Efficient Appliances for People & the Planet

3H ‘Hybrid Heat Homes’

An Incentive Program to Electrify Space Heating and Reduce Energy Bills in American Homes

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Executive Summary

The way we heat and cool American homes is on the verge of a revolution. The latest generation of electric heat pump products can deliver lower energy bills, cleaner air, and more comfortable homes in nearly every corner of the country. Heat pumps are unique because they can provide both cooling in the summer and heating in the winter, in each case delivering high performance with up to four times better energy efficiency than traditional equipment. Yet every day in America some 16,000 traditional one-way central AC units are installed instead of two-way heat pumps, locking in outdated infrastructure for 15 years or more. In each home that is equipped with a one-way AC, the homeowner has no choice but to continue to burn polluting fossil fuel or operate inefficient electric resistance heat for all their heating needs.

We propose to quickly and cost-effectively shift the entire US supply of unitary central ACs into heat pumps within the next decade through a '3H' Hybrid Heat Homes program. The 3H program aims to maximize the speed and scale of heat pump technology deployment in U.S. homes at the least cost and with the fewest barriers to market adoption. To accomplish this, we target the biggest segment of the residential market (unitary central AC equipment) and take a conservative and pragmatic approach to technology transitions (by installing drop-in replacement equipment at the time of AC failure), fuel switching (by leaving existing heating equipment in place), energy efficiency (by aiming for a modest SEER 15 heat pump efficiency level equivalent to the 2023 minimum standard), and heat pump usage (by assuming a heat pump low temperature cutoff of 41°F (5°C)).

> **The '3H' Hybrid Heat Homes program aims to maximize the speed and scale of heat pump technology deployment in U.S. homes at the least cost and with the fewest barriers to market adoption.**

The 3H program is centered around a targeted, temporary Federal subsidy beginning in 2022 with a regulatory backstop to take effect in 2029. We estimate that a payment to manufacturers or distributors, starting at $400 to $500 per unit and declining by $60 to $75 each year, would be sufficient to convert all new central ACs to heat pumps at a cost between $3 and $12 billion over the 4 to 7 year program period, and would lead to the deployment of 45 million new heat pumps.

We project that over the first ten years of the program, American consumers would save more than $27 billion on their heating and cooling bills. Over that same period, we estimate that lower air pollution would lead to $80 billion or more in additional societal benefits. The average participating household's energy bills will decrease by $169 per year. In 2032 alone, greenhouse gas emissions will be reduced by up to 49 million tons of CO_2e, and cleaner air will result in 888 fewer premature deaths, 920 fewer emergency room visits, 1,029 fewer nonfatal heart attacks, 24,476 fewer asthma exacerbations, 36,953 fewer respiratory and acute bronchitis incidents, 571,034 fewer minor restricted activity days, and 97,906 fewer lost workdays.

While the 3H program does not aim to achieve full electrification of residential space heating, by deploying 45 million new electric heating systems it aims to "raise the floor" in the residential HVAC market and pave the way for state or local programs that wish to push further towards electrification, either now or in the future.

Introduction

Targeted Federal incentives for residential heat pumps can save Americans more than $27 billion on their energy bills and deliver $80 billion in additional benefits over 10 years

Heating and cooling together are responsible for the majority (51%) of household energy use and a large share (40%) of energy bills. These sectors have long been dominated by inefficient equipment such as gas and electric resistance furnaces and air conditioners (ACs) which account for more than 80% of products in use (US Energy Information Administration 2018a,b,c; US Department of Energy 2016b, pp. 10–5 to 10–11). Today, however, the way we heat and cool American homes is on the verge of a revolution. The latest generation of electric heat pump products can deliver lower energy bills, cleaner air, and more comfortable homes than legacy equipment, in nearly every corner of the country.

Heat pumps are unique among home heating, ventilation, and air conditioning (HVAC) equipment products because they can provide both cooling in the summer and heating in the winter, in each case delivering high performance with up to four times better energy efficiency than traditional heating equipment.[1] In the vast majority of American homes a single high-tech heat pump system can successfully replace not just the AC but in many cases also the existing home heating equipment. The basic technology has been around for decades — in fact every AC and refrigerator in use today uses a heat pump to generate cooling. In the context of home HVAC equipment, a heat pump is essentially a "reversible" or "two-way" air conditioner.

The deployment of heat pump products in the US has been fairly slow; though more than 3 million heat pumps are sold each year, sales of one-way ACs are far greater at more than 5 million units per year. This slow pace comes at a heavy price: **every day in America some 16,000 one-way central AC units are installed instead of two-way heat pumps, locking in outdated infrastructure for 15 years or more.** In each home that is equipped with a one-way AC, the homeowner has no choice but to continue to burn polluting fossil fuel or operate inefficient electric resistance heat for all their heating needs. Why install a traditional one-way AC when a two-way heat pump can deliver superior performance and flexibility for nearly the same price?

To solve this problem, we propose that the Federal government deploy a targeted, temporary subsidy to help the country get over the deployment hump. **We estimate that a payment to manufacturers or distributors, starting at $400 to $500 per unit and declining by $60 to $75 each year, would be sufficient to convert all new central ACs to heat pumps at a cost between $3 and $12 billion over the 4 to 7 year program period.** Manufacturers or wholesalers would receive a payment for each heat pump sold, conditional on permanently converting their entire future supply of central ACs to heat pumps.

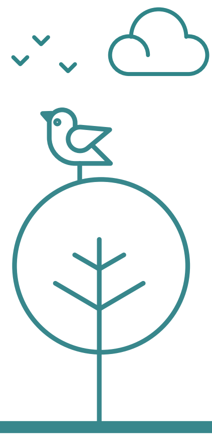
1. This is in terms of site efficiency. There are similar inefficiencies when converting fossil fuels to electricity, but these are decreasing as the electricity grid decarbonizes.

The average participating household's energy bills will decrease by

$169 per year

In 2032 alone, greenhouse gas emissions will be reduced by up to

49M tons of CO_2e



Annually, by 2032

Cleaner air will result in

888 fewer **premature deaths**

920 fewer **emergency room visits**

1,029 fewer **nonfatal heart attacks**

24,476 fewer **asthma exacerbations**

36,953 fewer **respiratory and acute bronchitis incidents**

97,906 fewer **lost workdays**

571,034 fewer **minor restricted activity days**

We project that over the first ten years of the program, consumers would save more than $27 billion on their heating and cooling bills. Over that same period, we estimate that lower air pollution would lead to $80 billion or more in additional societal benefits. The average participating household's energy bills will decrease by $169 per year. In 2032 alone, greenhouse gas emissions will be reduced[2] by up to 49 million tons of CO_2e, and cleaner air will result in 888 fewer premature deaths, 920 fewer emergency room visits, 1,029 fewer nonfatal heart attacks, 24,476 fewer asthma exacerbations, 36,953 fewer respiratory and acute bronchitis incidents, 571,034 fewer minor restricted activity days, and 97,906 fewer lost workdays.

From a manufacturer's perspective, the changes driven by this program will be modest: most AC models already have a heat pump version. The difference of only a few hundred dollars in component costs will be covered by the subsidy, and consolidation of product lines may lead to additional benefits in terms of reduced complexity in production, distribution, training, sales, and marketing.

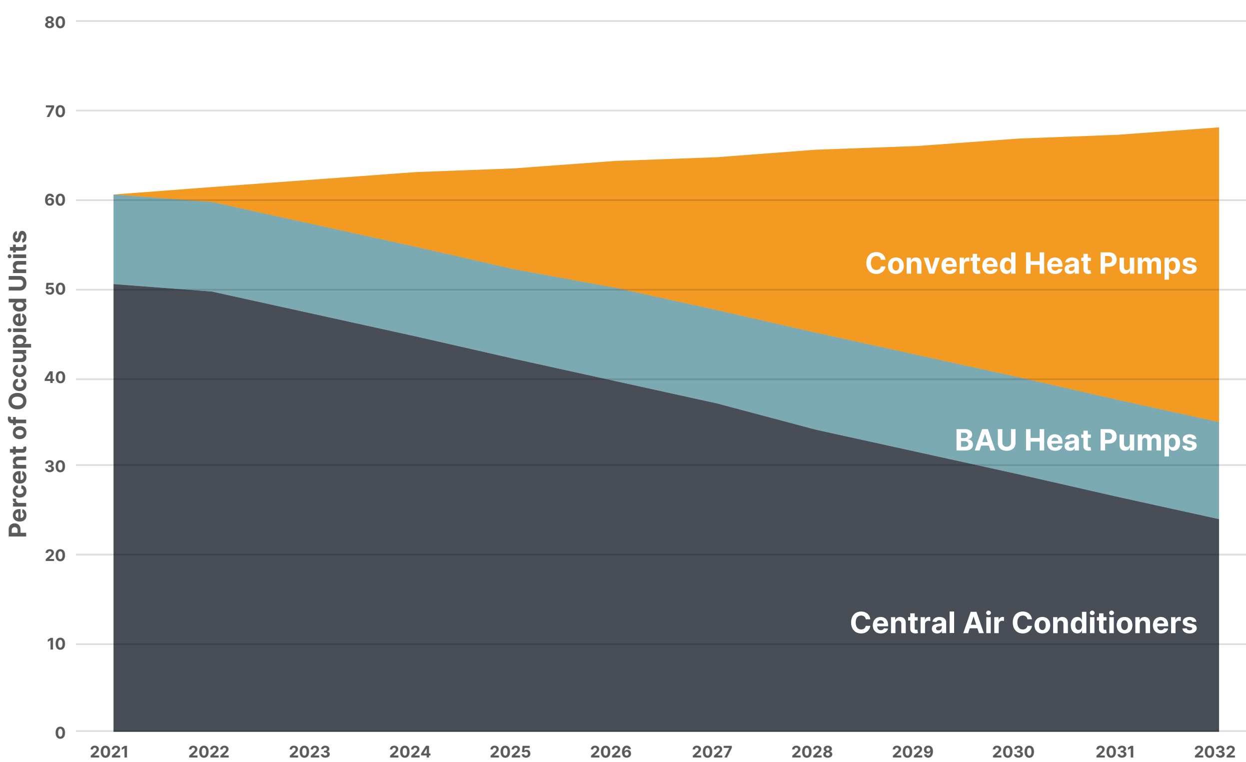
2. CO_2 reductions were calculated using a heating electrification model developed at Columbia University (Waite and Modi 2020a). We conservatively assume a 15 SEER/8.5 HSPF heat pump (non-cold climate) and backup fossil fuel (if present) switchover at 41°F (5°C); lower 48 states and DC. Reported results are under current average CO_2 equivalent emissions rate of 401 kg/MWh (US Environmental Protection Agency 2021a). (Under a "Low Renewable Energy Cost" scenario with an average CO_2 emissions rate of 192 kg/MWh (National Renewable Energy Laboratory 2020) savings are roughly equivalent at 45 million tons due to higher savings from offset gas use (+8 million tons), but lower savings from offset electric resistance (-12 million tons).

