2021

Self-powered Heating: Efficiency Analysis

Kyle R. Gluesenkamp
Oak Ridge National Laboratory, United States of America, gluesenkampk@ornl.gov

Tim J. LaClair

Praveen Cheekatamarla

Ahmad Abu-Heiba

Self-powered Heating: Efficiency Analysis

Kyle R. GLUESENKAMP[1]*, Tim J. LACLAIR[1], Praveen CHEEKATAMARLA[1],
Ahmad ABU-HEIBA[1]

[1]Oak Ridge National Laboratory, Energy and Transportation Science Division,
Oak Ridge, TN, USA
gluesenkampk@ornl.gov

* Corresponding Author

ABSTRACT

Conventional fuel-fired heating devices such as furnaces, boilers, and water heaters have fuel efficiency less than 100% on the basis of higher heating value. They also require electricity from the electric grid to power parasitic loads such as blowers, pumps, fans, and ignitors. The primary energy efficiency of the device accounts for both fuel used on-site and primary energy used off-site to produce electric power used by the device. This work compares conventional fuel-fired heating devices to two types of self-powered devices. A self-powered device (SPD) integrates a power cycle onboard to eliminate consumption of grid electricity. We assume that all heat rejected by the onboard power cycle is added to the process fluid, so that, compared with a conventional device, the same amount of heat is provided to the process fluid and the same amount of fuel is consumed, but grid electricity consumption is eliminated. The first SPD type is the basic one: exactly the electricity required is generated. The second type considered is the SPD with heat pump (SPD-HP), in which the power cycle generates more electricity than needed for parasitic loads, and the excess electricity is used to power a heat pump. The heat pump extracts additional heat from the ambient to boost efficiency. Both SPD and SPD-HP self-consume all the generated electricity, in contrast to combined heat and power (CHP) systems that export electricity. In this work, equations are derived to express the efficiency of three classes of heating devices: conventional (consuming grid electricity), self-powered (consuming no grid electricity), and self-powered with heat pump. The efficiency of each is derived as a function of up to six factors: (1) the fraction of combustion heat captured, (2) the rate of parasitic power consumption, (3) the fraction of electric energy dissipated as useful heat, (4) the power cycle conversion efficiency, (5) the grid efficiency, when applicable, and (6) the heat pump COP, when applicable. Scenarios are identified in which it is possible to achieve efficiency greater than 100% on a higher heating value basis. Plausible configurations using existing technology options are outlined.

1. INTRODUCTION

* Corresponding author. Tel.: +1-865-241-2952.
E-mail address: gluesenkampk@ornl.gov

Fuel fired heating devices include furnaces, boilers and water heaters. In the US, according to DOE's Scout tool (https://trynthink.github.io/scout/calculator.html), residential furnaces and boilers consume 2.9 Quad/yr of natural gas and 0.4 Quad/yr of fuel oil, (DOE Scout), and gas water heaters consume another 1.2 Quads/yr. Commercial furnaces and boilers consume 1.6 Quads/yr of natural gas and 0.2 Quads/yr of fuel oil; and water heaters consume 0.3 Quads/yr. Altogether, this is 6.6 Quads/yr. In the US, furnaces and boilers are rated on a fuel-only metric (AFUE), and water heaters are rated on a site energy metric (UEF).

