

Resilience, Emissions and Costs of Various Residential Space Heating Technologies

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ABSTRACT

Electrification will be an important decarbonization strategy for residential space heating and cooling, but a common point of resistance from consumers is the fear of loss of heating during power outages. In this paper we investigate various options for delivering reliable space heating in the event of a power outage and compare them on the dimensions of costs, emissions, and reliability. We compare the most common electricity-dependent heating appliances (gas furnaces, electric resistive and electric heat pumps) to one another and to backup options including diesel generators, battery storage, thermal energy storage, wood burning stoves, gas fireplaces and outage preparation strategies. Using historical data on frequency and duration of outages, estimates of infrastructure and appliance costs, we estimate how different technologies could respond to outages, and at what costs. We show how different reliability benefits can be achieved at various costs. Costs are evaluated on a levelized basis that includes capital, operating, and maintenance costs under warranted lifetimes. Findings show that most power outages do not necessitate backup heating options for temperate climates. The emissions from the heating/reliability options also vary because of differing direct emissions and differing grid impacts. Some measures that improve reliability also provide demand flexibility which can be an important resource for integrating renewables. Emissions include scope one direct greenhouse gas emissions and electric power grid dependent scope two greenhouse gas emissions. Direct combustors such as gas and wood stoves are the most affordable backup heat strategies. Unleaded gasoline generators powering existing home heating options such as a furnace or heat pump is the next most affordable strategy.

Introduction

For basic survival we require in order of urgency: air, shelter, water and food. Only under extreme temperatures does shelter become an urgent need, but these extreme temperatures are experienced by a greater share of peoples living in mid-latitudes due to climate change. The American and Canadian Pacific Northwest experienced unprecedented heat in June 2021 and Texas experienced an unprecedented period of subfreezing temperatures in February 2021. Residents in locations unaccustomed to severe and prolonged temperatures below freezing, such as Texas and surrounding regions, suffered from widespread and prolonged power outages and lack of household heat that led in part to over 200 deaths (Paz 2021; Hauser and Sandoval 2021). Those most susceptible to hypothermia include the young, elderly, and those suffering from alcoholism, diabetes or anorexia (Mayo Clinic 2022).

Meanwhile, numerous local, state, and national governments in the United States and abroad are implementing policies to electrify household heating as a spike in a three-pronged-approach to reduce GHG (greenhouse gas) emissions: *electrification, efficiency, and renewable generation*. These policies create anxiety among some residents living in locations that mandate

climate action policy that shifts residential and commercial heating to electric heat pumps from natural gas (Baker 2020). Residents are worried about a lack of heat during power outages. A common misconception among consumers is that their natural gas appliances can operate during an outage while in fact their electric starters and fans render many of them inoperable (Baker 2020). This paper asks two questions: a) do we need backup heating in temperate climates in the event of a power outage? and b) what are the most cost-effective options and/or lowest GHG options?

Power Outages

The Annual Electric Power Industry Report (EIA-861) records the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI), where a ‘system’ is defined as a United States electric utility. These values allow for a determination of the average duration of a single outage (ignoring very short interruptions) from all utilities that report (EIA 2021). Data from the 652 utilities in the United States that reported values for 2020 indicate that the average duration of an outage is 189 minutes. These data were recorded by year and therefore lack seasonal fidelity. The distribution of these average outage durations is shown in Figure 1 where frequency is the count of utilities suffering an average outage duration measured in minutes.