From a homeowner's perspective, at the time of AC replacement a new clean and efficient heating system will be delivered at little to no additional up-front cost, requiring no major renovations or electric panel modifications. In summertime the new heat pump will function the same as their previously installed AC, and when cold weather arrives they will have the choice to heat with either their new heat pump or their existing furnace by changing settings on their thermostat.

This program will dramatically shift the trajectory of the residential HVAC market to a place where one-way ACs are no longer available. Once production has shifted fully to heat pumps, every time a new home is built or an existing home is retrofitted, it will receive a modern high-performance HVAC system. **Based on the historical rate of HVAC replacements, this will increase the projected total share of new and existing homes with heat pumps from 11% to 44% by 2032 — a total of 45 million additional installations over a 10 year period** (Figure 1).

We have a tremendous and immediate opportunity to accelerate the transformation of home heating and cooling in America to more efficient electric alternatives. This opportunity is only possible because the price difference between heat pumps and air conditioners is small enough that a temporary subsidy can move the whole supply chain. But these benefits will only come if we act quickly.

FIGURE 1: HEAT PUMP STOCK PROJECTIONS



What is a Heat Pump?

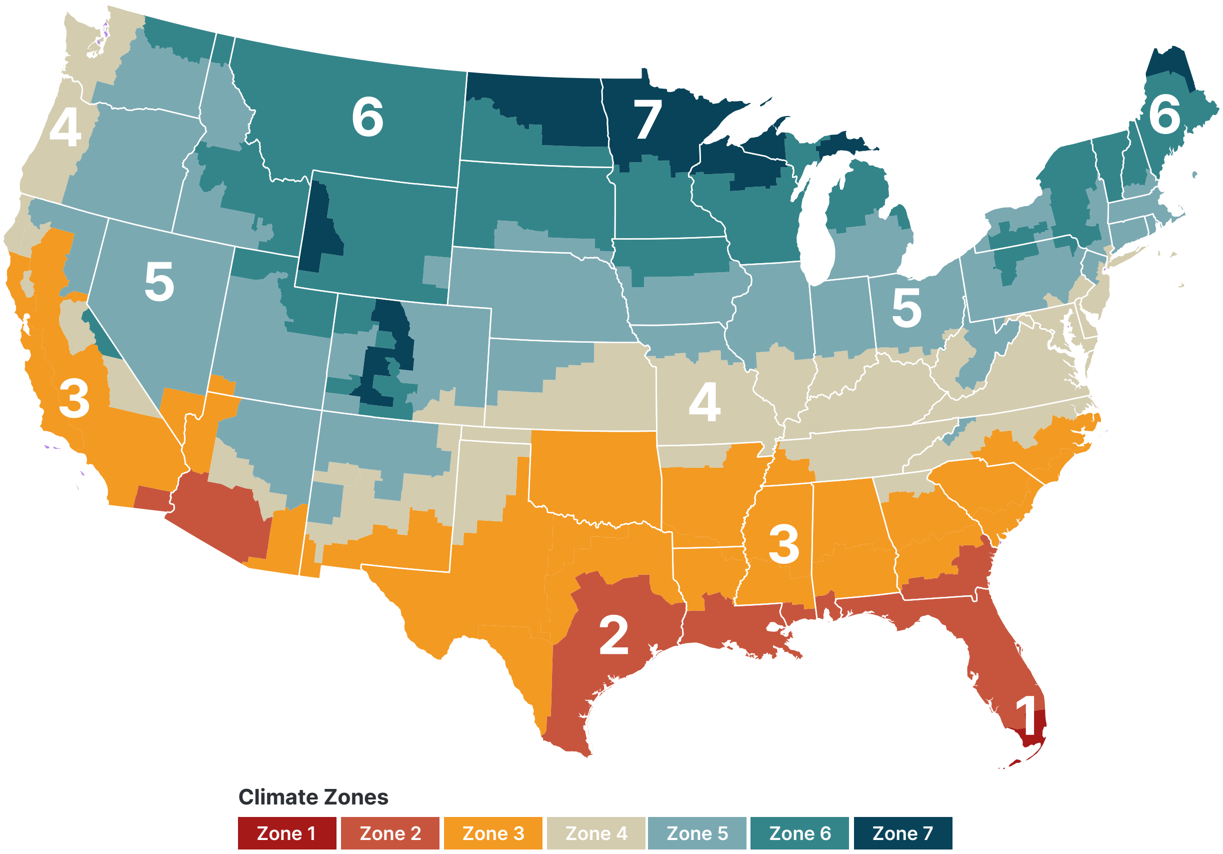
Heat pumps are essentially air conditioners that can heat as well as cool. Because heat pumps move heat from one place to another rather than actually creating heat, even basic models are 3 to 4 times more efficient than combustion or electric resistance systems that generate heat directly. Variable speed heat pumps are the most efficient, followed by dual-stage and single-speed. As the proportion of electricity generated from renewable sources increases, heat pumps will also reduce CO_2 emissions.

Heat pumps come in two main varieties: air source (ASHP) and ground source (GSHP). ASHPs exchange heat with the surrounding air, are more common, much less expensive than GSHPs, and are easier to sell, design, and install. GSHPs are more complex to install, since they exchange heat with underground pipes, but are generally more energy efficient. If a home has existing ductwork (using central AC for cooling and a furnace for heating), the AC can be replaced with a unitary heat pump. If a home does not have ductwork, or if a room requires a dedicated supplemental HVAC system, ductless mini-split heat pumps are often the preferred solution.

Heat pumps are already commonplace in some parts of the country. Most of the 3 million unitary heat pumps sold annually can be found in the South and Southeast US, though there are also growing markets in places like New York, New England, and the Pacific Northwest thanks to state- and utility-sponsored efficiency and electrification programs.

Heat pumps come in a range of sizes that can meet the heating needs of nearly every building. Depending on the local climate and the energy

FIGURE 2: INTERNATIONAL ENERGY CONSERVATION CODE (IECC) CLIMATE REGIONS



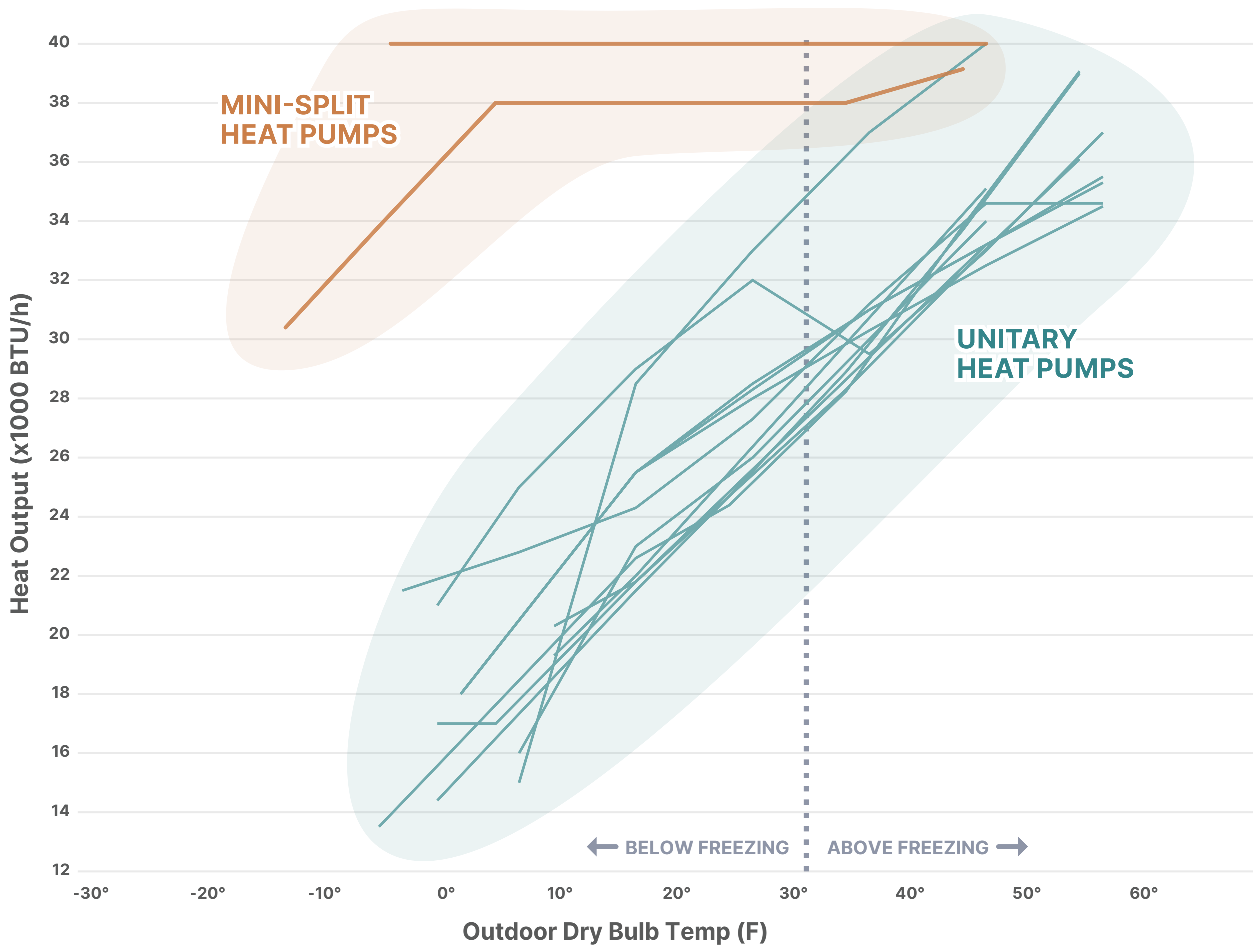
performance of the house, a backup heat supply may be needed on the coldest days. The backup heat supply can be an existing furnace (left in place when the AC is upgraded) or an electric resistance heater incorporated into the new heat pump.

