Optimizing Energy Efficiency in Residential Heating Applications - What are the Options? What are the Impacts?

Thomas Manjarres, Franklin Energy
Allen Dusault, Franklin Energy

ABSTRACT

Saving energy in home heating and cooling applications no longer guarantees lower monthly bills. Under some circumstances, high efficiency measures can result in higher energy bills, and even increase greenhouse gas emissions. Data from the Carbon Management Information Center's (CMIC) Source Energy and Emissions Analysis Tool (SEEAT) suggest that saving energy, lowering utility bills, and reducing carbon emissions can be at odds.

In this paper, the cold climate performance of various electric and natural gas space heating technologies are evaluated in a representative residential context and compared to that of a baseline 80% AFUE natural gas furnace. The technologies included in the analysis are: a condensing natural gas furnace (96% AFUE), an electric air-source heat pump (3.8 SCOP/13 HSPF) and a natural gas-fired absorption heat pump (1.4 SCOP). Under the northern Illinois residential scenario evaluated, results indicate that the electric heat pump is the most efficient alternative using home energy consumption (site energy) as the metric. However, the electric heat pump also consumes the most total (source) energy, produces the most greenhouse gas emissions, and is the most expensive system for utility customers to operate annually.

This analysis suggests that electrification of space heating in cold climates should be carefully considered. More specifically, what should be the priority of electrification initiatives and utility energy efficiency programs: reducing energy consumption in the home, reducing customer utility bills, or reducing total energy consumption and overall carbon emissions?

Background

Advances in new home construction practices and deep energy retrofits of existing homes are resulting in better insulated, less leaky homes. Heat pump technology has also evolved in recent years, enabling this equipment to better perform in cold climates. These advancements make heat pumps potentially competitive with natural gas furnaces, depending on the regional climate and the relative gas and electricity prices where it is to be installed. Not well known is the development of natural gas absorption heat pumps, an emerging technology that has been used in commercial applications and large (4,000+ ft^2) residential applications and will soon be available for the rest of the residential heating and cooling market. With these technologies now able to perform in cold climates, it is important to understand how natural gas and electric heat pumps compare to each other and to other space heating options.

Builders and homeowners in cold climates across the U.S. increasingly will have multiple efficient heating systems to choose from, including:

- Modulating, condensing natural gas furnaces (90-98% AFUE)
- Electric air-source heat pumps (SCOP of 3.8 or more)
- Natural gas absorption heat pumps (SCOP of 1.4/AFUE of 140% or more)

To aid in decision making, the above options were evaluated for their energy efficiency, greenhouse gas (GHG) emissions and annual operating costs. The results indicate that choosing between efficient heating systems in cold climates can have unintended outcomes.

Modulating, Condensing Gas Furnace

A modulating, condensing gas furnace offers two efficiency improvements over the more conventional single stage or two stage, non-condensing furnaces. The modulating function varies the burner heat output and blower fan speed to match heating demands. This extends furnace runtimes, which result in less frequent cycling and therefore less energy loss during startups. The condensing feature utilizes a second heat exchanger to extract additional heat from the exhaust gasses. As such, some modulating, condensing furnaces are capable of achieving an annual fuel utilization efficiency (AFUE) of 96%.

Electric Air-Source Heat Pump (ASHP)

Heat pumps operate by moving heat from one area to another. When properly sized and installed, some air-source heat pumps can deliver over three times more heat energy to a home compared to the energy they consume. Electric ASHPs are an established technology that have been used for years throughout much of the Unites States. In recent years, the technology has advanced so that it can now meet space heating demands in many colder regions of the country.

An electric heat pump's refrigeration system consists of a compressor, refrigerant, indoor heat exchanger coils, and outdoor heat exchanger coils. In heating mode, liquid refrigerant in the outdoor heat exchanger extracts heat from the ambient air as it evaporates. The compressor then increases the pressure and temperature of the gaseous refrigerant, which then releases heat as it condenses back to a liquid in the indoor heat exchanger. This is like running air conditioner in reverse—taking heat from outside the house and moving it inside.

Gas Absorption Heat Pumps (GAHP)

Gas absorption heat pumps, also referred to as gas-fired heat pumps, are air-source heat pumps driven not by electricity, but by a heat source—typically natural gas (propane, biomethane and other fuels also possible). Like their electric counterparts, gas-fired heat pumps can be reversible and can serve a home's space heating and cooling needs. Residential gas absorption heat pumps typically use an ammonia-water absorption cycle. As in an electric heat pump, the refrigerant (ammonia in this case) is condensed in one area to release heat and evaporated elsewhere to absorb heat. The differences between electric and gas heat pumps are primarily in the refrigerant and how the refrigerant is pressurized.

