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REWIRING SEATTLE

THE ECONOMICS OF SEATTLE'S NEW ELECTRIC HEATING MANDATE

OCTOBER 2021

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October 2021

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

On February 1, 2021, the city council of Seattle voted unanimously to adopt a new building code restricting natural gas in all new commercial construction, and residential construction over three stories. Specifically, the new rules (which took effect on June 1, 2021), mandate the following for buildings affected by the new rules:

- Eliminating all natural gas and most electric resistance heating systems;
- Eliminating natural gas water heating in affected residential buildings and hotels (effective in 2022); and
- Requiring affected residential buildings with gas appliances such as stoves to install outlets for future electrical conversion.

While much of the attention surrounding these new rules has focused on the ban on natural gas heat, the ban on most electric resistance heating is equally important in the context of Seattle, with its high concentration of electric resistance users.

THE THREE TYPES OF HEATING

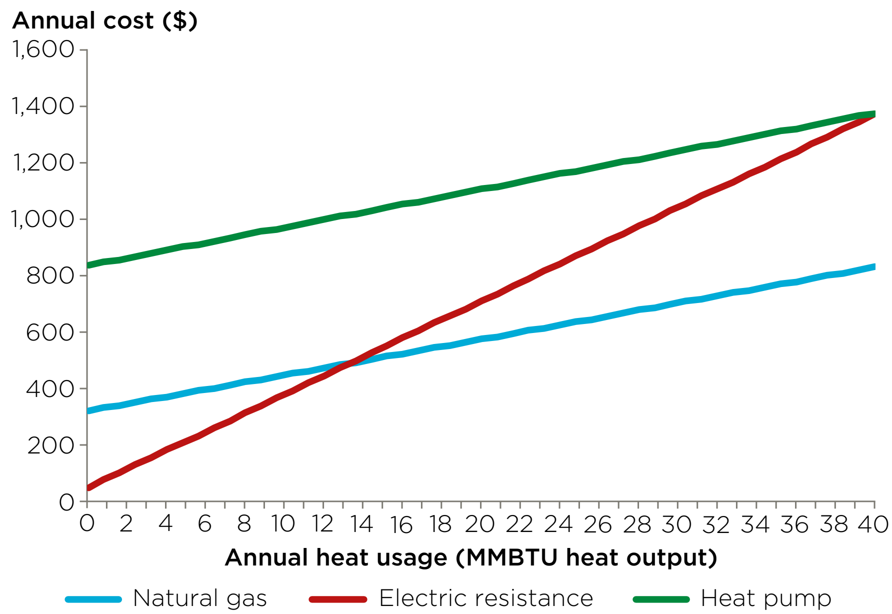
Most building space heating is accomplished in one of the following three ways:

- **Burning natural gas** in a furnace or boiler (in areas without utility gas, fuel oil, or propane are sometimes used),
- Converting electrical energy into heat through **electric resistance**, or;
- Moving heat energy from the outside using a **heat pump**.

The economic characteristics of these three heating methods are quite different. Electric resistance generally has low equipment costs, but high costs of use. Electric heat pumps, by contrast, have high equipment costs but are two to three times more efficient than electric resistance, and proportionally less expensive per unit of heat. Natural gas heat offers an attractive middle ground, with equipment costs significantly below those of heat pumps (though higher than electric resistance), and—at current energy prices—variable costs per unit of heat similar to that of heat pumps. This relationship is shown in Fig. ES-1.

Thus, electric resistance makes the most sense in situations where very little heat is required, while the cost advantage of natural

Fig ES-1. Annual total cost of space heating as a function of annual heat usage



Source: Oxford Economics

gas heat over heat pumps is not very sensitive to amount of heat used, and comes to approximately $525 annually per residence.

One additional factor specific to heat pumps requires consideration: while heat pumps are usually the most energy efficient of the three heating technologies, their efficiency and their capacity both fall as temperatures drop. At low temperatures (typically below about 30°F), heat pumps require supplemental heat, either from burning natural gas or a similar fuel, or from electric resistance. While the new Seattle rules ban both natural gas and electric resistance in most circumstances, they make an exception for electric resistance when used as backup heat for heat pumps, but not for natural gas in similar circumstances. This is despite the superior characteristics of natural gas heating over electric resistance, including both lower costs and, depending on the specifics of the power grid, often lower emissions. This policy decision creates a concerning vulnerability in the power grid, as demand for electricity from inefficient electric resistance heating will spike on the coldest nights of the year, precisely when new wind and solar electricity generation—necessary to make electrification mandates effective on their own terms at reducing carbon emissions—are at their nadir.

SEATTLE-SPECIFIC FACTORS

Seattle is unusual in having both mild winters and summers, with two important ramifications for building electrification:

- Because of the mild summers, the majority of Seattle area homes (78%) currently lack central air conditioning. This undercuts the value of heat pumps, which inherently provide AC.
- Because of the mild winters, approximately 59% of households, and 87% of the residents of the large apartment buildings targeted by the new rules, already use electric heating, but largely electric resistance. Because these households use low amounts of heat, the cost to them of the new rules is larger than it is for natural gas customers.

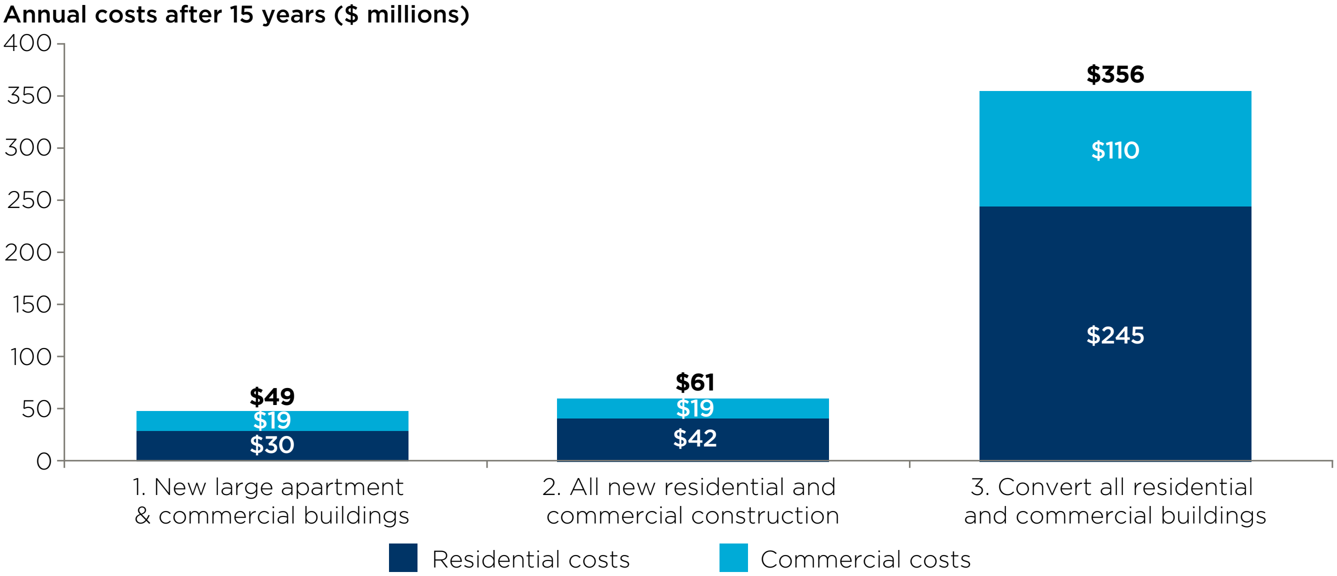
Additionally, Seattle is unusual in its low-carbon electrical grid, made possible by the region's historic embrace of hydroelectric and nuclear power.

COST IMPLICATIONS

We estimate the costs of electrification under three scenarios (see Fig ES-2).

- Scenario 1 approximates the new Seattle rules with applicability only to new commercial and new large residential construction. The cost of the new rules grows over time as more buildings covered by the rules are built. After 15 years, we estimate the annual cost of the rules at $49 million.
- Scenario 2 extends the electrification mandate to all new residential construction, regardless of size. After 15 years, we estimate the annual cost under this scenario at $61 million.
- Scenario 3 assumes the retrofitting of all existing residential and commercial buildings in Seattle to heat pump technology, in addition to requiring new buildings to install heat pumps. We estimate the annual cost under this scenario at $356 million.

Fig. ES-2. Scenario costs summary[1]



Source: Oxford Economics

The effect of the new rules on water heating is more uncertain, as the cost advantage of natural gas water heaters over heat pump water heaters is more modest. In the case of water heating, however, unlike for space heating, the new rules continue to allow electric resistance. Although our cost modeling suggests most households would do best to select a heat pump water heater over electric resistance, the relatively low market penetration of heat pump water heaters to date suggests that other obstacles remain to their widespread adoption that are not accounted for in our cost modeling. If this is the case, the new rules may have the undesired effect of pushing hot water users towards inefficient and expensive electric resistance.

IMPACTS ON LOW-INCOME HOUSEHOLDS

There are several reasons why the new rules will impact low-income households the most:

- Even a fixed cost burden across all households will burden low-income households more as a fraction of annual income.
- Low-income households are more likely to live in apartments that are affected by the new rules than in detached houses, which are more likely to be the homes of the city's wealthy.
  - Over time, however, the new rules are likely to push low-income households into older buildings not subject to the new rules, or out of the city of Seattle altogether.
  - Low-income households are more likely to economize on heating by using electric resistance heating sparingly, and thus the burden of being made to switch to heat pumps is greater (see Fig ES-1).
  - Since much of the value households receive from the high cost of the heat pump mandate comes in the form of "free" air conditioning, less well-off households are less likely to be willing to make that trade.

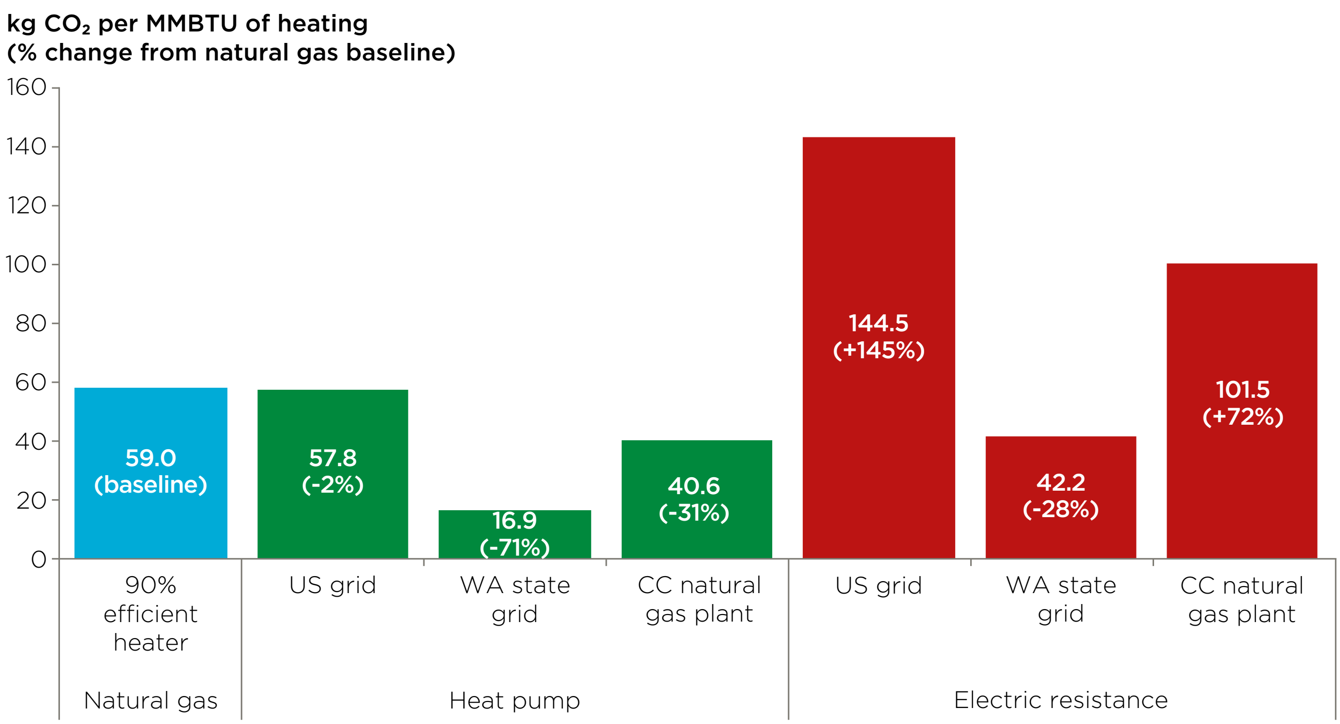
[1] Some totals will not add due to rounding. This is the case throughout the document.

CARBON IMPLICATIONS

The stated purpose of the electrification rules is to reduce carbon emissions, but this goal is only accomplished to the extent that the electric energy used to power heat pumps is zero- or low-emission. In fact, when benchmarked against average emissions of the US electric grid as a whole, there is only a 2% reduction in emissions from a shift from natural gas heat to electric heat pumps (Fig ES-3).

However, the most appropriate comparison is not to average grid emissions, but to the emissions of the new power generation capacity that will be added to the grid to power the heat. In many parts of the US, new reliable grid power is derived from combined cycle natural gas power plants, which are significantly more efficient than legacy fossil fuel plants. Using this as the benchmark, a shift from burning natural gas on-site in a furnace or boiler to an electric heat pump powered by a new natural gas power plant results in a 31% reduction in the carbon emissions from building heat—a real, if limited, reduction, achieved at high cost. However, when natural gas heat is replaced by electric resistance heat—such as when it is used as backup heating for heat pumps in cold temperatures—overall carbon emissions rise by 72% when the electricity is provided by a combined cycle natural gas plant, and by 145% when benchmarked to the average emissions of the US power grid as a whole.

Fig. ES-3. CO_2 emissions per MMBTU of heat output



Source: EIA, Oxford Economics

1. INTRODUCTION

On February 1, 2021, the Seattle City Council voted unanimously to amend the city's building code to restrict the use of natural gas in new commercial buildings and new residential buildings over three stories.[2] Although the Seattle rules do not ban all new natural gas use (gas is still allowed for cooking, for example), the new rules place Seattle in the so-called "Electrify Everything" movement with other cities such as Berkeley, CA. To date, roughly 30 cities, mostly in California, have passed measures to limit or prohibit the use of natural gas in various types of new construction.[3]

Much of the media coverage surrounding the electrification movement in general, and the new Seattle rules in particular, has framed the issue solely as a question of electric versus gas heat.[4] This framing, however, misses an important dimension to the story: "electric heat" comes in two fundamentally different forms:

- The first of these is **electric resistance** heating, which transforms electrical energy transmitted along copper wires into heat. This is similar in some ways to how heat is produced by burning natural gas, except that the energy source is electrical instead of chemical.
- The second of these is **electric heat pumps**, which use electric power to transport heat energy against the thermal gradient from the cold outside to the warm inside of a building. This is often compared to an air conditioner working in reverse. Unlike in natural gas or electric resistance heating, heat is not created but moved.

In fact, the new rules specifically require heat pumps for space heating. While the economic tradeoff between heat pumps and gas and electric resistance heating is complex, and discussed in considerably more detail below, the high initial capital costs of heat pumps combined with their shorter lifespans and greater maintenance costs, as well as their operational limitations in very cold temperatures, mean that heat pumps are often a more expensive option for heating than natural gas, and in some cases (generally when little heating is used) more expensive than electric resistance.