Various self-powered fuel-fired heating devices have been previously investigated. For example, Qiu and Hayden (2008) reported development of a self-powered residential hydronic heating system. A thermoelectric generator (TEG) based on PbSnTe was used as the electricity generation device. The system generated 553.9 W of electric power at a hot surface temperature of 637°C and a cold surface temperature of 85°C. The authors also presented an analytical model to optimize the heat source temperature and the heat transfer coefficient of the hot side of the TEG. The results showed that increasing the heat source temperature increases the electric generation efficiency up to a certain temperature. Beyond that temperature, the temperature of the hot side of the TEG increases and the percentage of the heat that is transferred to the hot side decreases. Alptekin et al. (2017) experimentally evaluated the performance of a self-powered condensing combi boiler that used TEG to generate electricity. The system was evaluated experimentally at different firing and water flow rates. The boiler reached a maximum efficiency of 90%, at which the power generated was 34 W. The authors indicated in their conclusion that the design of the boiler could be improved further to achieve higher efficiency and better economics. Butcher et al. (2011) built an oil-fired self-powered boiler that used a thermophotovoltaic (TPV) module for power generation with a design power generation target of 100 W. The authors analyzed three different TPV arrays and emitter systems: a Silicon Carbide (SiC) emitter with four 1 cm^2 GaSb TPV cells, a quartz emitter with four 1 cm^2 GaSb TPV cells and a porous SiC/Alumina composite emitter with 99 GaSb TPV cells. The authors showed that for the first two configurations, direct radiation was the most significant heat transfer mechanism to the TPV cells and convection heat transfer did not play a significant role. Therefore, higher flame temperature was required, which increases NOx and increases sensitivity to the air-fuel ratio. The third configuration reduced sensitivity to the air-fuel ratio and could be used to couple both radiation and convection heat transfer mechanisms to achieve higher emitter temperature. Qiu and Hayden (2014) integrated a GaSb TPV generator into a residential combi boiler. The TPV array had a total cell area of 576 cm^2 and the emitter was made of SiC. A full-scale prototype was evaluated experimentally. It generated a maximum power of 246.4 W at an emitter temperature of 1265°C and fuel input of 12.3 kW. The authors showed that the integration of the TPV generator into the boiler has little effect on the efficiency of the baseline boiler. The authors mention in the discussion that the electrical generation efficiency can be improved by employing a recuperator to use the heat content of the exhaust to preheat the combustion air.

A systematic analytical treatment of the primary energy efficiency potential of self-powered devices has not previously been presented. This work derives equations to express the efficiency of three classes of heating devices: conventional (consuming grid electricity), self-powered (consuming no grid electricity), and self-powered with heat pump.

2. PRIMARY ENERGY RATIO DERIVATIONS

Efficiencies are derived for three system types: 1. conventional, 2. self-powered, and 3. self-powered with heat pump.

2.1 Definitions

Several terms are defined here in order to facilitate definitions for the three system types, as follows.

For all system types in this work, the primary energy ratio (PER) is defined in Eq. 1 as the total useful heat supplied to the building (Q_{supply}, including heat direct from burner heat exchanger, heat rejected by the power cycle, and electrical waste heat) per unit primary energy consumed.

$$PER = \frac{Q_{supply}}{Primary\ Energy\ Consumed} \quad (1)$$

Gas utilization efficiency (GUE) is defined in Eq. 2 as the useful heat from fuel per unit fuel consumed, on a higher heating value (HHV) basis. GUE can be applied to an entire system, or to an individual component (such as an integrated burner-heat exchanger).

$$GUE = \frac{UsefulHeatFromFuel}{FuelConsumed\,(HHV)} \tag{2}$$

Gas coefficient of performance (GCOP) is the total useful heat (Q_{supply}) per unit fuel consumed.

$$GCOP = \frac{Q_{supply}}{Fuel\ Consumed\ (HHV)} \tag{3}$$

Next, the term κ is introduced in Eq. 4 as the amount of electricity that must be consumed to operate the device, per unit useful heat supplied to the load (Q_{supply}). This definition differs slightly from the definition in Gluesenkamp (2019), which defined κ based on the input rating. Here it is defined based on the useful heat supplied because, for air-based distribution systems common in the US, the electrical loads will scale more closely with the heat supplied, since the supply air blower is the largest electric load.

$$\kappa = \frac{Electrical\ Consumption}{Q_{supply}} \tag{4}$$

All electricity consumed by the device will be converted to waste heat, but only some of that waste heat will add to the useful heating supplied by the unit. The term α in Eq. 5 is the fraction of the electrical consumption turned into waste heat that ultimately helps supply the load.