Gas heat pumps do not use environmentally damaging hydrofluorocarbons (HFCs) or chlorofluorocarbons (CFCs) as the refrigerant. Instead, ammonia (NH_3), considered a natural refrigerant by the EPA, is used as the working fluid. In a gas heat pumps, the evaporated ammonia is absorbed into water and a relatively low power pump pumps the solution up to a higher pressure. Then, the natural gas heat source is used to boil the ammonia out of the ammonia-water mixture, and the ammonia vapor continues through the cycle. A diagram of gas absorption heat pump operation is included below in Figure 1.

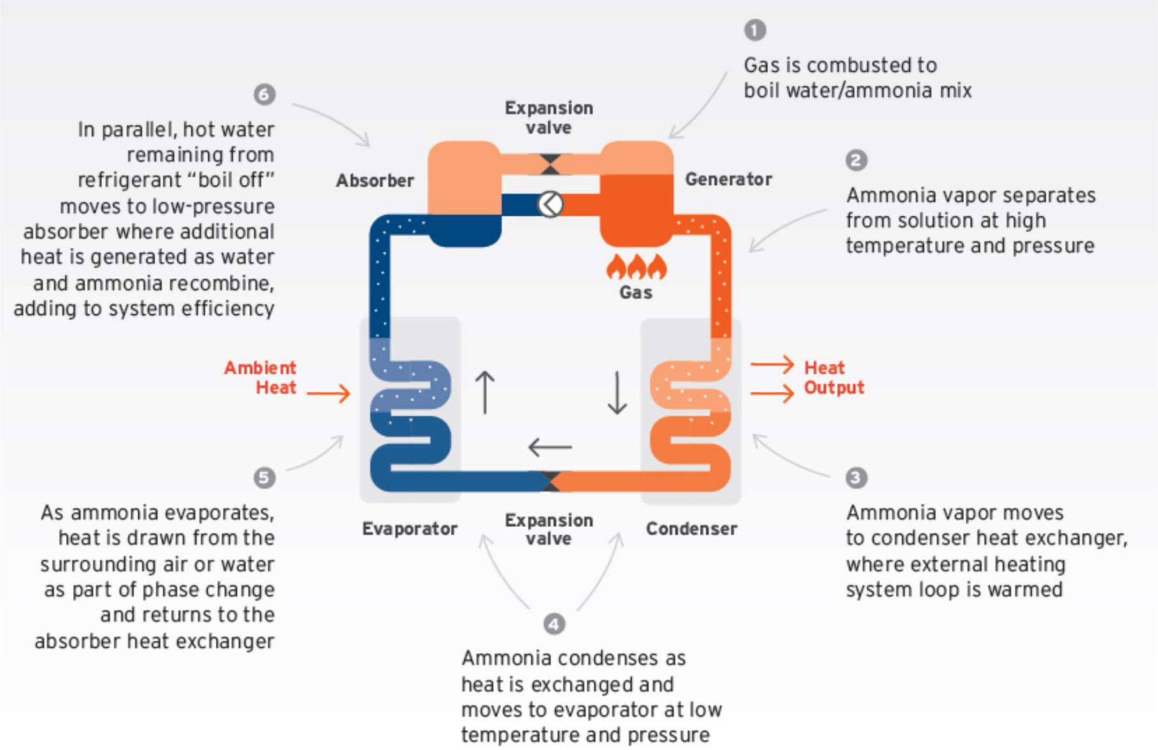


Figure 1. Ammonia-based gas absorption heat pump operating principle. *Source:* TAF 2018.

Key Terminology and Application Context

For this analysis, two terms are needed to compare the true lifecycle costs of equivalent electricity-driven and combustion-driven technologies: site energy and source energy. The differences between the two are a result of the boundary conditions that define each term. These boundary conditions are discussed further below and represented visually in Figure 2.

Site energy is the energy consumed in the home by an appliance, as recorded by the gas or electric utility meter. To date, most energy efficiency programs are designed to reduce site energy consumption through incentivizing customers to choose products that will minimize site energy use (maximize site energy savings).

Source energy is the total amount of raw fuel required to operate an energy consuming appliance. It represents the most inclusive and most equitable boundary conditions on which to analyze the impact of building or appliance energy consumption. This is why ENERGY STAR includes source energy calculations in their widely used Portfolio Manager tool for tracking and benchmarking commercial buildings (U.S. DOE 2019).

