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Heat Pump Primer: Understanding the Technology That Will Drive Decades of Residential Decarbonization

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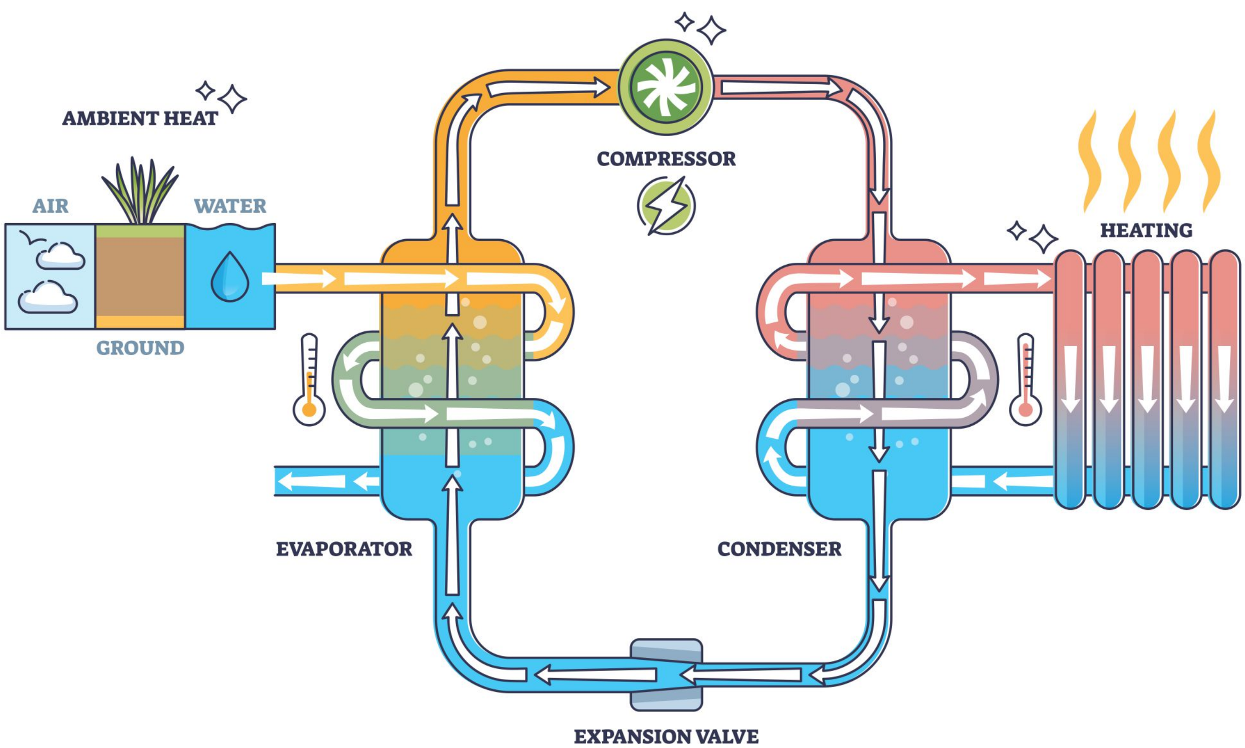
Introduction

Residential heat pump installations are poised to rapidly accelerate over the next decade as part of the effort to electrify homes and reduce greenhouse gas emissions. As of 2020, only 14% of America's 124 million housing units used heat pumps for space heating[1]. To help households make sense of this technology and understand system and operational costs considerations, we discuss the benefits and challenges of scaling heat pump technology and use data from our national residential research network to explore regional variations in heat pump system performance.

Heat Pump 101

Heat pump systems absorb heat and move it from one area to another via refrigerant piping. This differs from traditional furnaces, which burn fuel or use electric resistance to create heat. A traditional furnace is often paired with a separate air conditioning system for homes with heating and cooling. Heat pump systems however can use the same equipment to heat and cool a home. This is accomplished through a reversing valve that enables the heat pump to move heat either into or out of a home. Even when it is extremely cold outside, a heat pump system can extract heat from the outside air to heat a home.

Heat Pumps and Decarbonization



Heat pump HVAC systems use electricity to move heat from one place to another, instead of generating heat directly. In heating mode, shown above, heat is absorbed from the outside air or ground and released inside the building. In cooling mode, the process is reversed.