$$\alpha = \frac{Useful\ Elec\ Waste\ Heat}{Electrical\ Consumption} \tag{5}$$

The fraction f_{PC} is the fraction of fuel that goes to the power cycle (the remainder goes to a burner).

$$f_{PC} = \frac{Fuel\ to\ Power\ Cycle\ (HHV)}{Fuel\ Consumed\ (HHV)} \tag{6}$$

The heating coefficient of performance of the heat pump, COP_h, is the amount of heat supplied by the heat pump (Q_h) per unit electrical power consumed by the heat pump (W_{hp}).

$$COP_h = \frac{Q_h}{W_{hp}} \tag{7}$$

The efficiency of the power cycle is denoted η_{PC}.

$$\eta_{PC} = \frac{W_{PC}}{Fuel\ to\ Power\ Cycle} \tag{8}$$

2.2 Electrical Requirements for Fuel-fired Heating Devices

Typically a fuel-fired heating device relies on electricity from the grid to power various electrical loads. A single example is shown here, for electrical loads measured for a conventional off the shelf residential furnace. These were measured for one off the shelf commercially available residential furnace. This is provided as a guide, and the precise numbers with uncertainty are not important for the present work. Thus the full details of the measurement techniques and equipment are excluded from this work for brevity.

Table 1. Energy flows in 92 AFUE condensing furnace

Energy type	**Component**	**Energy flow rate [kW]**	**Notes**
Chemical	Natural gas	23.4 (80 kBtu/h)	Primary energy input from fuel
	Non-ideal products of combustion (HCs, CO, NOx)	Negligible	
Thermal	Primary heat exchanger	18.7	Part of Q_{supply}
	Secondary (condensing) heat exchanger	2.8	Part of Q_{supply}
	Flue gas thermal energy flow content	1.9	Energy lost through flue
Rotational (shaft power) (supplied by 120 VAC)	Supply air blower	~0.6	The electrical loads
	Combustion air blower	~0.1	
Electrical (120 VAC)	Ignitor	~1 (instantaneous) ~0.03 (time-averaged)	
Electrical (24 VAC)	Control signals (e.g. thermostat, solenoids, electrical relay coils)	~0.01	
Electrical (5-24 VDC)	Controls and digital signals	~0.02	

In this work, all electrical loads are lumped together under the term κ. For the measured loads on this appliance, κ is about 0.032. In other words, the electric site consumption is 3.2% as large as the gas consumption during operation. The value of κ will vary with equipment, depending especially strongly on the efficiency of the supply air blower system. An analysis of publicly available information on commercially-available residential furnaces by the authors found that κ is typically in the range of 1 to 4%.

2.2 Conventional Heating Devices

The conventional heating device consumes both fuel and electricity. Figure 1 shows a Sankey diagram of the energy flows in a conventional device.