For homes, source energy includes the energy used in the home (the site energy), plus the total energy required to produce and transport that energy to the home. In this analysis, source energy includes the following:

1. Energy required to convert fuel to electricity
2. Energy required to transmit and distribute electricity to the site
3. Energy required to distribute natural gas to the site
4. Energy consumed by the appliance in the home, as measured by the gas and electric utility meters

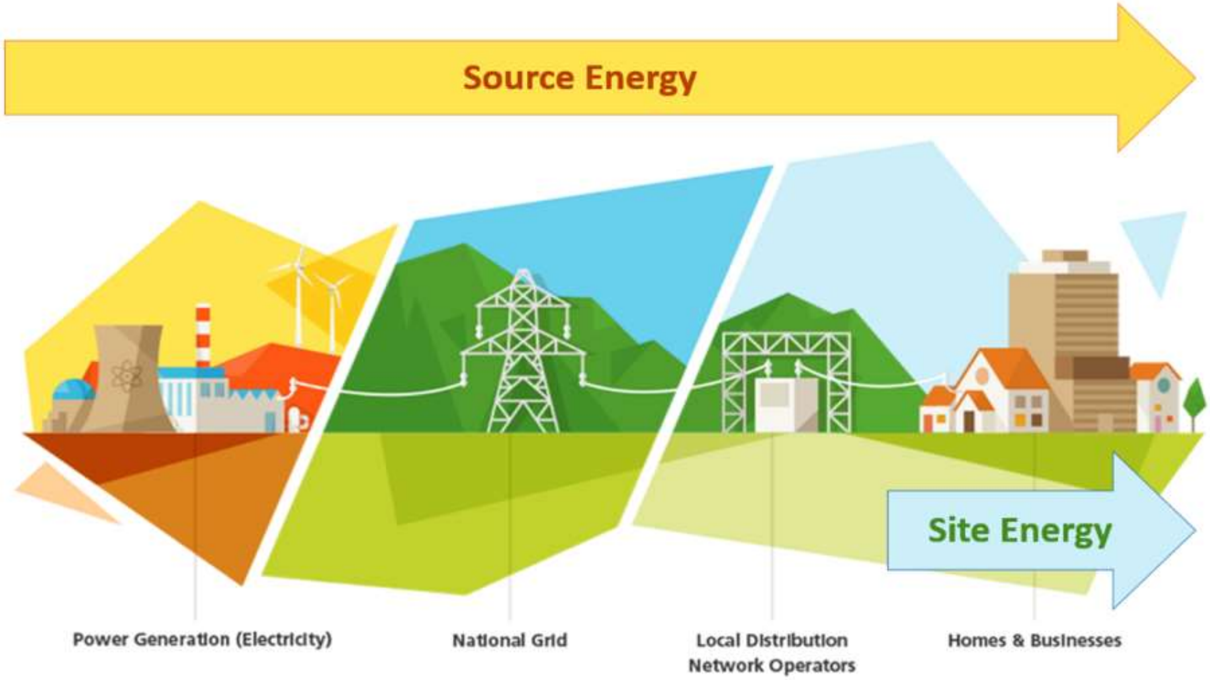


Figure 2. Source energy and site energy boundary conditions. *Source:* University of Strathclyde Glasgow 2016.

Site energy is a convenient metric to track because it can be easily measured directly at the energy-consuming appliance or the utility meter. EPA's ENERGY STAR Label program provides independent ratings for energy efficient appliances based on the site energy consumption of the appliance. However, site energy is a misleading and incomplete metric on which to base any program, regulation, policy or investment decision whose goal is to reduce total energy consumption, site energy costs, or greenhouse gas (GHG) emissions, especially when comparing appliances that are fueled by multiple energy sources (i.e. natural gas furnace vs. electric heat pump) (Leslie 2019).

This is because site energy measurements do not account for the energy lost and GHG emissions resulting from converting raw fuel to secondary forms of energy (i.e. electricity or heat), nor the energy losses incurred while transmitting and delivering that energy to the site. Furthermore, most initiatives based on site energy savings do not account for the total energy consumed when more than one energy source is used in an appliance, such as a natural gas furnace containing an electric blower fan. The source energy calculation is more expansive and accounts for all forms of energy consumed on-site in addition to the energy needed to produce and transport that electricity or fuel to the site for consumption.