[2] The legislation itself is available here: http://seattle.legistar.com/LegislationDetail.aspx?ID=4763161&GUID=A4B94487-56DE-4EBD-9BBA-C332F6E0EE5D. Smaller residential construction is excluded because Washington state law restricts the authority of localities to independently impose restrictions on this type of construction.
[3] The Wall Street Journal (May 14, 2021). "The Electrification of Everything: What You Need to Know." https://www.wsj.com/articles/electrification-of-everything-11620843173.
[4] Other combustible heating fuels, such as propane and fuel oil, are similar to natural gas for these purposes. They are discussed further in section 2.1; however, in an urban setting like Seattle, natural gas is by far the most common heating fuel alternative to electric heat.

Specifically, the new rules (which took effect on June 1, 2021), mandate the following:[5]

- Eliminating all natural gas and most electric resistance heating systems in all affected buildings;[6]
- Eliminating natural gas water heating in affected residential buildings and hotels (effective in 2022); and
- Requiring affected residential buildings with gas appliances such as stoves to install electrical outlets for future electrical conversion.

The restriction on electric resistance heating has particularly significant implications for the city of Seattle, where the mild climate has resulted in unusually widespread usage of electric resistance heating. This is especially true for low-income residents, who tend to live in smaller residences and are more willing to economize on heating costs by limiting their use of heat.

The stated purpose for natural gas restrictions in Seattle and other cities is to help cities to meet aggressive decarbonization targets.[7] In doing so, however, the city has imposed significant costs on its residents for relatively modest carbon reductions that are highly dependent on the installation of new renewable energy generation. Moreover, because heat pumps lose heating power on the coldest nights of the year, specifically when these renewable sources provide the least power, forced electrification imposes a dangerous vulnerability in the power grid that natural gas heating—either on its own or as a backup to heat pumps—does not.

1.1 OVERVIEW OF THIS STUDY

This study explores the broad constellation of issues relating to the electrification movement, and the new Seattle rules in particular. Section 2 provides additional background on the three principal types of heating, with particular focus on heat pumps; as well as background on how the unique aspects of the city of Seattle affect the economics of electrification there. Section 3 reviews the literature surrounding heating electrification, with particular emphasis on previous cost estimates, and considerations for the electrical grid.

Section 4 presents original estimates of the cost of the electrification mandate in the city of Seattle. All the assumptions behind these estimates are fully documented, with precise numerical values given in the appendix. Section 5 shows how these costs disproportionately affect low-income and BIPOC communities. Section 6 considers the implications of electrification for carbon emissions, and section 7 provides key conclusions.

[5] Beveridge & Diamond (December 6, 2020). "Seattle Proposes Natural Gas Ban for New Buildings." https://www.bdlaw.com/publications/seattle-proposes-natural-gas-ban-for-new-buildings/.

[6] Exceptions to the ban on electric resistance heating are made for certain specialty situations, such as small or lightly used rooms, where the low-upfront cost high-operating cost characteristics of electric resistance heating is acceptable. Importantly, one permissible use for electric resistance heating is as backup heat for heat pumps when they lose power in cold temperatures—see section 2.1.1.

[7] See, for example, the statement by Seattle Mayor Jenny A. Durkan about the new rules (January 13, 2021). https://durkan.seattle.gov/2021/01/mayor-durkan-transmits-legislation-to-ban-fossil-fuels-for-heating-in-new-construction-to-further-electrify-buildings-using-clean-energy/.

2. BACKGROUND ON HEATING TECHNOLOGY AND SEATTLE

2.1 THREE TYPES OF HEATING

With some minor exceptions (e.g., on-site solar and district-level heat), building heating (both space and water) can be accomplished in three ways:

- By **burning a fuel** (typically natural gas) on-site.
  - Fuel oil and propane, and less commonly coal and wood, are also sometimes used. This is typically done when piped natural gas is not available, and so is rare in urban settings like Seattle.
  - The heat generated is typically distributed through the building either using hot air, in which case the appliance generating it is called a furnace, or using hot water, in which case it is called a boiler. For our purposes, this distinction is of little significance.
  - Furnaces and boilers must vent their combustion products (mostly CO2 and water) to the outside, and lose some heat in doing so. For this reason, they cannot achieve 100% efficiency. Natural gas equipment is typically 80-97% efficient.
- Converting electric power into heat energy using **electric resistance heating**.
  - This can be done in a central electric furnace; however, one advantage of electric resistance heating is that it can be done safely at small scale right where the heat is needed, using a space heater or wall unit, and thereby avoiding the need for expensive ducting or piping.
  - Electric resistance is considered 100% efficient, meaning 100% of the electric energy is converted to heat. However, this does not factor in losses in electricity generation, transmission, and distribution.
- Moving heat energy from the outside using a **heat pump**.
  - Most heat pumps exchange heat with the outside air and are referred to as air source heat pumps. Ground source heat pumps are also available, but are significantly more expensive to install, and so are not economical for most uses.
  - Because they move heat rather than create it, heat pumps can achieve much higher efficiencies, measured as the amount of heat energy delivered divided by the energy consumed to move it. The efficiency of a heat pump falls as the temperature falls, but typically averages around 200-300% (i.e., two to three times as much output heat as electric resistance for the same amount of electricity consumed). The term Coefficient of Performance (COP) is used to refer to a heat pump's average efficiency, measured across a range of temperatures according to a government standard.
  - Heat pumps lose efficiency and capacity as the temperature falls, and so require a backup source of heat on the coldest days. This is discussed further in section 2.1.1.

Fig. 1 summarizes key differences between these three heating methods. More quantitative assumptions around these three heating options are developed in section 4.

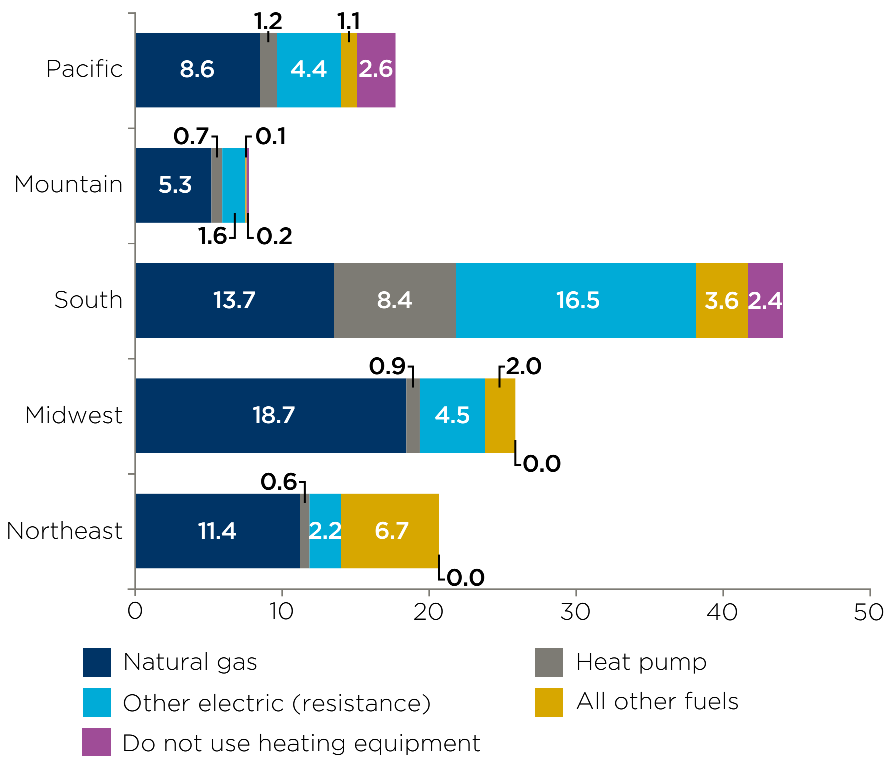
Fig. 1. Characteristics of three heating options

	Burning natural gas	Electric resistance	Heat pump
Energy source	Natural gas	Electricity	Electricity
Upfront cost	**Medium** Gas furnaces are generally cheaper and easier to install than heat pumps.	**Low** Electric resistance heaters are cheap to manufacture and to install since they do not require pipes, ducts, or vents.	**High** Heat pumps are complicated devices that are more expensive to manufacture, and often require greater time and expertise to install correctly.
Lifespan, maintenance, and reliability	**Good** Generating heat through furnaces and boilers is relatively simple and a very mature technology.	**Excellent** Electric resistance heaters are simple devices with no moving parts. They require little to no maintenance and have long lifespans.	**Fair - poor** Because of their more complicated design, heat pumps require more maintenance and earlier replacement. Newer models may improve on this over time.
Operational cost	**Low** Although the nominal efficiency is much lower than heat pumps (around 80-97%), they do not suffer from the losses inherent in electric power generation and transmission.	**High** While the efficiency is nominally 100%, generating and transmitting electricity incurs significant losses, resulting in high energy costs.	**Low** Since heat pumps move heat instead of generating it, the heating output is typically two to three times the input energy. However, because of energy losses in electric power, overall operational cost is similar to that of natural gas (at current energy prices).
Additional considerations	Requires a natural gas hookup. (Similar systems using fuel oil or propane use a refillable on-site tank, and are generally more expensive.)	Because of high operational costs, electric resistance heating is most suited to low-use situations in small spaces and/or warm climates, or as a backup heat source.	- Heat pumps lose efficiency and capacity as the temperature falls, and require a backup heat source (electric resistance or gas/other fuel) when the temperature falls below about 30°F. (See section 2.1.1 for more on this.) - Heat pumps also provide air conditioning, which can help offset the high equipment cost.

Overall, electric resistance heating is very cheap to install, but expensive to operate over time, which makes it most suited for low-use situations (small spaces, warm climates, and backup heating systems). Heat pumps, by contrast, have high fixed costs, but are very efficient (although their efficiency falls as temperatures drop, as discussed in section 2.1.1). Natural gas heat offers an attractive middle ground to consumers: equipment costs that are lower than for heat pumps, but fuel costs that are lower than electric resistance and roughly on par with heat pumps.

Currently, approximately 71% of the heat pump usage in the United States is in the South, which represents only 38% of total households (see Fig. 2). This is because the South generally has both mild winters, allowing heat pumps to operate at maximum efficiency most of the time, and hot summers, meaning that most households choose to install air conditioning. Heat pumps can be run in reverse, eliminating the need for separate air conditioning equipment and helping to offset the high cost of the equipment.

Fig. 2. Primary residential space heating fuel by region of the country, 2015[8]



Source: EIA 2015 RECS

2.1.1 Heat pumps in focus

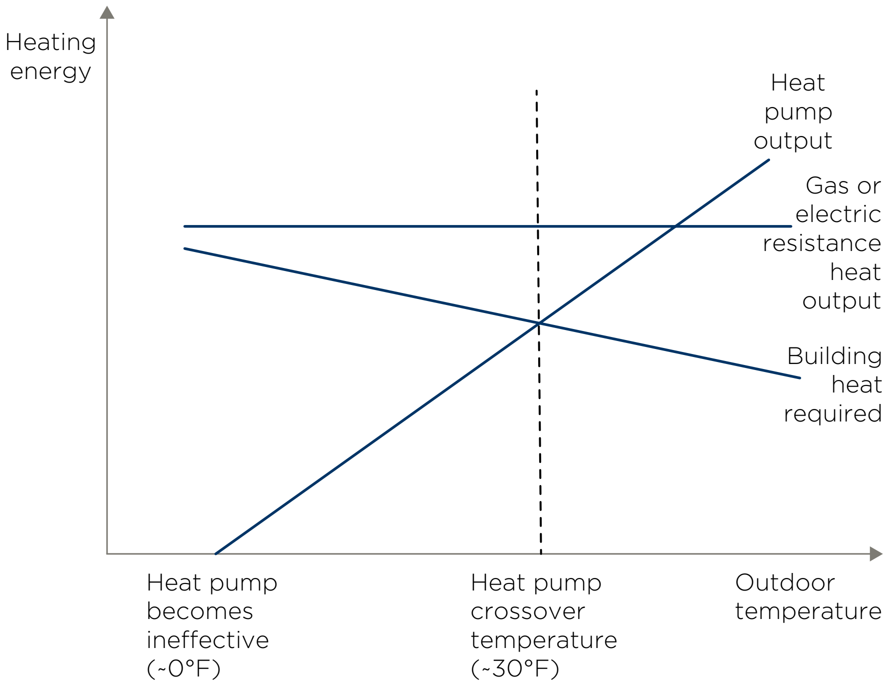
Heat pumps are impressive technology with many appealing characteristics. Because they move heat rather than generate it, they are able to achieve higher efficiencies than either electric resistance or natural gas heating. They can also transfer heat in both directions, meaning they provide space cooling (air conditioning) as well as space heating. The technology can also be adapted to other uses, such as generating hot water, and cooling electronics.

However, heat pumps also come with limitations. As noted above, they are more complex devices than furnaces and boilers, and so have higher upfront and maintenance costs, shorter lifespans, and require more expertise to properly tailor to a building and to install.

Additionally, because heat pumps move heat energy from the cold outside to the warm inside, both their efficiency and their capacity (their maximum heat output) fall as the outdoor temperature falls, precisely when the most heat is needed. This is in contrast to gas and electric resistance heaters, whose efficiencies and capacities are not affected by the outdoor temperature. As a consequence of this, heat pumps have a **crossover temperature**, below which they are unable to provide the full amount of heat required and so must be supplemented by another heat source. This is illustrated in Fig. 3.

[8] Data from the 2015 Energy Information Administration's Residential Energy Consumption Survey.

Fig 3. Heat pump heating as a function of outdoor temperature



A number of specific factors influence the value of this crossover temperature—including the model and size of the heat pump, and the thermal characteristics of the building—but typical values are around 30°F. Because heat pumps continue to lose power as the temperature falls, there are limited gains to be had from installing an oversized heat pump. Eventually, if the temperature continues to fall, a heat pump will be unable to provide any significant contribution to building heating—this typically occurs around 0°F.

One option to overcome this problem is to install a ground source (as opposed to air source) heat pump, which exchanges heat with the ground at a depth where the temperature remains fairly constant year-round, instead of with the outside air. However, ground source heat pumps are much more expensive to install than air source heat pumps, and so are not a practical option for most applications. Additionally, ground source heat pumps require a significant enough footprint that they are not an option for adjacent multi-story buildings in an urban setting like Seattle.

The typical solution is to rely on an auxiliary heat source when the outdoor temperature falls below the crossover temperature. This auxiliary heat source could be electric resistance heat or natural gas heat (or another fuel like propane or fuel oil). When the backup heat is gas or a similar fuel, this is referred to as a "dual fuel system." When the backup is electric resistance, it is frequently built into the heat pump itself, and in this case the system suffers from the typical downsides of electric resistance heating at low temperatures: high energy usage and associated high costs, along with the need for high-capacity wiring. Systemwide, if most buildings in an area use heat pumps with electric resistance backup heat, the electrical grid will need to accommodate the peak demand from inefficient resistance heating on the coldest days, and so will be vulnerable to failure when needed the most.

Recent advances in heat pump technology have led to the development of "cold climate heat pumps," whose heat output and efficiency are less sensitive to the outdoor temperature, at least to significantly lower temperatures than 30°F. (In Fig. 3, this would mean the line representing heat pump output would be less steep than pictured.) While these developments are promising, this is still relatively new technology that may not live up to its promise over time. Most heat pumps on the market today are not of this type, and the cold climate heat pumps that are currently available commercially are significantly more expensive than conventional heat pumps.[9]

[9] One concern expressed by the HVAC experts we spoke to is that experimental cold climate heat pumps rely on refrigerants at very high pressures, with inherent safety concerns in residential buildings.