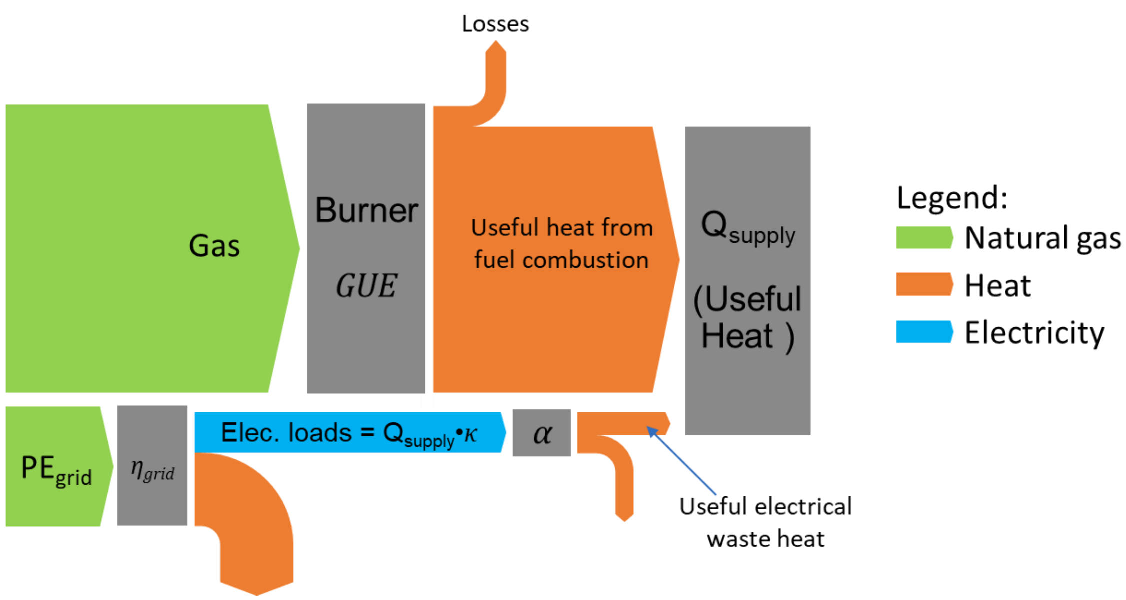

Figure 1: Sankey diagram of energy flows for a conventional heating device that draws electricity from the grid for electrical loads.

For the conventional heating device, Eqn. 9 was derived for the PER.

$$PER = \frac{GUE}{1 + \kappa\left(\frac{GUE}{\eta_g} - \alpha\right)} \tag{9}$$

A few thought experiments help to confirm the soundness of Eqn. 9: first, as κ approaches zero, *PER* approaches *GUE*, as expected. Second, as the grid efficiency approaches zero, the *PER* also approaches zero, as expected.

2.3 Self-powered Heating Device (no power import or export)

The self-powered device neither exports nor imports electrical power. A new term is introduced for the efficiency of the power cycle, η_{PC}, as defined in Eqn. 10.

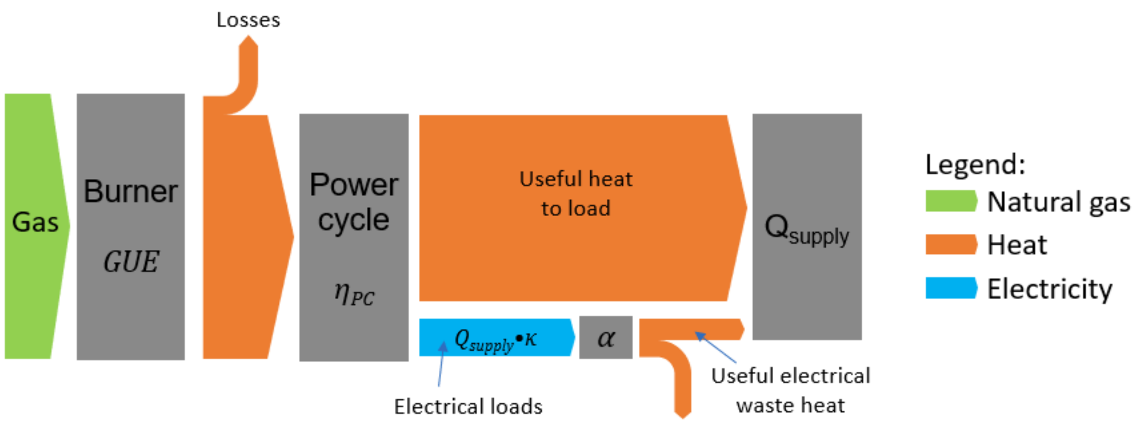

Figure 2: Sankey diagram of energy flows for a self-powered heating device.