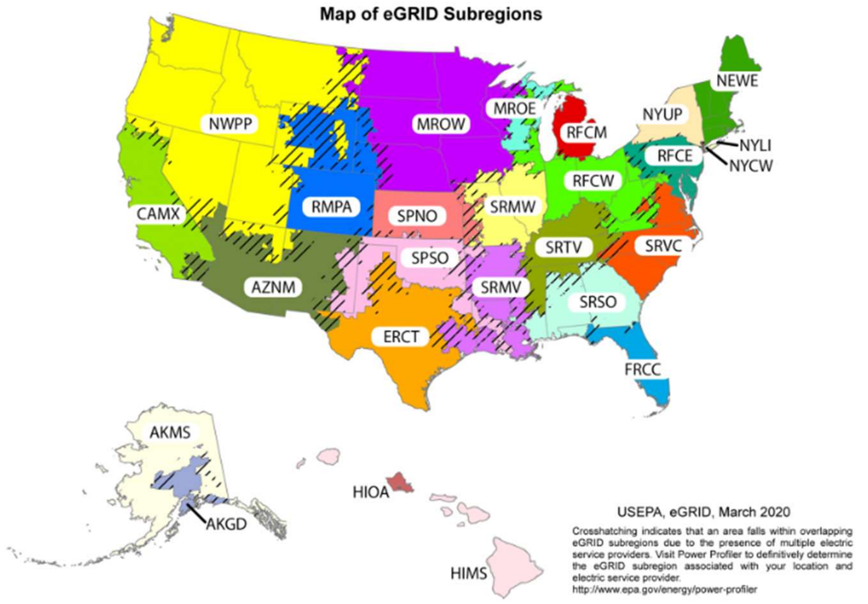
Assumptions and Analysis

Source Energy Conversion Factors

Source energy conversion factors can be used to calculate the impact of every kWh and BTU (or therm) consumed in a home. Source energy conversion factors are the ratio of total energy consumed globally for every unit of energy used on-site. The annual source energy consumption of an appliance is calculated by multiplying the appliance's annual site energy use by the appropriate source energy factor(s). Similarly, greenhouse gas emissions resulting from the total source energy consumption are calculated using data from the U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID). This is done by multiplying the annual source energy consumption (via source energy factor times site consumption) by the corresponding eGRID greenhouse gas emission rates (U.S. EPA 2020).

eGRID Subregions

It is nearly impossible to attribute the movement of electrons to specific electricity generation stations when multiple facilities are feeding electricity into the same network/grid. Therefore, eGRID subregions are drawn using transmission system operator (TSO) maps, distribution grids, and utility service territories to determine the generation stations most likely to be serving customers within a defined geographic area at any given time. When electricity demand increases or decreases within the subregion, the marginal generation stations within that subregion are the first to increase or decrease electricity output. Figure 3 is a map of eGRID subregions across the U.S.



USEPA, eGRID, March 2020

Crosshatching indicates that an area falls within overlapping eGRID subregions due to the presence of multiple electric service providers. Visit Power Profiler to definitively determine the eGRID subregion associated with your location and electric service provider.
http://www.epa.gov/energy/power-profiler

Figure 2. Subregions are defined using the transmission, distribution and utility service territories of power plants. *Source:* U.S. EPA 2020.

Marginal Electricity Generation

Electric loads and renewable generation fluctuate throughout the day. Therefore, power plants that can quickly ramp up or reduce production are essential for maintaining the stability of the electric grid. Referred to as marginal power plants, they are brought online and taken offline as necessary. Because these marginal plants are the last to be turned on and the first to be turned down, the DOE and EPA use marginal electricity generation conversion factors by eGRID subregion to assess energy efficiency programs and rate energy efficient products (Leslie 2019). According to the EPA, marginal impact methodologies are more useful than national, regional, or state average electricity generation conversion factors because the marginal plants will be the first to reduce electricity production as a direct result of efficiency measures. Average electricity generation conversion factors include baseload generators that run all the time, such as nuclear and some hydropower, that will be largely unaffected by energy efficiency improvements (U.S. EPA 2009). If electric loads were to *increase*, which would be the case if space heating was electrified, the power plants on the margin will be the first to increase electricity production.

According to the EPA, the non-baseload (marginal) output emission rates were developed to provide an estimate of emission reduction benefits resulting from energy efficiency and clean energy projects (Rothschild and Diem 2009). In this context, "baseload" refers to those plants that supply electricity to the grid when demand for electricity is low. Baseload plants provide electricity to the grid regardless of fluctuations in electricity demand and generally operate continuously except when undergoing maintenance.

In eGRID, the capacity factor of each plant is used as a surrogate for determining whether or not the plant generates baseload electricity and how much of each plant's generation is considered non-baseload. Two criteria are used to qualify non-baseload plants:

1. Combust fuel
2. Have a capacity factor less than 0.8

eGRID subregion CO_2 non-baseload emission rates are the underlying data used in EPA's Greehouse Gas Equivalencies Calculator and the underlying data for EPA's Green Power Equivalency Calculator. However, the authors propose using updated assumptions on non-baseload efficiency and emission rates than the rates calculated in eGRID 2018. Among other reasons, the efficiency of combined cycle natural gas plants and the decline in natural gas prices in recent years have allowed natural gas power plants to assume more of the non-baseload generation than is reflected in the eGRID 2018 data. This more conservative approach will tend to show higher efficiency and lower greenhouse gas emissions from the electric grid, at least in the Midwest, compared to the eGRID 2018 marginal data (U.S. EPA 2020).

