Dual Fuel Space Heating in Cold Climates: Optimizing Cost, Emissions, and Grid Flexibility

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ABSTRACT

Space heating comprises 47% of U.S. residential building energy use and is a major electrification opportunity given that about 60% of U.S. households burn fossil fuel for heat. Heat pump technology offers an efficient electric space heating solution that can deliver up to three or more times the heat energy than the electrical energy it consumes. Even the most advanced cold climate air source heat pumps (ASHPs), however, lose both capacity and efficiency when outdoor air temperature drops below about 5 °F. In cold climates, therefore, heat pump systems must include some form of backup heating. Electric resistance backup is typically integrated into heat pump systems, but is less efficient and can cause electricity demand to increase during periods when the grid may already be stressed due to extreme weather. Alternatively, nonelectric backup systems, such as fossil fuel furnaces, could be used during periods that are either too cold for the heat pump to operate economically, or when grid supply is limited. Focusing on cold climates in the Midwest and Northeast, we discuss how dual fuel systems might be implemented in new and existing homes. We evaluate the related cost, emissions, and grid flexibility benefits of central, ducted, dual fuel ASHP systems relative to single-fuel (fossil fuel or electric) systems. We find that dual fuel systems have potential to provide cost effective, emissions-reducing space heating in some situations. With grid-interactive controls, they can provide load flexibility and be incorporated in grid-interactive efficient buildings, further improving grid resilience and economic performance.

Introduction and Motivation

Many governments, companies, and other organizations recognize an urgent need to greatly reduce carbon emissions to address the risk of climate change. Electrification of fossil fuel end uses is one key strategy identified in all leading analyses of pathways to a deeply decarbonized, affordable, and technically feasible energy future (Williams et al. 2014; The White House 2016; Gowrishankar and Levin 2017; Billimoria et al. 2018). Some potential opportunities for electrification, however, raise important challenges that must be addressed to ensure that switching from fossil fuels is clearly beneficial. In this context, an electrification strategy is beneficial if it:

1. Reduces consumer cost while performing as well or better than the prevailing fossil fuel product,
2. Reduces atmospheric emissions, and
3. Fosters a resilient energy network, including grid flexibility (Farnsworth et al. 2018; BEL 2020).

One major electrification opportunity in buildings is space heating: about 60% of U.S. households use fossil fuels like natural gas, propane, and fuel oil for space heating (EIA 2017). Conversely, electric space heating is well demonstrated and widely adopted in many circumstances, e.g., representing about 40% of current U.S. households. However, electrification of space heating in cold climates raises a number of important challenges. Most notably, if not properly implemented, electrification of space heating in cold climates might place enormous stress on electricity grids particularly during rare, extreme weather events. Unaddressed, this might entail large capital costs for the electrical grid, high consumer costs, possible degraded heating performance, and reduced resilience and reliability.

Several efficient heating technologies exist, including standard and cold climate air source heat pumps (ASHP, discussed at length below), ground source heat pumps (GSHP), and renewable gas. These technologies may be combined with weatherization measures, dual fuel back up heating, and grid-interactivity for load management as pathways to decarbonizing space heating. All of these pathways are technically feasible and could in the future be key technologies utilized at scale to achieve deep decarbonization, but presently nascent in terms of adoption. Each approach has advantages and disadvantages.

This paper examines one subset of prospective solutions, specifically, the use of dual fuel systems that partly electrify space heating using central, ducted ASHPs, but rely on fossil fuel heating for backup during periods when it is more economic, cleaner, aids resilience and reliability, or the ASHP cannot meet heating demand. This paper does not advocate for one particular approach or solution, but rather aims to expand and accelerate the consideration of one promising approach. We welcome and encourage others to assess other approaches, and aspire to integrate their learning into the model developed in this paper.

The calculations and results presented here are a first attempt to understand the viability of central, ducted, dual fuel ASHP systems to address heating loads in cold climates. Our calculations use several simplifying assumptions as noted below. We find that these systems have the potential to save money, reduce emissions, and provide a flexible resource in some conditions. Future iterations of the calculations that incorporate ASHP field data, time of use electricity pricing, forward-looking emissions and fuel costs, and location- and building-specific weather and heating load information, will help better constrain the potential benefits of these systems in specific locations.

Decarbonizing Space Heating with ASHP Systems

Heat pumps, which can heat spaces efficiently because they move heat rather than produce it, are an efficient space heating solution, and are commonly used for space conditioning (heating and air conditioning) in mild climates. Heat pumps extract heat from a reservoir – typically the outside air or ground - and move it into the building. GSHPs draw heat from the ground, a reservoir that maintains a relatively constant temperature of about 50 °F regardless of the weather. This consistency allows GSHPs to maintain a nearly constant and high coefficient of performance (COP, the amount of heat moved into a space divided by the amount of electricity consumed to do so). GSHPs have significant adoption barriers, however, including high installation cost and space requirements for the ground loops. In contrast, ASHPs are less expensive to install, can be used in virtually any building, and have gained far more market adoption. They are, however, exposed to large swings in ambient temperature since they draw heat from outdoor air. In extreme cold climate conditions this leads to significantly reduced efficiency and capacity, and increased demand on the electric grid. Because we are particularly interested in exploring the grid implications of cold climate space heating electrification in the near term, we focus on the more common, faster growing, and potentially more operationally challenging case of ASHPs.

