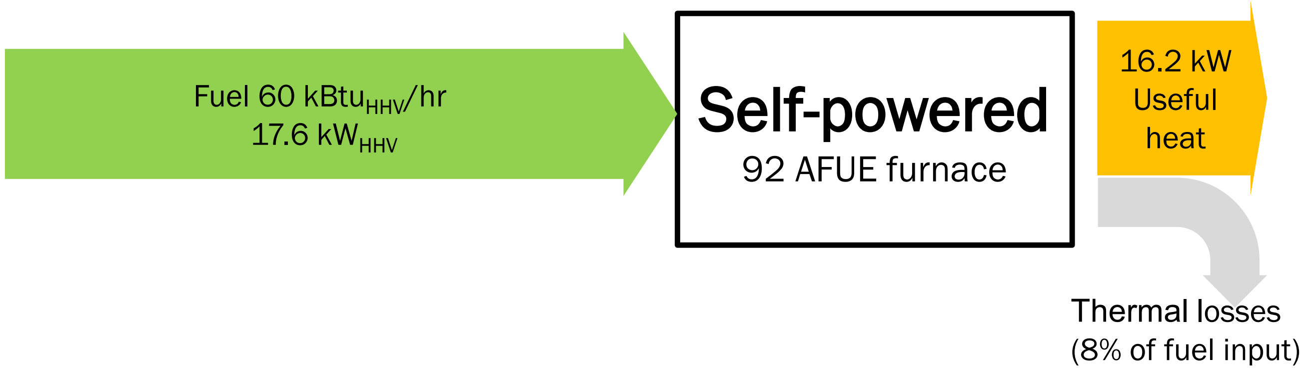
- Self-powered furnace technology enables more resilient and efficient furnace operation
  - Higher primary energy efficiency at same AFUE
  - No consumption of electric grid power



$$\text{PER} = \frac{16.6}{17.6 + 1.7} = \mathbf{0.86}$$

Generalized expression:

$$PER = \frac{GUE}{1 + \kappa\left(\frac{GUE}{\eta_g} - \alpha\right)}$$



$$\text{PER} = \frac{16.2}{17.6} = \mathbf{0.92}$$

$$PER = \frac{GUE}{1 + \kappa(1 - \alpha)}$$

Equations derived in:
Gluesenkamp, et al. (2021)
"Self-powered Heating: Efficiency Analysis"

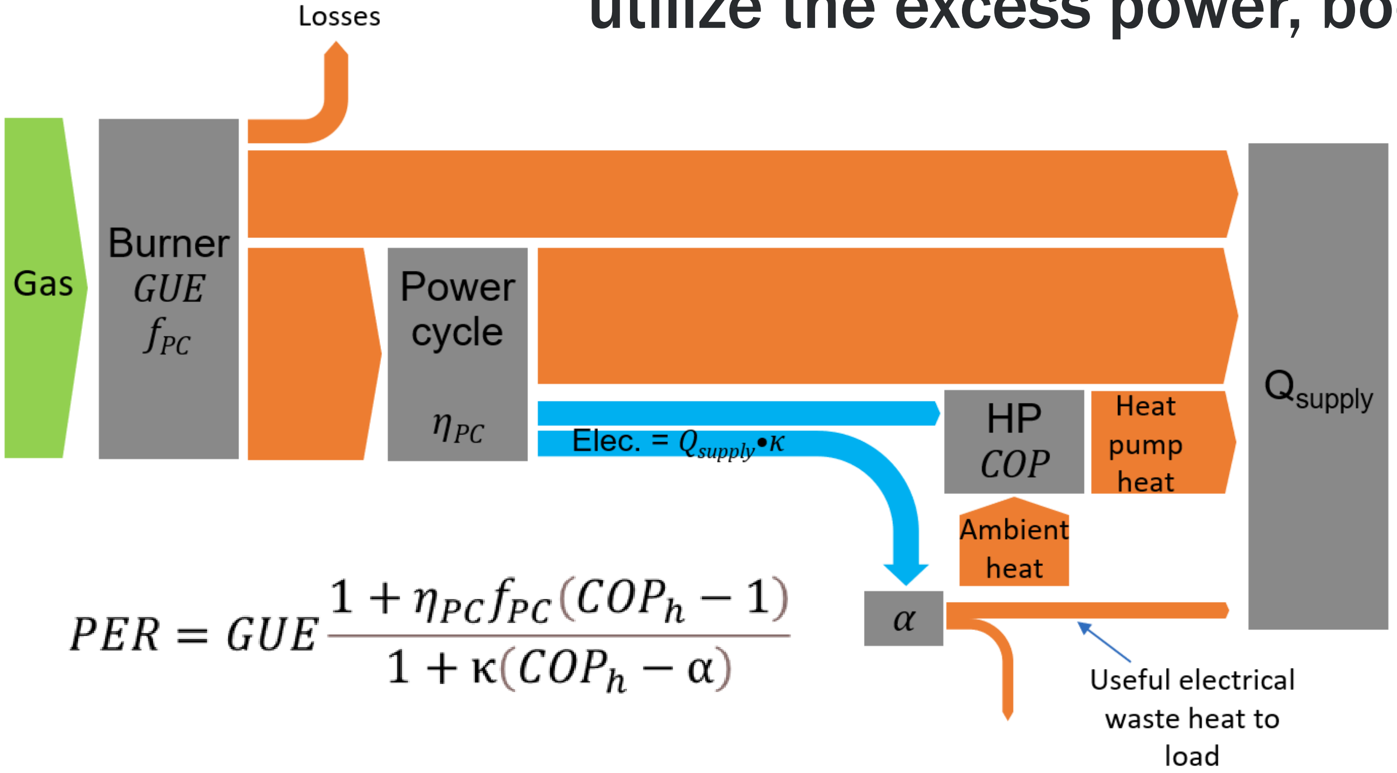
Impact – technology development and commercialization