The Case for Using a 100% Natural Gas Marginal Mix for Analysis

Although some coal plants fit the usage threshold to be considered marginal plants according to the eGRID criteria, they more frequently operate at near fixed loads and are usually not the first to be ramped up and down throughout the day. Of the three marginal electricity generating fuels in use in Illinois, coal, natural gas and biomass, natural gas plants are typically the most efficient and cheapest to operate. As such, the natural gas plants are likely the first to ramp up as electric loads increase. Including the marginal coal plants as defined in eGRID 2018 would further lower the source efficiency of the grid while not accurately reflecting how the grid operates on a day-to-day basis.

This assertion is further supported by the U.S. National Electrification Assessment published by the Electric Power Research Institute (EPRI) in 2018. According to EPRI research, in the near through intermediate term (2020 through 2050), electrification may result in a total natural gas consumption *increase* of anywhere form 18%-40% over the baseline, which is taken from the U.S. Energy Information Administration's Annual Energy Outlook 2017 (EPRI 2018). These estimates are consistent with the national average source efficiency of natural gas delivered to the home (98%) compared to the average source efficiency of marginal natural gas-generated electricity (42.5%). When natural gas consumption is shifted from inside the home to electricity generation stations, the result is a drop in source energy efficiency.

For these reasons, the comparisons presented below use a marginal source energy conversion factor of **2.87 (34.8%),** which is the source energy conversion factor for marginal natural gas power generation in the RFCW subregion (U.S. EPA 2020). The average source efficiency for all natural gas plants (baseload + marginal) in the RFCW region is slightly better at 41.7 %. This leads to a lower source energy factor of **2.40.** Source energy factors for the two eGRID subregions that cover Illinois are included below in Table 1. The difference between marginal and average source energy factors is due to the age and efficiency of the marginal natural gas plants compared to the baseload natural gas plants. Typically, the newer and more efficient combined cycle natural gas plants supply baseload electricity and the older, less efficient and non-combined cycle natural gas plants operate on the margin. The most likely scenario is that these marginal natural gas power plants will be the first to increase production as new space heating loads are added to the grid.

A related point is how the power plant mix will change over the life of the heating technology, or at least by 2025 with a 25% renewables target. In Illinois, as in some other states, baseload renewable power plants are not incentivized like wind and solar. As such, very little baseload renewables are slated to come online. Most new renewable power generation that will be built will be intermittent and is unlikely to displace the marginal plants. In fact, it could increase the utilization of those plants. Also note that the winter seasonal heating demand in Illinois can be extreme and no battery storage technology has yet been devised that could meet that demand and approach being cost effective. At best, construction of a few more efficient natural gas plants could slightly improve the overall efficiency of marginal natural gas generation, but any change is unlikely to be significant. It is also important to recognize that coal plant closures, to the extent they occur, will have little or no effect on the marginal plant mix focused on in this analysis. The coal plants are assumed not to be part of the marginal mix.

Natural Gas Source Energy Conversion Factor

Due to the inherent inefficiency associated with generating and distributing electricity from centralized generating stations, average and marginal electricity generation source energy factors are higher than the average natural gas for building use (as opposed to electricity generation) source energy factor. This means more energy input is required for every Btu of electricity used in a home when compared to the energy input required for every Btu of natural gas used in the home. As depicted in Table 2 below, the average natural gas source energy factor in the U.S. is **1.01** whereas the average electricity source energy factor is **2.56**.

Table 1. Marginal and average source energy factors by eGRID sub-region in Illinois

eGRID sub-region acronym	eGRID sub-region name	Marginal (non-baseload) source energy factor	Average source energy factor
RFCW	RFC West	3.13	2.31
SRMW	SERC Midwest	2.99	3.02
Natural gas-generated electricity		2.87[1] (100% marginal natural gas plants)	2.4[2] (100% natural gas—all plants)

[1] Value used in this analysis

[2] Weighted average of all baseload and marginal natural gas plants in Illinois.

Source: U.S. EPA 2020.

Table 2. U.S. average source energy factors for electricity and natural gas.

Energy form	**Conversion**	**Distribution**	**Aggregated efficiency**	**Source energy factor**
Natural gas (building used)	---	99%	98%	1.01
Electricity —all fuels	41.1%	95.1%	39.1%	2.56
Electricity—Natural gas fueled	44.7%	95.1%	42.5%	2.35

Source: U.S. EPA 2020.