Since ASHPs draw heat from outdoor air, their performance depends on outdoor air temperature. Standard ASHPs tend to lose capacity below about 47 °F and do not operate in heat pump mode at temperatures below about 30 °F (EPRI 2019), switching to much lower efficiency electric resistance mode. Recent advances in heat pump technology, including variable speed compressors that can match heating load requirements, allow ASHPs to operate at subfreezing temperatures (Williamson and Aldrich 2015). These cold climate models have gained attention in cold regions such as the Northeast. Northeast Energy Efficiency Partnerships (NEEP) has been working to increase adoption of heat pumps, and as part of that effort, has developed a cold climate ASHP specification and maintains a database of qualified products. To qualify for the current NEEP specification, cold climate ASHPs must have a COP of at least 1.75 at 5 °F (NEEP 2019). For many models in the NEEP database, performance steeply decreases at lower temperatures. However, some ASHPs show particularly good performance in cold temperatures, including the Mitsubishi Hyper Heat, Samsung Max Heat, and Eocer Hyper Heating lines. Manufacturer specifications indicate that these ASHPs, used in single-zone, central, ducted systems with an accompanying air handler, can maintain 100% of their heating capacity at 5 °F, and about 90% at -13 °F. These models seem more specifically designed and particularly promising for cold regions, and we examine these in this research. Because these models are not designed to operate below -18 °F, they still require some form of backup heating to meet heating loads in cold regions of the U.S.

Even with these advanced ASHPs, all-electric space heating poses challenges, particularly in cold climates. First, since it adds significant electricity demand to the grid, it can exasperate an already strained electric supply due to extreme weather or other events. In these, or other situations, the added load of electric heating could cause electric demand to exceed supply. Second, although ASHPs can heat buildings more efficiently than other forms of space heating, they do lose performance in cold weather as noted above. As temperature drops, therefore, heat pump electricity demand increases not only to address additional heating requirements of the building, but also because the heat pump is using more electricity to move an equivalent amount of heat. If temperatures become too cold, the heat pump may use electric resistance heating to provide supplemental heat, further increasing electric load. These issues may rarely occur in moderate and mild climates, but in cold climates like the Northeast, Midwest, and Rocky Mountain regions of the U.S., ASHPs must be paired with a backup heating system that can operate when the ASHP cannot meet the building load. Finally, heat pumps used for space heating are not completely flexible. Heat pumps are generally most efficient when they operate at a constant set point, or with small setbacks of a few degrees or less (Foster, Lyons, and Walker 2017). When recovering from large setbacks, heat pumps must run their compressors at maximum, impacting efficiency and causing potentially large rebound peaks after a demand response or other load management event.

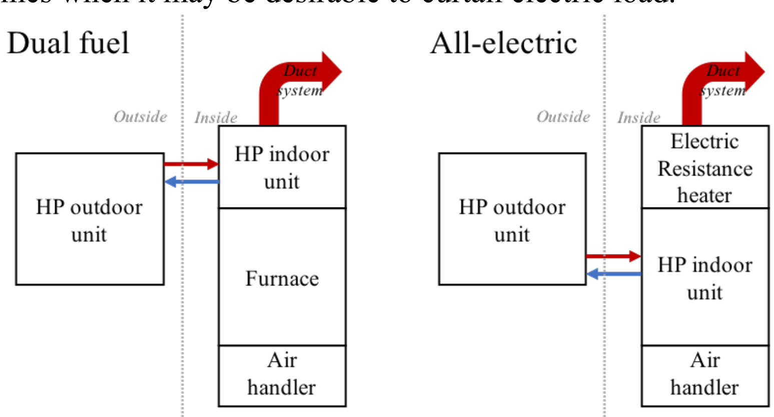
One solution to electrifying much of the space heating load, while still providing space heating at low temperatures and the flexibility to remove load from the grid at constrained times, is dual fuel heating systems. The systems examined here are made up of a central, ducted ASHP, a forced-air furnace, and local controls that orchestrate their operation for optimal results given outdoor air temperature and fixed (i.e., not dynamic) time-of-use rates. In this project, we examine residential ducted dual fuel systems to understand under what conditions are they potentially cost effective to the consumer, reduce atmospheric emissions, and provide a lower anticipated peak impact on the grid. We explore how dual fuel systems can be implemented in homes, and the circumstances under which dual fuel systems can be cost effective and reduce emissions in single family homes in the Midwest and Northeast U.S.