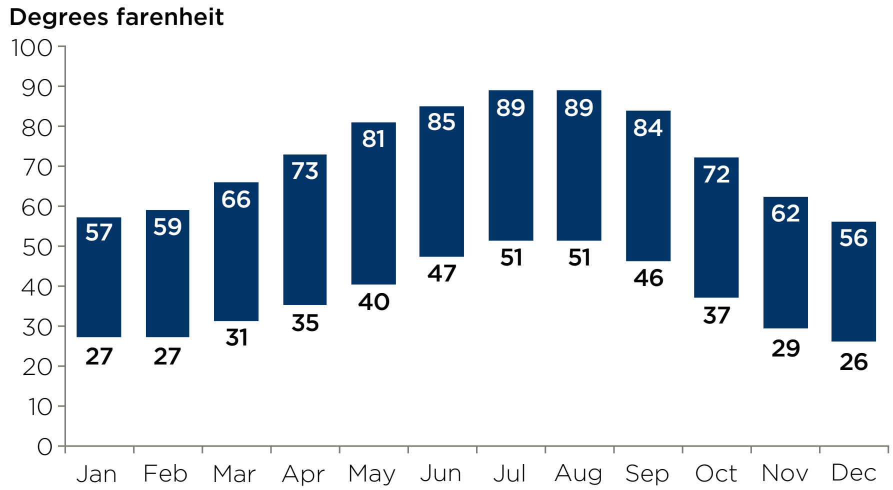
In Seattle, with its moderate temperatures and high densities, it is unlikely that cold climate heat pumps or ground source heat pumps will be widely adopted, at least in the near term. Rather, most heat pump users will need to rely on backup heating on the coldest days of the year. Dual fuel systems using heat pumps for heat on warmer cold days, as well as backup gas heat for the coldest days, could be a sensible option for some Seattleites; however the new rules prohibit this, and effectively require an electric resistance backup. This places a serious burden on the electrical grid on the coldest days—a grid-level consideration likely to be even more of an issue if electrification is rolled out in colder locations.

2.2 SEATTLE CLIMATE CONTEXT

Seattle has a mild climate, with both warm winters and moderate summer temperatures (see Fig. 4). This has two important implications for policy relating to heat pump adoption:

1. The majority of Seattle area homes currently lack air conditioning (AC); and
2. The majority of Seattle area homes, especially those in new multi-unit buildings that are affected by the new rules, currently rely on electric resistance heat.

Fig. 4. Seattle average daily high and low temperatures by month, 2000-2020

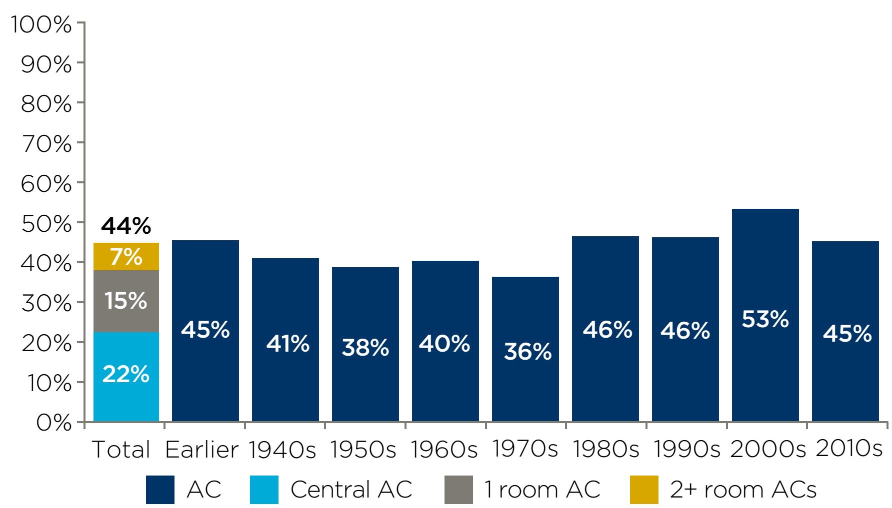


Source: NOAA, Oxford Economics

According to the 2019 American Housing Survey (AHS), only 22% of the homes in the Seattle Metropolitan Statistical Area (MSA) currently have central AC, and an additional 22% have room air conditioners, mostly window models (see Fig. 5).[10]

This helps to explain some of the poor penetration of heat pumps in the Seattle market already, as much of the economic case for heat pump adoption comes from the added value of air conditioning that heat pumps provide.[11]

Fig. 5. Primary air conditioning in Seattle MSA by decade of residence construction, 2019



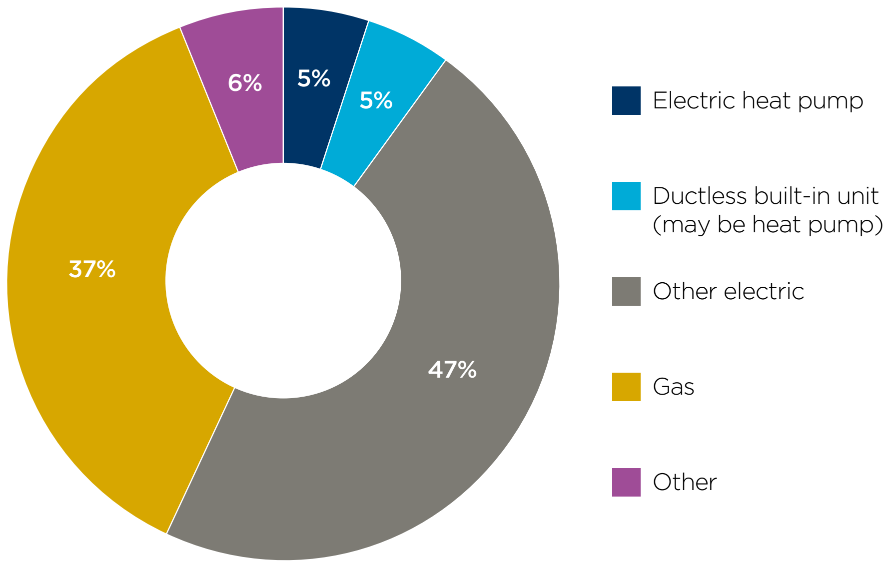
Source: 2019 AHS, Oxford Economics

[10] The AHS, a biennial survey of over 100,000 housing units nationally, is the best available source for these data. However, it only provides data at the level of the Seattle MSA, rather than the city itself. Arguably, data on the region may provide a better indication of consumer demand given the Seattle climate than would data for appliances in the city itself, which are more subject to the whims of city-specific building codes.

[11] The documentation for the AHS is somewhat unclear, but we believe that residences with heat pumps are counted as having AC.

Additionally, Seattle's mild winters have led many residents to choose electric resistance heating, with its low upfront but high operating costs. According to the 2019 AHS, 57% of Seattle area residences use electric heating, with only 5-10 percentage points of this being electric heat pumps.[12]

Fig. 6. Main heating equipment in Seattle MSA, 2019



Source: 2019 AHS, Oxford Economics

An implication of these two factors—the relative lack of AC, combined with the abundance of electric resistance heating—is that Seattle's electricity grid is currently winter-peaking, that is, it experiences its peak electricity demand in winter months. Most locations in the US are currently summer-peaking, driven by the power demand of electric air conditioning. Unlike Seattle, summer-peaking cities currently have at least some spare electricity generation and transmission capacity to accommodate increased electrification of space heating, because their current peak winter electricity usage is below their generating capacity—although full electrification would lead winter electricity demand to exceed current grid capacity in all but the warmest regions of the country.[13]

Another factor specific to Seattle is the degree to which the city currently enjoys unusually low-carbon electricity, owing to the significant hydroelectric resources of the Pacific Northwest and the region's historical embrace of nuclear power. This factor is discussed more in section 6, which focuses on the carbon implications of electrification.

[12] Identification of heat pumps in the AHS is based on the survey documentation. American Community Survey (ACS) data presented in section 4 show the share using electric heating in the city of Seattle (rather than the MSA) is similar—59% of those using either gas or electric (i.e., excluding "other"); however, those data do not distinguish between electric resistance and heat pumps.

[13] The increased efficiency of heat pumps relative to electric resistance heating might at first seem to counter this point. However, as noted in section 1.2.3, on the coldest days when electricity demand is at its peak, heat pumps will lose power and fall back on backup electric resistance heat, as required by the new rules.

3. LITERATURE REVIEW

The economics literature on residential fuel choice is relatively sparse. An important exception is a 2021 NBER working paper by Davis, written in the context of the current electrification movement.[14] Davis explores the history of heating fuel choice in the US from 1950 to 2018, and documents the increase in the share of newly built homes with electricity as the primary heating fuel from 1% in 1950 to 8% in 1970, 26% in 1990, and 39% in 2018. Using a discrete choice model, Davis finds electricity is more likely to be the heating fuel of choice when:

- Electricity is cheaper or gas/ oil more expensive. Changes in **energy prices** explain 70% of the increase in electric heating since 1950.
- The **climate is warmer**. The shift in new construction towards warmer regions of the country, together with a warming climate, explain 15% of the increase in electric heating.
- **Residences are smaller, rentals, and/or in multi-unit buildings**. Changes in these variables account for 4% of the increase in electric heating.

Using the discrete choice model parameters, and modeling the annual heating fuel cost to households, Davis estimates the amount an average household would be willing to pay to avoid an electrification mandate, effectively the perceived cost of the mandate as revealed through consumer behavior. This cost varies by geography from $85 per year per household in Florida to $4,232 in New Hampshire. In Washington State, Davis estimates that an electrification mandate would cost the average household $1,163 per year.

While Davis provides important context for the electrification debate, he was not able to distinguish between electric resistance heating and heat pumps, owing to limitations in the data available. This lumping together of two very different heating methods with different economic characteristics may bias his results.

3.1 STUDIES ESTIMATING THE COSTS OF RESIDENTIAL ELECTRIFICATION

Unlike the Davis study above, which uses a revealed preference framework based on consumer choices, a number of studies attempt to estimate the costs of residential electrification by accounting for the cost differences in appliances and annual energy costs (as we do in this paper). Key cost assumptions, and overall cost differences from these studies are summarized in Fig. 7 below. (This table focuses on costs for new construction; premia to retrofit existing buildings are discussed in section 3.1.2 below. Where a study focuses on multiple cities, we select the most similar to Seattle climate-wise.)[15]

[14] Lucas Davis (July 2021). "What matters for electrification? Evidence from 70 years of US home heating choices". NBER WP 28324; Energy Institute WP 309R. https://haas.berkeley.edu/wp-content/uploads/WP309.pdf.

[15] Two additional studies were identified that present cost estimates for heat pumps against natural gas that not included in Fig. 7. The first is from Columbia University's Center on Global Energy Policy. (CGEP, December 2019. "Decarbonizing Space Heating with Air Source Heat Pumps." https://www.energypolicy.columbia.edu/research/report/decarbonizing-space-heating-air-source-heat-pumps.). This study found an annualized cost savings of $50 per year for gas appliances in San Diego and $200 per year in Fargo, ND, with much of the savings from annual fuel costs from backup electric resistance heating. The CGEP study assumed much lower installation costs for both gas heaters and heat pumps, and generally seemed of a lower quality than the other estimates presented here. The second study was produced for the University of California Office of the President and looked at costs for the UC system's academic, laboratory, and residential buildings (Point Energy Innovations, July 23, 2017. "Final Report UC Carbon Neutral Buildings Cost Study." https://www.ucop.edu/sustainability/_files/Carbon%20Neutral%20New%20Building%20Cost%20Study%20FinalReport.pdf.) This study considered a number of green energy technologies including heat pumps, and found cost savings of 0.7%-3.5% from using heat pump space and water heating over natural gas heating and electric air conditioning. Most of the savings was from upfront capital costs; the effect on annual operating costs ranged from a 14% savings to a 16% loss from heat pumps as compared to natural gas. The different context of these estimates make them difficult to present on a like-for-like basis with the other studies reviewed here.

Fig 7. Literature estimates of gas vs. heat pump costs[16]

		AGA	RMI	Navigant	E3
		National	Oakland	California	California
Fixed costs (equipment)	Gas heat + AC	$6,281	$8,017	$4,923	$12,000 - $14,000
	Heat pump	$5,991	$4,931	$4,839	$7,000 - $20,000
	Net savings from gas over HP	-$290	-$3,086	-$84	
Annual variable costs (energy)	Gas heat	$998	$61		
	Heat pump	$1,475	$192		
	Net savings from gas over HP	$477	$131	-$91 - $387 (includes HW + cooking + clothes dryer; range includes retrofit and new homes)	-$50 - -$600
Total annualized cost savings (fixed + variable costs) of gas over HP		• $548 (new construction) • $910 (national overall average including retrofits) • $230 (Western region average including retrofits)	• -$147 (Oakland; includes HW) • -$287 (Seattle; includes HW + cooking)	-$119 - $1,302 (range includes retrofit and new homes)	-$130 - -$540 in homes with AC

[16] Source notes for these four studies are presented in footnotes to the text below, which discusses each study in turn.

In a 2018 report prepared by ICF Consulting, the American Gas Association (AGA) models the national costs of electrification in both new and existing homes.[17] They estimate a small upfront capital cost advantage ($290) for heat pumps over a new natural gas furnace plus AC, which is more than offset by lower annual energy costs of $477. Taking into account maintenance and other costs, they find an overall annual cost advantage of gas over heat pumps of $548 for new construction. Taking into account retrofit costs, they find an overall annual cost of $910 per household on average to switch to heat pump heating, or $230 overall in the Western region of the country.

The Rocky Mountains Institute (RMI), a major proponent of heating electrification, has estimated the costs for a "mixed-fuel" new home (that is, gas space and water heating with electric AC space cooling but no heat pump) versus the costs of all-electric new homes in eleven American cities, including Seattle.[18] They find a total 15-year cost of installing and operating these mixed-fuel systems in Seattle would be $17,900 versus $13,400 cost to install an all-electric heat pump system for a new home in Seattle, or an annual savings of $287 for all-electric appliances (including hot water and cooking). RMI's presentation of its Seattle modeling provides limited details on the specific cost assumptions behind these estimates, so in Fig. 7 we also present their assumptions for the city of Oakland, CA, which are better documented and result in a $147 annual cost savings from electrification.

A 2018 Navigant study focusing on five California cities generally finds a cost advantage from gas appliances relative to heat pumps.[19] For new homes, it estimates a one-time capital cost advantage for heat pumps over a gas furnace plus AC of $84. At the same time, the Navigant study finds a strong capital cost advantage for gas water heaters of $811 in upfront costs. Across the six cities and a variety of home types, they find a range of $91 higher to $387 lower annual energy costs for gas as against all electric (heat pump) appliances, with most of the cost comparisons favoring gas.

A study by Energy + Environmental Economics (E3) focusing on six cities in California presents a fairly wide range of estimates for the cost differences between gas heating and heat pumps, but generally finds heat pumps to be cheaper.[20] Overall, they estimate a $130-540 annualized cost advantage of heat pumps over gas heat for homes requiring air conditioning.

3.1.1 Analysis of cost differences

All of the four studies considered above take for granted that a gas-heated home will also install central air conditioning, something only a minority of Seattle households currently have (see Fig 5). This significantly affects the equipment cost comparison, as just the cost of the AC is often close to the cost of a heat pump, before the cost of gas heating equipment is even considered. In fact, in the RMI estimates, the upfront capital cost of just the air conditioning exceeds that of the heat pump ($5,428 for central AC vs. $4,931 for a heat pump, including installation).[21] Since heat pumps provide space cooling as well as space heating, if heat pumps were broadly available at prices lower than central AC, one would expect to see most consumers selecting heat pumps over AC—perhaps along with gas heating

[17] American Gas Association (AGA) (July 2018). "Implications of Policy-Driven Residential Electrification: An American Gas Association Study prepared by ICF." https://www.aga.org/research/reports/implications-of-policy-driven-residential-electrification/.