- **Lab R&D de-risks technology for furnace OEMs. Impact on other stakeholders.**
  - *Power cycle manufacturers*: see potential to reconfigure cycle for unique design needs of self-powered furnace
  - *Furnace OEMs*: see potential to offer a unique and very strongly differentiated product to consumers
  - *Installers*: differentiated product with upsell and early upgrade potential
  - *Utilities, efficiency program developers*: opportunity to support a technology providing popular consumer benefits, delivering peak electric demand reductions, unprecedented natural gas efficiency
  - *Homeowners*: observe benefits of low-maintenance, readily retrofitted unit enhancing power outage resiliency

The BTO Multi-Year Program Plan, HVAC/WH/Appliances Strategies:
"R&D Strategy—**Next-Generation Technology Development**: Develop the next generation of technologies that represent entirely new approaches and cost-effectively achieve significant performance improvement." …with emphasis on grid resiliency and improved efficiency.
(https://www.energy.gov/sites/prod/files/2016/02/f29/BTO%20Multi-Year%20Program%20Plan%20-%20Final.pdf)

Impact: Potential for SPF with AFUE>100%

If a higher efficiency generator is used, a vapor compression heat pump can utilize the excess power, boosting efficiency.

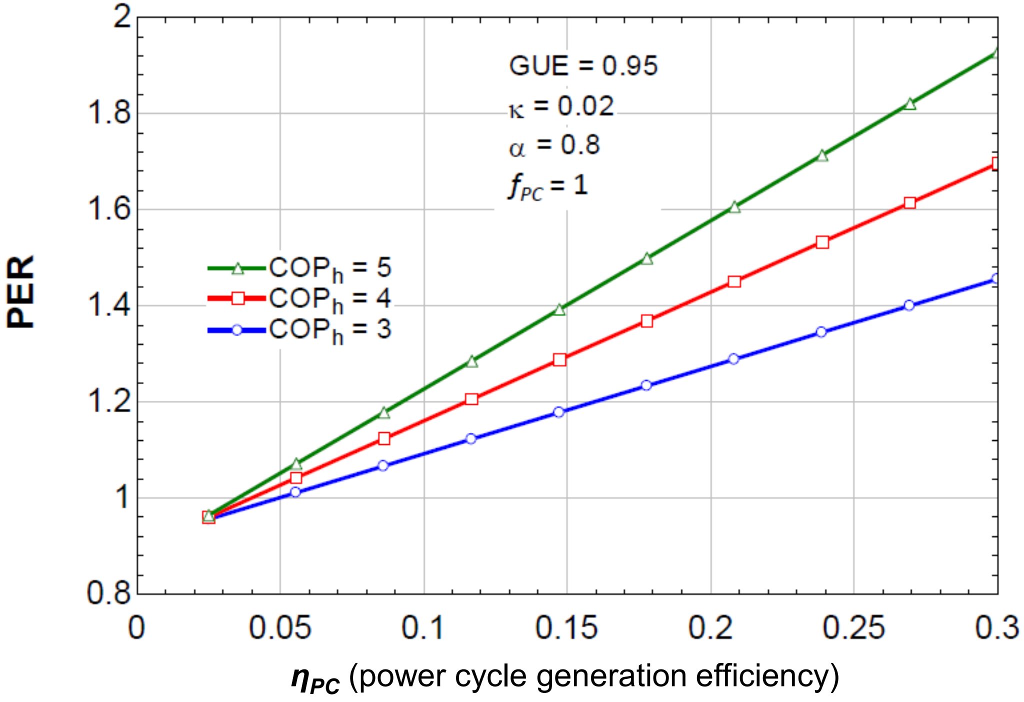


$$PER = GUE \frac{1+\eta_{PC} f_{PC}(COP_h - 1)}{1+\kappa(COP_h - \alpha)}$$

$$GUE = \frac{UsefulHeatFromFuel}{InputRating}$$

$$\kappa = \frac{ElectricalConsumption}{InputRating}$$