Approach and Methodology

Installation Scenarios

To evaluate the benefits and challenges of dual fuel and all-electric residential space heating strategies in cold climates, we examine three central, ducted ASHP installation configurations with backup heat. These ASHP scenarios are compared to a baseline propane or fuel oil furnace.[1] The installation scenarios examined are:

1. Dual fuel replacement (Figure 1, left panel): In situations where an existing furnace must be replaced, or in new construction, a dual fuel system of an ASHP and a fossil fuel furnace is installed together. The ASHP shares the existing air handler with the furnace and is the primary heating equipment. The furnace is reserved for backup when temperatures are too cold for the heat pump to run, or during a load control event.
2. All-electric replacement (Figure 1, right panel): Similar to scenario #1, except that the backup heating system is electric resistance heating to create a fully electrified space heating system.
3. Heat pump add-on (Figure 1, left panel): If the existing fossil fuel furnace is in good working order and still has useful life remaining, an ASHP can be added to create a dual fuel system. Like scenario #1, the ASHP shares the existing air handler with the furnace, which operates when temperatures are too cold for the heat pump to run, or during other times when it may be desirable to curtail electric load.



[1] We also compared dual fuel and all-electric systems to a natural gas furnace baseline and found that neither dual fuel nor all-electric systems are currently cost-effective relative to natural gas systems due to the low cost of natural gas. In the near term, we do not expect electrified space heating systems to be cost competitive with natural gas ones; however, if gas costs rise or other economic variables reduce the cost of electrified solutions, natural gas replacement could be a similarly viable decarbonization strategy. For brevity, we focus this discussion on the electronification strategies that can be cost effective now or in the near future.

Figure 1: Simplified configuration of dual fuel (installation scenario #1 and #3) and all-electric (scenario #2) space heating systems examined in this study.

For this analysis, we assume that the equipment and controls are optimized for each configuration under examination. This includes the air handler, which must be able to match air flow with output from both the heat pump compressor and the furnace. In practice, this requires the air handler to be capable of multiple speeds that match the needs of the two heating components. Often this requires that all the equipment is made by the same manufacturer. In addition, controls are necessary to coordinate running and switching between heating components. Many smart thermostats have this capability for central ducted systems, although variable speed ducted heat pumps typically require a thermostat made by the same manufacturer.

Key Inputs and Assumptions

To estimate benefits of central, ducted ASHP systems, we perform a suite of calculations that estimate energy use, cost, and emissions under various input conditions. We drive the calculations using hourly heating load, which is based on hourly outdoor temperature. We first estimate the relationship between outdoor air temperature (as a function of heating degree day (HDD)) and heating load in the two regions of interest. Annual heating load is estimated using annual fuel use for space heating in climate zones 6 and 7 in the Midwest and Northeast from the Residential Energy Consumption Survey (RECS 2018). This heating season load is segmented into hourly heating load proportional to HDD, the difference between the current thermostat set point and the outdoor air temperature. We use 30-year average hourly temperature data from the National Centers for Environmental Information to generate heating load assumptions in Minneapolis, MN and Burlington, VT as example locations in the Midwest and Northeast regions, respectively.

The relationship between HDD and heating load is then applied to the temperature record of a single heating season.[2] In the estimates presented below, we use the heating season of 2017-18 as a relatively typical year in the past 20 years, which experienced a period of sustained cold temperatures in late December and early January. This data was gathered from Weather Underground stations in the example cities. We perform calculations for both constant setpoints and twice-daily temperature setbacks over the nighttime and daytime hours.

Heating equipment is sized to meet 100% of heating load at 5 °F. For the heating loads generated for both regions examined, a 3-ton system meets this requirement.[3] Equipment performance determines the electricity or fuel consumed by the equipment to meet the home's heating load. Energy use calculations assume furnace efficiencies of 80% and 95%, 98% electric resistance efficiency. COP inputs for central, ducted ASHP are from manufacturer specifications, and listed in Table 1. These COPs do not include performance reductions associated with real-world usage such as duct losses or defrost cycle.

We estimate performance impacts due to defrost cycles that ASHPs run in sub-freezing outdoor air temperatures to remove frost from the outdoor unit's heat exchanger. The defrost cycle has a significant impact on the performance of the system in cold temperatures. The colder

[2] Because temperature peaks and valleys are smoothed out in 30-year average hourly temperature data, using average data significantly increases minimum temperature and allows the heat pump to address most of the heating load. Using a single heating season provides more realistic conditions in which to test the benefits and limitations of the ASHP systems examined here.

[3] Future work can examine the impact of weatherization and home size on the viability of dual fuel systems.

and more humid the outdoor air temperature, the more frequently the defrost cycle must run, resulting in decreased performance. For simplicity, our calculations assume the ASHP runs a 5-minute cycle every hour when the outdoor air temperature is 30 °F or lower. Incorporating data from current field studies of ASHP performance will inform and improve this assumption.

Table 1. Assumed COP as a function of temperature for standard and cold climate ASHP

Outdoor air temperature (°F)	Standard ASHP COP	Cold climate ASHP COP
47	3.20	3.58
17	2.30	2.00
5		1.88
-5		1.68
-13		1.48

Sources: NRCan (2004), Mitsubishi (2016). Note that the COP listed here are not adjusted for performance reduction caused by defrost cycles, which are accounted for separately in the calculations.

ASHP systems switch between the ASHP and backup heating at outdoor air temperatures appropriate for the type of ASHP. For dual fuel systems, we use switching temperatures of 30 °F and -5 °F for standard and cold climate systems, respectively. For all-electric systems, electric resistance heat supplemented the ASHP below these temperatures, and addressed 100% of the heating load at 10 °F and -18 °F for standard and cold climate ASHP systems.

