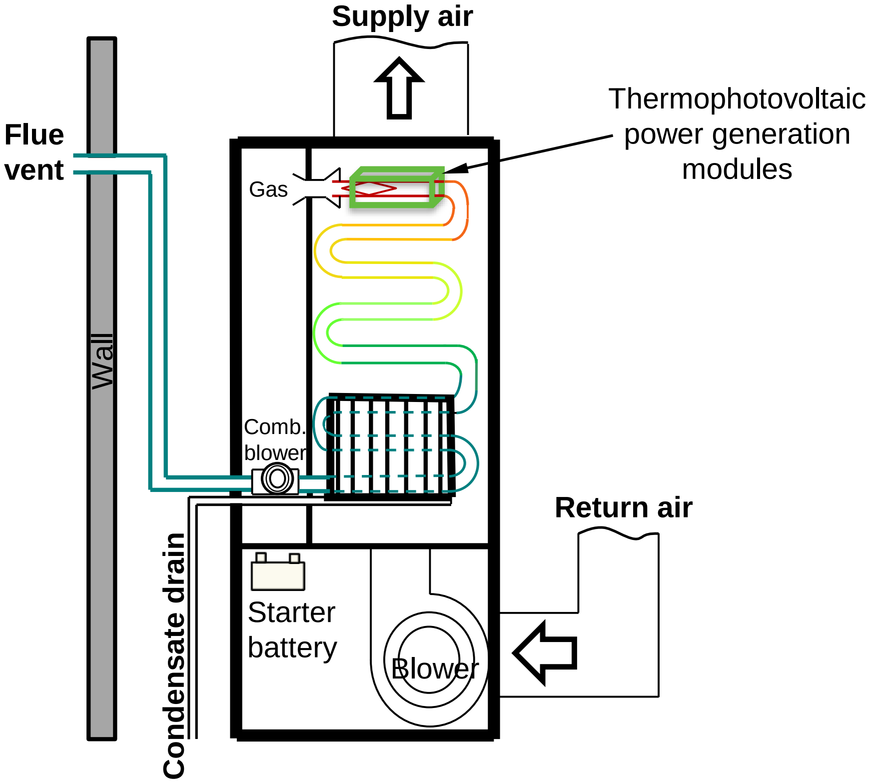
Drop-in, Retrofit Furnace with Maximum Efficiency – Self Powered System



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Project Summary

Timeline:

Start date: 10/1/2017

Planned end date: 9/30/2021

Key Milestones

1. Complete specifications for a full-scale proof of concept prototype, 6/30/2019
2. Fabricate full-scale proof of concept prototype system, 8/31/2019

Budget:

Total Project $ to Date:

- DOE: $550
- Cost Share: $0

Total Project $:

- DOE: $1050k
- Cost Share: $0 (FY17-18); TBD (FY19-20)

Key Partners:

MTPV Power Corporation (thermophotovoltaic systems manufacturer)
Ongoing discussions with Furnace OEM

Project Outcome:

The project team will develop a new high efficiency natural gas furnace technology that generates all electric power required for its operation and air distribution via an internal power cycle.

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

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

Team: ORNL and MTPV Power Corp

- **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
- **Partners**
  - ORNL
  - MTPV Power Corporation
  - Ongoing discussions with furnace OEMs

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Challenge

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

- **Consumer safety and resilience:** *power outage = no heat*
  - Consumers currently take on significant expenses to overcome power outage issue (frozen pipes, hotel stays, backup generators, stress, lost sleep, medical problems, etc.)
- **Efficiency:** PER < GUE (and PER < GCOP)
  - PER: primary energy ratio. Heating energy delivered per unit primary energy consumed.
  - GUE: gas utilization efficiency. Fraction of gas energy turned into useful heat. (AFUE)
  - GCOP: gas coefficient of performance. Heating energy delivered per unit gas consumed.