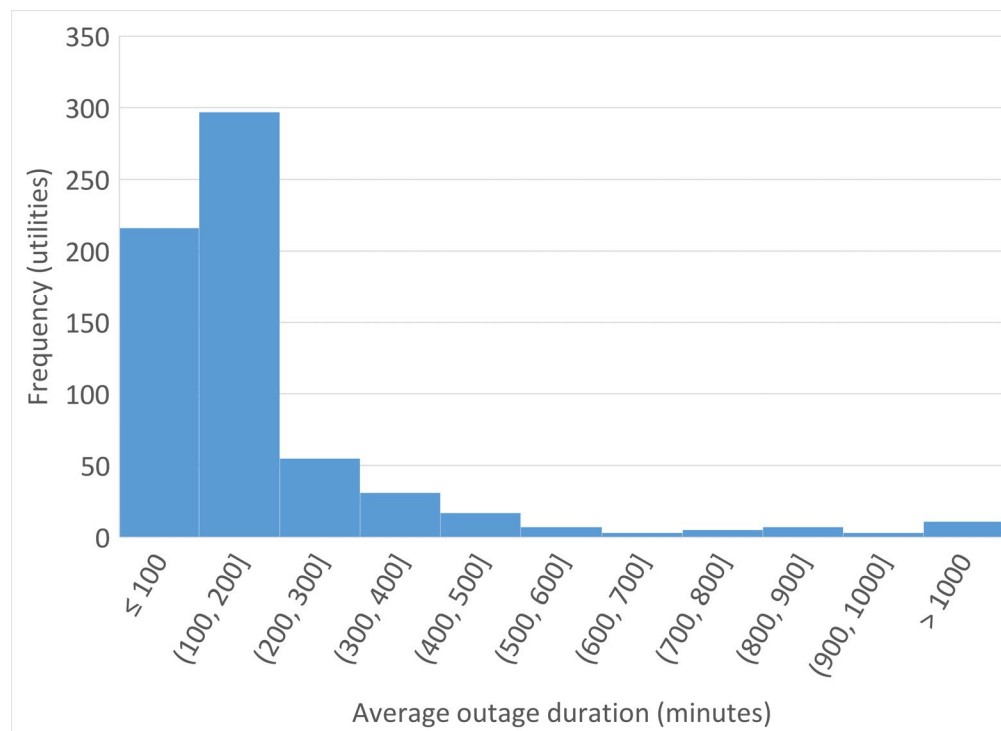


Figure 1. Histogram of outage duration for 652 utilities in the United States. Average outage duration is 189 minutes.

While the average duration of an outage is three hours, the data do not tell us anything about the distribution of all outages; we only see how the average duration of outages is distributed across utilities. The data do not show how frequent very long outages are or if they occur during the heating season. We also cannot say that the average duration for a customer is

three hours, but rather than the average among utilities is three hours. Given the average utility, the following example illustrates how a typical home can withstand a three-hour outage without heating backup.

Depending on the attributes of the building and outside temperature, the inside temperature will fall at different rates. Assuming a house with a UA value, *i.e.* heat transfer coefficient, of 300 BTU/hr/F° and a thermal capacitance of 4000 BTU/F°, we show in Figure 2 how the inside temperature would fall, starting at 70°F and with a 32°F outside temperature. At the 3-hour mark (average outage duration), the house is still 62°F, a safe and reasonably comfortable temperature.

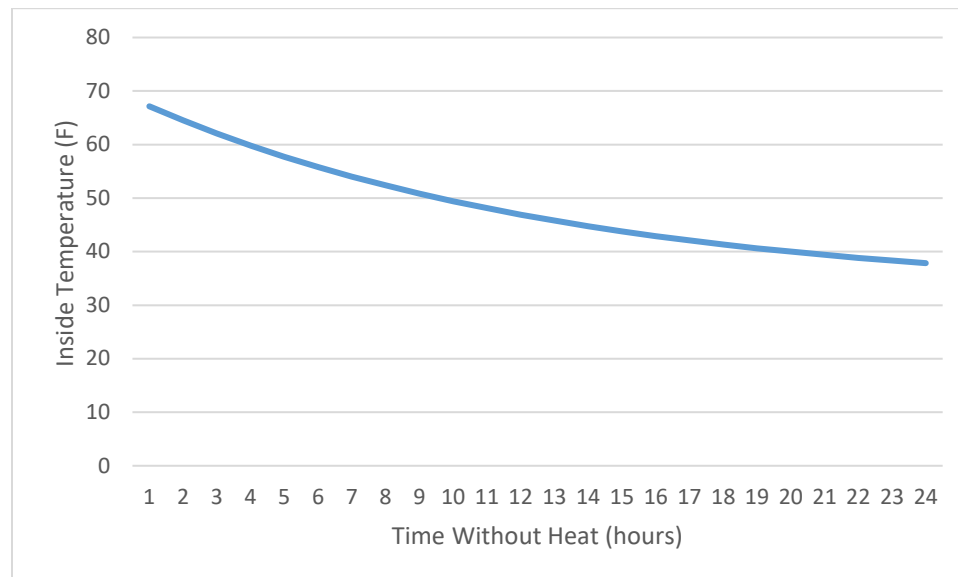


Figure 2. Modeled inside temperature hours after a heating system outage, assuming 32°F outside temperature.

Backup Heat Appliances and Strategies

Two classes of backup heating strategies are considered here: direct combustion heaters that do not require power, and powered heaters that require a backup source of electricity. Direct combustors include wood stoves, natural gas (NG) stove fireplaces, and propane stove fireplaces. Open air gas or wood fireplaces were not considered due to their poor efficiency (10%) and correspondingly high emission rates and fuel consumption rates (~30 kg wood for 48kBTU). Powered heaters include electric resistance space heaters, electric heat pumps, NG furnaces, and pellet stoves. We selected two backup power options: a Tesla Powerwall 2 (13.5kWh/5kW) with an efficiency of 92.5% and a commonly sized 8kW unleaded gasoline generator with a 7.5-gallon fuel tank and a peak efficiency of 16% at 4000kW load. The choice of generator size, while arbitrary, represents a readily available option from hardware stores throughout the United States with adequate power delivery and targeted efficiency curves for operating a 240V, 15A heat pump.