[18] See RMI (2018) "The Economics of Electrifying Buildings" https://rmi.org/insight/the-economics-of-electrifying-buildings/, and RMI (2020) "The New Economics of Electrifying Buildings" https://rmi.org/insight/the-new-economics-of-electrifying-buildings. The former piece provides cost estimates for Oakland, Houston, Providence, and Chicago; while the latter considers Austin, Boston, Columbus, Denver, Minneapolis, New York, and Seattle.

[19] Navigant Consulting Inc. (August 31, 2018). "Impacts of Residential Appliance Electrification." https://efiling.energy.ca.gov/GetDocument.aspx?tn=224761. Because of the number of scenarios considered, including different types of new and old residences in different locations in California, it was difficult to separate out the cost categories that were most comparable to the other studies presented here.

[20] Energy + Environmental Economics (April 2019) "Residential Building Electrification in California." https://www.ethree.com/wp-content/uploads/2019/04/E3_Residential_Building_Electrification_in_California_April_2019.pdf.

[21] We believe that RMI is relying here on Homewyse estimates that are not comparing like-for-like, and are including more of the costs for ancillary equipment and installation for AC than for heat pumps. As we are well aware, it is very difficult to obtain reliable estimates of costs for generic HVAC equipment and installation given the large number of case-specific factors that come into play.

backup—and government policies supporting heat pump adoption would be largely moot. Since we in fact see many households make the opposite choice, it is likely that this modeling is misestimating costs or failing to capture important dimensions of the tradeoff.

There is significant dispersion between the four studies in the overall costs of heat pumps versus natural gas heating plus electric AC. AGA and Navigant generally find gas to be cheaper, with a small upfront cost advantage for heat pumps over gas heating and central AC offset by lower operating costs over time. RMI and E3, in contrast, find heat pumps to be cheaper, driven by significantly larger upfront cost advantages. In RMI's Oakland model, this capital cost advantage of heat pumps is offset by somewhat higher operating costs, whereas E3 estimates lower operating costs for heat pumps versus natural gas in California.

Finally, all the works referenced above evaluate the total cost of gas heat vs. heat pumps using net present value over a fixed (usually 15-year) timeframe. Because heat pumps generally have shorter lifespans than do gas furnaces or boilers, this fixed timeframe will bias cost comparisons in favor of heat pumps over longer-lived gas appliances.[22] In our cost estimates in section 3, we use an annual equivalent cashflow method to better account for these lifespan differences between gas and heat pump appliances.

3.1.2 Retrofit cost premium

The Seattle legislation, like other electrification legislation to date, focuses on newly constructed buildings and major renovations.[23] This policy decision is an implicit recognition of something that both proponents and opponents of electrification mandates agree upon: retrofitting existing buildings' heating, ventilation, and air conditioning (HVAC) systems to use heat pumps can be significantly more expensive than designing new buildings to accommodate heat pumps.

The degree of difficulty and expense in an individual building depends on many factors. Some existing buildings with forced-air HVAC distribution will allow for a heat pump to be integrated into the existing duct work relatively smoothly. There may still be problems, however, because heat pumps, unlike furnaces but like most central AC, require an outdoor component to handle the heat exchange with the outside air. Additionally, many older buildings' electric system may require upgrading to handle the higher power consumption of heat pump space and/or water heating. The E3 report cited above assesses that single-family homes lacking a 200amp electrical panel (in their California context, mostly those built before 1978) will require an upgrade costing between $2,000-$4,000, in addition to any costs from retrofitting the HVAC system itself. And buildings with existing hydronic systems (where heat is distributed through the house using piped hot water instead of forced air) may be considerably harder and more expensive to retrofit.[24]

Both the AGA and RMI reports cited above provide estimates of installation costs in both new and existing homes, allowing one to implicitly calculate a retrofit premium. Since retrofit costs vary considerably between different buildings, these estimates should be considered averages between both easy and difficult cases. Overall, the two estimates are surprisingly similar. Expressed as the total (i.e., appliance plus installation) percentage cost increase for a heat pump system in a retrofit scenario versus new construction, RMI estimates a 75% retrofit premium, and AGA an 82% premium. We adopt the midpoint of these estimates (78.5%) as our assumption for the retrofit premium in section 4.2.2.

[22] To see this, imagine that heat pumps have an average lifespan of 15 years and gas furnaces 20 years. At the end of the 15-year timeframe, the heat pump household would need to immediately pay the upfront capital cost of a new heat pump, whereas the gas household would have five more years before having to replace their furnace.
[23] What precisely constitutes a major renovation and what is routine maintenance can, of course, become tricky to define in practice.
[24] One option in difficult retrofit cases are so-called mini-split heat pump systems, which connect room units, often affixed to a wall near ceiling height, to an outdoor heat exchanger using a small pipe of refrigerant, which must be connected through an exterior wall. While a good solution in some cases, such systems nevertheless have their own drawbacks and are not practical in every thorny retrofit scenario.

3.2 INFRASTRUCTURE COSTS AND CONSIDERATIONS

Much of the literature on building electrification has focused on the direct capital and operational costs to consumers or building managers from the equipment that they own and operate, which is also the primary focus of this paper. It is understood that shifting a significant share of total energy consumption from one distribution system to another would entail enormous infrastructure costs from the necessary upgrades to the electrical system, while also potentially realizing savings from foregone natural gas distribution infrastructure—although these savings are more uncertain, as discussed below.

On the costs side of the ledger, electricity generation, transmission, and distribution infrastructure would need to be massively expanded.[25] Assuming an unrealistic 100% conversion of residential buildings to heat pump space and water heating, the AGA report cited above estimates that the US's peak electricity demand, currently 856GW in the summer (coinciding with air conditioner use) would nearly double to 1,679GW in the winter. In a more realistic scenario in which 60% of homes are converted by 2035, they estimate additional electrical generation costs of $102-319 billion and transmission costs of $54-107 billion.[26] Distribution costs are not explicitly modeled.

It is instructive to consider the extent to which such costs are accounted for in the consumer operating costs calculations discussed, in the context of prior studies, in section 3.1, and, in the context of our own estimates, in section 4. Pricing for electricity and natural gas are often highly regulated at the local level. Ultimately, however, consumers of both gas and electricity bear the costs of the energy infrastructure they rely upon. Today's electricity and gas prices implicitly include costs related to past capital investment. To the extent that the amortized capital cost of new electrical infrastructure were to exceed that of existing infrastructure on a per kWH basis, electricity prices would need to rise to accommodate these costs. In this case, the consumer cost forecasts made by ourselves and others based on existing price forecasts would fail to capture the full infrastructure cost associated with new electric power. It is worth noting however, notwithstanding the regulated nature of energy distribution monopolies noted above, that eliminating gas as a competitor energy source might tend to increase the economic rents that electric power utilities and related industries (e.g., electric equipment manufacturers) are able to extract from their end customers.

The converse of the increased infrastructure costs of electrification are the potential savings from foregone natural gas distribution infrastructure. While the potential for such savings, especially in the case of new development, are real, these savings are limited by the need to maintain existing infrastructure in locations where some buildings still rely on natural gas for essential heating. This leads to the **stranded asset problem**, where natural gas utilities must bear the costs of maintaining vital existing infrastructure with an ever-diminishing customer base. As this process continues, the existing customers who are least able to convert will see their energy bills rise unless subsidized.[27]

[25] Electricity transmission refers to high-voltage transmission of electricity over long distances, while distribution refers to the local networks of wires that bring electricity into buildings.
[26] In the AGA model, lower generation and transmission capital costs are achieved under a "market" scenario. Higher costs result when there is a requirement that all new generating capacity must come from renewables. Paradoxically, the renewables-only scenario results in higher carbon emissions because older, more polluting plants are taken offline more slowly because replacements are more expensive.
[27] For a discussion, see Bryce, Robert (August 9, 2020) "Natural Gas Bans Will Worsen California's Poverty Problem." RealClear Energy. https://www.realclearenergy.org/articles/2020/08/09/natural_gas_bans_will_worsen_californias_poverty_problem_501330.html.

The pro-electrification literature, such as the RMI report cited above, devotes considerable attention to the potential advantages that heating electrification confers from **load shifting**, that is, from adjusting the precise timing of electricity use by minutes or hours based on the real-time capacity constraints of the grid. This is particularly important in the context of renewable energy sources like solar and wind, whose electricity output can be highly variable.

While load shifting of ordinary residential electrical equipment may indeed be possible, such schemes remain uncommon, and most new household electrical HVAC and other equipment is not designed to do this. And while heating equipment like heat pumps and water heaters are potentially conducive to load shifting in a way other equipment like TVs and electronics are largely not, so are many other electrical appliances, such as refrigerators and electric vehicles. Additionally, shifting peak power demand from summer to winter, as electrifying heating would do in most places, would not play to the strengths of wind and solar power, which are generally at their maximum capacity in the summer.

Finally, a number of other considerations potentially come into play in electrification, which are difficult to shoe-horn into a standard cost-benefit framework. For example, electrification may improve local safety or environmental conditions relative to natural gas, although electricity is not without its own safety considerations (including, at the transmission level, wildfires),[28] and, given the extent of its use, natural gas has an impressive safety record. On the other hand, natural gas heating may provide important back-up to electrical systems that could fail in extreme weather events when heating is required most, as happened in Texas in February 2021.[29]

[28] See, for example, Wall Street Journal (January 13, 2019). "PG&E Sparked at Least 1,500 California Fires. Now the Utility Faces Collapse." [https://www.wsj.com/articles/pg-e-sparked-at-least-1-500-california-fires-now-the-utility-faces-collapse-11547410768]
[29] See, for example, Reuters (February 20, 2021). "Why a Predictable Cold Snap Crippled the Texas Power Grid." [https://www.reuters.com/article/us-usa-weather-texas-power-insight/why-a-predictable-cold-snap-crippled-the-texas-power-grid-idUSKBN2AL00N]

4. COST IMPLICATIONS

In this section, we develop our own estimates of the cost of heating electrification mandates in the city of Seattle. We focus first on the implications for residential space heating. Section 4.1 lays out the key assumptions in our modeling (precise numerical values for key parameters are given in the appendix). Then, in section 4.2, we consider three cost scenarios:

- Scenario 1, which is intended to approximate the new Seattle rules, focuses on new residential construction in large apartment buildings.
- Scenario 2 considers all new residential construction.
- Scenario 3 explores the costs of retrofitting all existing residential buildings.

Additionally, in section 4.3, we make a high-level assumption to extend these estimates to commercial buildings. In section 4.4, we explore possible reasons for the differences between our estimates and those in the prior literature presented in section 3.1, especially the role of air conditioning. Finally, in section 4.5, we explore the issue of water heating.

A fundamental difficulty in this modeling work is that HVAC systems, especially for the large buildings that are targeted by the Seattle rules, are highly complex and require specialized engineering knowledge to design and install, and consequently, to estimate the costs of. Heat pump technology in particular is still evolving in large-scale applications, and generally requires specialized design services that are themselves costly, and that make it difficult for non-experts to price such systems. By contrast, HVAC equipment installed in a single-family house, although it still requires professional qualifications to select and install, is nevertheless fairly standardized and consistently priced.

For this reason, while we understand that the situations are different, we use price estimates for residential (i.e. single family home) HVAC equipment as a stand-in for costs *on a per residential unit (i.e., per apartment) basis* in large residential buildings. Our view, which we developed in consultation with Seattle-based HVAC experts, is that these cost estimates represent a reasonable stand-in for the relative cost differences between the three principal heating options available: natural gas heat, electric resistance, and heat pumps.[30] We recognize however that this view may not be entirely accurate if large-scale systems achieve economies of scale not available in smaller systems. The potential for such scale economies is probably greatest for natural gas boilers, which can be scaled up in size relatively cheaply. However, there are potentials for such economies for heat pumps as well, for example from large-scale heat exchangers in the outdoor units. This sort of technical analysis is well beyond the scope of this work.[31]

4.1 MODELING ASSUMPTIONS

4.1.1 Seattle residential construction market

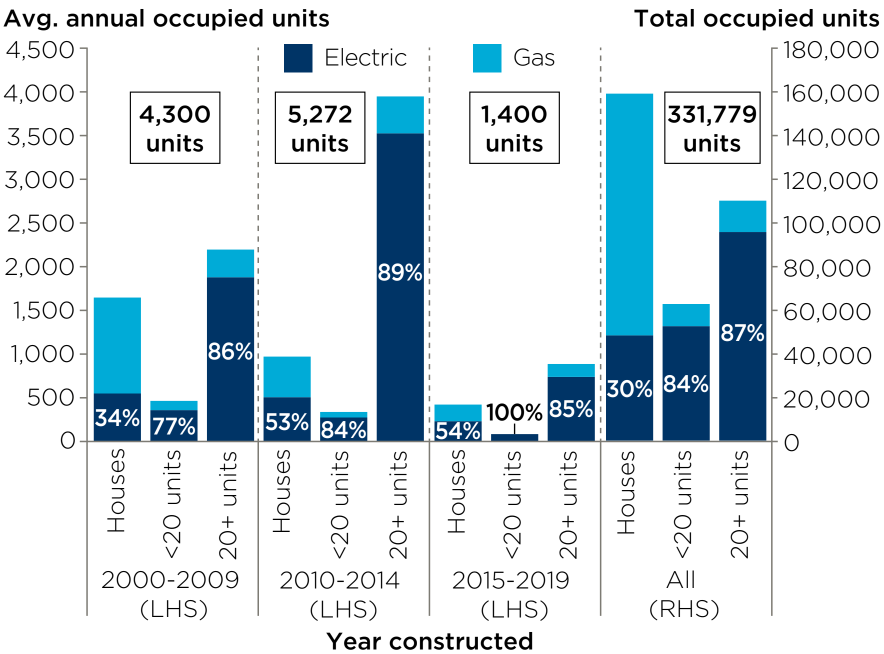
Our primary source for assumptions relating to the Seattle residential construction market is the 2015-2019 American Community Survey (ACS). Fig. 8 presents these ACS data by average number of units constructed per year, by housing type (detached houses, apartment buildings with less than 20 units, and apartment buildings with 20 or more units), and by the primary heating fuel (gas or

[30] Note that we emphasize here cost differences. In principle, costs may be uniformly higher or (less likely) lower across these three options without affecting our overall conclusions. Fixed system costs across the systems, for example for heat distribution through ducting or piping, can broadly be ignored if they are similar between the three options. Likely this approach understates the upfront cost advantages to electric resistance heating, which doesn't require expensive heat distribution through a building, helping to explain the relatively high uptake of this heating choice in Seattle currently.

[31] HVAC experts consulted by Oxford Economics for this work felt that our overall cost estimates—based, as described below, on EIA figures and Homewyse—were on the low side for both natural gas and heat pump systems, and that maintenance cost estimates were particularly low, especially for heat pumps. Upfront heat pump costs were reckoned to be underestimated more so than upfront natural gas costs, but it was thought this could be a transitory market effect from post-Covid shortages combined with a rapid increase in heat pump demand caused in part by the new Seattle rules.

electric).[32] Importantly, the ACS only collects construction year and heating fuel data from the residents in occupied housing units, meaning the total number of units is underestimated. This is especially true for recently constructed residences, as these units take time to be sold or rented. This is the primary reason the number of units is so much lower during the 2015-2019 period than 2010-2014, although changes in the housing market during those years also have an effect.