Conventional furnace technology	GCOP	GUE	PER
Non-condensing	0.844	82%	0.768
Condensing	0.944	92%	0.859

5 to 6% lower than advertised 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

The self-powered furnace utilizes thermophotovoltaics (TPV) to generate all the power required for its operation and air distribution, leading to:

- **Increased consumer safety and resilience:** *power outage = warm home*
  - Saves cost of frozen pipes, hotel stays, backup generators, etc.
  - Saves cost with single utility connection to appliance
- **Increased efficiency:**
  - A change to self-powered operation delivers **similar energy savings as the change from non-condensing to condensing**, but with much stronger consumer benefits

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

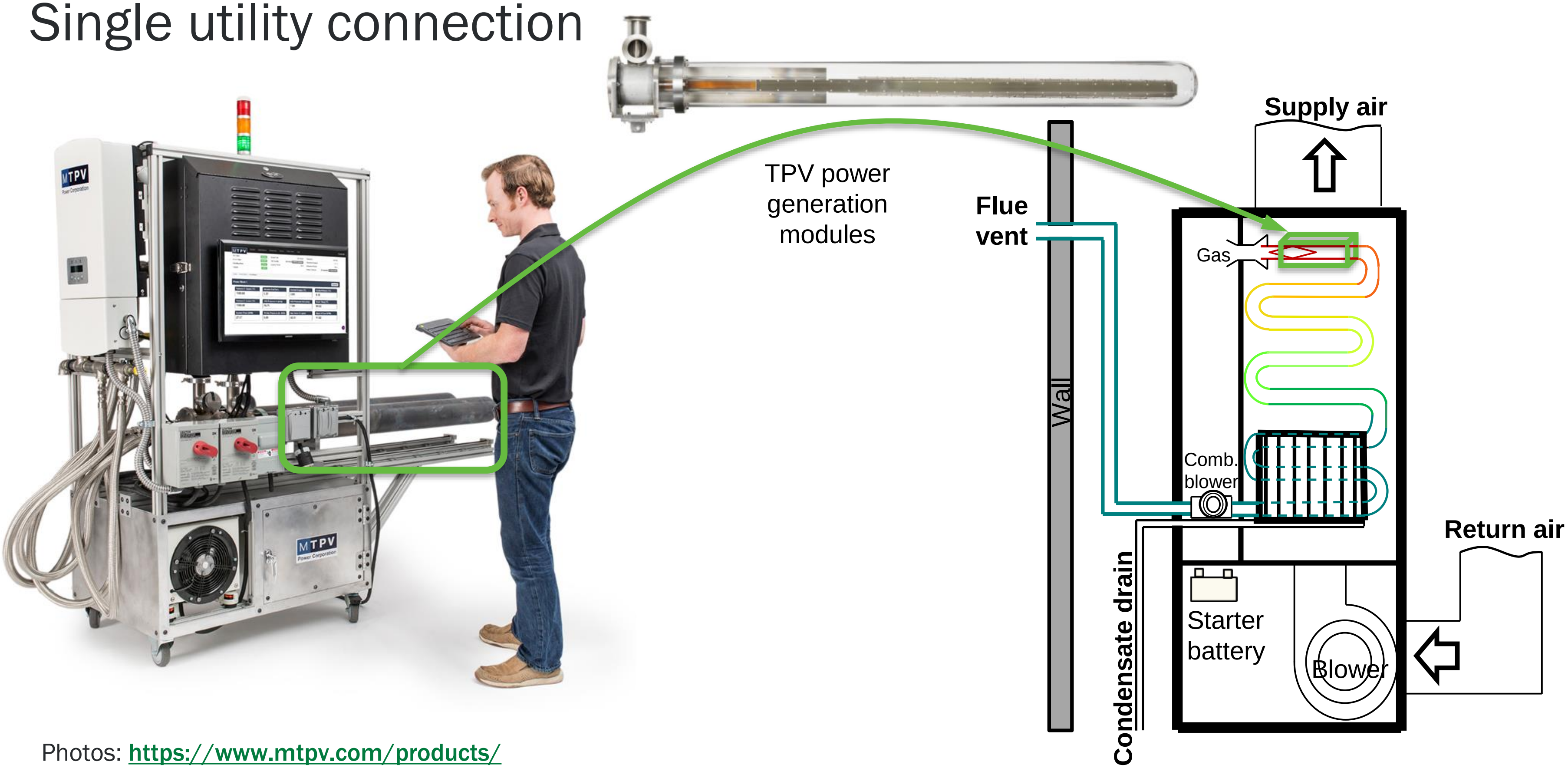