$$\eta_{PC} = \frac{W_{PC}}{Fuel\ to\ Power\ Cycle} \tag{10}$$

For the SPF, Equation 11 was derived for the PER. Note that, under the assumption that no power is imported nor exported, the power cycle efficiency depends on the parameters α and κ and thus does not appear in the PER equation. If all of the electrical waste heat is captured and utilized, then α=1, and PER=GUE. If some of the electrical waste heat is lost, then the PER will depend on the value of κ.

$$PER = \frac{GUE}{1 + \kappa(1 - \alpha)} \tag{11}$$

Pursuant to the assumption that no power is imported nor exported, the power cycle efficiency must be equal to the value in Equation 12.

$$\eta_{PC} = \frac{1}{\frac{1}{\kappa} + 1 - \alpha} \tag{12}$$

If α=1, then the required power cycle efficiency is given by the simple expression in Equation 13. Equations 12 and 13 yield a similar value of η_{PC} in all cases, since α is between 0 and 1, and typical values of κ are in the range 0.01 to 0.04. For example, if α=0 and κ=0.04, then the required η_{PC} is 4.2%, compared to 4.0% when α=1.

$$\eta_{PC} = \kappa \tag{13}$$

Since κ is typically on the order of 1 to 4%, Equation 13 shows that a power cycle for a self-powered device need only have 1 – 4% efficiency. This is much lower than practically required for power cycles in other applications (such as power generation, transportation engines, or combined heat and power).

2.4 Self-powered Heating Device with Heat Pump

When the power cycle efficiency is higher than the requirement of Equation 12, then the self-powered device can produce more power than needed for the electrical loads (and still avoid exporting electricity) by sending the excess electricity to an onboard heat pump. In this case, an additional pathway is opened in the Sankey diagram, with an additional term, the heating COP of the heat pump.

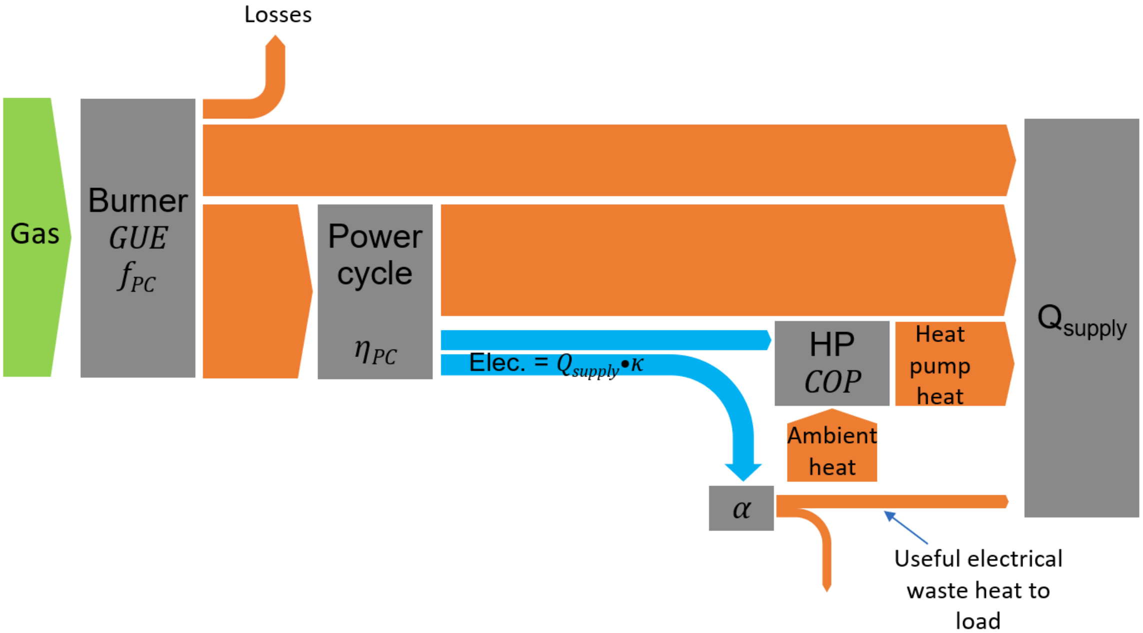

Figure 3: Sankey diagram of energy flows for a generic self-powered heating device, in which only some of the fuel is consumed by the power cycle, some of the electricity produced powers a heat pump, and some of the electrical waste heat is useful.