Fig. 8. Building size and primary heating fuel of occupied Seattle residential units by construction year



Source: 2015-2019 ACS, Oxford Economics

According to Fig. 8, roughly 85-90% of recently constructed apartment buildings with 20+ units—which are stand-ins for the newly constructed apartment buildings of four+ stories that are subject to the new Seattle rules—use electric heat, with only 10-15% using gas heat. Unfortunately, the ACS does not record whether these buildings use electric heat pumps or electric resistance heating. However, given the result from the American Housing Survey—the best available source on heat pump prevalence in Seattle—that only 5-10% of residences in the Seattle MSA currently use heat pump heats (see Fig 6), we surmise that the large majority of affected units currently use electric resistance heating.[33]

Based on the ACS data presented above, we assume an annual average number of new residential units in Seattle of 6,000.[34] The shares of gas versus electric heating were estimated based on the ACS shares recorded above. To be conservative, we assumed that 10% of each housing type would use heat pumps in the absence of the new rules, the upper end estimate of heat pump prevalence in Fig. 6, and this total was taken out of the electric resistance category. The precise numerical assumptions resulting from these assumptions are presented in the appendix.

4.1.2 Energy prices

Historical electricity and natural gas prices were taken from the Bureau of Labor Statistics' average energy prices for the Seattle MSA.[35] These estimates are presented on an energy equivalent basis in Fig. 9.[36]

[32] Approximately 3% of post-2000 units use neither gas nor electric heat, with the largest share of those reporting either no heating fuel or propane. These responses have been dropped and the number of gas and electric units scaled up proportionally by construction year and building type. Unusual housing types, such as RVs and houseboats, which are not common, are grouped with houses.

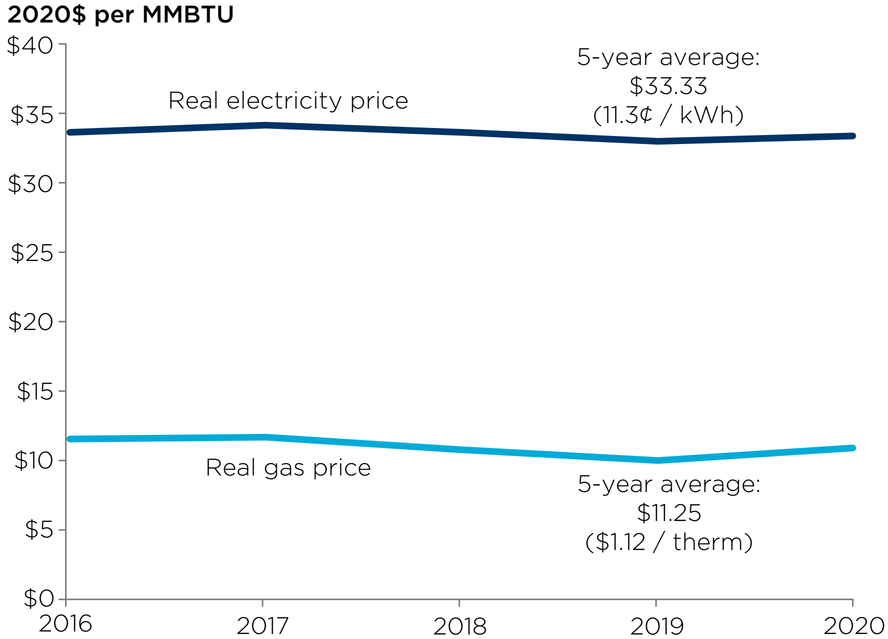
[33] Because of data suppression, only a limited breakout of heat pump prevalence by type of Seattle area home is available from the AHS. According to the 2019 AHS, however, 78% of the heat pumps in Seattle area homes were in single-family detached houses.

[34] Again, this exceeds the annual number of new units in the ACS presented in Fig. 8 because those ACS data do not cover vacant units.

[35] See https://www.bls.gov/regions/west/news-release/averageenergyprices_seattle.htm. These BLS estimates, which are developed as part of the Consumer Price Index (CPI), include relevant fees paid by consumers that can be difficult to estimate from cost schedules provided by local utilities.

[36] Natural gas prices are quoted by BLS in dollars per therm, where one therm is equivalent to 100,000 British thermal units (BTUs) of energy content (alternately written 100 kBTU or 0.1 MMBTU—note that by convention one million BTU is abbreviated MMBTU rather than MBTU), or just under 100 cubic feet of natural gas. Electricity prices are quoted per kWH, or 1,000 Watt-hours. A fundamental equivalence is that 1 WH = 3.412 BTU, allowing conversion between the energy content of natural gas and electricity. Together with the appliance efficiencies referenced below (defined as heat energy output per unit of energy input, a dimensionless quantity), this allows the calculation of costs per unit of heat energy output for each of the three heating technologies.

Fig. 9. Real historical energy prices, Seattle MSA[37]



Source: BLS, Oxford Economics

For our cost modeling, we use the five-year historical real average prices for both electricity and natural gas from 2016-2020. Fixed prices were selected over a changing energy price forecast to better illustrate the fundamental trade-offs between natural gas and electric heating.

Fig. 10. Annual household energy input usage for space heating

	Input energy (MBTUs)
US	35.3
Western region	22.1
Pacific division	17.5
Urban areas	34.8
Marine climate	20.7
Detached houses	44.9
Apartments with 5+ units	9.7
Natural gas as primary fuel	47.5
Electricity as primary fuel	13.6

Source: EIA RECS

The relationship between natural gas and electricity prices is expected to remain relatively unchanged as long as natural gas remains the marginal energy source for electricity generation, as it is today in most parts of the US today. This relationship would be undercut, however, if in the future the effective price of renewable-sourced electricity (including storage costs) falls significantly below that of natural gas-sourced electricity. Although this does not appear likely in the immediate future, if this were to happen, the economic case for electric heating would be strengthened.

4.1.3 Household space heating energy use

The amount of space heating an individual household uses depends on a large number of factors, including the climate, the size, and thermal characteristics (e.g. insulation) of the dwelling, the preferences of the household, and the marginal cost of heat. Households vary considerably in the amount of space heating that they use.

[37] Adjusted for inflation to 2020$ using CPI.

Fig. 10 presents average energy use for space heating for a variety of regions and home types from the EIA's Residential Energy Consumption Survey (RECS). It is important to note that these are *input* energy values, rather than the amount of heat *output*, which is what we need for modeling. The ratio of energy output to energy input is the efficiency, which varies from about 80-97% for gas heat, to 100% for electric resistance heat, to about 200-300% for heat pumps.

Based on these levels of energy inputs, we assume that Seattle households use an average of 40 million British thermal units (MMBTUs) of heat energy *output* for space heating annually, while Seattle apartments use 10 MMBTUs. As discussed below in section 4.1.4, these assumptions are relatively inconsequential for households that select natural gas heat (prior to the heat pump mandate), but more so for electric resistance households.

It should be noted that our simplifying assumption—that households select a certain amount of heating to use independent of what type of heating equipment they have installed and the prices they face as a consequence—is surely incorrect. Households that are made to switch from electric resistance heating to a heat pump would likely choose to use more heat once its marginal cost drops.[38] Although this implies higher total heating costs for households under the mandate than our estimates, households will derive more value from this heat than what they pay for it (or else they would not choose to consume it). This will therefore cause our model to slightly overstate the welfare cost to households of the mandate, although we believe the magnitude of this effect to be small.

4.1.4 Heating equipment

Our primary data source for assumptions relating to space and water heating equipment is the US Energy Administration Administration's (EIA) June 2018 publication "Updated Buildings Sector Appliance Equipment Costs and Efficiencies."[39] This document provides assumptions for both residential and commercial appliances for the EIA's Annual Energy Outlook. Specifically, for each type of appliance (e.g. air source heat pump or natural gas boiler) it provides estimates for:

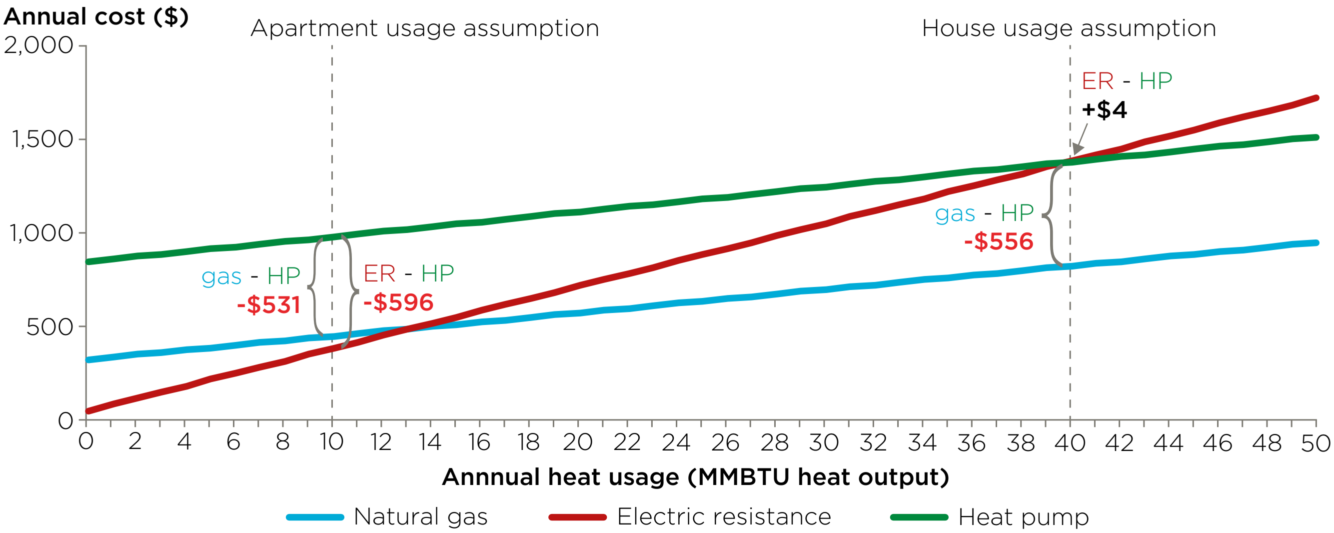
- The heating capacity (in kBTU/h) of a typical unit;
- The unit's upfront appliance and installation costs;
- The expected lifespan of the unit;
- Average annual maintenance costs for the unit; and
- The energy efficiency of the unit.[40]

Because of concerns about outdated upfront cost estimates, we adjusted these costs using estimates from the online residential costing service Homewyse, but took other assumptions from the EIA publication.[41] Specific numerical assumptions are given in the appendix.

The annualized total cost for the three different types of space heating, conditional on the amount of heat used, are presented in Fig. 11.[42] This figure also shows the cost differences between the heating technologies at the usage levels assumed for houses and apartments in our scenarios.

[38] This is the substitution effect from the price of heating dropping. There is also an income effect since households are poorer as a result of the mandate; however we would expect the substitution effect to dominate.
[39] See https://www.eia.gov/analysis/studies/buildings/equipcosts/.
[40] As discussed in section 2.1.1, heat pumps do not have a fixed efficiency for space heating; rather their efficiency falls as temperatures do. Estimates here use a fixed value of 250%, that is, a "coefficient of performance" (COP) of 2.5, as an overall average efficiency for heat pumps.
[41] Homewyse is an online service to help homeowners estimate costs for home improvement projects. See https://www.homewyse.com/costs/index.html.
[42] We use an annualized equivalent cashflow methodology to account for the differing lifespans of the equipment. The premise of this technique is that the individual paying the costs takes out a loan—which differs in duration across the three different heating types—in the first period at a fixed interest rate, then makes equivalent annual payments each year. All our costs are in real terms to begin with, and we use a 3% discount rate for the calculations.

Fig. 11. Annual total cost of space heating as a function of annual heat usage



Source: Oxford Economics

Splitting the total cost into two categories helps to interpret this figure:

- **Fixed costs** reflect the cost of the equipment itself, independent of how much heat is being used.
  - Fixed costs include appliance costs, installation costs, and maintenance costs.
  - In Fig. 11, the fixed costs are reflected in the y-intercept of the cost line for each technology.
- **Variable costs** are the energy costs to produce a certain amount of heat output.
  - *Variable costs* ($ per heat energy output) = *Energy costs* ($ per unit energy for gas or electricity) ÷ *Equipment efficiency* (heat energy output per energy input)
  - In Fig. 11, the variable costs are reflected in the slope of the cost lines for each technology.

It is apparent that the variable costs of natural gas and heat pump heating, reflected in the slopes of these two lines, are similar, implying that the cost difference between natural gas and heat pump heat is driven by differences in the fixed costs of these two systems. This implies as well that, for households that would otherwise select natural gas heat, a heat pump mandate imposes an annual cost burden of approximately $500-600, and this cost is largely insensitive to the amount of heat the household uses.

The story is different for electric resistance heat, which has low fixed costs, but high variable costs of use. As a result, households that use little heat will do better to install electric resistance heating, while households that use more than about 13 MMBTUs of heat per year will do better to install natural gas. Moreover, the cost of a heat pump mandate on a household currently using electric resistance heating will vary significantly based on how much heat they use, up to about $800 a year for households that use almost no heat.

4.2 RESIDENTIAL COSTS

The four sets of assumptions in section 4.1—on Seattle residential construction, energy prices, heating equipment, and average annual household energy usage—together allow us to estimate the costs of a Seattle space heating electrification mandate. The results of this analysis are presented below.

4.2.1 Scenario 1: New large apartment buildings (approximating new rules)

We estimate that the cost of an electrification mandate requiring heat pumps and prohibiting natural gas for space heating in all newly constructed large apartment buildings (current rules) will be $2.0 million per year for each year of new construction (for example, for all buildings built in 2022, the added cost will be $2.0 million each year thereafter). This equates to an annual average cost of $587 per affected household. After 15 years of new construction, the total annual cost would be $30 million (see Fig. 12—note that the cost per household in this figure and the following one match the values given in Fig. 11).

Fig 12. Results for Scenario 1

	ER	Gas	Total
# New households affected annually	2,987	473	3,460
Cost per household	-$596	-$531	-$587
Total annual cost of 1 year of construction ($ thousands)	-$1,779	-$251	-$2,030
Annual cost after 15 years of new construction ($ millions)	-$26.7	-$3.8	-$30.5

4.2.2 Scenario 2: All new residential construction

We estimate that the cost of an electrification mandate requiring heat pumps and prohibiting natural gas for space heating in all newly constructed residential buildings (houses and apartments of all sizes) would be $2.8 million per year for each year of new construction (for example, for all buildings built in 2022, the added cost will be $2.8 million each year). This equates to an annual average cost of $521 per affected household. After 15 years of new construction, the annual cost would be $42 million (Fig. 13).

Fig. 13. Results Scenario 2

	Houses		Apartments		Total
	ER	Gas	ER	Gas	
# New households affected annually	549	957	3,332	562	5,400
Cost per household	$4	-$556	-$596	-$531	-$521
Total annual cost of 1 year of construction ($ thousands)	$2	-$532	-$1,984	-$298	-$2,812
Annual cost after 15 years of new construction ($ millions)	$0.0	-$8.0	-$29.8	-$4.5	-$42.2

4.2.3 Scenario 3: Conversion of all residential structures

Under Scenario 3, we assume that all residential structures in the city are converted to heat pumps over a 15-year period. The costs for all new construction (Scenario 2) are included in this scenario, plus conversion costs for the remaining housing stock in Seattle, which we estimate as the size of the current housing stock (from the ACS) minus the total number of new residential units constructed over this period.[43] Costs for retrofitting existing households are calculated by scaling up the installation cost of heat pumps by 78.5%, based on the estimates in the literature discussed in section 3.1.2 above.

Overall, we estimate that the annualized cost to retrofit the existing housing stock is $203 million, or an average of $934 per affected household on an annualized basis (Fig. 14).[44] Adding in the cost for newly constructed units from Scenario 2 above, the total annual cost for Scenario 3 after 15 years is $245 million.