Historically, heat pumps were only economical in warm climate zones with low to moderate heating needs. Recent technological developments mean they can now work efficiently in all parts of the United States (McKenna et al. 2020). Higher-efficiency variable speed heat pumps have been shown to deliver better cold-climate performance, greater energy savings, and greater levels of control and improved comfort (EERE 2017).

Figure 3 displays the heat output as a function of outdoor temperature for a variety of heat pump models on the market today. The latest generation of variable-speed ASHPs work well at outdoor temperatures as low as -15°F, so they are suitable for use in Climate Zone 5 and some of Climate Zone 6 (see Figure 2). In addition, all models that meet the latest ENERGY STAR specification provide at least 70% of their rated capacity down to 5°F (U.S. Environmental Protection Agency 2021b). This means that even in northern states, heat pumps can cost-effectively displace a traditional furnace on all but the coldest days (Waite and Modi 2020a).

However, as shown in this analysis even single-speed heat pumps, when combined with a fossil fuel furnace for backup, can dramatically reduce the demand for fossil fuels for home heating, leading to big cuts in air pollution.

FIGURE 3: 3-TON HEAT PUMP OUTPUT VS. OUTDOOR TEMPERATURE



MINI-SPLIT HEAT PUMPS: Daikin RZQ36 + FTQ36, Mitsubishi PUZHA36 + PVAA36

UNITARY HEAT PUMPS: Carrier VNA036, Carrier VNA836, Carrier VNA837, Trane 18 4TWV8036A, Trane 18 4TWV8037A, Trane 20 4TWV0036A, Bosch 36 AHU + BOVA 36, Goodman GSZC180361C, York YZE03611, Armstrong (Lennox) 4SHP20LX36, Armstrong (Lennox) 4SHP16LS36

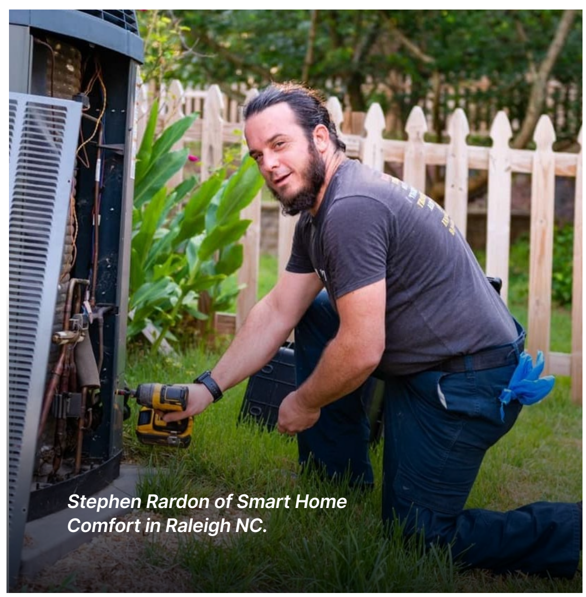
The Problem

Despite their benefits, heat pumps are unlikely to reach 100% market share on their own.

Despite the benefits of heat pump technology, factors such as the modest price differential between heat pumps and ACs, lack of product availability in some regions, low consumer and installer familiarity with the latest cold-climate products, inertia to retain incumbent technology, and competing financial incentives for new gas line connections and gas appliances mean that heat pumps are unlikely to reach 100% market share on their own.[3]

> **The challenge of accelerating heat pump adoption is particularly acute in existing buildings where cooling service is provided by a one-way central AC. It is estimated that 85% of HVAC system replacements are done on an emergency basis, and when the AC fails homeowners frequently choose another one-way AC, since it is often the most accessible and affordable replacement option**

The challenge of accelerating heat pump adoption is particularly acute in existing buildings where cooling service is provided by a one-way central AC. It is estimated that 85% of HVAC system replacements are done on an emergency basis, and when the AC fails in one of these homes — typically at the peak of summer — homeowners frequently choose the most accessible and affordable replacement option. When heat pumps are either unavailable or substantially more expensive, the consumer often defaults to a like-for-like replacement of their traditional AC system, even if it means higher energy bills in the future. This perpetuates a two-track market in which heat pumps and ACs remain locked in competition.



Stephen Rardon of Smart Home Comfort in Raleigh NC.

3. Based on AEO (2021) projections, without intervention the future stock of heat pumps as a share of combined air conditioners and heat pumps will not exceed 17%.

The ‘3H’ Solution

The goal of the ‘hybrid heat homes’ (3H) program is to maximize the speed and scale of heat pump technology deployment in U.S. homes at the least cost and with the fewest barriers to market adoption.

In a 3H, occupants will be able to use their heat pumps as the primary source of both cooling and heating but will retain their existing furnace to provide backup heat on the coldest days.[4] Since a heat pump is no different than an AC in the summer, from the perspective of the occupant there will be no change in equipment or energy service during the cooling season. Yet in the winter months the occupant will now have the option to use their energy efficient heat pump to provide some or all heating in place of their dirty furnace. Homes with existing electric resistance furnaces will see even greater energy bill reductions from heat pumps, which will deliver the same amount of heating for less than half the operating cost.

The goal of the 3H program is to maximize the speed and scale of heat pump technology deployment in U.S. homes at the least cost and with the fewest barriers to market adoption. To accomplish this, the 3H program aims for the biggest segment of the residential market (unitary central AC equipment) and takes a conservative and pragmatic approach to technology transitions (by installing drop-in replacement equipment at the time of AC failure), fuel switching (by leaving existing heating equipment in place), energy efficiency (by aiming for a modest SEER 15 heat pump efficiency level equivalent to the 2023 minimum standard), and heat pump usage (by assuming a heat pump low temperature cutoff of 41°F [5°C]).

The 3H program does not aim to achieve full electrification of residential space heating; rather by deploying 45 million new electric heating systems it aims to “raise the floor” in the residential HVAC market and pave the way for state or local programs that wish to push further towards electrification, either now or in the future. The proposed hybrid heat approach will also provide some flexibility on the path to power sector decarbonization by minimizing new heating peak loads that would otherwise have to be met with high-emissions fossil generation.