+9.1%, major retrofit challenge

+6.0%, strong consumer benefits

- **Reduced peak demand (grid resilience):** No grid electricity consumption

Approach

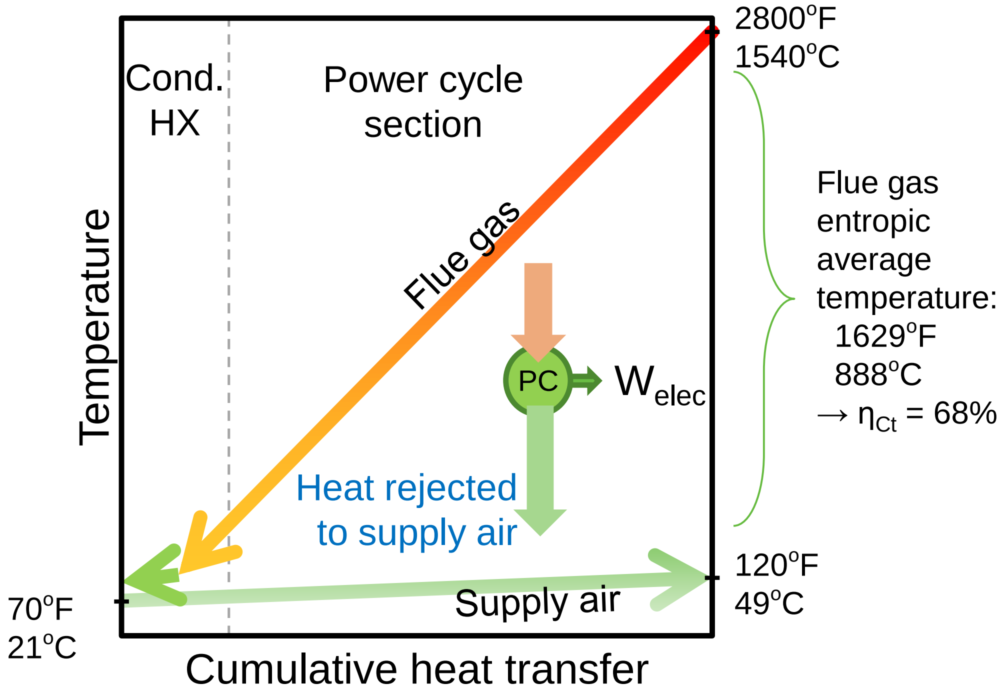
- Scale-down and configure TPV technology to the self-powered furnace application
- The onboard TPV power generator rejects its waste heat for useful building heating
- Single utility connection



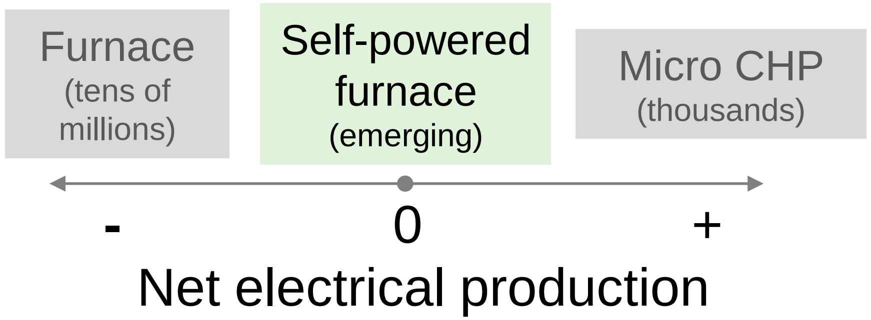
Photos: https://www.mtpv.com/products/

Approach

- **Concept:**
  - High Carnot availability of hot flue gas is utilized to deliver high efficiency
  - No electricity export
  - Single utility connection
- **Research tasks:**
  - Demonstrate proof of concept prototype system
  - Engage with stakeholders and partners to explore commercialization potential