$$\alpha = \frac{UsefulElecWasteHeat}{ElectricalConsumption}$$



Published in: Gluesenkamp, Kyle R.; Tim J. LaClair, Praveen Cheekatamarla, Ahmad Abu-Heiba (2021). "Self-powered Heating: Efficiency Analysis," ***18th International Refrigeration and Air Conditioning Conference***, virtual online, May 24-28, 2021.

Progress – power cycle selection

TPV selected for prototyping

Config-uration	Technology	Sub-category	NOx, CO emissions	Noise	Maintenance interval	Rapid cycling	Heat exchanger requirements	TRL	$/W
Topping cycles	ICE (internal combustion engine)	4-stroke recip.	Moderate[1]	High	Poor to acceptable [3]	V. good	Good[4]	7-9	$$
		2-stroke recip.	V. high	High	Poor to acceptable	V. good	Good[4]	7-9	$
	Fuel Cell	SOFC (Tubular)	Undetectable NOx, CO<2ppm	Low	Good (Yearly)	Good	Excellent (all heat in exhaust)	7-9	$$$
		PEMFC	Low	Low	Good	Poor[1]	Moderate	6-9	$$$
	MT (microturbine)		Moderate1	V. High	Good	Good	Excellent (all heat in exhaust)	6-9	$$
	TPV (thermophotovoltaic)		**Low**	**None**	**Good**	**Good**	**V. good**	**4-7**	**$$$**
Heat engines	Thermoelectric	BiTe, SiGe	None	None	V. Good	Moderate	Good[5]	5-8	$$$
	MHD (magnetohydrodynamic)		High or None[2]	None	Long	V. Good	Good[5]	5	$$$$
	Stirling		None	Low	Poor	Moderate	Poor[5]	6	$$$
	ORC (organic Rankine cycle)		None	Low	Long	V. Good	Poor[5]	8	$$$
	Thermionic		None	None	Long	V.Good	Good	5	$$

[1] can be mitigated by feeding the exhaust to the main combustors

[2] when configured as bottoming cycle, it does not produce emissions

[3] 10 – 5000 hr (high end reflects engines optimized for long maintenance intervals)