Fig 14. Results for Scenario 3

	Houses		Apartments		Total
	ER	Gas	ER	Gas	
Remaining housing stock	24,210	96,318	81,025	16,048	217,601
Cost per household	-$423	-$983	-$1,023	-$958	-$934
Total cost for retrofit of old buildings ($ millions)	-$10.2	-$94.7	-$82.9	-$15.4	-$203.2
Plus: Scenario 2 costs	$0.0	-$8.0	-$29.8	-$4.5	-$42.2
Total costs for new and old structures	-$10.2	-$102.7	-$112.7	-$19.8	-$245.4

4.3 COMMERCIAL COSTS AND SCENARIO SUMMARY

In line with most of the existing literature on building electrification, we have focused on residential electrification costs, because it is easier to obtain data for residential construction and HVAC equipment. However, the new Seattle rules apply to new commercial structures (of all sizes) as well as to residential buildings of over three stories.

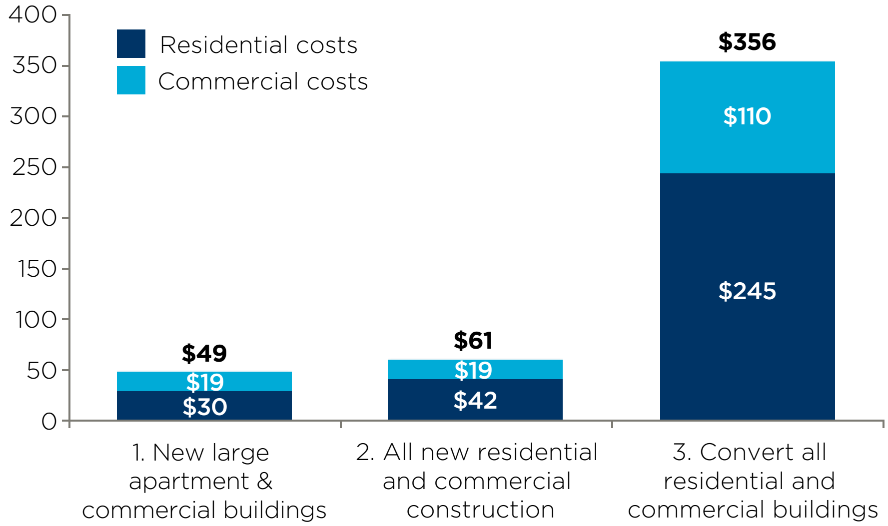
Detailed modeling of the costs of heat pumps for commercial buildings is beyond the scope of this work. Instead, we offer a ballpark estimate of commercial costs as a fraction of residential costs based on overall energy use by residential and commercial buildings. Specifically, based on EIA data, we observe that, nationally, commercial buildings use approximately 45% of the energy for space heating as do residential buildings.[45] Given this, we make a very high-level estimate of the costs of mandating heat pumps for space heating of commercial buildings as 45% of that for residential buildings. Because the new Seattle rules apply to all commercial buildings, not just those over three stories, we use 45% of the residential values under Scenario 2 for both Scenarios 1 and 2.

[43] Implicitly, we're assuming the total housing stock remains constant and new units are replacing old ones. This is obviously not likely to be literally true for the city of Seattle, but is a reasonable framework for our purposes.
[44] This analysis amortizes the retrofit cost over the assumed 15-year lifespan of the newly installed heat pumps. Subsequent replacements of the heat pumps with new heat pumps at the end of their usable lives would presumably not require additional retrofitting, and so the cost per household would fall from the $934 estimated in scenario 3 to around the $521 per household estimated in scenario 2, although not precisely that value since the mix of housing types differs somewhat.
[45] Based on total energy consumption for space heating from the 2015 EIA Residential Energy Consumption Survey (3,945 trillion BTUs) and the 2012 EIA Commercial Energy Consumption Survey (1,756 trillion BTUs).

Fig 15 presents the annual cost to affected households and commercial building owners of the three scenarios after 15 years of construction / retrofitting. Note that these costs are cumulative, not additive—that is, Scenario 2 includes the cost of Scenario 1, and Scenario 3 includes the cost of Scenario 2.

Fig. 15. Scenario annual costs summary

Annual costs after 15 years ($ millions)



Source: Oxford Economics

4.4 ANALYSIS OF COSTS AND THE ROLE OF AIR CONDITIONING

Relative to the studies reviewed in section 3.1, we generally obtain higher estimates for the cost burden of heat pumps relative to natural gas and electric resistance heat (although those studies largely ignored electric resistance). In part, this is the result of specific numerical assumptions relating to equipment, installation, maintenance, and energy costs (which we fully document in the appendix). However, two specific methodological differences with past studies are specifically responsible for our higher heat pump cost estimates:

- We account for differences in the lifespans of heating equipment. Most past studies have instead used a fixed time horizon, typically 15 years.
- Given the Seattle context, we do not assume that all households selecting gas or electric resistance heating also install central air conditioning (AC).

Heat pumps provide AC inherently, and so selecting (or being compelled to select) a heat pump for heating provides the benefits of AC as part of the upfront cost.[46] Our analysis above implicitly values this bonus AC at $0. The alternative in most of the literature is to value the AC at the cost of a central air conditioning system, or equivalently, to make the comparison not between a heat pump and gas heat, but between a heat pump on the one hand, and gas heat plus central AC on the other.

Based on assumptions about the appliance, installation, and maintenance costs, and lifespan of a central AC unit analogous to those considered in section 4.1.4, and similarly documented in the appendix, we estimate the annualized equipment cost of central AC at $436.[47] Accepting this as the value households derive from having access to AC would lower the absolute value of the “costs

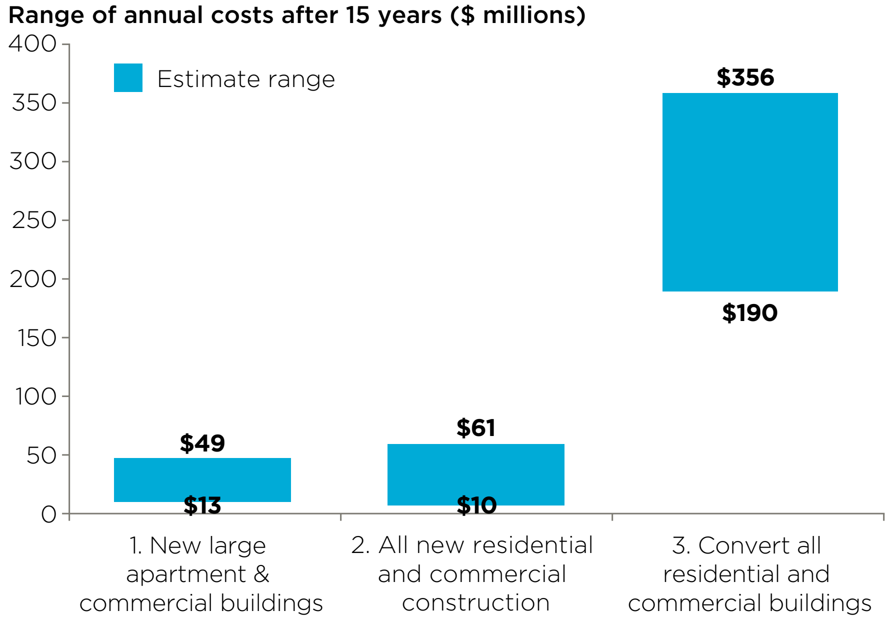
[46] Heat pumps operate at approximately the same space cooling efficiency as do air conditioners More precisely, both heat pumps and air conditioners are available at different efficiency levels, with more efficient units generally costing more.

[47] Using the same methods, the annualized equipment cost of a heat pump (which includes installation and maintenance costs) in our modeling is $744, or 71% more expensive. This is a significantly wider gap than our simple upfront (appliance plus installation) cost assumptions for air conditioners and heat pumps of $5,000 and $6,500 (30% more expensive) respectively. This is a result of differing assumptions we make on appliance longevity and average annual maintenance costs between air conditioners and heat pumps. As we noted in section 3.1.1, when heat pumps are assumed to cost essentially the same amount as air conditioners, there is little reason for households to select central AC rather than a heat pump, while revealed consumer behavior shows many households making that choice.

per household" rows presented in Figs. 12, 13, and 14 by this amount. However, the fact that most households in Seattle have not chosen to install central AC suggests that they in fact value AC less than this cost.

In Fig. 16, we present a range of estimates for the three cost scenarios based on valuing the AC services of heat pumps between zero (the upper bound estimates, identical to Fig. 15 above) and the full cost of AC (the lower bound estimates). For example, assuming that households derived value from AC equivalent to the cost of a central AC system would reduce our estimate of the annual costs after 15 years for Scenario 1 from $49 million to $13 million.[48]

Fig. 16. Range of scenario costs from valuing AC fully (lower cost estimate for scenarios) to not valuing AC at all (upper cost estimate for scenarios)



Source: Oxford Economics

4.5 WATER HEATING

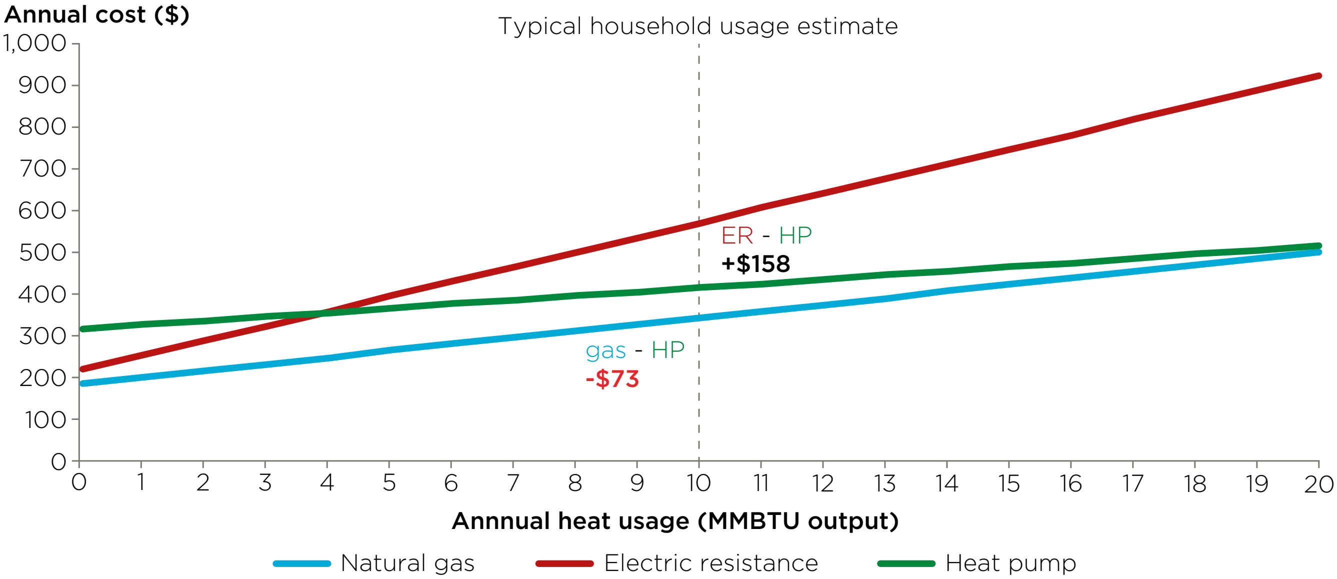
The above analysis has focused exclusively on space heating, although the new Seattle building rules apply to water heating as well. However, whereas the space heating provisions of the new rules specifically electric heat pumps (except in a few special cases where electric resistance is allowed), the provisions around water heating similarly ban natural gas, but allow both heat pump water heaters and electric resistance water heaters as well.

Using a similar methodology to that outlined in section 4.1 for space heating, and with assumptions similarly documented in the appendix, we obtain a schedule of heating costs for the three types of water heaters based on the annual amount of water heating energy output used (Fig. 17).[49] The cost structure here is similar in some respects to the space heating case (Fig. 11), although there are important differences. Electric resistance water heaters again have the highest variable cost of use, but they have only a small upfront cost advantage over heat pump water heaters, and none over gas water heaters. Heat pump water heaters have distinctly lower variable costs than natural gas water heaters, unlike in the space heating case where the two had very similar variable costs. However, because the upfront cost of gas water heaters is lower, households would have to consume approximately 22 MMBTUs of water heating annually for heat pump water heaters to pay for themselves given our assumptions.

[48] Valuing AC fully reduces the costs of Scenario 2 more than Scenario 1 because the average cost per household in Scenario 2 is lower (owing to the larger share of affected households that use natural gas in Scenario 2). Costs for Scenario 3 are reduced the least because its cost per household is largest (owing to the added costs of retrofits).

[49] We consider storage water heaters, with a built in tank of hot water, rather than instantaneous water heaters, which are available for gas or electric resistance, but not heat pumps. Instantaneous water heaters have somewhat higher efficiencies and offer other advantages (like never running out of hot water), but are significantly more expensive upfront, and are generally considered a premium option.

Fig. 17. Annual total cost of water heating as a function of annual water heating energy output usage



Source: Oxford Economics

Based on our analysis of the EIA RECS data, we estimate that typical households use approximately 10 MMBTUs of water heating energy output per year, and we find that this usage is far more similar across households than is the case for space heating. Given this level of usage, natural gas water heaters are the cheapest option, although their advantage over heat pump water heaters is relatively small, only about $73 annually. By contrast, electric resistance water heaters are a good bit more expensive, $232 more than natural gas water heaters, and $158 more than heat pump water heaters given this average usage.

Given these results, there would seem to be little reason for consumers to select electric resistance water heaters, unless they did not have access to natural gas and used very little hot water. In fact, however, the market penetration of heat pump water heaters is still limited relative to that of electric resistance water heaters. The reason for this appears to be a combination of lack of familiarity with, and poor performance of, heat pump water heaters. Because heat pump water heaters heat water more slowly, they run out of hot water more often, and typically have an electric resistance backup to deal with periods of high demand. This also means that they operate at peak capacity for longer periods and therefore, according to HVAC experts we consulted, suffer from more maintenance and reliability problems than do electric resistance or natural gas water heaters that may not be fully factored into our pricing model.

While heat pump water heaters may have a promising future, their present drawbacks may lead some Seattleites to discount them altogether. For those who would otherwise have selected a natural gas water heater, the new rules would instead force them into an electric resistance water heater with high operating costs and low efficiency. Depending on the grid supplying the electricity, this may also lead to increased carbon emissions relative to natural gas (see section 6). It is worth noting in this context that many apartment dwellers in warm climates like Seattle use about as much or more energy for water heating as they do for space heating.

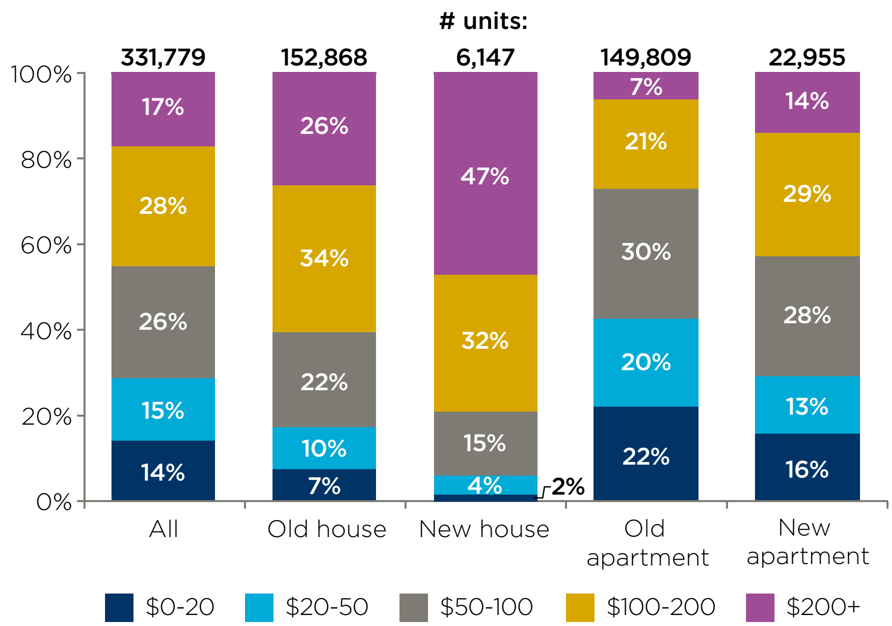
5. IMPACT ON LOW-INCOME AND BIPOC HOUSEHOLDS

Government mandates requiring households to purchase specific products generally burden the least economically well-off for the simple reason that these households have the least ability to absorb the costs. For example, our estimate of the average annual cost of the new rules per affected household of $587 (see Fig. 12) represents only about 0.3% of annual income for a household making $200,000 per year, but about 1.5% of annual income of a household making only $40,000 per year.