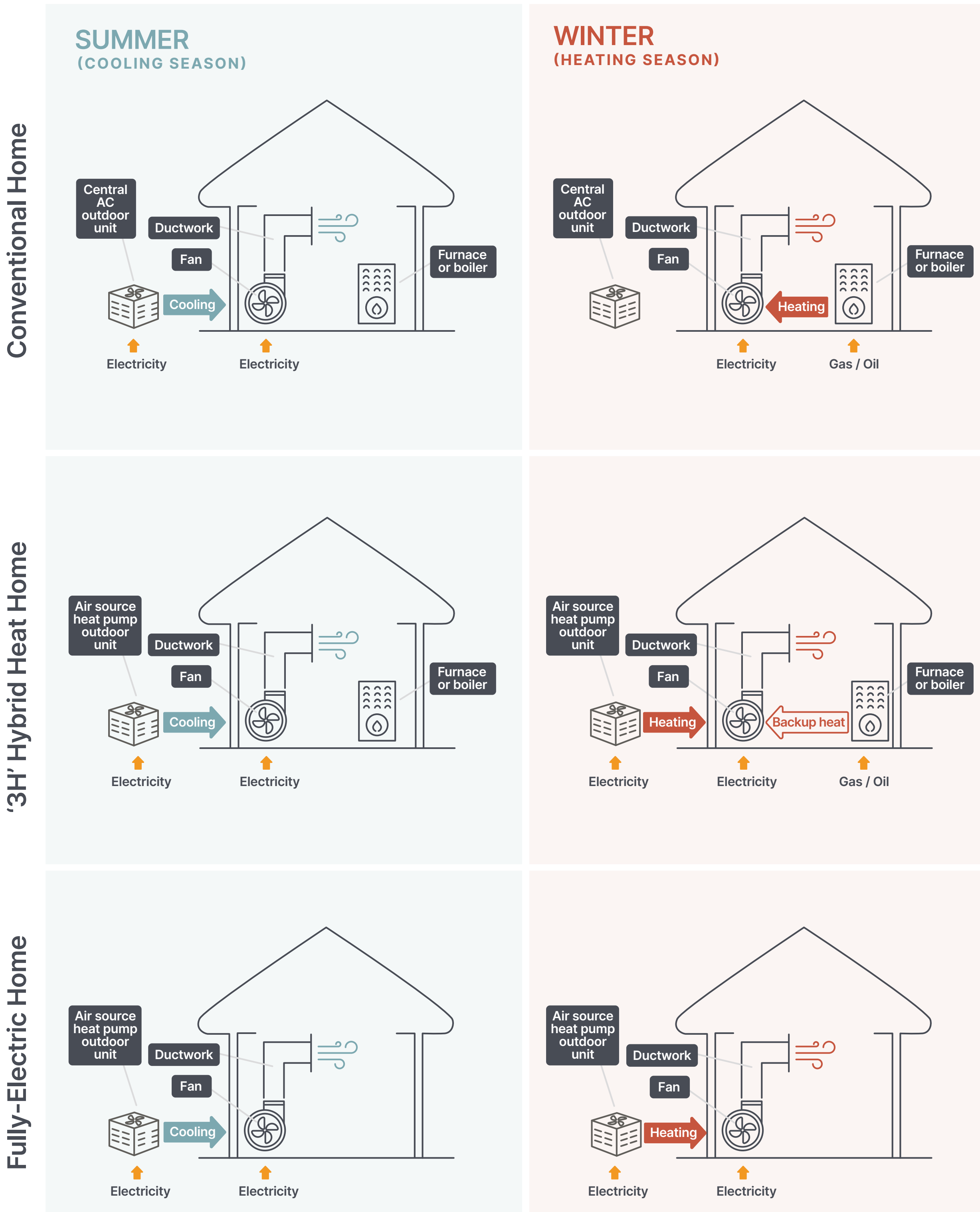
Much like a hybrid electric vehicle that uses electric motors to offset a portion of its internal combustion engine use — a technical solution that has even made its way into Ford’s iconic F-150 pickup truck, whose 2021 hybrid offers better performance and fuel efficiency than its conventional siblings[5] — **a 3H can offset on average 39% of a home’s fossil fuel use for heating, improve comfort,[6] and save consumers money on their home energy bills**. A 3H is also a stepping-stone to an all-electric home, much the same way early hybrid-electric vehicles like

4. Home heating systems that couple a heat pump with a gas furnace are sometimes referred to as “dual-fuel systems.” We coin the term ‘3H’ here, but the concepts are equivalent.

5. https://www.ford.com/trucks/f150/models/

6. Heat pumps will generally be sized smaller than furnaces, and will thus provide more gradual and consistent heating to a conditioned space, reducing temperature ramps and improving occupant thermal perceptions (Bean p. 63.).

FIGURE 4: EVOLUTION OF HOME HEATING SYSTEMS



the Toyota Prius prepared the market for the first all-electric Tesla. As consumers become more familiar with their heat pumps and the benefits they deliver, they are likely to offset more and more of their fossil fuel use and may someday decommission their furnace entirely.

Homeowners and occupants who receive a heat pump through the 3H program will reap additional benefits in the years to come. For example, after a heat pump is installed the home will have redundant heating equipment, so when the furnace eventually fails there will be less urgency and opportunity to improve the efficiency of the backup furnace or transition to 100% heat pump use. 3H beneficiaries will also have the ability to arbitrage between energy prices; if gas prices spike or the local electric utility offers better rates in the future, the heat pump can be used to carry a greater portion of the heating load, further reducing energy bills.

Every home with central AC should be a hybrid heat home (3H) or all-electric home instead. The 3H program would ensure this outcome.

EVERYONE BENEFITS FROM ACCELERATED DEPLOYMENT

The longer we remain in a two-track market where ACs and heat pumps are in direct competition, costs and complexity will be unnecessarily high for manufacturers, distributors, installers, and consumers.

For **manufacturers**, the two-track market slows the transition to heat pumps. We conservatively estimate that heat pumps cost on average about $400[7] more to produce than a comparable central air conditioner, mostly because of the cost of additional components such as a reversing valve and defrost board. We surveyed available data on commercially available products and found that most of the unitary AC products on the market today have a heat pump version, with a wholesale price difference of about $200 to $500 depending on cooling capacity and efficiency.

Based on interviews with industry participants, we found that these costs are likely to come down if manufacturers fully commit their production lines and research divisions to focus on heat pumps. Several HVAC manufacturers are already focused on innovating with heat pumps, yet firms are reluctant to make the move alone because of the risk that they will be undercut on price by competitors producing one-way ACs. This collective action problem slows the technological development that will eventually bring down heat pump prices. The 3H program will offset the cost of manufacturing line upgrades, training, and additional components. It will accelerate technological learning and cost reductions for high-efficiency heat pump technology and pave the way for easier compliance with future appliance standards.

For **distributors**, the two-track market means higher inventory costs. Having to stock both central ACs and heat pumps requires more warehouse space and more complicated logistics. In places where heat pumps have not gained a foothold in the market, some supply houses end up with only a limited selection of heat pump models. This lack of stock is a big problem because most replacement installations are done on an emergency basis. In a crisis, even if a customer wants an efficient heat pump they may not be willing or able to wait days or weeks for the right equipment to be delivered. As with manufacturers, supply houses cannot unilaterally switch to heat pumps if competitors are still supplying one-way ACs.

For **installers**, the two-track market means higher ongoing training costs and lower customer satisfaction. As with any HVAC product, poor installation risks sacrificing the promised efficiency benefits, and proper installation requires specific training. It can be costly to retrain people when heat pumps only represent a small fraction of the market. This program will help bring the price of mass-market heat pumps closer to parity with mass-market ACs, improving the value, comfort, and satisfaction provided to customers, and it will build awareness and confidence in heat pump technology. Furthermore, keeping existing furnaces in place as a backup heating source will lessen short-term impacts on installers during the transition to electric heating.

7. In 2015, DOE found a $131 difference for a 3-ton 15 SEER heat pump versus an equivalent air conditioner, which equals $145 in 2020 dollars (US Department of Energy 2016b, pp. 5-21, 5-23). This suggests that a subsidy of less than $400 could be effective. A reduced subsidy would decrease the costs of the program proportionally.

For **consumers**, the two-track market means that many end up buying obsolete technology, sacrificing value, comfort, flexibility, and satisfaction. HVAC equipment purchases are few and far between for most homeowners, so there is substantial lag time between technological development and consumer awareness. This program will deliver benefits to all centrally-cooled American homes, including ones where renters would otherwise be saddled with low-efficiency heating systems due to split incentives, whereby landlords do not pay energy bills and are therefore not compelled to invest in energy efficient appliances. As the carbon intensity of grid electricity declines, it will ensure lower-pollution heating in homes across the country. As people experience the comfort and energy bill savings offered by their heat pump, there is potential for word-of-mouth to drive uptake even faster, and for customers to further decrease their furnace use. Finally, when the backup furnace in a 3H home is in need of replacement in the future, homeowners will have the choice to downsize or eliminate their fossil fuel heating system entirely, saving even more money.

> We propose a policy package to eliminate the ongoing lock-in of one-way conventional central ACs: a targeted, temporary, conditional incentive beginning in 2022 with a regulatory backstop to take effect in 2029. This policy package is intended to quickly and cost-effectively shift the entire US supply of unitary central ACs into heat pumps within the next decade.

PROGRAM DESIGN

We propose a policy package to eliminate the ongoing lock-in of one-way conventional central ACs: a targeted, temporary, conditional incentive beginning in 2022 with a regulatory backstop to take effect in 2029. This policy package is intended to quickly and cost-effectively shift the entire US supply of unitary central ACs into heat pumps within the next decade.

The proposed program aims to convert the market for central AC replacements and new installations (versus targeting proactive retrofits, or furnace replacements) because it provides low transaction costs and delivers substantial stock turnover during the 4 to 7 year program period. **Central ACs represent the greatest market share among cooling products in the US. The heat pumps that would be eligible for the incentive are essentially drop-in replacements for central AC products; they look the same and are installed in essentially the same way.**[8] We have excluded mini-split and window AC units from this proposal because of their comparatively small market share, and the fact that almost all mini-splits are already reversible heat pumps.

The 3H program would begin by providing a $400 to $500 incentive for every unitary, whole-home ducted heat pump[9] sold in the US by participating manufacturers. The incentive would cover the additional cost of manufacturing a heat pump instead of a traditional central AC unit. The incentive could be delivered as a cash payment, or potentially as some form of tax adjustment, and it could either be targeted upstream at manufacturers or mid-stream at distributors.

8. Heat pumps have essentially the same install process ACs, so the process will be familiar to all installing technicians. Most installs will only take 10-30 minutes longer due to the need to change thermostat settings.