The spectrum of heating products



Approach

Strong, unique value proposition for end user (consumer)

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

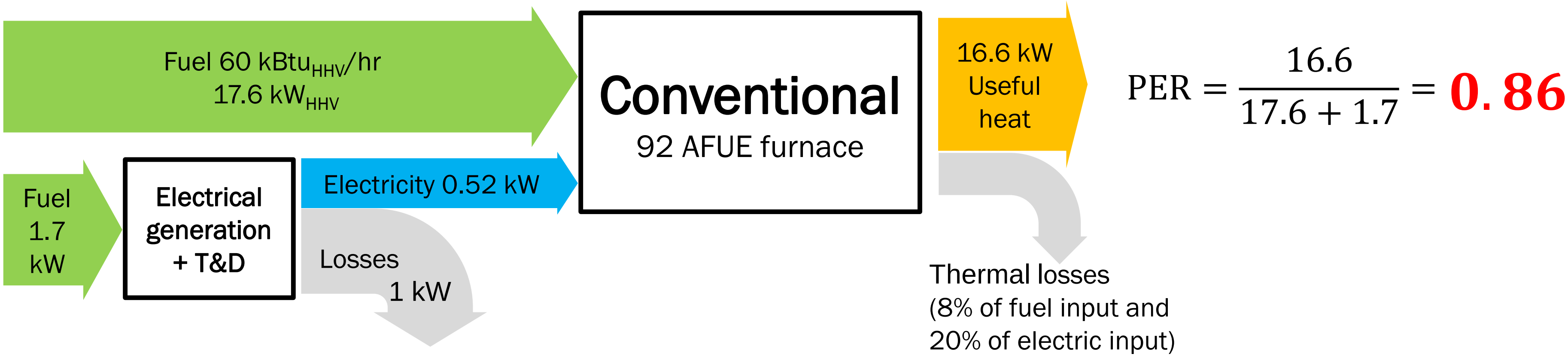
Impact

- **Deliverable: Demonstrate proof-of-concept prototype**
- **Audience/customer and use:**
  - *Power cycle manufacturers (FY19+)*: see potential to reconfigure cycle for unique design needs of self-powered furnace
  - *Furnace OEMs (FY20-21)*: 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