The PER of this system was derived as in Eqn. 14.

$$PER = GUE\frac{1+\eta_{PC}f_{PC}(COP_h-1)}{1+\kappa(COP_h-\alpha)} \quad (14)$$

Note that, with COP_h =1, Equation 14 reduces to Equation 11, as expected.

3. SUMMARY OF RESULTS AND SIMPLIFIED FORMS

To summarize, the efficiency of each heating device class was derived as a function of up to six factors:

(1) *GUE*, the fraction of combustion heat captured,
(2) κ, the rate of parasitic power consumption,
(3) α, the fraction of electric energy dissipated as useful heat,
(4) η_{PC}, the power cycle conversion efficiency,
(5) η_g, the grid efficiency, when applicable, and
(6) the heat pump heating COP_h, when applicable.

The results are summarized in Table 1 for convenient reference and cross comparison.

Table 1: Summary of expressions

	Equation	Additional notes
Conventional furnace	$PER = \dfrac{GUE}{1 + \kappa\left(\dfrac{GUE}{\eta_g} - \alpha\right)}$	
Self-powered device (SPD)	$PER = \dfrac{GUE}{1 + \kappa(1 - \alpha)}$	When α=1, then *PER*=*GUE* Required power cycle efficiency: $\eta_{PC} = \dfrac{1}{\dfrac{1}{\kappa} + 1 - \alpha}$
Self-powered device with heat pump (SPD-HP)	$PER = GUE\dfrac{1 + \eta_{PC} f_{PC}(COP_h - 1)}{1 + \kappa(COP_h - \alpha)}$	When COP_h=1, this reduces to the simple SPD equation

4. SYSTEM COMPARISONS AND DISCUSSION

The equations derived above were used to plot the feasible ranges of primary efficiency for each class of device. Figure 4 shows the PER for conventional, SPD, and SPD-HP as a function of κ. Three different values of α are shown. A fixed primary grid efficiency of 33% and fixed burner GUE of 95% are assumed. The conventional system's PER rapidly declines with increases in κ. Typical furnaces with a κ of 0.03 would have a PER of only 0.90 with a GUE of 0.95. In contrast, the SPD is relatively insensitive to κ. In fact, if all dissipated electrical waste heat is utilized (α=1), then PER=GUE. For the SPD-HP, a PER above 100% is possible when κ is low. Additional scenarios are analyzed in Figure 5.