9. For simplicity we refer to "unitary, whole-home ducted heat pumps" as "heat pumps" in the remainder of this paper.

This incentive would be conditional: to qualify recipients would be required to stop producing and stocking one-way ACs and move to heat pumps. If the program targets manufacturers, they would be required to produce and sell only heat pumps. If the program targets distributors, they would be required to buy and sell only heat pumps. Participants would be given a short grace period to run down existing inventories. In our models we assume that it takes two years to fully transition. This requirement could be enforced through new regulation or a contractual agreement between firms and the implementing federal agency.[10] **This requirement is feasible because the manufacturing process for unitary heat pumps and air conditioners is almost entirely the same: all manufacturers can make both, and all suppliers can sell both.**

This incentive would also be temporary: it would decline by $60 to $75 each year from its initial value. The cost differential between heat pumps and air conditioners should come down as the switch occurs, both due to technological learning and economies of scale. The temporary nature of the incentive ensures that recipients switch over as quickly as possible to maximize their returns under the program and prevents the program from becoming an ongoing liability.

Finally, the incentive would be accompanied by a regulatory backstop to ensure that the switch remains permanent. The proposed backstop would be an updated appliance standard — to be published by the US Department of Energy in 2023 with an effective date in 2029[11] — which would require all residential air conditioners to be reversible heat pumps.[12] We anticipate that once the manufacturers have switched over their AC production lines, there will be little incentive to switch back. The backstop also ensures that first-movers know they will not be undercut later, and all stakeholders will be compelled to opt in and take advantage of the incentive because they know a new mandatory standard will come into place at the end of the incentive period.

> **Central ACs represent the greatest market share among cooling products in the US. The heat pumps that would be eligible for the incentive are essentially drop-in replacements for central AC products; they look the same and are installed in essentially the same way.**

10. The program should also include a compliance mechanism to ensure that recipients abide by their commitments following the grace period, and an audit mechanism to ensure that consumer cost savings are delivered. Because the program affects a relatively small number of manufacturers or distributors, monitoring should not require a heavy administrative burden.

11. The direct final rule for residential air conditioners and heat pumps published on January 6, 2017 (82 FR 1786) became effective on May 8, 2017. Compliance with these standards is required on January 1, 2023. The compliance date for any subsequent regulation (e.g., to require all air conditioners to be reversible heat pumps) is required by statute to be no earlier than January 1, 2029.

12. While the last DOE standards rulemaking treated ACs and heat pumps as separate "product classes" with separate analyses and requirements, the differences between the products are hidden from the user allowing the two products to be compared against each other. A fuller accounting should capture the benefits of heat pumps relative to ACs, allowing for a single standard that requires heat pumps.

Program Benefit-Cost Analysis

To evaluate the costs and benefits of the 3H program, we compared two example HVAC systems for single-family homes in each of three US climate zones

METHODOLOGY

To evaluate the costs and benefits of the 3H program, we compared two example HVAC systems for single-family homes in each of three US climate zones. The base case system is a central AC for cooling and a natural gas furnace or electric resistance system for heating, and the program case is a heat pump for both cooling and heating with either a natural gas backup furnace or electric resistance auxiliary to provide additional heat on the coldest days. (Appendix 2: Methodology)

DETERMINING THE INCENTIVE VALUE

Even though heat pumps will provide lifetime savings in most homes, the higher up-front costs and inertia to keep existing equipment discourage technology switching. These market barriers can be modeled as reductions in the expected market share of a technology despite a high ratio of benefits to costs.[13]

DOE has developed generic curves of efficient heat pump adoption illustrated in Figure 5. These curves are intended to reflect the number and intensity of barriers such as: lack of information, performance uncertainties, lack of access to financing, transaction costs, habits and customs, etc. (Rufo and Coito 2002, p. B-20). By following the curves one can calculate the amount of benefit (and corresponding incentive) necessary to achieve a desired market share for heat pumps.

According to DOE projections, heat pumps are currently estimated to equal 20% of all AC shipments (both reversible and non-reversible) in the North, 22% in the Southwest, and 48% in the Southeast.[14] Recent DOE analysis of furnaces, ACs, and heat pumps finds that the lifetime economic benefits from heat pumps in a 3H home (displacing 50% of gas furnace use) exceed costs by a factor of 4 in the North and are approximately equal in the Southwest and Southeast. These market penetration rates therefore represent moderate barriers in the North, low barriers in the Southwest, and no barriers in the Southeast.

13. We note that according to this model, used in the evaluation of utility efficiency programs and alternatives to DOE standards, benefits must outweigh costs by a factor of 10 or more for a technology to become widely adopted. (Blum et Al. 2011)

14. Southwest includes AZ, CA, NV, NM; Southeast includes AL, AR, DE, FL, GA, HI, KY, LA, MD, MS, NC, OK, PR, SC, TN, TX, VA, DC; North includes all other states. (U.S. DOE 2016b, Ch. 17)

Using the adoption curves in Figure 5, we developed projections of heat pump market penetration under a variety of incentive levels. As can be seen in Table 1, in the Southwest market share does not respond until a sizable incentive is provided, perhaps reflecting lack of experience with heat pumps. The recommended case (highlighted), a consumer incentive of $1000, achieves the greatest transformation before reaching diminishing returns.

We next estimated the per-unit incentive cost if applied at different points in the supply chain, based on a markup analysis from US DOE (Table 2). Markups are compounded, so for example the recommended $1000 consumer incentive translates to $676 at the installer ($1000/1.48), $499 at the distributor ($676/1.353) and $373 at the manufacturer ($499/1.34).

FIGURE 5: IMPLEMENTATION RATE CURVES

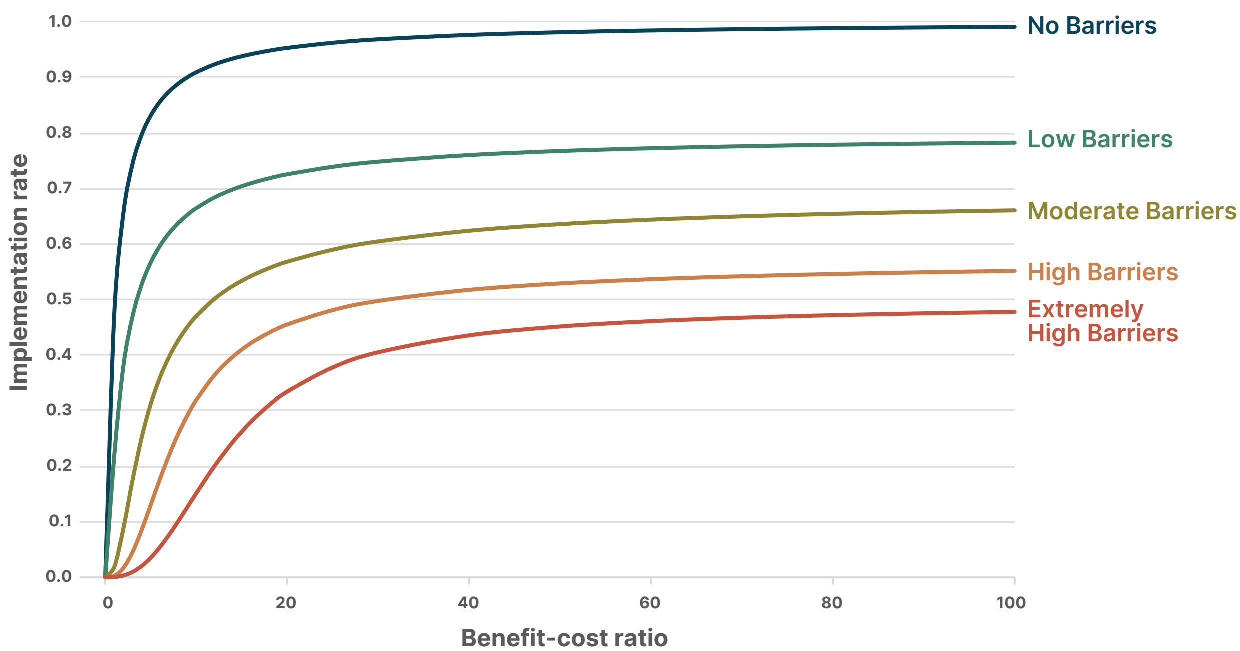


TABLE 1: ESTIMATED EFFECT OF CONSUMER INCENTIVES ON HEAT PUMP MARKET PENETRATION

PER-UNIT CONSUMER INCENTIVE	ANNUAL BUDGET (BILLIONS)	MARKET SHARE OF HEAT PUMPS IN REGION				TOTAL ACS REPLACED WITH HPS (MILLIONS)	TOTAL HPS INSTALLED (MILLIONS)
		NORTH	SOUTH-WEST	SOUTH-EAST	NATIONAL		
$0 (BAU)	$0	20%	22%	48%	34%	N/A	29
$200	$0.2	26%	22%	63%	44%	6	38
$400	$0.5	35%	22%	63%	47%	9	41
$600	$0.9	49%	22%	73%	57%	16	50
$800	$1.4	65%	22%	84%	69%	25	60
$1,000	**$2.0**	**67%**	**37%**	**96%**	**78%**	**30**	**68**
$1,200	$2.5	67%	59%	99%	82%	33	71

TABLE 2: ESTIMATED INCENTIVE COSTS COMPOUNDED THROUGH THE SUPPLY CHAIN

PER-UNIT CONSUMER INCENTIVE	INSTALLER INCENTIVE (1.48X MARKUP)	DISTRIBUTOR INCENTIVE (1.353X MARKUP)	MANUFACTURER INCENTIVE (1.34X MARKUP)
$200	$135	$100	$75
$400	$270	$200	$149
$600	$405	$300	$224
$800	$541	$400	$298
$1,000	**$676**	**$499**	**$373**
$1,200	$811	$599	$447

The calculations in Table 2 show that it is substantially less expensive to subsidize the conversion of ACs to heat pumps at the upstream or midstream level, while the adoption curves in Figure 5 demonstrate the challenge of transforming the entire market with incentives alone (e.g., even in regions with low barriers, heat pump market penetration will not exceed 80%).