Not all backup strategies provide the same amount of heat. We selected a functional unit to normalize backup heating strategies. The functional unit of the heating appliances is 48 kBTU/h. This heating power is typical of furnaces and heat pumps appropriately sized to 1000+ sq ft. homes (Navigant Consulting 2018). The two backup strategies with either a generator or a

battery paired with an electric resistive space heater only provide 15.6 kBTU/h due to the power limitations of the Tesla Powerwall and reasonable backup generators. Therefore, this was used for heat output for electric resistance heaters. The propane and gas stoves are limited to 40kBTU/h based on widely available models for purchase.

The following tables contain the data used for our economic and GHG analyses for transparency and reproducibility. Table 1 lists backup heating appliances considered and their financial characteristics. We assumed a discount rate of 5% and annualized capital expenditure (CAPEX) over appliance lifetimes as indicated by Navigant Consulting and Tesla (Navigant Consulting 2018; Tesla 2019). A Powerwall stores a finite supply of electricity that can only power backup appliances for a limited time dependent on their power draw as listed in Table 2. Runtimes for a Powerwall paired with a heat pump, furnace or pellet stove are 3, 20 and 80 hours, respectively. Table 2 lists these appliances and their GHG emissions. Table 3 lists emission factors with associated fuel costs for backup heating appliances used to calculate the operational expenditure (OPEX) and GHG emission rates. Emissions data were taken from the EPA (2018). Fuel cost assumptions are shown in Table 3 (Nalley and LaRose 2022).

Table 1. Primary and Backup heat appliance financial data

Appliance	CAPEX	life (y)	Annualized at 5%	heat (kBTU/h)	OPEX/h	Fuel Types
Gas Stove	\$4,500	20	\$361.09	40	\$0.58	natural gas (NG)
Propane Stove	\$4,500	20	\$361.09	40	\$1.75	propane
Wood Stove	\$4,700	25	\$333.48	48	\$0.82	wood
Wood Fireplace	\$4,500	25	\$319.29	48	\$6.55	wood
Gas Generator 4.5kW	\$1,279	10	\$165.64			unleaded
Tesla Powerwall (PW) 2	\$10,500	10	\$1,359.80			electricity
Space Heater (SH) 1.5kW	\$110	10	\$14.25	5.2		electricity
3 SH w/gen			\$208.37	15.6	\$3.07	unleaded
3 SH t w/PW			\$1,402.53	15.6	\$0.73	electricity
Heat Pump (HP)	\$5,749	20	\$461.31	48	\$0.59	electricity
HP w/gen			\$626.95	48	\$2.66	unleaded
HP w/PW			\$1,821.11	48	\$0.63	electricity
Gas Furnace (GF)	\$4,664	20	\$374.25	48	\$0.75	NG
GF w/gen			\$539.89	48	\$1.07	NG + unleaded
GF w/PW			\$1,734.05	48	\$0.76	NG + electricity
Pellet Stove (PS)	\$2,126	10	\$275.33	48	\$1.04	pellets
PS w/gen			\$440.96	48	\$1.11	Pellets + unleaded
PS w/PW			\$1,635.12	48	\$1.04	Pellets + electricity

Table 2. Primary and backup heat appliance GHG emission data

Appliance	Fuel/hour	Units	Scope 1 (kgCO ₂ /h)	Elec./h (kWh)	Scope 2 (kg CO ₂ /h)	total (kg CO ₂ /h)
Gas Stove	0.053	MMBTU	2.81			2.81
Propane Stove	0.584	Gallons	3.34			3.34
Wood Stove	4.080	Kg	5.63			5.63
Wood Fireplace	32.700	Kg	45.09			45.09
Gas Generator	0.767	Gallons	6.73			6.73
3 SH w/gen	0.767	Gallons	6.73			6.73
3 SH t w/PW				4.865	2.43	2.43
Heat Pump				3.900	1.95	1.95
HP w/gen	0.665	Gallons	5.84			5.84
HP w/PW (3 hour limit)				4.216	2.11	2.11
Gas Furnance	0.060	MMBTU	3.18	0.600	0.30	3.48
GF w/gen	0.102	Gallons	4.08			4.08
GF w/PW (20 hour limit)			3.18	0.649	0.32	3.51
Pellet Stove	6.440	lbs	1.13	0.150	0.08	1.21
PS w/gen	0.026	Gallons	1.35			1.35
PS w/PW (80 hour limit)			1.13	0.162	0.08	1.21