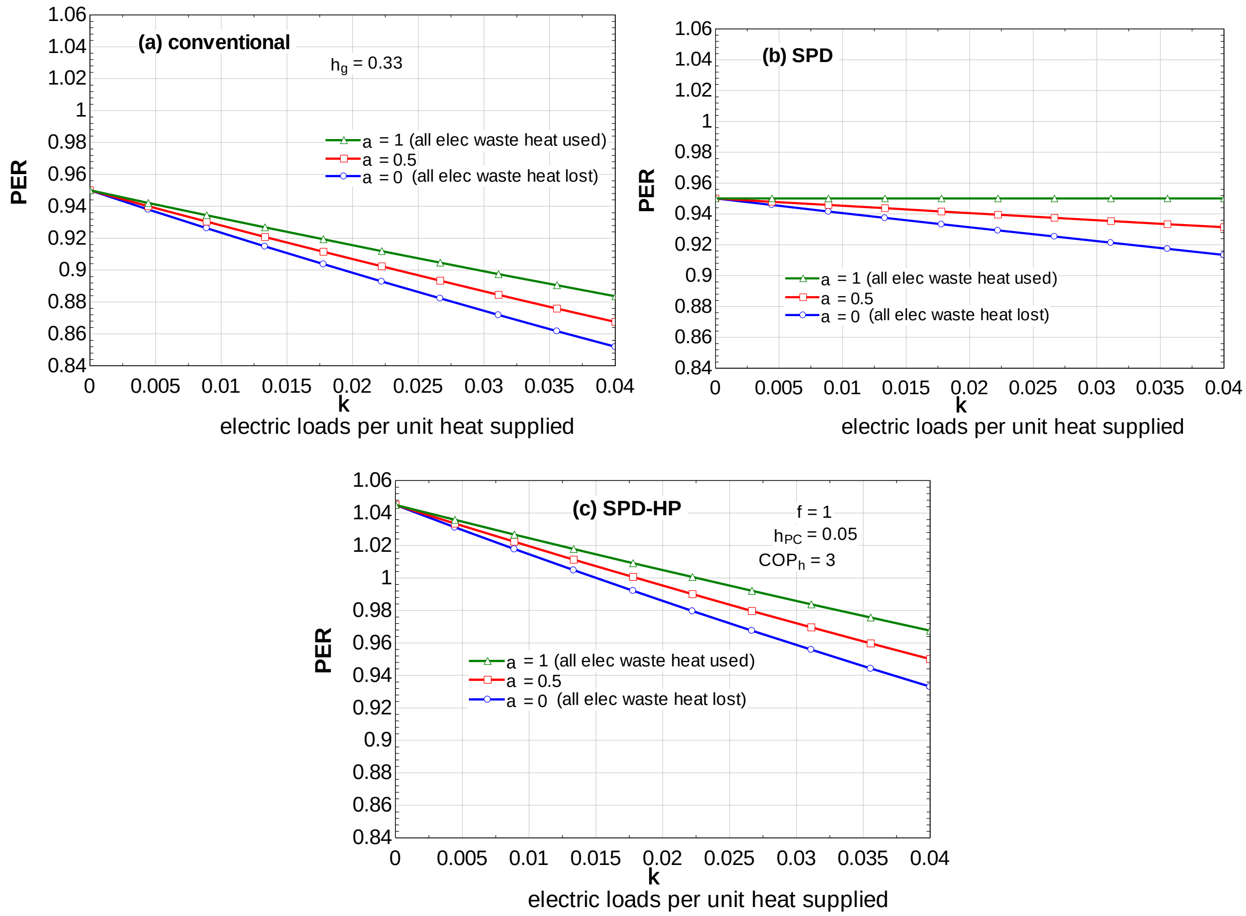

Figure 4: PER as a function of electric loads (κ), with contours for various values of waste heat capture (α), for (a) conventional device, (b) self-powered device, and (c) self-powered device with heat pump.

Figure 5 shows that, for the SPD-HP, PER approaching 2 can be achieved with favorable heat pumping COP, moderate κ (0.02), high α (0.8), and a high power cycle efficiency of η_{PC}=0.3. For lower power cycle efficiencies of 5 – 10% (as would be expected for TE or TPV technology), the PER can still exceed 1.

An additional discussion point is raised regarding the power cycle requirements. As established in Equation 12, a fairly low power cycle efficiency (1 to 4%) is required by self-powered devices. The allowability of low efficiency power generation cycles presents an opportunity. For example, it means that self-powered devices may provide an early market for new power generation technologies that have not yet become efficient enough for traditional power generation applications. It could also mean that many technologies with high efficiency could be re-engineered for lower cost at lower efficiency, and be suitable for use in self-powered devices.