In light of these market dynamics, we propose an incentive of $400 at the manufacturer level or $500 at the distributor level to maximize impact with minimal consumer and program costs, and we couple this with a commitment to manufacture or sell only heat pumps to maximize the speed and breadth of market transformation

BENEFIT-COST PROJECTIONS

Over the first ten years of its operation, the proposed program will produce $22 billion in net economic benefits, and $80 billion in indirect benefits from reduced air pollution.[15] These figures are based on modelling the deployment of 3H across the continental United States. We take existing shipment projections for central AC units and heat pumps (U.S. DOE 2016c, Shipments Tab) and use a census-tract level temperature and energy demand model (Waite and Modi 2020a) to calculate the impact of shifting AC units to heat pumps. The results show substantial reductions in combined heating and cooling costs across most modelled states, and only marginal cost increases in a few states.[16] All values are expressed in 2020 dollars with a 3% discount rate.[17] Notably, our results contrast with other recent studies which find that heat pumps are not cost-effective when replacing gas furnaces in existing homes in northern states (e.g., Billimoria et al. 2018). The primary reason is that the 3H approach retains the gas furnace and only assumes that the heat pump operates at outdoor temperatures above 41°F (5°C) when it is at its most efficient.

There are three sources of program costs: a subsidy cost between $3.1 and $11.7 billion, a 10-year increase in installation costs of $3.3 billion, and a 10-year increase in maintenance costs of $2.7 billion.[18] The subsidy costs depend on the particular design of the program: it is cheaper to subsidize manufacturers than distributors (because you avoid the distributor markup), to pay for additional heat pump sales instead of all heat pump sales, and to maintain the subsidy for 4 rather than 7 years. The impact of different combinations of decisions are shown in Table 3.

15. Our projections show that these benefits would only increase after the 10-year window; restricting our focus on the first ten years is a conservative modelling approach.

16. State-level projections are detailed in Appendix 3.

17. Costs inflated to December 2020 using the U.S. Bureau of Labor Statistics CPI Inflation Calculator (2021) , available at https://www.bls.gov/data/inflation_calculator.htm.

18. Installation estimates are based on the difference between typical air conditioner and heat pump installation prices net of equipment costs (Navigant 2018, pp. 25-29). Maintenance estimates are based on rates of failure and costs of replacing typical components and routine maintenance for typical heat pumps and comparable ACs (U.S. Department of Energy 2016c, PC Inputs Tab; U.S. Department of Energy 2016, pp. 8-33--8-43)

TABLE 3: GOVERNMENT COST ESTIMATES FOR ALTERNATIVE PROGRAM DESIGNS (BILLIONS USD)

TARGETING	DURATION	UPSTREAM ($400 MANUFACTURER INCENTIVE)	MIDSTREAM ($500 DISTRIBUTOR INCENTIVE)
Subsidize only additional heat pump sales	4 years	3.1	3.8
	7 Years	5.0	6.3
Subsidize all heat pump sales	4 years	5.9	7.3
	7 Years	9.3	11.7

In return, the 3H program is projected to produce direct savings for consumers of $27 billion over ten years. Most of these savings come from substantially lower heating bills ($154 per year, on average).[19] Cooling costs will also be marginally lower ($4 to $11 per year).[20] 3H homeowners will pay a higher upfront price for installation labor ($53 to $158 per unit) and marginally more in maintenance costs ($14 to $15 per year), but these additional costs will be more than made up for by annual savings. The relatively small increase in equipment and installation costs is due to the fact that the program subsidizes conversion upstream at the manufacturer or distributor stage, bringing down the cost of heat pumps to consumers.

To calculate the wider societal benefits of the program, we use the Energy Policy Simulator (EPS), an open source program with the ability to project the impact of various energy system changes on health and climate outcomes (Rissman et al. 2021). Within the EPS, we model our program as an increase in the share of new residential heating equipment that is electrified, compared to a baseline scenario. Each heat pump installed instead of a central AC has the potential to displace a substantial portion of fossil fuels used for heating. Of course, not all homes have central AC, and many homes will continue to use traditional fossil fuel technology for backup heat.[21] Taking these limits into account, **we conservatively project that replacing all sales of central AC units with heat pumps will displace 39% of fossil fuel for heating in converted homes by the end of the 10 year program period.**

In addition to direct consumer savings, heat pump deployments through the 3H program are expected to produce more than $58 billion in monetized health and social benefits over the next ten years due to decreased air pollution. This benefit comes from two sources: the immediate benefit of avoiding premature deaths ($35 billion) and the long-term benefit of reducing annual greenhouse gas emissions ($23 billion). In 2032, we will avoid 888 premature deaths and save 49 million metric tons of greenhouse gas emissions.[22] These benefit projections are conservative: they do not include annual reductions in lost workdays, respiratory problems, and hospital admissions (see Table 4). If these other benefits were monetized, the total benefit of the program would be even greater.[23]

19. Heating cost reductions are most substantial for homes with electric resistance heating, but most states see reductions for homes with gas furnaces as well. In states where heating costs for gas homes go up, the increase is less than $13 a year

20. In the northern tier of the country, the 3H program will drive adoption of more efficient equipment for air conditioning in the summer months. High efficiency ACs are typically difficult to justify in these regions of the country because they are used only a short time during the year. In a 3H the heat pump will run almost all year long, justifying a higher efficiency product that uses less energy for both heating and cooling while providing better comfort.

21. We begin by assuming that there is no overlap in the sales of new furnaces and new central ACs. This is a conservative assumption: accounting for overlap would raise the replacement rate). We calculate that homes which add a heat pump instead of a central AC and use traditional furnaces only as backup heat below 41°F (5°C) will replace 39% of the heating capacity currently dependent on fossil fuels. This is also a conservative assumption: Waite and Modi (2020a) calculate a fossil fuel heating displacement potential of 97%, without increasing grid capacity.

22. These benefits were derived from a customized version of the Energy Policy Simulator (J. Rissman et al. 2021). This customized model only projects benefits from displacing fossil fuel heating; it does not consider any potential benefits from displacing biomass (traditionally a major source of health and climate benefits from heating electrification).

23. The EPS does not monetize these other impacts because in other valuation studies their collective magnitude tends to be dwarfed by the monetized benefits of avoided deaths. Similarly, these projections do not place any monetary value on the enhanced comfort experienced by users of heat pump systems.

TABLE 4: HEALTH IMPACTS FROM ENERGY POLICY SIMULATOR

IMPACT	INCIDENTS AVOIDED IN 2032
Premature Deaths	888
Lost Workdays	97,906
Respiratory Symptoms and Bronchitis	36,853
Hospital Visits and E.R. Admissions	920
Asthma Exacerbation Incidents	24,476
Nonfatal Heart Attacks	1,029
Minor Restricted Activity Days	571,034

Reducing air pollution is especially important for protecting marginalized communities. Black Americans are disproportionately likely to suffer from emissions related to fossil fuel production and distribution (Fleischman and Franklin 2017) and suffer higher rates of air pollution-related health impacts as a result. The air pollution benefits generated by the 3H program would help address this historical inequity.

The net benefits of the program are displayed in Table 5. The Reference Case is calibrated using a 4-year subsidy for all units targeted at the manufacturer level. The Low-End projection is a 4-year manufacturer subsidy for only marginal units. The High-End projection is a 7-year distributor subsidy for all units. **The 3H program is projected to deliver 10-year direct benefits in excess of $22 billion and total benefits greater than $80 billion, with a benefit-cost ratio greater than eight to one.** Even in the High-End subsidy case, direct benefits exceed $16 billion, total benefits exceed $74 billion, and benefit-cost ratios are greater than five to one.

TABLE 5: CUMULATIVE PROGRAM BENEFITS OVER 2022-2031, IN BILLIONS OF USD

IMPACT AREAS	LOW-END COSTS	REFERENCE CASE	HIGH-END COSTS
Subsidy Costs	-3.06	-5.05	-11.69
Additional Installation Costs	-3.30	-3.30	-3.30
Additional Maintenance Costs	-2.66	-2.66	-2.66
Heating Savings	32.26	32.26	32.26
Cooling Savings	1.46	1.46	1.46
Net Direct Benefits	**24.70**	**22.71**	**16.07**
Avoided Mortality Benefits	35.12	35.12	35.12
Avoided Climate Damage Benefits	23.10	23.10	23.10
Net Direct + Indirect Benefits	**82.92**	**80.93**	**74.29**

Discussion: The Future of Fossil Heat

Even with current technology and energy costs, heat pumps are the most sensible choice for home heating in all American climates for much of the year.

The 3H program aims to overcome many of the market barriers (first cost, product availability, etc.) that are currently inhibiting heat pump deployment while preserving consumer choice and setting the stage for greater use of clean electric heating in the future.

In the near term, since these new heating options will primarily be installed at the time of AC replacement, residents of hybrid heat homes converted by the 3H program will retain the same equipment and functionality they have today and will be able to use their fossil fuel backup systems as often as they wish. Due to the energy bill savings and home comfort benefits of heat pumps, we expect the vast majority of 3H beneficiaries will begin to use their new heat pumps to offset a substantial portion of their home's fossil fuel use from day one.