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



Fuel 60 kBtu_{HHV}/hr
17.6 kW_{HHV}

Conventional
92 AFUE furnace

Fuel
1.7
kW

Electrical generation + T&D

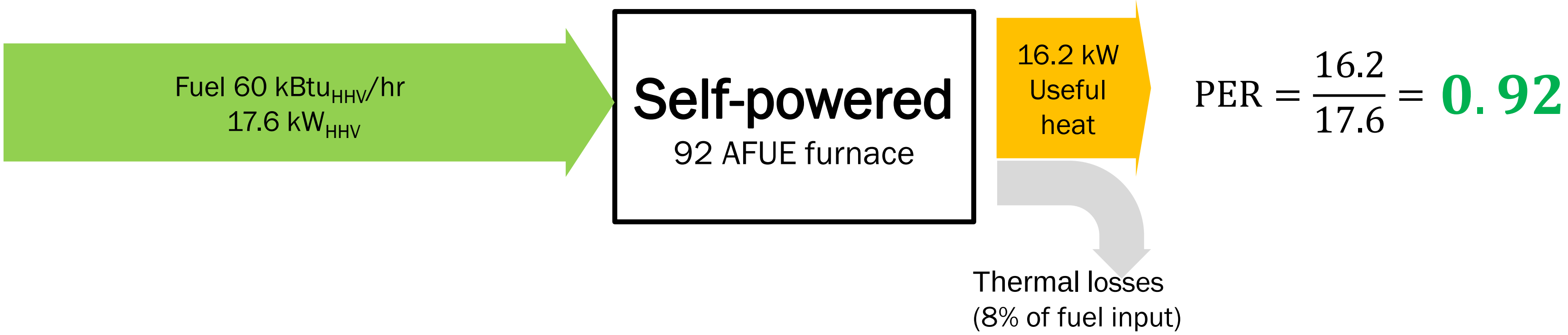
Electricity 0.52 kW

Losses
1 kW

16.6 kW
Useful
heat

Thermal losses
(8% of fuel input and
20% of electric input)