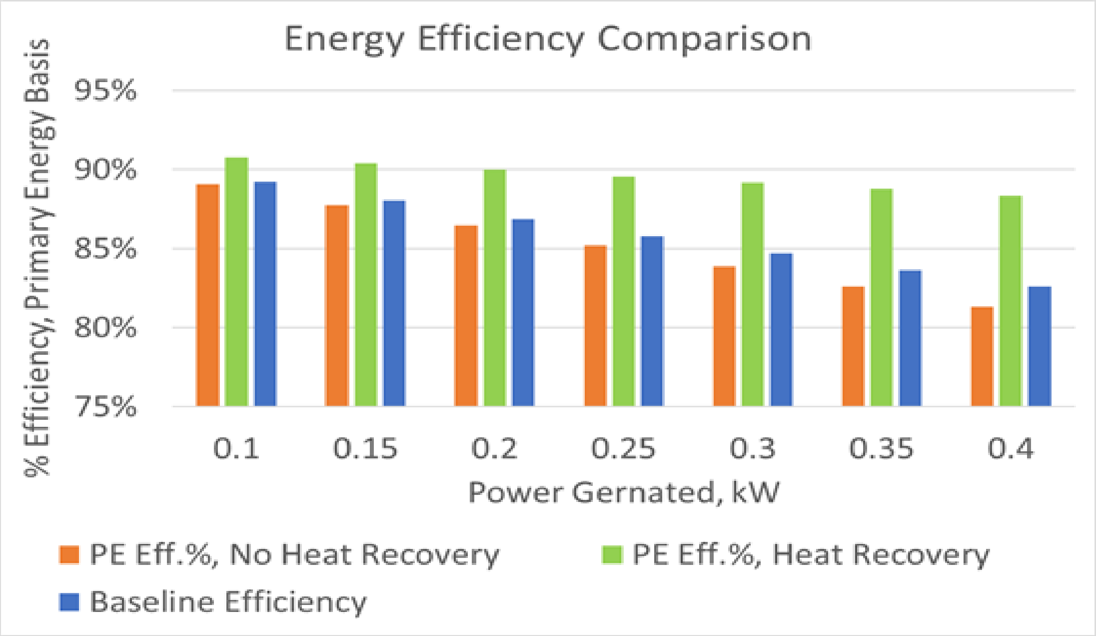
[4] 50% of heat rejected in exhaust; air cooling is feasible for the remainder

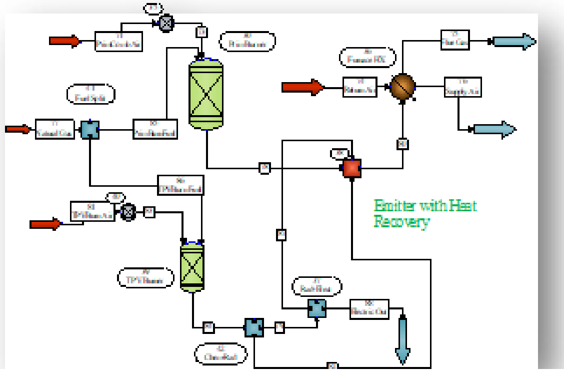
[5] all heat engines must reject their heat to the supply air stream through a heat exchanger. The better requirements are when the heat rejection temperature can be very high.

An adapted version published in: Ahmad Abu-Heiba, Kyle R. Gluesenkamp, Tim J. LaClair, Praveen Cheekatamarla, Jeff Munk, John Thomas, Philip Boudreaux (2021). "Analysis of power conversion technology options for a self-powered furnace," ***Applied Thermal Engineering***, Volume 188, April 2021, 116627.

Progress - modeling

- Integrated TPV-Furnace system modeling
- Primary energy efficiency improvement compared to the baseline system at different power output levels
- Heat recovery from the power module impact on overall system design and integration analyzed