Over the next 20 years, all the remaining fossil fuel heating equipment in 3H homes will need to be replaced as it reaches the end of its useful life. Homeowners will thus be faced with a new set of choices: they can either install a new fossil fuel furnace, potentially reducing its size to better match their backup heating needs, or they can eliminate their furnace (and possibly their gas connection) entirely and use electric resistance for backup heat. We believe that 3H homeowners will be much more likely to choose all-electric heat in the future, once they have become accustomed to the benefits of heat pumps. The case for all-electric homes may be stronger still due to continued heat pump performance improvements and complementary policies like carbon pricing or demand response capability that can be put into place to encourage greater heat pump use. In any scenario, the owner of a hybrid heat home will have more and better choices to optimize their home HVAC system in the future.

Suppliers of fossil fuel and combustion equipment for home heating are already preparing for a world in which clean electric heating provides larger and larger shares of demand. Our proposed program would catch this trend and provide a clear signal to suppliers about future demand pathways, making it easier to rationally plan future investments. In the long term, this will reduce stranded assets and avoid burdening consumers with paying for unnecessary gas pipelines.

APPENDIX 1

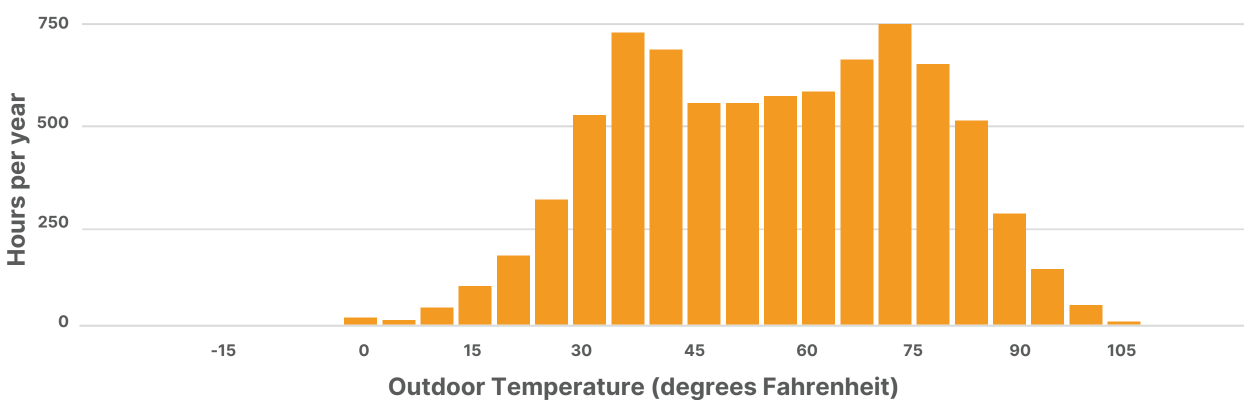
Case Studies from Cleveland

Detractors will say that older homes in cold climates are not good electrification candidates, but the owner of this 1900's home in Cleveland begs to differ. This house has been electrified and no longer has a gas meter. It now has "womb-like comfort" according to commercial HVAC expert Cameron Taylor. Traditional thinking is due for a shift.

Cleveland is in Climate Zone 5, the first of the four cold US climate zones. Below is a chart of how many hours per year Cleveland spends in 5 degree temperature "bins", averaged over 30 years. Most of the heating season is spent between 25°F and 65°F, a temperature range in which air source heat pumps are very efficient. Colder climate zones will spend less time in this band, but in most places a majority of the heating season is spent in moderate temperatures. In Climate Zones 1 through 4, which spend almost all of the year above 20°F, it is not uncommon to have the heat pump in a hybrid system contribute 100% of the heating.

In the experience of Energy Smart Home Performance, an insulation and HVAC consultancy in Cleveland, Ohio, the use of hybrid/dual fuel HVAC systems leads to 40% to 90% reductions in gas usage.

FIGURE 6: OUTDOOR TEMPERATURE (F) IN CLEVELAND OHIO



3H RETROFIT EXAMPLE

The first example is a retrofit of a 3500 square foot, 2-story detached house in Cleveland built in 2006. This home previously consumed approximately 975 therms of gas per year for space heating.[24] After the retrofit, gas consumption for space heating was reduced by 85% to an average of 145 therms per year with a hybrid furnace + heat pump HVAC system. About 20% of this drop can be attributed to building efficiency improvements such as insulation and air sealing that were completed at the same time as the retrofit, and the remaining 80% of the improvement is due to electrification with an 18 SEER inverter-driven heat pump.

ANNUAL ENERGY CONSUMPTION BEFORE AND AFTER RETROFIT

	BEFORE RETROFIT	AFTER RETROFIT	
	2015	2019	2020
Natural Gas (thm)	**1,237**	**212**	**71**
Heat pump heating (kwh)	—	4,477	5,682
Continuous fan (kwh)	—	300	757

24. According to EIA, 79% of natural gas consumption in the average single-family detached home in the Midwest was used for space heating (EIA 2015, Table CE4.8)

3H NEW BUILD EXAMPLE

In a second example, a newly-built (2018) 4,000 square foot ranch with a fully-finished basement in Cleveland and the same hybrid HVAC system as above uses an average of just 188 therms of gas per year for space heating; the heat pump carries the heating load to about 25°F.

ENERGY CONSUMPTION FOR SPACE HEATING (2019–2020)

	2019	2020
Cooling	1,071 kwh	1,532 kwh
Heatpump heating	5,423 kwh	6,156 kwh
Continuous fan	84 kwh	70 kwh
Fan with gas heat	0 kwh	0 kwh
Total Electric	6,575 kwh	7,758 kwh
Gas heating	**215 thm**	**160 thm**

It is clear from these examples that even hybrid heat homes can substantially contribute towards residential electrification and avoid missing near term decarbonization opportunities. They are also likely to open consumers up to a fully electrified home the next time their HVAC is replaced.

APPENDIX 2

Methodology

Our model assumes that the entire supply of central air conditioners converts to heat pumps. As a baseline, we assume that these new heat pumps match the operating characteristics of a widely-used heat pump model that meets the minimum efficiency level in the forthcoming 2023 DOE standard, the Goodman 15 SEER.[25] For comparison, we assume that existing fossil fuel furnaces have an efficiency of 85%, and that electric heating systems (a combination of electric resistance furnaces and legacy heat pumps) have a COP of 1.2. We assume cooling cost differences based on data from (U.S. Department of Energy 2016b, p. 7.25, U.S. Department of Energy 2016c, Energy Price Tab) on the cooling energy consumption at 15 SEER versus 14 and 14.5 SEER levels (the forthcoming 2023 DOE standard for ACs).

For homes with an existing gas furnace, we conservatively assume that all heating load is provided by the furnace when the temperature is below 5°C (41°F). This allows the heat pump to operate at its highest efficiency where it provides the most benefit. For homes with existing electric resistance heat, we assume that the heating system is replaced outright by a new heat pump with electric resistance backup, and that the heat pump and backup run concurrently below 5°C with a diminishing COP as outdoor temperature decreases (see table below). These are conservative assumptions: if technology continues to improve then average performance should also improve over the program period.

To calculate the energy and cost impacts of changing new AC units to heat pumps, we use an electrification model developed by Waite and Modi (2020a). This model combines data on monthly state-level energy usage, local hourly temperatures, census tract-level heating fuel and building floor area to estimate the impact of heating electrification on fuel and electricity demand and household energy expenditures. Given the hourly temperature data, we can estimate with a reasonable degree of precision how much of current heating capacity will be shifted from non-electric to electric sources by our program. This model is only available for the continental United States, restricting our analysis to the lower 48 states and Washington, D.C.

We estimate the average change in heating and cooling costs at the state level, based on the difference between gas prices and electricity prices, current gas and electric heating energy consumption at different temperatures, and the efficiency of the baseline heat pump compared to furnaces and air conditioners. We did not explicitly analyze oil and propane furnaces, but included them in the natural gas furnace total because of their low share of the installed base. Since the cost of operating oil and propane furnaces is higher than natural gas (with similar CO_2 emissions), this is a conservative assumption.

We assume that central air conditioner deployment follows annual projections by the U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy (US Department of Energy 2016c, Shipments Tab). These projections are available annually for the period 2021–2052 and are broken out into three climate zones: North, Hot-Humid, and Hot-Dry. We allocate the deployment during our program period across the states in each zone, weighted by the regional share of housing units with central AC in the last Residential Energy Consumption Survey (2015) and the number of occupied units in each state.[26] We assume that it takes two years for targeted firms to switch their supply of air conditioners to heat pumps.

25. Data for GSZ140361K* / ARUF37C14** + TXV (Goodman 2020, p. 34).

26. The AEO (U.S. Energy Information Administration 2021a) provides national projections for occupied housing units; we allocate these according to state-level population growth projections from the University of Virginia Weldon Cooper Center (2018).

Because our program eliminates the cost differential for heat pumps versus central AC units at the distributor or manufacturer level, we assume there is no additional equipment cost to pass on to consumers. We account for an increase in installation costs by comparing the retail equipment cost and total installation cost for a typical central air conditioner and heat pump. By subtracting the equipment cost from the total installation cost, we derive the labor cost to actually install the system. The underlying data are available for two U.S. climate zones in 2020 and 2030 (Navigant 2018), and we linearly interpolate the values between these years.

To calculate these consumer costs, we consider how many years each unit will be in operation. Since we are only analyzing our program over ten years, we track a unit installed in 2022 for the full ten years while we only track a unit installed in 2031 for one year. Considering effects for a longer window (the lifetime of each unit, for example) would increase our projected benefits relative to costs. We then multiply the average state-level change in heating costs by the number of unit-years converted from AC to heat pumps under our program. We also multiply average climate zone-level change in cooling and maintenance costs by unit-years in the same way. We sum these changes across all states to derive our total expected consumer costs over the study period.