Table 3. Fuel Prices and Emission Factors

Fuel	Price	Units	Emission Factor	Units CO ₂
natural gas	11.00	\$/MMBTU	53.06	kg/MMBTU
propane	3.00	\$/gal	5.72	kg/gal
wood	0.20	\$/kg	93.8	kg/MMBTU
pellets	0.16	\$/lb	23.44	kg/MMBTU
unleaded gas	4.00	\$/gal	8.78	kg/gal
electricity	0.15	\$/kWh	0.50	kg/kWh
we assume	14700	BTU/kg seasoned mix of soft/hardwood		
	16500	BTU/kg pellet		

Results

For an average outage duration of 3 hours and for a typical home sized at 1000 ft², we found that backup heat is not necessary to maintain safe and comfortable indoor temperatures. However, in prolonged outages, colder outdoor temperatures, and/or poorly insulated homes backup heat becomes necessary. We find the most cost-effective back up power option is a

natural gas stove fireplace that does not require electricity to light or operate. The option with the lowest GHG emissions, barring a zero-emission electricity source, is a pellet stove powered with a Powerwall or similar battery backup. Figure 3 shows the cost and GHG emissions for heating appliances as a function of runtime in hours. Some backup strategies can run indefinitely, so long as there is fuel.

We calculated annualized costs for backup heat operation from 1 to 1000 hours to explore intersections in which OPEX began to overtake CAPEX for various strategies for possible rural locations at grid network termini that may suffer hundreds of outages per year. Our analysis ignores escalating fuel costs and thus most likely underestimates fossil fuel costs over a 10-year lifetime in comparison to electricity costs given historical and predicted fuel markets (Nalley and LaRose 2022). The y-intercept of Figure 3B (bottom) shows CAPEX for strategies annualized at 5% for their lifetimes. Powerwall options have the highest capital costs but become more affordable than powering a heat pump with an unleaded gasoline generator after 600 hours. However, most homes will not experience outages at this rate to justify the capital costs. Using a Powerwall to store onsite residential solar generation for backup heating is, however, a well-advised backup strategy as it is a complimentary service to a low or zero carbon residential power solution.