Energy costs and emissions are estimated using regional average prices for propane, fuel oil, and electricity (EIA 2019a; EIA 2019b), as shown in Table 2. We run calculations assuming both flat rates and time-of-use rates. For this initial investigation, we do not consider demand charges, grid-interactive program operation, or time-varying rates related to varying fuel mix over the season or day such as critical peak pricing. Similarly, we use regional average electricity CO_2 emissions intensities from EIA (EPA 2018a). We recognize that marginal or incremental emissions rates are typically lower than the average rates we assume, with new generation including only natural gas fired generation or zero emissions renewables. This is particularly significant in the Midwest, where there is considerable coal generation in the existing average mix. As a first examination of forward-looking emissions intensity, we also estimate heating system emissions assuming electricity is generated from 50% natural gas and 50% renewable sources. Again, we do not consider seasonal or daily variation in emissions due to changes in fuel mix for this preliminary evaluation. We use emissions intensity for propane and fuel oil from EPA (EPA 2018b). These are all areas for further enhancement to the analysis.

Table 2. Regional fuel cost and CO_2 emissions intensity used in cost effectiveness and emissions impact calculations.

	Fuel cost			CO_2 emissions intensity		
Region	Propane ($/kBtu)	Fuel oil ($/kBtu)	Electricity ($/kWh)	Propane (lb/kBtu)	Fuel oil (lb/kBtu)	Electricity (lb/kWh)
Northeast	0.0350	0.0210	0.188	0.14	0.16	0.56
Midwest	0.0197	0.0196	0.146			1.24

Sources: EIA 2019a, EIA 2019b, EPA 2018a.

Equipment and installation costs for central, ducted ASHPs are highly variable by region and even by contractor. Consequently, we use national-scale estimates from NREL's National Residential Efficiency Measures Database (NREL 2019) and manufacturer information. We assume that cold climate ASHPs cost 30% more than standard models (Nadal 2018).

We again note that these calculations are but a first, generalized evaluation of the viability of central, ducted, dual fuel ASHP heating systems in cold climates. Future iterations of the analysis that incorporate field performance data, better constrained installation cost information, and more specific electricity cost and emissions information are needed to verify the results discussed below.

Results

In this section, we first discuss benefits of dual fuel and all-electric space heating systems compared to fossil fuel ones, then the benefits of dual fuel over all-electric systems. Results of a suite of sensitivity tests indicate that small variation in inputs related to heat pump operation, including switching temperature, defrost cycle, and thermostat set points, do not significantly change annual energy use, cost, and emissions. Inputs with the largest impact on the results are regional parameters (heating load, outdoor air temperature, electricity and fuel prices, and grid emissions intensity) and equipment performance (furnace efficiency and heat pump performance). Consequently, we show a set of results based on region and equipment performance below.

Energy Use, Cost, and Emissions of ASHP Systems Relative to Fossil Fuel Furnaces

Heating systems that utilize ASHPs as their primary heating source use less site energy than fossil fuel furnaces, and yield reduced energy costs and emissions in some cases under current regional average fuel prices and grid conditions.[4] Figures 2, 3, and 4 show heating season energy use, cost, and emissions estimates, respectively, for the three system types in the Northeast and Midwest. The calculations assume a fuel oil furnace in the Northeast, and a propane furnace in the Midwest.

In all cases, dual fuel and all-electric systems use about 20 to 65% less site energy over the heating season than fossil fuel furnaces depending on heating load and equipment type (Figure 2). Cold climate ASHPs can operate during more hours of the heating season than standard ASHPs, and therefore yield more energy savings. All-electric systems use less total site energy than their dual-fuel counterparts.

Consuming less site energy does not necessarily mean that the cost of operating ASHP systems is less than that of a furnace (Figure 3). The price per unit energy of electricity averages 2 to 2.5 times more than that of fossil fuel in the regions studied under current rate designs; therefore, one can expect energy cost savings only if the dual fuel or all-electric system uses half or less the energy that a furnace does to meet the home's heating load. (A further enhancement of this analysis will be to represent advanced grid-interactive controls and utility program design, which would likely lower consumer costs.) Dual fuel systems can avoid ASHP operation when performance begins to drop, and therefore annual energy costs can be slightly lower than for a

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[4] Because consumer energy costs (discussed below) are based on site energy consumption, we present site, rather than source energy use in this section.

furnace. All-electric systems, however, supplement the ASHP with electric resistance heating, and their annual energy costs are about as much or more than furnaces.