Methodology

Heating system performance was evaluated and compared to the baseline, which was set to an 80% AFUE furnace—the current Federal Standard. A 1,000 ft^2, two bedroom townhome in Rockford, IL was used as the reference case. The technologies selected for comparison were:

1. Modulating, condensing natural gas furnace with a rated annual fuel utilization efficiency (AFUE) of 96%
2. Electric air-source heat pump with a seasonal coefficient of performance (SCOP) of 3.8
3. Natural gas absorption heat pump with a seasonal coefficient of performance (SCOP) of 1.4

These three technologies and the baseline furnace were analyzed and ranked based on four evaluation criteria:

1. Site energy consumption
2. Source energy consumption
3. Annual operating cost
4. Greenhouse gas emissions

The simulated results and rankings for each criterion are discussed below.

Source Energy and Emissions Analysis Tool (SEEAT)

The results were computed using the Carbon Management Information Center's (CMIC) Source Energy and Emissions Analysis Tool (SEEAT). SEEAT is available free to the public (http://seeatcalc.gastechnology.org/) and uses five public domain data sources to calculate source energy and emissions factors for electricity and fossil fuels typically used in residential and commercial buildings. These five data sources include EPA, Energy Information Administration (EIA), Argonne National Laboratory (ANL), National Renewable Energy Laboratory (NREL), and National Hydropower Association. (Leslie 2019). The default assumptions in SEEAT define source energy as encompassing the full fuel cycle. This includes all energy consumed during extraction, processing and transportation of raw fuel to the power plant in addition to the energy consumed in conversion, transmission and distribution of electricity to the home and the electricity used in the home (site energy). The default source energy boundary conditions were changed to align with the U.S. EPA definition of source energy used in this paper, which is to say source energy calculations were restricted to only include conversion to electricity at the power plant through end use in the home.

In SEEAT, annual energy consumption for each appliance and the entire building are calculated based on modeled energy loads of relatively energy efficient building envelope configurations. This results in an annual consumption estimate that is closer to what would be measured in the field compared to an annual consumption estimate computed from an ENERGY STAR rated efficiency or energy factor (CMIC 2020).

Results

Criteria 1: Site Energy

These output values are specific to the reference home. Heating systems were ranked according to their annual site energy consumption, with the heating system consuming the *least* amount of site energy ranking first.

Table 3. Heating system ranking based on site energy consumption.

Rank	Heating System	Site Energy	Site Energy (MMBtu)
1	Electric heat pump (3.8 SCOP)	4,951 kWh*	16.89
2	Natural gas heat pump (1.4 SCOP)	229 therms and 442 kWh**	24.41
3	Condensing gas furnace (96% AFUE)	347 therms and 288 kWh***	35.68
4	Baseline gas furnace (80% AFUE)	417 therms and 278 kWh***	42.65

* Nadel, S. and C. Kallakuri, May 2016. "Opportunities for Energy and Economic Savings by Replacing Electric Resistance Heat with Higher-Efficiency Heat Pumps." ACEEE Report A1603.

**Annual kWh includes energy to operate refrigerant pump and air handler blower fan during both heating and cooling operation.

***Annual kWh includes energy to operate the draft inducer fan and air handler blower fan during both furnace and A/C operation.

Criteria 2: Source Energy

The heating systems were then ranked according to their calculated annual source energy consumption. The heating system that consumed the *least* amount of source energy throughout the year was ranked first for this criterion.

Table 4. Heating system ranking based on source energy consumption.

Rank	Heating System	Source Energy (MMBtu)
1	Natural gas heat pump (1.4 SCOP)	27.46
2	Condensing gas furnace (96% AFUE)	37.87
3	Baseline gas furnace (80% AFUE)	44.84
4	Electric heat pump (3.8 SCOP)	48.48

Criteria 3: Annual Operating Cost

Annual operating cost was the next criterion evaluated. Annual operating costs were calculated by multiplying the annual electricity and natural gas consumption outputs from SEEAT by the 2019 average utility rates in Illinois. According to the Energy Information

Administration (EIA 2020), the 2019 Illinois average natural gas rate for residential customers was **1.077 $/therm** and the average electricity rate for residential customers was **0.1295 $/kWh**.

Table 5. Operating costs based on 2019 average utility rates in Illinois (EIA 2020.)