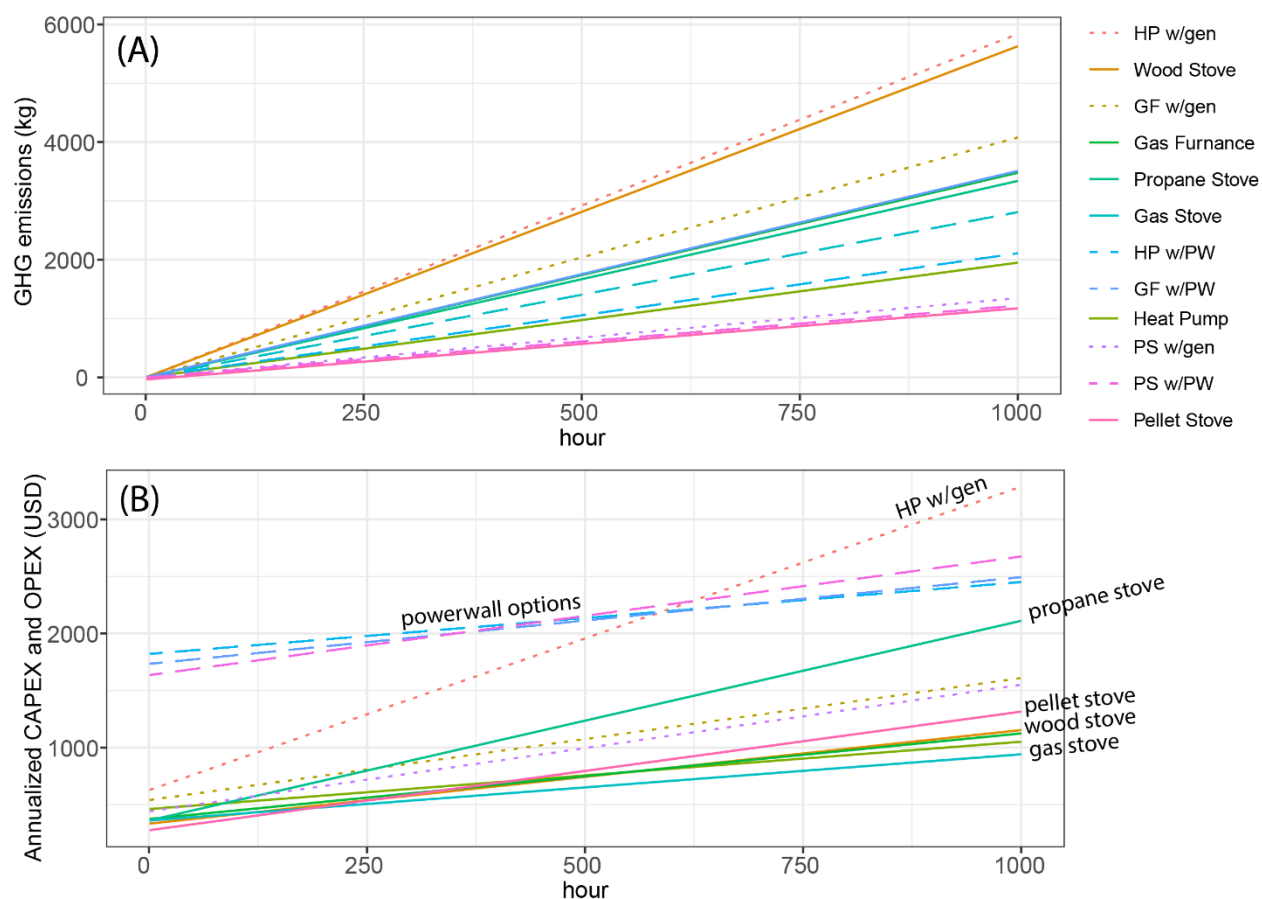


Figure 3. A) GHG emissions as function of runtime in hours for backup heat appliances and B) Cost (Annualized CAPEX plus OPEX). Heating appliances are listed in the legend in the same vertical order from greatest GHG emissions to least as shown in figure 3A. Backup options paired with a Powerwall are shown in dashed lines. Backup options paired with a generator are shown in dotted lines.

A heat pump is the most affordable method for heating a home assuming current fuel prices and a reliable electricity source. For backup, however, a gas stove is a reliable heating source and the most affordable option, followed by a wood stove and next, a pellet stove paired with a generator. If a household does not have a wood burning stove and would therefore rely most commonly on a gas furnace or heat pump paired with backup power, the most affordable options for 3 hours of heat a utilize gas generator: \$543 and \$644 for a furnace and heat pump respectively. A Powerwall's capital cost increases these backup options for 3 hours to \$1736 and \$1823 respectively.

The GHG emissions as function of runtime are shown on the top plot of Figure 3A. They depend on the emission factor (mass of GHG per unit energy) of the fuel used. The legend in figure 3 lists the backup strategies in order of emissions from greatest to smallest. A heat pump paired with a generator produces the most emissions due to a generator's poor efficiency (~16%). Pairing a pellet stove with a Powerwall produces the least number of emissions assuming that the pellets are formed from waste wood products. Gas stoves produce more emissions than a Powerwall paired with either a heat pump or generator. Wood stove emissions can be as low as a pellet stove if wood is sourced from fast growing renewable forests but otherwise can be one the highest emitters if the wood is not replanted following harvest. Table 4 lists the cost and emissions for backup options providing 3 days of heat.

Table 4. Backup Costs and Emissions for 72 hours

Backup	Cost (USD)	CO2 (kg)
Wood Stove	393	405
Pellet Stove with Generator	521	97
Gas Furnace with Generator	617	294
Heat Pump with Generator	818	420
Pellet Stove with Powerwall	1710	88
Gas Furnace with Powerwall	1789	253
Heat Pump with Powerwall	1866	152

Conclusion

Former U.S. President Carter's call for Americans to pull on their sweaters to cut energy use during the 1970s oil crisis may have been a public relation *faux pas*, but it is the most affordable and carbon conscience resilience solution for cold snaps corresponding with power outages. With an average power outage duration of only 3 hours, backup heat is rarely needed. In extreme cases, for example the daylong outage in much of Texas February 2021, interior temperatures can become hazardous, dropping below 40 F. When it is required, heaters fueled only by natural gas, propane, or wood can provide adequate and affordable heat. Not many homes have these appliances, however, and for these cases a backup generator powering existing heaters, *i.e.*, furnaces or heat pumps, is the most affordable option. For those interested in producing the least amount of GHG emissions, while expensive, a Powerwall paired with a pellet stove only produces 1.21 kg of CO₂ for 48kBTUs of heat. Policy makers and homeowners should be aware that natural gas may be unavailable during a power outage as well. For this reason, as a point of pure resiliency, the humble wood stove provides.

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