There are also more specific reasons, however, to believe the new Seattle rules will disproportionately affect economically-disadvantaged communities in Seattle. First, the current rules apply only to newly-built apartment buildings over three stories, and not to houses. As Fig. 18 shows, households making less than $50,000 a year represent 29% of residents in apartments constructed since 2010 in Seattle, but only 6% of residents in houses constructed since 2010.

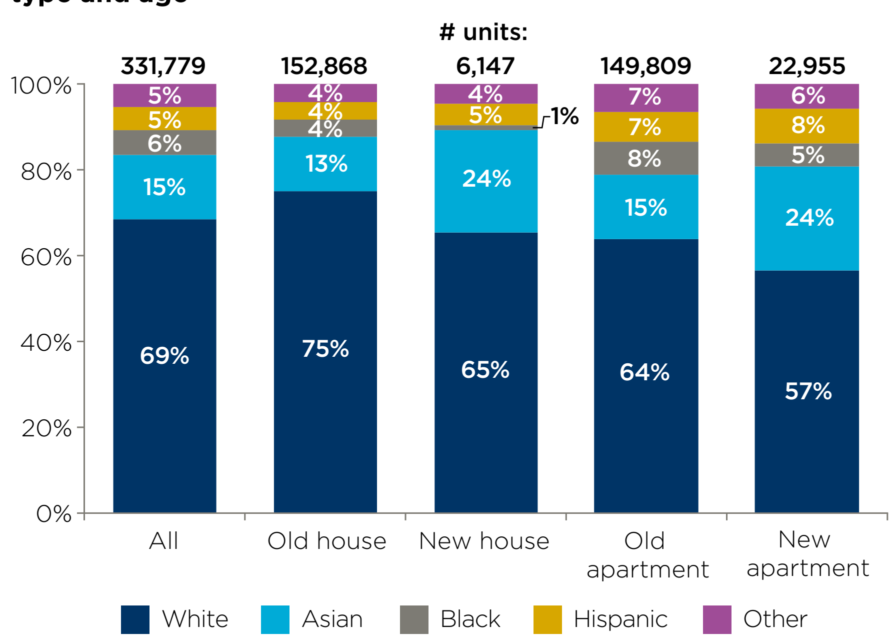
Similarly, 19% of residents in recently constructed apartment buildings are black, Hispanic, or mixed or other race, compared to only 11% of residents in recently constructed houses (Fig. 19). This is not surprising given the strong relationship between race and income, as show in Fig. 20.

Fig 18. Seattle household income ($000s) by housing type and age[50]



Source: 2015-2019 ACS, Oxford Economics

Fig. 19. Race and ethnicity of Seattle householders by housing type and age[51]



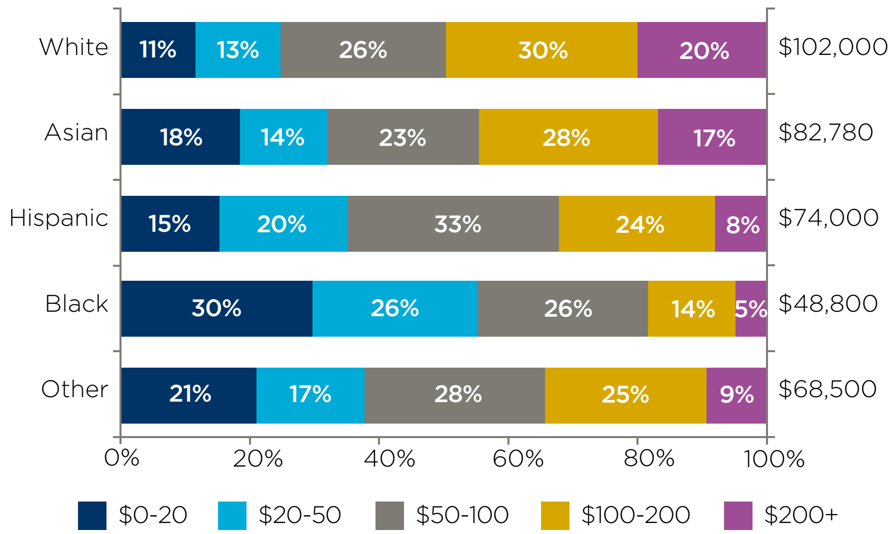
Source: 2015-2019 ACS, Oxford Economics

[50] The "house" category includes single family attached and detached houses as well as small (<10 units) apartment buildings and a very small number of other house types (e.g. mobile homes and house boats); the apartment category includes residences in 10+ unit buildings. Old homes are those constructed through 2010; new homes are those constructed since 2011. The "new apartment" category is constructed to approximate those affected by the new rule.
[51] Hispanic category includes Hispanic householders of all races.

Moreover, costs to low-income households are likely higher than average because these households are the most likely, especially in Seattle's mild climate, to economize on heating through the sparing use of electric resistance heating. (Fig. 21 confirms that lower-income Seattle households are more likely to rely on electric, rather than natural gas heating, which in the Seattle context is mostly electric resistance rather than heat pump.) Forcing households to adopt heat pumps, with their high upfront but relatively lower operating costs, will cost these households the most. For example, while we estimate the average annual cost to affected households of the electrification mandate at $587, the cost to a household with electric resistance heating using only 5 MMBTUs of heat per year is $696, or 1.7% of annual income for a household making $40,000 a year. (See Fig. 11.)

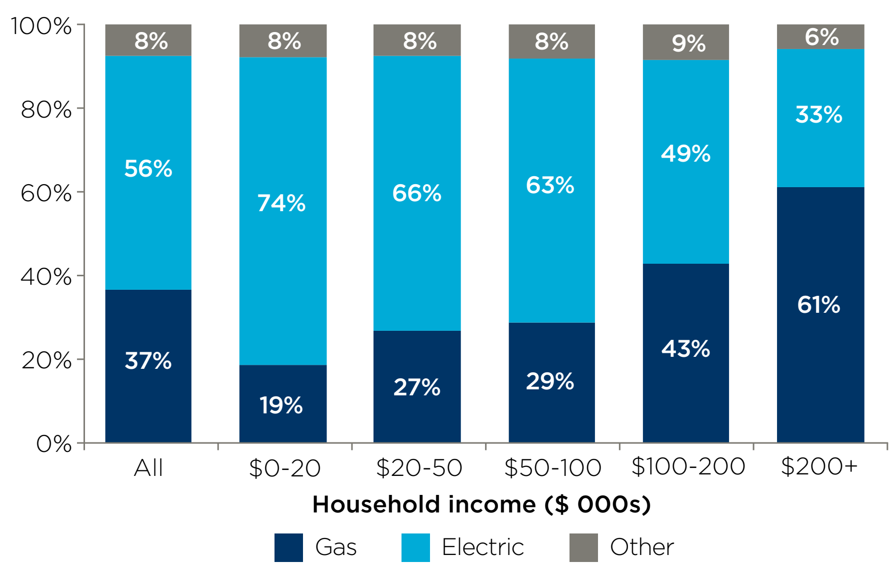
Additionally, as discussed in section 4.4, the cost to a household of the electrification mandate is significantly reduced if the household would have installed central AC anyway. Currently, only about 22% of Seattle households have central AC (see Fig. 5), and it is likely that these households are disproportionately wealthier than households without central AC.

Fig. 20. Household income by race and ethnicity of householders in Seattle



Source: 2015-2019 ACS, Oxford Economics

Fig. 21. Primary heating fuel by household income



Source: 2015-2019 ACS, Oxford Economics

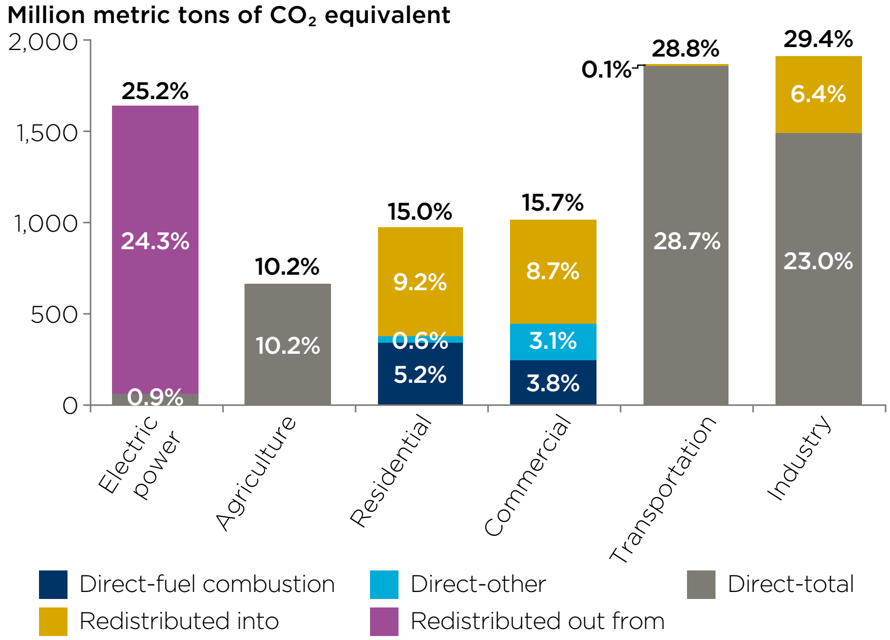
Finally, since the new rules require new large residential construction to install expensive heat pumps, they effectively act as a tax on the construction of new affordable housing. This will tend to push poorer households towards older buildings, or out of the city of Seattle altogether.

6. CARBON IMPLICATIONS

The stated purpose for electrification of building heat is to reduce greenhouse gas (GHG) emissions. Nationally, residential structures account for approximately 15% of GHG emissions, and commercial structures another 16% (see Fig. 22). However, the majority of these emissions (58%) are already from indirect GHG emissions relating to electric power usage, for heating and all other purposes. Another 12% of residential and commercial emissions are from other sources not relating to fuel combustion for heating.[52]

The remainder of the residential and commercial emissions, 9.1% of total national GHG emissions, represents emissions from residential and commercial fuel burning for heat. These are the emissions potentially reducible through heating electrification. Importantly though, as discussed below, they are reducible only to the extent that the carbon intensity of the electric heating replacement is lower than that of the on-site fuel consumption being replaced.

Fig 22. US GHG emissions by source and sector[53]



Source: EPA, EIA, Oxford Economics

Although direct emissions from residential and commercial structures are a relatively small share of total emissions, they have the distinction of being emissions directly addressed by local planning bodies, some of which have adopted extremely aggressive GHG emissions reduction targets. This leads to a situation where marginal GHG emission reductions from structures are being pursued at high cost, while other, more cost-efficient reduction strategies that require higher-level action are underinvested in.[54]

GHG emissions reductions from electrification are highly dependent on the emissions associated with the electrical power sources for the electricity that is replacing the natural gas fuel for heating. The US electric grid is currently far from zero emission, meaning that a transition from burning natural gas on premises for heating to relying on electrical power does not eliminate the GHG emissions associated with space and water heating, but merely—potentially—reduces them.

[52] The largest share of these emissions, entirely in the commercial sector, is from landfills and waste services. A smaller share is from the use of fluorinated gases.

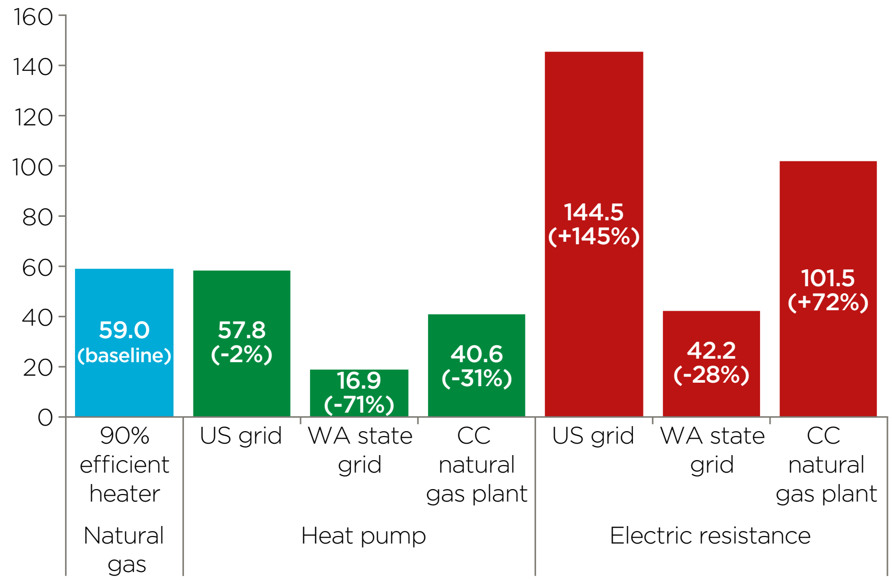
[53] This figure is constructed by combining data from the EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks" (https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks), and the EIA's "Electricity Explained: Use of Electricity" (https://www.eia.gov/energyexplained/electricity/use-of-electricity.php), and was inspired by a similar figure in AGA (July 2018), "Implications of Policy-Driven Residential Electrification: An American Gas Association Study prepared by ICF" (https://www.aga.org/research/reports/implications-of-policy-driven-residential-electrification/).

[54] The AGA study in the previous footnote estimates the following types GHG reduction interventions to be more cost effective than residential electrification: transportation fuel efficiency measures, power sector GHG credits, policy-driven coal generation retirement, renewable natural gas, transportation low-carbon fuel standards, demand side natural gas management, and atmospheric CO2 removal.

Fig. 23 demonstrates this point by comparing the CO_2 emissions associated with burning natural gas for heat with the emissions from electrical heat in a variety of contexts.[55] The energy and carbon content of natural gas are fixed chemical constants, and so emissions from burning natural gas depend only on the efficiency of the furnace or boiler being used. As in our modeling in section 4, we assume a 90% efficient system, which is relatively efficient for residential equipment and relatively inefficient for commercial equipment. Heat pump efficiency falls as the temperature drops, but 250%—again, the same value as our section 4 modeling—is a good average value.

Fig. 23. CO2 emissions per MMBTU of heat output[56]

kg CO_2 per MMBTU of heating (% change from natural gas baseline)



Source: EIA, Oxford Economics

We consider three emissions profiles for electrical power generation:

- The average value for the national grid as a whole;
- The average for Washington state, with its heavy reliance on zero-emission hydroelectric and nuclear power, and;
- The emissions from a new combined cycle natural gas power plant, which represents a significant portion of new generating capacity in much of the US, including the Pacific Northwest, and which is much more efficient than many older fossil fuel plants.

A discussion of the city of Seattle's own power supply is given in section 6.1.