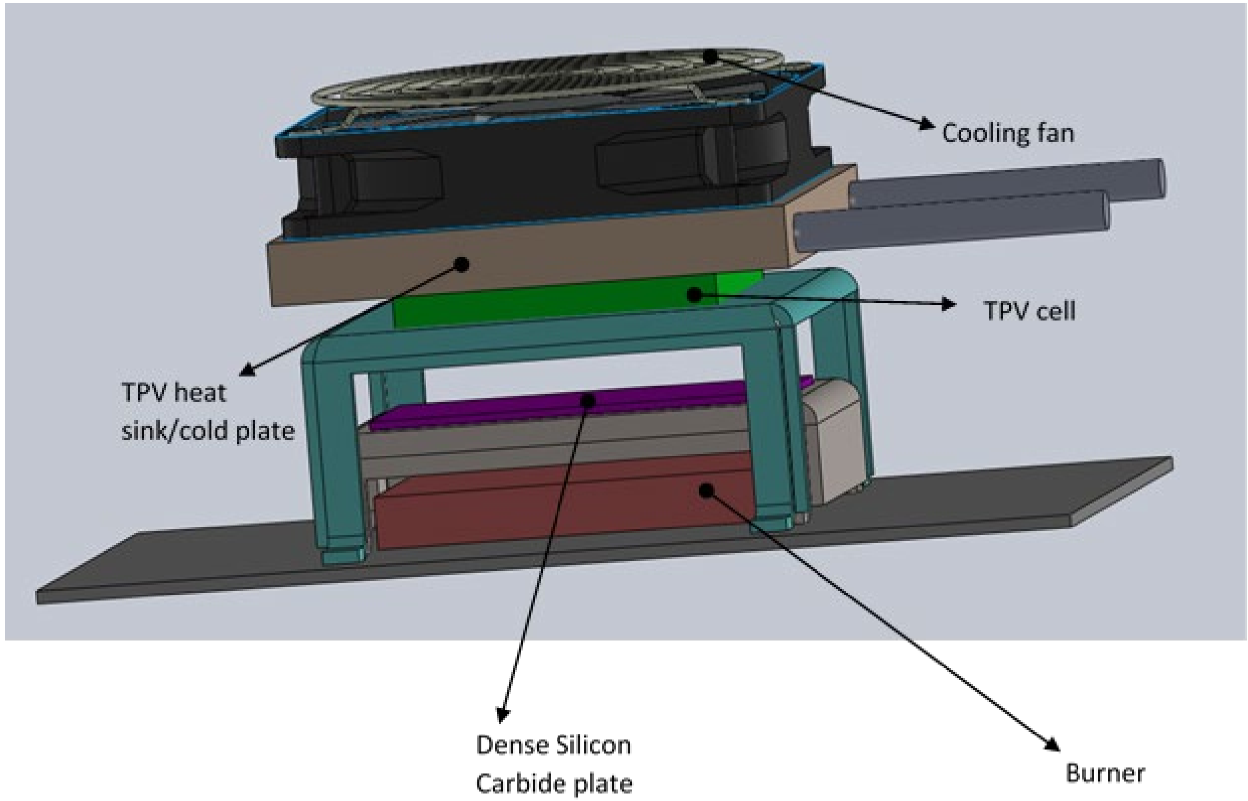


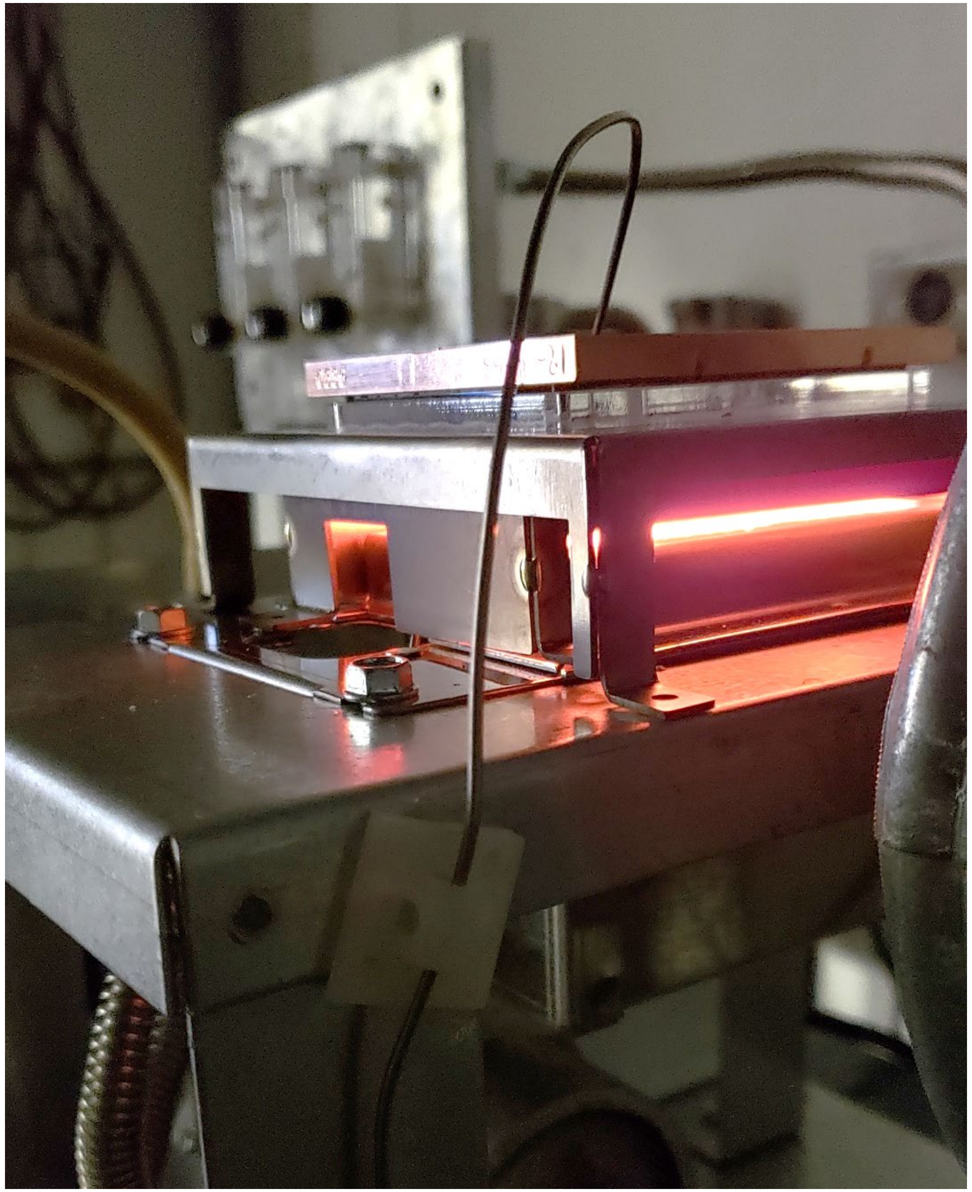


Screenshot of ChemCAD user interface, ORNL's TPV-furnace model

Progress - TPV benchtop evaluation

- Designed, fabricated and commissioned a single cell TPV module testing platform
- Burner, SiC emitter, and TPV cell are integrated
- Evaluation in progress





Progress: project timeline

FY18

- Survey of power generation technologies and choice of TPV
- **MTPV, a TPV manufacturer identified for CRADA partnership**
- Engineering analysis of TPV integration into furnace

FY19

- Identified donor furnace
- Measurement of baseline furnace power
- **Negotiated CRADA terms and scope with MTPV**
- Self-powered furnace prototype specifications developed
- **CRADA re-negotiated with additional partner (3-way CRADA)**

FY20

- **3-way CRADA SOW finalized and sent to DOE for approval**
- Heat transfer requirements analysis performed
- **MTPV went out of business (pandemic)**
- Combustion system design developed, and components procured

FY21

- New TPV subcontractor identified
- TPV cells and emitter integrated ready for evaluation
- New CRADA pursued but not finalized due to changing priorities
- Final reporting

Selected project outcomes:

- Established models of generic self-powered systems (applies to any generating technology) and TPV SPF
- Developed modeling framework to evaluate CO2 benefit of the technology: has CO2 emissions benefit in certain locations