We use the Energy Policy Simulator (J. Rissman et al. 2021) to estimate two kinds of benefits: near-term health impacts from avoided air pollution and long-term benefits from avoided climate change. The relevant input in the Energy Policy Simulator is the share of new, non-electric residential heating capacity that is displaced by electric sources each year. For this calculation we start with natural gas furnace shipment projections from EERE (U.S. Department of Energy 2014). Though these are the dominant non-electric residential heating technology in the United States, there are other technologies as well. In the absence of shipment projections for these systems, we assume their shipments are the same share of their projected stock as furnaces are.

We then divide the shipments of heat pumps converted by our program by the sum of shipments of non-electric systems, plus converted heat pumps, in each year. One of the outputs of our model is the proportion of time that 3H systems in each state rely on fossil fuel backups: we reduce the new capacity by this proportion. Over 10 years, the shipments of converted units rises to 51% of the combined total of non-electric and converted electric units. Reducing this by the fossil fuel backup factor means that our program grows to displace 20% of the new non-electric heating capacity supplied each year. This is likely to be a conservative estimate, since it does not account for the possibility that fewer non-electric units will be sold over the program period, or improvements in heat pump technology that could enable full displacement of fossil fuel backups in some states.

The EPS provides health and social benefits in two forms. The EPS monetizes the value of avoided premature deaths using the value of a statistical life (these are primarily due to reductions in particulate emissions). The EPS also monetizes the discounted future value of avoided climate change damages due to decreased emissions using the social cost of carbon. In addition, the EPS provides a range of non-monetized benefits (lost workdays, asthma attacks, hospital visits, etc.). Monetizing these would further increase the projected benefits of the program. See https://us.energypolicy.solutions/docs/additional-outputs.html for further details.

In the online version of the EPS, health and climate benefits from displacing fossil fuel heating are driven in large part by shifting fuel consumption away from biomass. Though it is possible that our program will displace some biomass heating, we assume that most of the heating capacity displaced will be from fossil fuel sources. The Energy Policy Simulator team ran a custom version of the EPS model that excluded biomass from the benefits calculation. All our benefits calculations are based on this more conservative version of the model.

Current Fossil Fuel Heating System

For simplicity, natural gas assumptions used for all current fossil fuel heating. According to (Modi & Waite 2020a):

- Gas: Heats 49% of residential area; responsible for 53% of heating energy and 44% of heating emissions
- Fuel Oil: 6.7% res. area; 9.3% energy; 8.6% emissions
- Propane: 5.9% res. area; 6.6% energy; 5.2% emissions

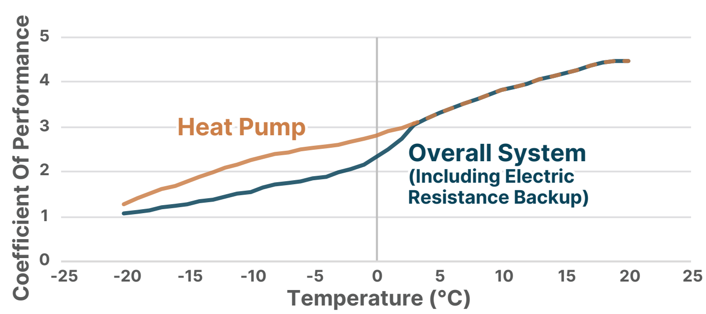
VARIABLE	VALUE	SOURCE AND NOTES
Efficiency	85%	Based on a mix of non-condensing (approximately 80%) and condensing furnaces.(90%). (Modi & Waite 2020a) used 78% "based on the authors' judgment and the performance of traditional heating systems and corresponds to average early-1990's era equipment.)
Average Lifetime	21.5 years	Based on gas furnace lifetime (U.S. Department of Energy 2016a, Table 11.3.1)
CO_2 emissions factor	66 kgCO_2e / MMBtu	(Modi & Waite 2020b) "Note that while emissions from combustion are 53 kgCO_2e / MMBtu [8], when one includes an estimated additional 13 kgCO_2e / MMBtu due to methane leakage [9], one arrives at GHG emissions of 66 kgCO_2e / MMBtu."
Proportion of residential floor area with fossil fuel heating	Varies by census tract	U.S. Census Bureau. (2010) American Community Survey American Community Survey 1-Year Estimates, Table B25040; Generated by Michael B. Waite Using American FactFinder [Accessed August 7, 2018].
Utility rates	Varies by state; Assumed constant over analysis period.	U.S. Energy Information Administration, "Natural Gas Annual", September 2020, data for 2019, https://www.eia.gov/energyexplained/natural-gas/prices.php U.S. Energy Information Administration, "Heat Content of Natural Gas Consumed", data for Dec 2020, https://www.eia.gov/dnav/ng/ng_cons_heat_a_EPG0_VGTH_btucf_m.htm

Current Electric Heating System

- 35% residential area
- 27% heating energy
- 42% heating emissions

VARIABLE	VALUE	SOURCE AND NOTES
CO_2 emissions factor	Varies by NERC / eGRID subregion or state. U.S. average is 401 $kgCO_2e/MWh$ in 2019 and 192 kgCO/MWh in 2032.	eGRID 2019 subregion annual CO_2 equivalent total output emission rate (U.S. Environmental Protection Agency 2021a) Cambium Low Renewable Energy Cost Scenario for 2032 (National Renewable Energy Laboratory 2020)
Proportion of residential floor area with electric heating	Varies by census tract	U.S. Census Bureau. (2010) American Community Survey American Community Survey 1-Year Estimates, Table B25040; Generated by Michael B. Waite Using American FactFinder [Accessed August 7, 2018].
Utility rates	Varies by state; assumed constant over analysis period.	U.S. Energy Information Administration, “State Electricity Profiles”, November 2, 2020, data for 2019, https://www.eia.gov/electricity/state/

Proposed 3H System

VARIABLE	VALUE	SOURCE AND NOTES
Penetration	Varies by state	Nationally, we would expect 34% of homes to have central ACs replaced by heat pumps by 2032, with equal replacement rates for electric and fossil fuel homes. Based on forecast HP and AC sales (U.S. Department of Energy 2016c, Shipments Tab) and forecast AC stock (U.S. Energy Information Administration 2021a).
Average Equipment Lifetime	North: 16.4 years Southwest: 15.4 years Southeast 15.1 years	(US Department of Energy 2016b, Table 8.2.59)
Fossil Fuel System Switchover Temp	41°F (5°C)	For the 34% of fossil fuel systems where the AC has been converted to an HP, heat pump runs above 5°C (> 3 COP), existing fossil fuel system runs as backup below 5°C (85% efficiency). For the 34% of electric systems where AC has been converted to an HP, the HP (variable COP) and its electric resistance backup (1 COP) operate in parallel to maintain capacity
Efficiency	Varies by temperature	Based on data for Goodman GSZ140361K* 3 ton Heat Pump (orange line) supplemented by electric resistance when the capacity drops below 2.25 tons or 75% of nominal (resultant system COP in blue).  Goodman Air Conditioning & Heating, "GSZ14 Energy-Efficient Split System Heat Pump Up to 15 SEER & 9.0 HSPF 1½ to 5 Tons", data sheet, 8/20, p. 34. https://www.goodmanmfg.com/pdfviewer.aspx?pdfurl=docs/librariesprovider6/default-document-library/ss-gsz14.pdf?view=true
CO_2 emissions factor	Same as for Current Scenario, above	
Utility Rates	Same as for Current Scenario, above	

APPENDIX 3

State-level Savings during Program Period

STATE	TOTAL SAVINGS OVER 10 YEARS ($M)	ANNUAL SAVINGS PER CONVERTED HOUSEHOLD ($/YEAR)			
		HEATING HOMES WITH GAS HEAT	HEATING HOMES WITH ELECTRIC HEAT	COOLING	MAINTENANCE
AL	643	131	521	4	-14
AR	451	101	466	4	-14
AZ	1034	50	394	5	-14
CA	3047	89	817	5	-14
CO	129	-8	632	12	-15
CT	157	9	2013	12	-15
DC	28	55	369	4	-14
DE	92	88	699	4	-14
FL	451	46	74	4	-14
GA	1039	94	520	4	-14
IA	350	-2	1022	12	-15
ID	299	14	878	12	-15
IL	956	0	1250	12	-15
IN	1055	-4	1112	12	-15
KS	414	24	1100	12	-15
KY	449	50	583	4	-14
LA	408	74	245	4	-14
MA	291	56	1652	12	-15
MD	478	90	561	4	-14
ME	94	65	2440	12	-15
MI	947	-13	1931	12	-15
MN	380	7	847	12	-15
MO	1221	48	846	12	-15
MS	238	59	469	4	-14
MT	162	12	1192	12	-15
NC	942	86	400	4	-14
ND	73	-7	493	12	-15
NE	320	22	928	12	-15
NH	88	55	2349	12	-15
NJ	322	-3	1657	12	-15
NM	177	19	898	5	-14
NV	335	33	639	5	-14
NY	621	47	1151	12	-15
OH	1695	11	1121	12	-15
OK	585	59	683	4	-14
OR	619	109	706	12	-15
PA	960	74	1042	12	-15
RI	37	71	1887	12	-15
SC	385	52	314	4	-14
SD	132	-11	901	12	-15
TN	354	15	345	4	-14
TX	2153	61	247	4	-14
UT	270	46	1088	12	-15
VA	1037	102	605	4	-14
VT	42	29	2747	12	-15
WA	860	125	534	12	-15
WI	452	-7	1129	12	-15
WV	378	58	954	12	-15
WY	110	43	1195	12	-15

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