Comparing natural gas to heat pumps, even a shift to the average emissions profile of the national power grid represents a decline in CO_2 emissions, albeit a very small one of 2%. With the emissions profile of the Washington state grid, a shift to heat pumps represents a larger reduction, of 71%. A shift from burning natural gas for heat to a heat pump powered by a combined cycle natural gas power plant represents an emissions reduction of 31%.[57]

[55] GHG emissions from leakage of methane, either from on-site combustion or associated with power generation, or from refrigerant leakages from heat pump or AC systems, are not considered in these estimates.

[56] Data on the overall emissions of the US and Washington state are calculated from 2019 EIA data—see https://www.eia.gov/electricity/state/. Combined cycle natural gas plants are typically 50-60% efficient at converting the chemical energy in natural gas to electric power, a large increase over older fossil fuel power plants, which were typically only around 35% efficient. We assume 55% efficiency for combined cycle plants, as well as 5% energy losses from transmission and distribution, based on EIA data; for the US and WA grid calculations, these losses are already factored into the underlying EIA data used to calculate emissions intensity.

[57] It is instructive to consider the math behind this last calculations. When natural gas is the fuel of choice both for on-site heating as well as electricity generation, the chemical properties of methane cancel out in the comparison, and the relevant factors are the efficiency of local combustion vs. the power plant's efficiency at generating electrical energy and the efficiency multiplier of the heat pump. Using the parameters provided in the text, combined cycle natural gas power plants are able to recover approximately 55% of the chemical energy in natural gas, or about 52% net of grid transmission and distribution losses. With an assumed efficiency of 250%, heat pumps can therefore deliver approximately 131% of the original energy content of the natural gas fuel, as against 90% from burning the fuel on-site. Emissions vary as the reciprocal of efficiency, so an increase from 90% to 131% efficiency represents an emissions reduction of (1/0.9 - 1/1.31) / (1/0.9) = 31%.

A shift from burning natural gas to inefficient electric resistance heating, however, would result in a sizable increase in CO_2 emissions both when assuming the average emissions profile of the national power grid (a 145% emissions increase), and when powered by a new combined cycle natural gas plant (a 72% emissions increase). In the case of the Washington state grid, it represents a moderate reduction in CO_2 emissions of 28%. It deserves repeating that, when heat pumps lose power in cold temperatures, electric resistance heat is the only backup heating method allowed under the new rules (see section 2.1.1).

A report from Energy + Environmental Economics (E3) forecasted a range of future scenarios for the energy supply in the Pacific Northwest between through 2050.[58] They conclude that new natural gas is an essential element of the energy mix to ensure reliable and affordable energy supply for the region. Of the five scenarios analyzed, the worst outcome was the 'no new gas' scenario, with a ban on all new gas electricity generation. According to E3, this offers "the least effective mechanism for addressing greenhouse gas emissions within the region." This is because new combined cycle natural gas plants are far more efficient and lower emission than legacy fossil fuel generation. Since renewable energy sources are inherently unreliable and must be supplemented by other energy sources, disallowing new natural gas generation has the unintended effect of keeping dirtier generation in service longer.

6.1 THE SEATTLE CONTEXT

Seattle's public utility, Seattle City Light, promotes itself as one of the few "carbon-neutral" electric power systems in the nation.[59] The majority of this power—approximately 84% according to Seattle City Light—is from existing hydroelectric dams on the Skagit and Pend Oreille Rivers.

The Puget Sound region's significant hydroelectric infrastructure entails a set of environmental implications that are complex and nuanced, and largely outside the scope of this work. On the one hand, Washington's hydroelectric dams produce clean, cheap energy and facilitate a vast network of efficient river-driven trade and irrigation in the state's farmlands. On the other hand, many environmental groups maintain

[58] Energy + Environmental Economics (December 2017) "Pacific Northwest Low Carbon Scenario Analysis." https://www.ethree.com/wp-content/uploads/2018/01/E3_PGP_GHGReductionStudy_2017-12-15_FINAL.pdf.
[59] See https://www.seattle.gov/city-light/energy-and-environment. According to Seattle City Light, its limited use of non-renewable electricity generation is due to purchases necessary to balance load demands, and legally mandated purchases from the Bonneville Power Administration, a New Deal-era federally owned power utility. These purchases, along with emissions from utility operations, are then offset with purchased carbon credits, making the utility "carbon neutral," but not strictly "zero-emission."

that the presence of the dams damage critical salmon spawning habitats, which in turn diminishes the orca whale population that feed on the salmon. This has led, according to *The Seattle Times*, to the removal of 33 Washington state dams as of 2019.[60]

While additional dam removals are uncertain, it is highly unlikely that the state's hydroelectric infrastructure will expand in coming years. The city of Seattle has essentially laid claim to a fixed resource of renewable power that is therefore unavailable to other localities. While the city surely has the wherewithal to add to this renewable generation capacity—or to purchase offsets to compensate for additional non-renewable sources—to provide for additional power demands from electrification, this alone does not imply that electrification will replace on-site natural gas combustion with carbon free power. Rather, this is only the case if the renewable energy that is added to the Seattle grid would not have been constructed in the absence of electrification.[61] Thus, the carbon emissions profiles presented above—the Washington State electrical grid and new combined cycle natural gas plants, may be more appropriate comparators.[62]

One final point deserves mention. Because the heat pump mandate involves giving air conditioning (which heat pumps inherently provide) to many households that now lack it (the majority of households in Seattle), this will likely increase electricity usage for space cooling in summer months, with consequences for emissions.

[60] Seattle Times (November 8, 2020). "A dam blocking 348 miles of salmon streams hasn't generated electricity since 1958. But who will take it down?" https://www.seattletimes.com/seattle-news/environment/a-dam-blocking-348-miles-of-salmon-streams-hasnt-generated-electricity-since-1958-but-who-will-take-it-down/.

[61] It is not our intent here to undermine the validity of purchased offsets altogether. By purchasing the rights to additional renewable generation, the city increases the demand for such resources, and therefore their price, which both encourages the construction of new renewable resources, as well as encouraging other marginal consumers of renewable power to purchase conventional electricity resources instead. This is a standard supply-demand problem; the point is simply that the effect is not one-for-one, and depends on the elasticities both of the supply of new renewable power and of other renewable power purchasers' demand.

[62] Of course, to the extent that the Seattle electrification mandate will result in heat pumps replacing not natural gas but electric resistance heating—and, as we've seen, a large portion of the existing heating in Seattle is electric resistance—this argument reverses itself, since electric power consumption is reduced, not increased, with this form of "electrification." To the extent that the electricity is considered carbon free to begin with, replacing less efficient electric heating with more efficient electric heating will not reduce emissions.

7. CONCLUSION

The new building code adopted by the Seattle city council in February 2021, although often described as merely "electrifying" building heating by banning new natural gas heat, actually imposes a more specific requirement: the adoption of heat pumps for space heating. To this end, both natural gas heat as well as electric resistance heat—historically a mainstay of space heating in Seattle due to the area's mild winters—are banned as the primary heating in affected buildings (all new commercial construction, as well as new residential construction over three stories).

However, there is an important asymmetry between the new rules' ban on natural gas and their ban on electric resistance. Conventional heat pumps of the kind used in most applications require a backup heat source when the temperature falls below about 30°F.[63] The Seattle rules specifically waive the ban on electric resistance heating when used as backup heat for a heat pump, as well as in a few other specialty applications, but do not do the same for natural gas heat. In effect, the new rules require the use of electric resistance heat on the coldest nights of the year. This creates a concerning vulnerability in the power grid as demand for electricity will spike precisely when new wind and solar electricity generation—necessary to make electrification mandates effective on their own terms at reducing carbon emissions—are at their nadir.

In Seattle, with its mild winters and history of extensive electric resistance heating (along with its abundance of reliable renewable hydroelectricity), this vulnerability may be manageable with modest (though still costly) improvements to the power grid. Colder regions of the country would need more extensive investments in transmission and distribution, as well as in new generation capacity, likely through the addition of modern combined cycle natural gas power plants. It is unclear, however, why such a scheme is desirable when dual fuel heating systems (using heat pumps as the primary heat on warmer days with natural gas rather than electric resistance as the backup) are also a viable option that provides redundancy to local heating in extreme cold temperatures, while avoiding the inefficiencies of electric resistance in locations where backup heat will be used extensively. All that would be required from a policy perspective would be to remove the asymmetry between the bans on natural gas and electric resistance, allowing either to be used as backup heat for a heat pump.[64]

The heat pump mandate in the new rules also imposes **significant costs** on affected households. Given currently prevailing energy prices in the Seattle area, natural gas heat and heat pumps have almost identical costs to operate, but heat pumps have significantly higher upfront costs. Electric resistance heat, by contrast, has very low upfront costs, but high operating costs, making it best suited to situations with low levels of total heat use, such as in the small apartments that are targeted by the new rules.

According to our estimates, the new rules will cost affected households an average of $587 annually in equipment and fuel costs. For households that would have used natural gas prior to the new rules, this value is a little lower ($531 annually) and largely independent of the amount of heat used. For households that would have used electric resistance, this value is a little higher on average ($596 annually), but highly dependent on the amount of heat the household uses, up to nearly $800 annually for households that use almost no heat.[65]

[63] The exceptions to this are ground source heat pumps, which are very expensive to install and not suitable for dense urban settings, and cold climate heat pumps, relatively new and uncertain technology that pushes the temperature limits of heat pumps lower, but also at significant cost and with uncertainties over safety and reliability that make them not yet suitable for widescale use.

[64] Given the slightly higher operating costs that we found for heat pumps relative to natural gas, one might be concerned that households would simply use their "backup" natural gas heat instead of their heat pump at all times. However, these slightly higher operating costs represent an average value over a range of temperatures, with heat pump efficiencies falling as temperatures do. At warmer temperatures, heat pumps are distinctly more efficient than natural gas, and households with dual fuel systems would be properly incentivized to rely on their heat pumps in warmer weather and switch to natural gas only when the temperature falls.

[65] These cost estimates are generally higher than those in previous literature in part because (owing to the Seattle context), we do not assume all non-heat pump households install central AC, and in part because we explicitly account for shorter lifespans and higher maintenance costs of heat pumps

At the aggregate level, costs are substantial for the city as a whole. We estimate:

- The annual costs of the new rules on residential construction to be $2.0 million per year of new construction.
- After 15 years of new construction, those costs will have reached $30.5 million annually.
- Analogous costs for the mandate imposed on all new commercial construction are estimated at about $19 million annually after 15 years of new construction.

The cost to retrofit all existing Seattle residences would be much larger: approximately $245 million on an annualized basis for residential buildings, with commercial costs estimated at $110 million annually.

These costs would hit low-income Seattleites the hardest for a number of reasons. First, even fixing the value of the costs, the burden as a share of income is larger for these households. But the costs are also largest for those households using electric resistance heat and economizing on their amount of heat use, which low-income households are more likely to do. To the extent that these costs are offset by the "free gift" of AC that heat pumps provide, low-income households are also the least likely to be willing to make that trade.

The effect of the new rules on **water heating** is more uncertain, as the cost advantage of natural gas water heaters over heat pump water heaters is more modest. In the case of water heating, however, unlike for space heating, the new rules continue to allow electric resistance heaters. Although our cost modeling suggests most households would do best to select a heat pump water heater over electric resistance, the relatively low market penetration of heat pump water heaters to date suggests that other obstacles may remain to their widespread adoption. If this is the case, the new rules may have the undesired effect of pushing hot water users towards inefficient and expensive electric resistance.

The stated purpose of the new Seattle rules, like similar electrification efforts elsewhere, is to reduce carbon emissions. However, replacing natural gas heat with heat pumps does not eliminate CO_2 emissions unless the new electric generation needed to power those heat pumps comes entirely from carbon free sources like wind and solar. When natural gas heat is compared to heat pumps powered by electricity with the average emissions profile of the US electric grid as a whole, the reduction in carbon emissions is trivial (2%). When they are powered by modern combined cycle natural gas power plants—the marginal generating capacity in many parts of the US—the reductions are real but modest, an approximately 31% reduction, achieved at high costs. However, when natural gas heat is replaced by electric resistance heat—such as when it is used as backup heating for heat pumps in cold temperatures—overall carbon emissions rise by 72% when the electricity is provided by a combined cycle natural gas plant, and by 145% when benchmarked to the average emissions of the US power grid as a whole.

APPENDIX: KEY ASSUMPTIONS

RESIDENTIAL CONSTRUCTION ASSUMPTIONS

The numerical assumptions for the number of housing units affected under the three scenarios are presented in Fig. A-1 below. The root assumptions are that the number of new units per year is 6,000, and that the shares of houses, apartments in small buildings, and apartments in large buildings; and of gas and electric heat, are distributed proportionally to the ACS data presented in Fig. 8 of the main text. A total of 10% of each housing type is assumed to already use heat pump heating in the case of existing housing, or to have chosen a heat pump in the absence of the new rules in the case of new housing, based on the data presented in Fig. 6. These units are all taken from the electric resistance share.

Fig. A-1. Modeling assumptions for number of units

		Heat pump	Electric resistance	Gas	Total
Annual construction	Houses	167	549	957	1,673
	<4 story apartments	48	345	89	482
	4+ story apartments	384	2,987	473	3,845
	Total	600	3,881	1,519	6,000
Total housing stock	Houses	15,901	32,445	110,668	159,015
	<4 story apartments	6,275	46,225	10,252	62,752
	4+ story apartments	11,001	84,783	14,228	110,012
	Total	33,178	163,454	135,148	331,779

Scenario 1: Affected by current Seattle rules (also part of Scenario 2)

Scenario 2: Affected by rules applying to all new construction.

Scenario 3: Affected by rules requiring retrofit of all residential buildings

EQUIPMENT ASSUMPTIONS

As referenced in the text, our primary data source for equipment assumptions is equipment profiles from the EIA, which we supplement with recent price data from Homewyse. In addition, we received input from Seattle-based HVAC professionals.

Below, we document the precise values used to derive the cost profiles of the three types of heating presented in Fig. 11. As we discuss in the text, the values here are an amalgamation of both residential and commercial equipment, and we accept that they do not perfectly reflect either. Rather, they are intended to capture the key economic tradeoffs between these three types of equipment. Information on central AC is also provided for the analysis presented in section 4.4.

Fig. A-2. Assumptions for space heating equipment

	Natural gas	Electric resistance	Heat pump	Central AC
Equipment costs				
Appliance cost	$2,000	$400	$4,000	$3,000
Installation cost	$1,000	$600	$2,500	$2,000
Distribution system cost	$2,000		$2,000	
Total upfront cost	$5,000	$1,000	$8,500	$5,000
Equipment lifespan (years)	25	30	15	20
Distribution system lifespan (years)	30		30	
Annual maintenance	$50	$0	$200	$100
Operating costs				
Operating efficiency	90%	100%	250%	
Fuel costs per MMBTU input	$11.25	$33.33	$33.33	
Cost per MMBTU heat output	$12.50	$33.33	$13.33	

Fig. A-3 similarly presents the assumptions behind the water heating equipment used to derive the cost profiles in Fig. 17.

Fig. A-3. Assumptions for water heating equipment

	Natural gas	Electric resistance	Heat pump
Equipment costs			
Appliance cost	$800	800	$1,500
Installation cost	$800	1,100	$1,100
Total upfront cost	$1,600	$1,900	$2,600
Lifespan (years)	12	12	12
Annual maintenance	$0	$0	$20
Operating costs			
Operating efficiency	70%	93%	330%
Fuel costs (original units)	$1.12 / therm	$0.113 / kWh	$0.113 / kWh
Fuel costs per MMBTU input	$11.25	$33.33	$33.33
Cost per MMBTU heat output	$16.07	$35.84	$10.10

Source: Oxford Economics

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