- Acquired TPV cells from MTPV, operational with planar burner
- Low power cycle efficiency requirement of (1 to 4%) presents a **market entry opportunity** for future low-cost power cycle technologies

Stakeholder Engagement – Dissemination

- Ahmad Abu-Heiba, Kyle R. Gluesenkamp, Tim J. LaClair, Praveen Cheekatamarla, Jeff Munk, John Thomas, Philip Boudreaux (2021). "Analysis of power conversion technology options for a self-powered furnace," *Applied Thermal Engineering*, Volume 188, April 2021, 116627.
- Gluesenkamp, Kyle R.; Tim J. LaClair, Praveen Cheekatamarla, Ahmad Abu-Heiba (2021). "Self-powered Heating: Efficiency Analysis," *18th International Refrigeration and Air Conditioning Conference*, virtual online, May 24-28, 2021.
- LaClair, Tim J.; Kyle R. Gluesenkamp, Hsin Wang, Ahmad Abuheiba, Praveen Cheekatamarla, Sandeep Alavandi, Hamid Abbasi, David Cygan, Alexander Kirk, Uttam Ghoshal (2021). "Material Selection and Sizing of a Thermoelectric Generator (TEG) for Power Generation in a Self-Powered Heating System," **6th International High Performance Buildings Conference**, virtual online, May 24-28, 2021.
- Gluesenkamp, Kyle R. (2019). " Drop-in, Retrofit Furnace with Maximum Efficiency – Self Powered System." DOE Building Technologies Office *7th Annual Peer Review*, April 15–10, 2019, Crystal City, Virginia.
- submitted seminar for ASHRAE Winter Conference, Las Vegas 2022, sponsored by TC6.10