Rank	Heating System	Annual Operating Cost
1	Natural gas heat pump (1.4 SCOP)	$302
2	Condensing gas furnace (96% AFUE)	$408
3	Baseline gas furnace (80% AFUE)	$482
4	Electric heat pump (3.8 SCOP)	$641

These results show that, although the electric heat pump will consume the least amount of energy on-site, it is over **1.5 times more expensive to operate** than a 96% AFUE furnace and over **two times more expensive to operate** than a natural gas heat pump for utility customers in northern Illinois. As a result, customers will end up paying the most for the most site-efficient configuration. This runs counter to the conventional wisdom of energy efficiency programs—that efficiency yields energy savings and energy savings equal dollars saved for the customer.

The most efficient system from a source energy perspective, the natural gas heat pump, is also the cheapest system to operate. Here, utility efficiency programs prioritizing *source* energy savings will benefit the customer the most because the most source-efficient product comes with the lowest annual operating cost.

Criteria 4: Greenhouse Gas Emissions

The annual greenhouse gas emissions calculations below account for methane (natural gas) leaks from pipelines and compressor stations as well as the emissions resulting from methane combustion. The CO_{2e} value is the carbon dioxide equivalent emissions. It represents the cumulative Global Warming Potential (GWP) of all greenhouse gas emissions expressed in terms of the global warming potential of carbon dioxide.

In this analysis, the 100-year Global Warming Potential of natural gas (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) were used to calculate CO_{2e} emissions. CO_{2e} conversions factors and GHG emission rates specific to the eGRID subregion (RFCW) are included below in Table 6.

Table 6. Carbon dioxide equivalent conversion and emission factors for RFCW subregion.

Greenhouse Gas	Chemical Formula	CO_{2e} Conversion
Methane (natural gas)	CH_4	1 CH_4 = 28 CO_{2e}
Nitrous oxide	N_2O	1 N_2O = 265 CO_{2e}
Carbon dioxide	CO_2	1 CO_2 = 1 CO_{2e}

Energy Form	CO_2	SO_2	NOx	CH_4	N_2O	Total CO_2e
Non-Baseload Natural Gas Generated Electricity (lb/MMBtu)	346.97	0.054	0.269	0.003	0.000	347.05
Natural Gas—Building Used (lb/MMBtu)	119.59	0.004	0.123	0.053	0.002	121.73

Source: U.S. EPA 2020.

Table 7. Heating system ranking based on annual greenhouse gas emissions.

Rank	Heating System	Greenhouse Gas Emissions (CO_{2e})
1	Natural gas heat pump (1.4 COP)	1.66 tons
2	Condensing gas furnace (96% AFUE)	2.28 tons
3	Baseline gas furnace (80% AFUE)	2.71 tons
4	Electric heat pump (3.8 COP)	2.93 tons

The results in Table 7 (above) indicate that electric heat pumps installed in this region cause higher GHG emissions than each of the natural gas appliances, including the baseline 80% AFUE furnace. Even though this analysis and others like it have demonstrated that electric heat pumps are more efficient from a site energy perspective, this does not correlate with less greenhouse gas emissions in northern Illinois.

Summary tables

The results from the four criteria above were combined and displayed in Table 8 below. Table 9 (below) shows how the above source energy and greenhouse gas emission calculations would be slightly worse across the board if all power plants in the RFCW subregion, including renewables and coal plants, were used. However, Table 9 also shows that the rankings for all criteria would not have changed had all plants in the RFCW region been used for the analysis.

Table 8. Energy consumption, costs and GHG emissions by heating system type (RFCW marginal natural gas generation).

Heating System Analysis for a 1,000 ft², 2br Townhome in Rockford, IL				
Electricity Generation fuel mix:	**2018 eGRID data—RFCW Marginal Natural Gas Plants**			
	80% AFUE Gas Furnace	**96% AFUE Gas Furnace**	**3.8 SCOP Electric Heat Pump**	**1.4 SCOP Gas Heat Pump**
Site Energy* (MMBtu)	42.65	35.68	16.89	24.41
Source Energy (MMBtu)	44.84	37.87	48.48	27.46
Annual Operating Cost ($)	$482	$408	$641	$302
Annual CO_{2e} Emissions (tons CO_{2e})	2.71	2.28	2.93	1.66

*NOTE: The electricity required to operate the draft inducer fan, blower fan and refrigerant pump are included in all calculations.

Table 9. Energy consumption, costs and GHG emissions by heating system type (RFCW average generation).