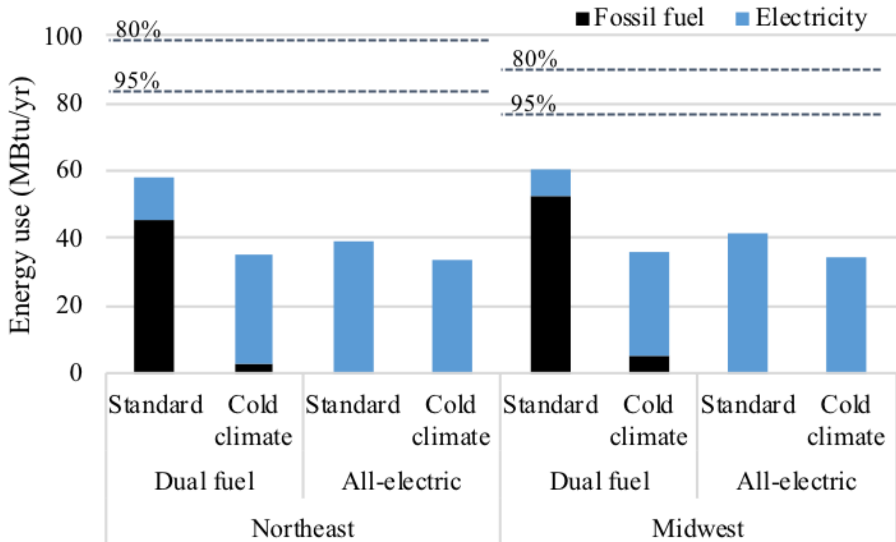

Figure 2. Estimated fossil fuel (black) and electricity (blue) use over the heating season for dual fuel and all-electric space heating configurations compared to a furnace (dashed lines) in the Northeast and Midwest. Dual fuel systems use a standard or cold climate heat pump with a 95% efficient furnace as back-up. All-electric systems also use a standard or cold climate heat pump but use electric resistance back-up heating. Horizontal dashed lines indicate energy use of fossil fuel furnaces of 80% and 95% efficiency to address the same heating load. The furnace is assumed to use fuel oil in the Northeast, and propane in the Midwest.

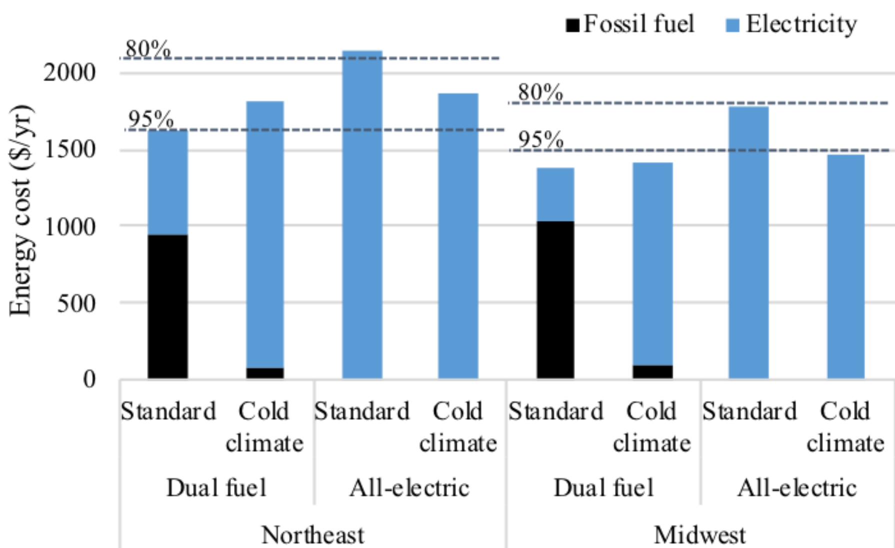

Figure 3. Estimated fossil fuel (black) and electricity (blue) cost over the heating season for dual fuel and all-electric space heating configurations compared to a furnace (dashed lines) in the Northeast and Midwest. Dual fuel systems use a standard or cold climate heat pump with a 95% efficient furnace as back-up. All-electric systems also use a standard or cold climate heat pump but use electric resistance back-up heating. Horizontal dashed lines indicate energy cost of fossil fuel furnaces of 80% and 95% efficiency to address the same heating load. The furnace is assumed to use fuel oil in the Northeast, and propane in the Midwest.

The main factor in emissions differences between equipment type and region is the average emissions intensity of the electric grid (Table 2). In the Northeast, grid emissions are low enough that all heat pump systems considered produce lower emissions than a high efficiency furnace, with all-electric systems producing fewer emissions than dual fuel systems (Figure 4). Higher average emissions intensity in the Midwest results in similar or higher emissions from heat pump systems relative to fossil fuel furnaces. Importantly, however, incremental emissions intensity can be much lower than average emissions intensity. A further enhancement of this analysis to account for forward-looking emissions intensity would yield more favorable results. As a first estimate, we calculate emissions assuming electricity is generated from natural gas and renewables in equal proportions (dotted lines across each bar in Figure 4). In this situation, electricity emissions intensity is reduced by 63% in the Midwest and 17% in the Northeast. Standard dual fuel systems will yield emissions reductions of a few percent with this grid mix, but dual fuel systems with cold climate heat pumps will yield almost as much emissions reductions as all-electric systems: 16% and 59% in the Northeast and Midwest, respectively.