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



Fuel 60 kBtu_{HHV}/hr
17.6 kW_{HHV}

Self-powered
92 AFUE furnace

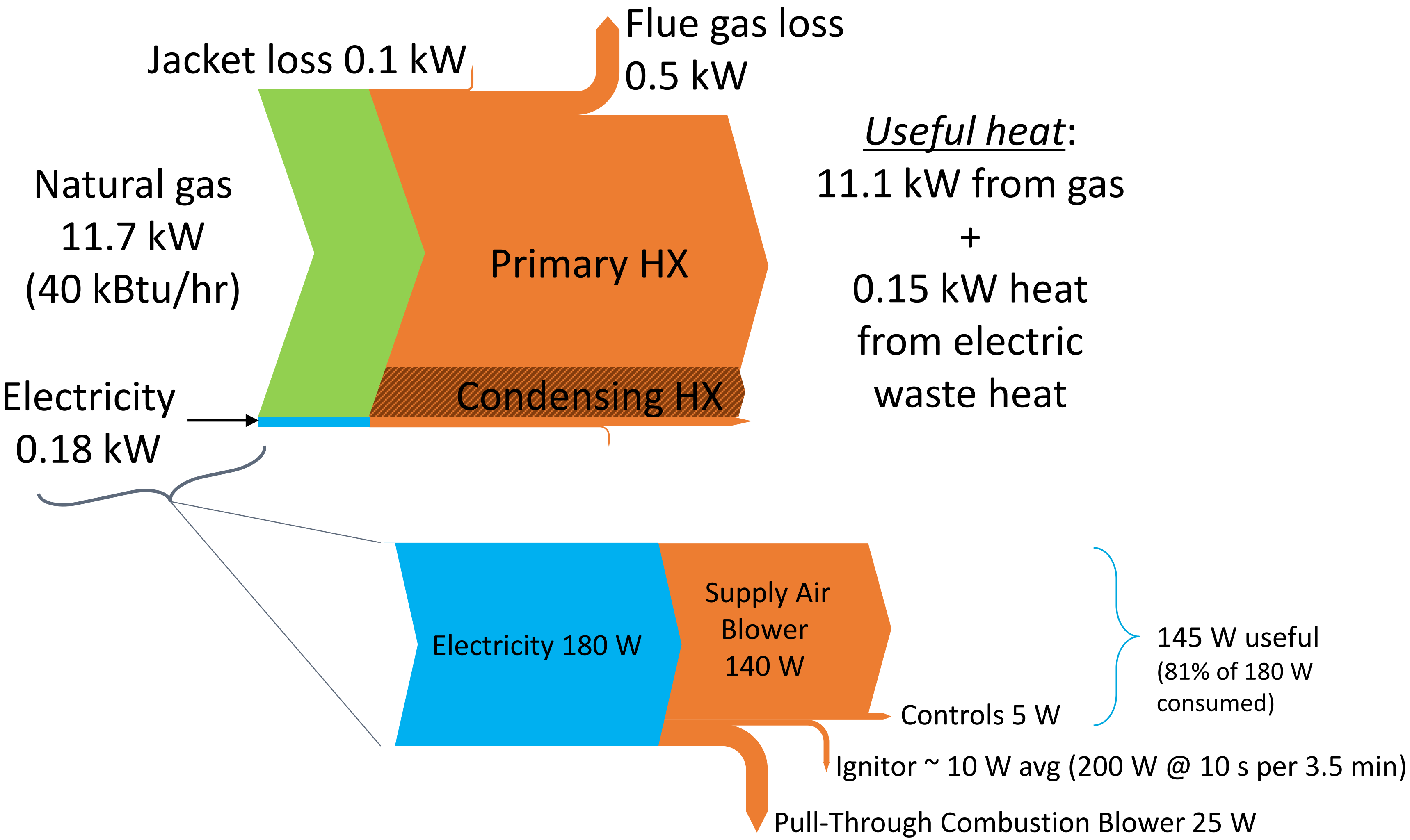
16.2 kW
Useful
heat

Thermal losses
(8% of fuel input)

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

Progress: early-stage project

- Identified; analyzed available unit with lowest electric consumption
- 96 AFUE, 40 kBtu/hr, 180 W average electric load while running



Progress

- **Analysis of furnace efficiency: electrical consumption significantly impacts PER (primary energy ratio), not captured in GUE (or AFUE)**
  - Typically PER = GUE minus (4 to 8)
  - Typically PER = GCOP minus (7 to 11)

$$PER = \frac{GUE + \alpha\kappa}{1 + \frac{\kappa}{\eta_{grid}}} = \frac{GCOP}{1 + \frac{\kappa}{\eta_{grid}}}$$

$$GCOP = GUE + \alpha\kappa$$

Where:

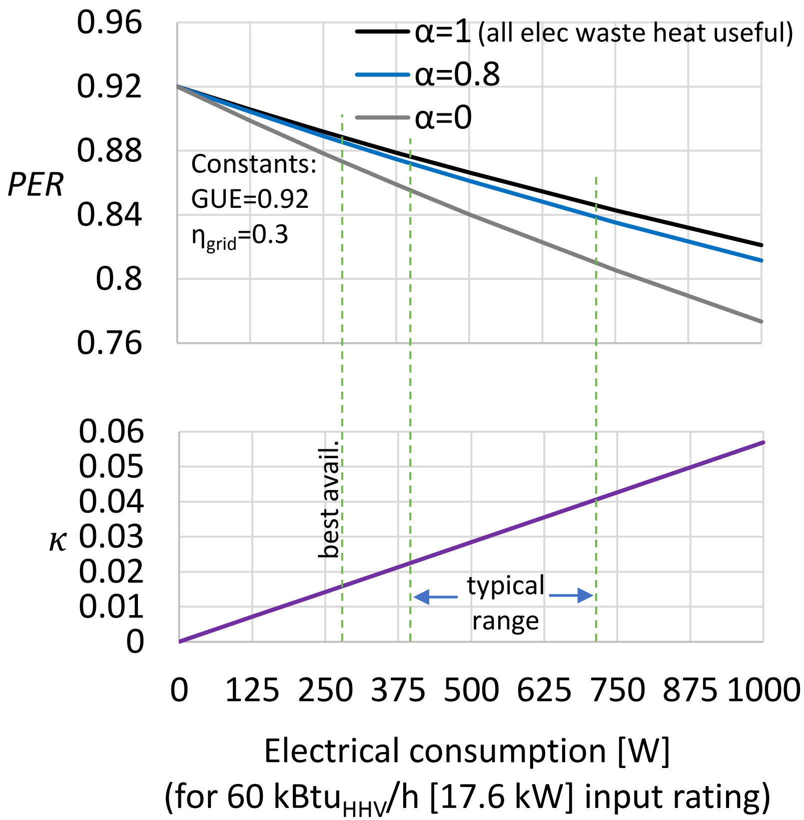
$$GUE = \frac{UsefulHeatFromFuel}{InputRating}$$