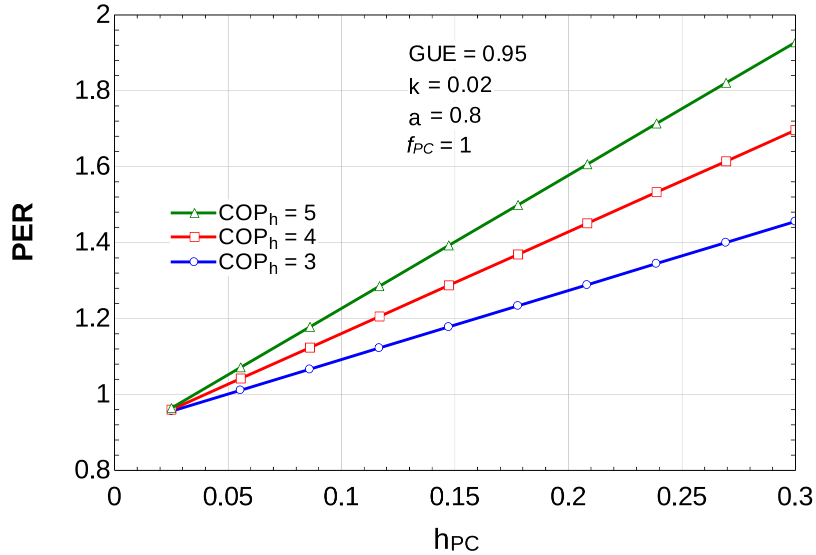

Figure 5: PER as a function of power cycle efficiency for a SPD-HP, with contours for various heat pump COP values.

5. CONCLUSIONS

In this work, the efficiencies of self-powered devices were compared with conventional heating devices. An improvement in primary energy efficiency can be accomplished by self-powering a furnace, boiler, or water heater with an onboard power cycle. If the power cycle generates more power than required for operation of blowers and fans, and the excess generation is used for heat pumping, then efficiencies above 100% can be achieved, without any requirement for power export.

NOMENCLATURE

CHP	combined heat and power	
COP_h	heating coefficient of performance	(–)
f_{PC}	fraction of fuel to power cycle	(–)
GUE	gas utilization efficiency	(–)
HHV	higher heating value	(J/g)
Q_h	heat pump heating capacity	(kW)
Q_{supply}	heating capacity	(–)
SPD	self-powered heating device	
SPD-HP	self-powered heating device with heat pump	
TEG	thermoelectric generator	
TPV	thermophotovoltaic	
W_{hp}	heat pump power consumption	(kW_{elec})
W_{PC}	power cycle power output	(kW_{elec})
VAC	alternating current voltage	
VDC	direct current voltage	
α	fraction of useful electrical waste heat	(–)
κ	ratio of electric consumption to Q_{supply}	(–)
η_g	grid efficiency	(–)
η_{PC}	power cycle efficiency	(–)

Subscript

g	grid
PC	power cycle

REFERENCES

M. Alptekin, T. Calisir, and S. Baskaya (2017). Design and experimental investigation of a thermoelectric self-powered heating system. *Energy Conversion and Management*, *146*, 244-252.

T. A. Butcher, J. S. Hammonds, E. Horne, B. Kamath, J. Carpenter, and D. R. Woods (2011). Heat transfer and thermophotovoltaic power generation in oil-fired heating systems. *Applied Energy*, 88(5), 1543-1548.

DOE Scout Baseline Energy Calculator, https://trynthink.github.io/scout/calculator.html

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. available at https://www.energy.gov/sites/prod/files/2019/05/f62/bto-peer%E2%80%932019-ornl-drop-in-retrofit-furnace-max-eff.pdf

K. Qiu, A. C. S. Hayden (2008). Development of a thermoelectric self-powered residential heating system. *Journal of Power Sources*, *180*(2), 884-889.

K. Qiu and A. C. S. Hayden (2014). Implementation of a TPV integrated boiler for micro-CHP in residential buildings. *Applied Energy*, *134*, 143-149,

ACKNOWLEDGEMENT

This material is based upon work supported by the U. S. Department of Energy's Building Technologies Office under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. The authors would like to acknowledge Mr. Tony Bouza, Technology Manager, U.S. Department of Energy Building Technologies Office.