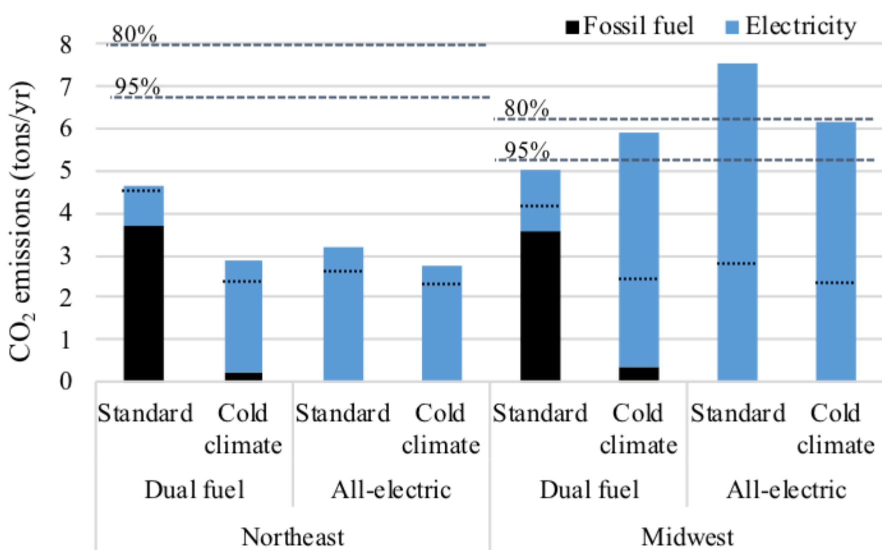

Figure 4. Estimated fossil fuel (black) and electricity (blue) CO_2 emissions over the heating season for dual fuel and all-electric space heating configurations compared to a furnace (dashed lines) in the Northeast and Midwest. Emissions if electricity generation mix is half natural gas and half renewables is shown by dotted lines across each bar. Dual fuel systems use a standard or cold climate heat pump with a 95% efficient furnace as back-up. All-electric systems also use a standard or cold climate heat pump but use electric resistance back-up heating. Horizontal dash lines indicate CO_2 emissions of fossil fuel furnaces of 80% and 95% efficiency to address the same heating load. The furnace is assumed to use fuel oil in the Northeast, and propane in the Midwest.

We reiterate that as a first assessment of viability of ASHP space heating systems in cold regions, the estimates presented here use present day, regional and annual average electricity prices and emissions rates. Because the results here are promising and indicate that dual fuel systems can be beneficial in some cases, additional research using seasonal and daily variation in prices and emissions should be conducted to better constrain the benefits of these systems.

Which Installation Scenarios are Beneficial?

The results above indicate potential for some space heating systems that use a heat pump with fossil fuel or electric back-up components to be beneficial from an annual fuel cost and emissions perspective. In this section, we estimate cost effectiveness of dual fuel and all-electric systems relative to a fossil fuel furnace, which is determined by equipment and installation incremental costs and fuel cost savings. Large variability in heat pump equipment and installation costs exists from region to region, and even contractor to contractor. As a first assessment, in this analysis we use cost information from NREL's National Residential Efficiency Measures Database (NREL 2019), which are national average prices.

We examine a simple cost effectiveness of the three installation scenarios described above, relative to a baseline fossil fuel furnace: (1) a furnace is replaced with a dual fuel system, (2) furnace replaced with an all-electric system, and (3) an ASHP is added to an existing furnace (Figure 1). In the first two scenarios, we assume that the old furnace has reached the end of its lifetime and is 80% efficient. The new dual fuel system consists of a standard or cold climate heat pump and a 95% efficient, variable speed furnace. The incremental cost of the upgrade is the cost of the heat pump and installation, plus the cost difference between a 95% and 80% efficient furnace in the dual fuel case, or the cost difference between an 80% efficient furnace and a 15-kW electric resistance heater in the all-electric case. In scenario 3, the existing furnace is a relatively new, 95% efficient variable speed furnace. Incremental cost in this case is the cost of the heat pump equipment and installation.

We also consider the situation in which the consumer wishes to install air conditioning. With warming summer temperatures, air conditioning is becoming more popular in these regions. Incremental cost in these situations is that described in the previous paragraph minus the cost of a traditional air conditioner.

We find that installation and fuel costs of dual fuel systems with either standard or cold climate ASHPs can be lower than that of baseline fossil fuel furnaces in both the Northeast and Midwest in the replacement case (scenario 1) if the consumer wants to install air conditioning (Table 3). Dual fuel systems with standard ASHPs are also cost effective in both regions even if the consumer is not adding air conditioning.

In many other situations, dual fuel and all-electric systems may reduce annual energy costs relative to a furnace, but not enough to pay back the initial investment. These cases include dual fuel and all-electric system replacements with cold climate heat pumps, and dual fuel add-on systems with standard heat pumps (Table 3). If incremental costs decrease, or can be offset by utility incentives, these use cases have the potential to be cost effective to the consumer. In the remaining situations, the measure does not yield annual energy cost savings. These situations could become cost effective if fossil fuel prices increase, and/or electricity prices decrease through special rate structures or program designs that reflect lower average system costs resulting from grid interactivity and avoiding extremely high cost periods.

As discussed above, dual fuel and all-electric systems yield emissions savings assuming average emissions intensities, except for some situations in the Midwest. If we assume that the electricity is generated from equal parts natural gas and renewables, however, all the scenarios in Table 3 reduce emissions relative to a fossil fuel furnace.