Heating System Analysis for a 1,000 ft^2, 2br Townhome in Rockford, IL				
Electricity Generation fuel mix:		**2018 eGRID data—RFCW All Plants**		
	80% AFUE Gas Furnace	**96% AFUE Gas Furnace**	**3.8 SCOP Electric Heat Pump**	**1.4 SCOP Gas Heat Pump**
Site Energy* (MMBtu)	42.65	35.68	16.89	24.41
Source Energy (MMBtu)	44.90	37.93	49.50	27.55
Annual Operating Cost ($)	$482	$408	$641	$302
Annual CO$_{2e}$ Emissions (tons CO$_{2e}$)	2.71	2.29	3.05	1.67

*NOTE: The electricity required to operate the draft inducer fan, blower fan and refrigerant pump are included in all calculations.

Conclusion

In the scenarios evaluated, an electric heat pump deployed in northern Illinois consumes the least site energy but the most total energy (source energy), results in the most greenhouse gas emissions, and has the highest annual operating costs compared to the natural gas heating technologies. This may change over time if higher performing, but more expensive cold climate heat pumps gain market traction. However, as newer generation gas heat pumps enter U.S. markets, the consumer response is likely to remain heavily influenced by upfront (e.g. equipment and installation) and annual operating costs.

This study suggests that site energy savings should not be the sole focus of energy efficiency programs. As the above data indicate, the pursuit of minimizing the utility customer's site energy consumption can have unintended consequences. It may cause the customer's utility bills to rise, and it can increase greenhouse gas emissions. In some scenarios, as was the case with the electric heat pump in northern Illinois, minimizing site energy consumption results in the highest operating cost and the most greenhouse gas emissions compared to all other technologies evaluated, including the baseline heating system (80% AFUE furnace). Prioritizing site energy efficiency over customer utility costs will be a difficult selling point for utilities promoting efficiency. From a policy perspective, promoting site efficiency at the expense of both increased costs to consumers and increased greenhouse gas emissions will be in opposition to the primary purpose of many legislatively mandated energy efficiency programs.

Ultimately, there are inherent inefficiencies associated with electricity generation. Therefore, in cold regions where fossil fuels dominate the marginal power plant fuel mix, converting natural gas to heat at the home may be more efficient (source efficiency) than electric heat pumps.

References

CMIC (Carbon Management Information Center). April 2020. "CMIC Source Energy and Emissions Analysis Tool Version 9.0 Description." Accessed July 24, 2020. http://seeatcalc.gastechnology.org/HelpPages/ToolDescription.pdf

EIA (U. S. Energy Information Administration). "Illinois State Profile and Energy Estimates" Last Update: July 16, 2020. Accessed July 24, 2020. https://www.eia.gov/state/data.php?sid=IL#Prices

EPRI (Electric Power Research Institute). April 2018. "U.S. National Electrification Assessment." Accessed July 24, 2020. https://www.epri.com/research/products/3002013582

Leslie, N. 2019. *Full-Fuel-Cycle Energy and Emission Factors for Building Energy Consumption – 2018 Update* Washington, DC: American Gas Association. https://www.aga.org/globalassets/research--insights/reports/22433-ffc-final-report-2019-01-14.pdf

Rothschild, S. and A. Diem, 2009. "Total, Non-baseload, eGRID Subregion, State? Guidance on the Use of eGRID Output Emission Rates." https://www3.epa.gov/ttn/chief/conference/ei18/session5/rothschild.pdf

Nadel, S. and C. Kallakuri, 2016. "Opportunities for Energy and Economic Savings by Replacing Electric Resistance Heat with Higher-Efficiency Heat Pumps." ACEEE Report A1603. Accessed July 24, 2020. https://www.aceee.org/research-report/a1603

TAF (The Atmospheric Fund). 2018. "Gas Absorption Heat Pumps Technology Assessment and Field Test Findings." https://taf.ca/wp-content/uploads/2018/10/TAF_GAHP-White-Paper_2018.pdf

University of Strathclyde Glasgow. *Energy Modeling and Efficiency Strategies for Zero Energy Buildings.* Sustainable Engineering Renewable Energy Masters Conference. 3 May 2016. Technology and Innovation Center of the University of Strathclyde. Accessed July 24, 2020. http://www.esru.strath.ac.uk/EandE/Web_sites/15-16/BRE/pages/conclusions/future_considerations.html

U.S. DOE (Department of Energy). 2019. "ENERGY STAR Portfolio Manager Technical Reference Document." https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf

U.S. EPA (Environmental Protection Agency). 2020. "The Emissions & Generation Resource Integrated Database Technical Support Document for eGRID with Year 2018 Data." https://www.epa.gov/sites/production/files/2020-01/documents/egrid2018_technical_support_document.pdf

U. S. EPA (Environmental Protection Agency). 2009. "Total, Non-baseload, eGRID Subregion, State? Guidance on the Use of eGRID Output Emission Rates." https://www3.epa.gov/ttn/chief/conference/ei18/session5/rothschild.pdf