Stakeholder Engagement – Outreach

- **TPV manufacturers**
  - Antora Energy (explored subcontract – project redirected)
  - MTPV (negotiated CRADA – company went out of business)
    - acquired TPV cells from MTPV. Available for further testing in a benchtop environment, and operational with planar burner
  - JX Crystals
- **Utilities**
  - SoCalGas (explored 3-way CRADA with MTPV)
- **Others**
  - University of Michigan (explored subcontract – project redirected)
  - GTI (proposed parallel work – successfully **funded** through BTO FOA)
  - Army Research Lab (Mike Waits)

Remaining Project Work

Illustrate to OEMs, suppliers, and consumers:

an easily-retrofitted furnace option with resilience and the highest gas efficiency

- Finalize analysis
  - Experimentally characterize performance of TPV module in benchtop setup
  - Analyze of performance feasible for SPF with heat pump
- Finalize reporting and dissemination
  - Publish final results
  - Outreach to furnace OEMs to communicate findings

Thank you

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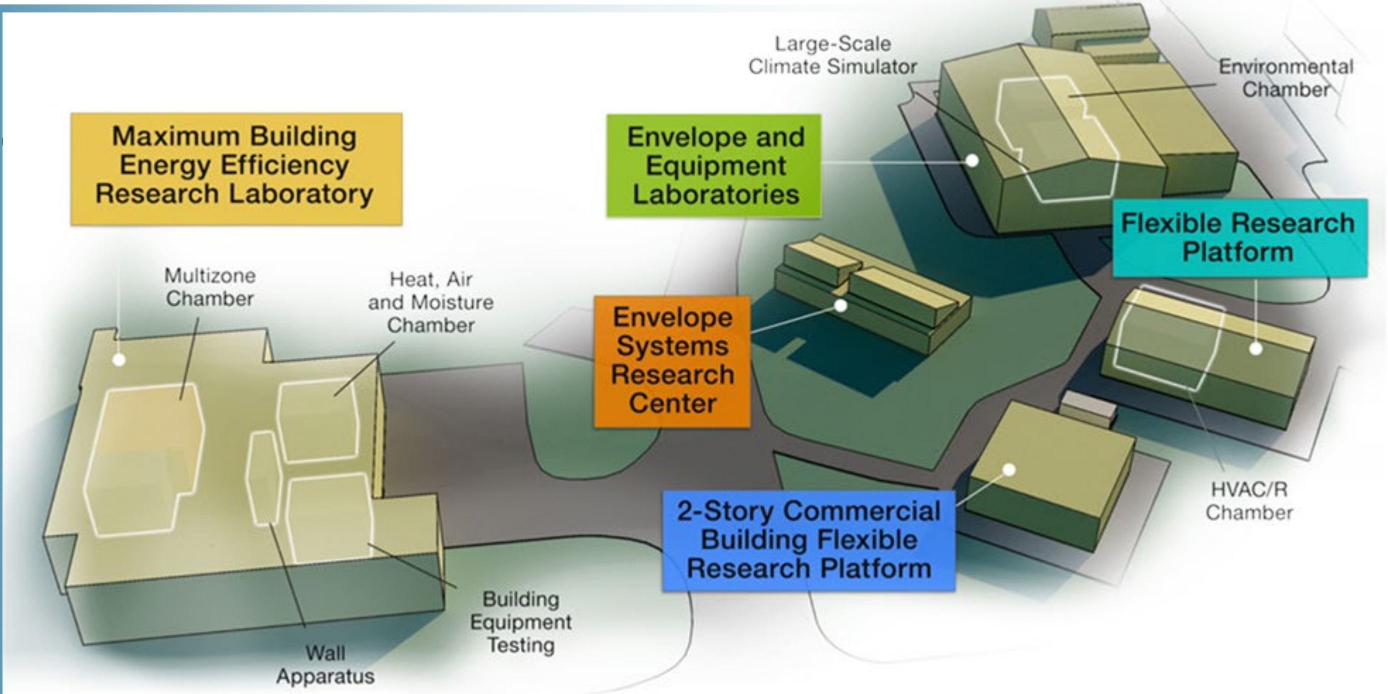

ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 50,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results
238 publications in FY20
125 industry partners
27 university partners
10 R&D 100 awards
42 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Budget

Project Budget: 785k
Variances: none
Cost to Date: 685k
Additional Funding: none

Budget History			
FY2018 – FY 2020 (past)		FY 2021 (current)	
DOE	Cost-share	DOE	Cost-share
$550k	$0k	$285k	$0K

Project Plan and Schedule