Table 3. Summary of cost effectiveness and emissions reduction potential of dual fuel and all-electric heating systems with standard and cold climate ASHPs relative to a fossil fuel (fuel oil in Northeast, propane in Midwest) furnace baseline.

	Northeast		Midwest	
	Standard	Cold climate	Standard	Cold climate
Scenarios 1 & 2: replace 80% efficient furnace with dual fuel (ASHP pump+95% efficient furnace back up) or all-electric (ASHP+electric resistance back up)				
Dual fuel	$ E	$ E	$ E	$ E
Dual fuel with air conditioning	$ E	$ E	$ E	$ E
All-electric	$ E	$ E	$ E	$ E
All-electric with air conditioning	$ E	$ E	$ E	$ E
Scenario #3: add ASHP to existing 95% efficient furnace				
Dual fuel	$ E	$ E	$ E	$ E
Dual fuel with air conditioning	$ E	$ E	$ E	$ E
$ E: System is cost effective and yields emissions reductions. $ E: System yields annual cost savings and emissions reduction, but is not cost effective over the lifetime of the product. Reduced initial cost or utility incentives may yield cost effectiveness. $ E: System yields emissions reductions but does not yield fuel cost savings or cost effectiveness. $ E: System does not yield fuel cost savings or emissions reductions under current average conditions. System would yield savings on a grid of 50% natural gas, 50% renewable generation.				

Flexibility of Dual Fuel Systems

As noted previously, an additional attribute of beneficial electrification is the ability to control and shape electric loads to match supply. Heat pumps can be somewhat flexible in their time of operation, but since they operate most efficiently at constant set point or with setbacks up to only a few degrees, they do not offer the ability to be completely curtailed unless they are paired with a non-electric backup heating system. Dual fuel systems offer that flexibility. To illustrate the benefits of dual fuel systems, we examine an extreme cold event: the Polar Vortex that caused many areas of the Midwest to experience sustained temperatures that were well below zero for four days in late January and early February 2019 (Figure 5).

An all-electric system, whether it employs a standard or a cold climate ASHP, must use electric resistance back up heating over much of the cold event to meet heating needs of the home. In the example shown in Figure 5, the all-electric system with a standard ASHP uses electric resistance below 10 °F in order to meet the home's electric load. It draws at least 8 kW and at most 13 kW during the cold event. The all-electric cold climate system consumes less total energy because the heat pump can operate to -18 °F. However, it too must use electric resistance heating below those temperatures, also drawing as much as 13 kW. In contrast, the dual fuel system with a cold climate heat pump in this example is set to switch to furnace operation at -5 °F, where the heat pump performance begins to degrade, and therefore operates the furnace through the entire cold event. This removes the electric load entirely for the duration of the event.

With today's average costs and emissions, fuel switching during cold events can also reduce energy costs to the consumer and in some cases reduce emissions. Table 4 summarizes estimated savings of dual fuel relative to all-electric systems for the 2019 Polar Vortex event. Although the dual fuel system uses slightly more energy, it costs 35% to 60% less to operate than an all-electric system over the five days of extreme cold. The dual fuel system yields lower CO_2 emissions in the Midwest as well, due to the higher emissions intensity of the grid. As the grid becomes less carbon intense, however, fuel switching will no longer be advantageous from an emissions standpoint, as shown by the emissions increases for a grid mix of 50% natural gas and 50% renewables in the bottom row of Table 4.