$$GCOP = \frac{UsefulHeatFromFuel + UsefulElecWasteHeat}{InputRating}$$

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

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

$$InputRating = FuelConsumed(HHV)$$



Progress

Conducted review of generator technologies suitable for SPF

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	$$
		2-stroke recip.	V. high	High	Poor to acceptable	V. good	Good[4]	7-9	$
	Fuel Cell	SOFC	High[1]	Low	Poor to acceptable	V. poor	Excellent (all heat in exhaust)	4-8	$$$$
		PEMFC		Low	Acceptable	Poor	Moderate	6-9	$$$
	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	$$$

[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.

Progress

Selection of thermophotovoltaic (TPV)

- **Two technologies not ruled out in screening:**
  - Thermoelectric
  - Thermophotovoltaic
- **Thermophotovoltaic generation technology selected for this project:**
  - High power density
    - Compact packaging
  - High input temperature (approaching flame temperature)
  - High theoretical efficiency limit
  - High-power radiative energy transfer (to get heat into TPV)
  - A low TRL solid state technology with promise for dramatic cost reductions with technology development and scale

Stakeholder Engagement: early stage project

- **The project is currently at early-stage**
  - A detailed engineering analysis of a system design and integration with TPV generation was completed in 2018, and the team is preparing to complete specifications for a full-scale proof of concept prototype
- **Reports and Publications**
  - Completed "Survey of existing and emerging power conversion technologies relevant to a self-powered furnace"
- **Discussions held with US manufacturers of TPV systems**
  - Negotiating CRADA with MTPV Power Corp
- **Discussions ongoing with gas furnace OEMs**
- **Team continues to coordinate closely with related BTO-sponsored ORNL furnace activities**
  - Novel Furnace Based on Membrane Technologies (BTO-03.02.02.26.1923)
  - Advanced Adsorption Technology for New High-Efficiency Natural-Gas Furnace at Low Cost (BTO-03.01.02.51.1928)

Remaining Project Work

- **FY 2019**
  - Establish CRADA with industry partner
  - Complete specifications for the full-scale proof of concept prototype
  - Develop model of power cycle and system
  - Fabricate full-scale proof of concept prototype system
- **FY 2020**
  - Partner with furnace OEM
  - Complete prototype evaluation and submit draft report
  - Validate model against experimental data
- **FY 2021**
  - Fabricate alpha prototype
  - Final evaluation and reporting
- **Future project:** achieve >100% PER by generating excess electricity to operate heat pump

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $550k
Variances: None
Cost to Date: $167k
Additional Funding: None

Budget History					
FY 2018 (past)		FY 2019 (current)		FY 2020 – FY2021 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$200k	0	$350k	TBD	$500k	TBD

Project Plan and Schedule

- Project original initiation date: 10/1/2017
- Project planned completion date: 9/30/2021
- Industry partner recruited in FY2018 – FY2019
- Full-scale specs milestone delayed to accommodate addition of industry partner
- Next steps are fabrication and evaluation of breadboard proof-of-concept prototype
- Packaged prototype planned in FY2021

Project Schedule												
Project Start: 10/1/2017	🟦	Completed Work										
Projected End: 9/30/2021	⬛	Active Task (in progress work)										
	♦	Milestone/Deliverable (Originally Planned)										
	◆	Milestone/Deliverable (Actual)										
	FY2018				FY2019				FY2020			
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												
M1: Review existing/emerging power gen tech	🟦 ◆											
M2: System engineering analysis and design		🟦	🟦	🟦 ◆								
M3: Specs for full-scale POC prototype					🟦	🟦 ♦	⬛ ◇					
Current/Future Work												
M4: Fabricate full-scale POC prototype							⬛	⬛ ◇				
M5: Prototype evaluation									⬛	⬛	⬛ ◇	
M6: Validate TPV and system-level models									⬛	⬛	⬛	⬛ ◇