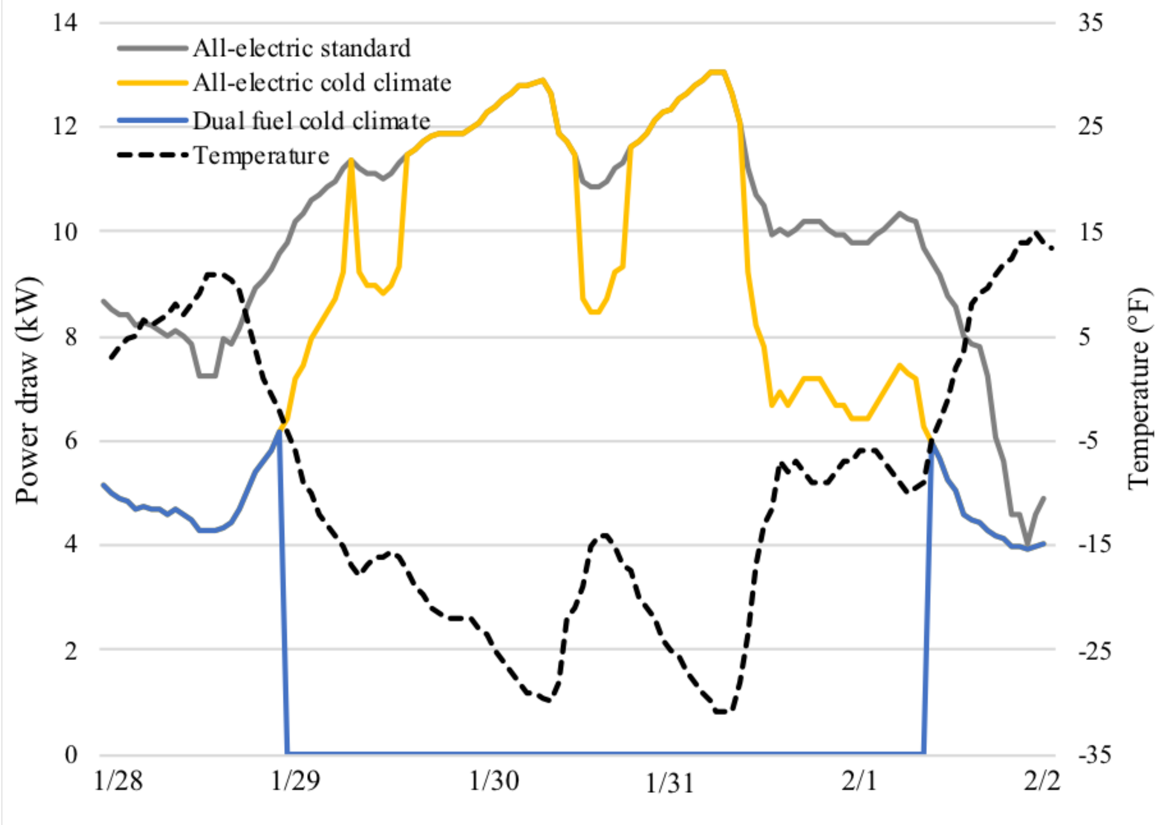

Figure 5. Estimated electric heating demand (left axis) over a polar vortex event from January 28 to February 2, 2019 for various heating systems: all-electric with standard ASHP (grey), all-electric with cold climate ASHP (yellow), and dual fuel with cold climate ASHP (blue). Note that a dual fuel system with a standard heat pump would operate the furnace during the entire event so that electricity demand is zero. Hourly outdoor temperature in Duluth, MN (black dotted line) is shown on the right axis.

Dual fuel systems can also curtail their electric load in other situations when extreme cold is not a factor. They can respond during demand response events and participate in grid-interactive efficient building or other local load control strategies, and be optimized to run the more cost-effective or less emissions-intense component at any one time. All-electric systems, on the other hand, can curtail and shift load to some degree (with the recovery issues discussed above), but are not as flexible as dual fuel systems because they do not have a non-electric option.

Table 4. Estimated savings of dual fuel over all-electric systems during five-day polar vortex event in 2019. Positive values indicate dual fuel system savings.

	Northeast		Midwest	
	Standard	Cold climate	Standard	Cold climate
Energy use	-7%	-18%	-9%	-19%
Energy cost	61%	44%	50%	35%
CO_2 Emissions (current average)	-9%	-18%	61%	52%
CO_2 Emissions (50% gas, 50% renewable grid)	-29%	-39%	-4%	-11%

Discussion and Next Steps

Our findings suggest that central, ducted dual fuel and all-electric ASHP systems in cold climates may be a beneficial electrification opportunity – that is, save consumers money, reduce emissions, and provide a flexible grid resource - in some cases, even without programs or rate designs that reflect highly dynamic system variability. These include cases in which the consumer wishes to install air conditioning, and standard ASHP dual fuel replacement in both regions studied. Dual fuel and all-electric systems could be beneficial in other situations if initial costs are lowered with utility incentives or if increased adoption drives costs down, or if fossil fuel costs rise and electricity rates decrease.

The flexibility of dual fuel systems is a significant benefit over all-electric systems. This flexibility allows dual fuel systems to be completely removed from the grid during periods of low or expensive supply, such as extreme cold events and demand peaks. All-electric systems, on the other hand, can shift and curtail their load to some degree, but eventually must recover from such events using their ASHP and electric resistance components. Additional study of dual fuel system operation in the context of time-varying electricity rates and emissions could show additional cost and emissions savings related to removing electric load from the grid, and help determine additional situations in which dual fuel systems may be beneficial, either now or over the lifetime of the product.

The calculations presented here are a first attempt to assess the viability of central, ducted dual fuel ASHP systems in terms of cost and emissions. Given that results indicate potential benefits related to these systems exist in some situations, the calculations can and should be refined with field performance data, better constrained installation cost information, and more specific electricity cost and emissions information. Additional research on dual fuel system implementation should focus on analyzing the efficacy of grid-interactive controls, and developing program designs that facilitate grid-interactive control operations and incentives to customers. Additional energy efficiency measures that reduce building heating requirements, such as deep energy efficiency improvements in the building shell and weatherization, could be combined with space heating electrification. Further research on this type of combined measure should assess cost effectiveness relative to electrification alone.

As we work towards a low carbon future, dual fuel systems may be a promising bridge technology that allow much of the space heating load to be electrified, while still supplying flexibility to the grid. As heat pump technology improves, as strategies to manage grid supply through extreme weather events or other constrained periods are developed, and as building heating load shrinks due to shell improvements, all-electric systems may become a better way to reduce costs and environmental impacts associated with space heating. However, in regions that experience cold winters, that future could be many years away. Dual fuel systems can offer beneficial electrification even now in some situations. Continued research can identify specific situations and regions where dual fuel systems should be promoted.

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