In most homes, space conditioning uses more energy than any load other than electric vehicle charging. Heat pumps are more efficient than natural gas or electric resistance heaters because they redistribute heat rather than create it. This means less energy is required to control the temperature of a home with a heat pump than with systems that burn fossil fuels or use electric resistance heating.

Electric heat pumps have the potential for deep decarbonization as our electric grids shift towards renewable power. Fossil fuel HVAC systems do not. A 2020 RMI study found that replacing natural gas furnaces with electric heat pumps will reduce carbon emissions in 99% of households in the continental United States.[2] Even if installing a heat pump leads to higher GHG emissions today, it can still be preferable to a natural gas furnace because low- and no-carbon electricity is scaling rapidly on most electric grids. As electricity generation becomes less carbon intensive, electric heat pumps will produce fewer greenhouse gas emissions when compared to a fossil fuel furnace.

Heat Pump Types

Ducted systems use the same system of ducts as traditional furnaces to distribute conditioned air throughout the home. Converting a ducted furnace to a heat pump is generally a simple replacement. Since the duct system is already in place, the furnace is replaced with a heat pump and refrigerant piping is added to connect the air handler to an outside condenser. If the home already has a central air conditioner, this piping is already in place and the new heat pump system can replace the air conditioner in the same footprint.

Ductless heat pumps – often called mini-split systems – are installed directly in the wall or ceiling of the space they condition and connect to an outside condenser. Ductless systems are generally best in homes without adequate attic or basement space for a ducted system. They are also more modular than central units, which is useful in cold regions when they are installed in tandem with a legacy HVAC system that can serve as a backup heat source. Ductless systems operate more efficiently at lower temperatures than ducted systems because they don't lose any heat when distributing the conditioned air through ducts in an attic or basement.

Other Heat Pump Types

Ducted and ductless systems use the outside air as a heat sink. These air source heat pumps (ASHP) are the most inexpensive and popular heat pump systems. Window-mounted heat pumps are another ASHP that can serve a smaller footprint (generally one room) with a smaller price tag.

Less common heat pump systems include ground source heat pumps (GSHP), which exchange heat underground and perform better in extremely cold climates but are generally more expensive to install. Water source heat pumps exchange heat with a pond or other body of water. Air-to-water heat pumps exchange heat with outside air and use a hydronic heating loop inside the home to distribute heat.

Comparing Technologies

Heat pumps have traditionally been installed in warmer climates because they were best suited for milder winter temperatures. In the last decade, however, heat pumps have become more capable of heating homes effectively in colder temperatures and are now a viable option as primary heating for all but the northernmost climates in the United States. Heat pumps can be installed in several different configurations to best suit a home.

Climate Zone

Regional climate – more specifically, how cold it gets – is a primary factor in heat pump system selection and will influence what backup heating system will be needed.

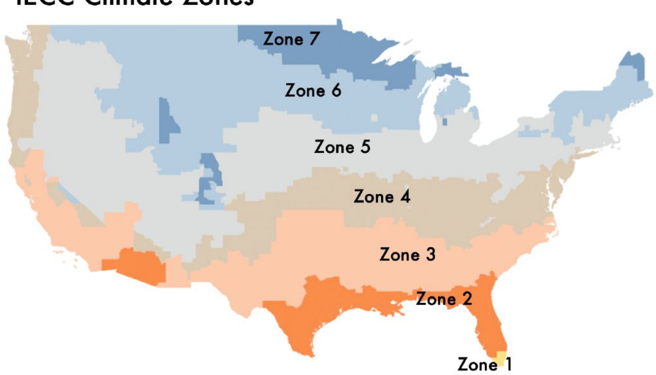
As climate regions get colder, heat pump systems with higher efficiencies are recommended. The Heating Seasonal Performance Factor (HSPF) and Coefficient of Performance (COP) are measures of a heat pump system's efficiency. Through the Energy Star program[3], the U.S. Department of Energy recommends efficiencies by climate zone in the table below (3). HSPF compares the heat output of an air source heat pump in British Thermal Units to the electrical input power, and is a measure of the system's heating performance. COP is also a measure of efficiency, but uses watt-hours for both the heat delivered and energy consumed. HSPF can be converted to COP by multiplying the HSPF by 0.293.

Both ducted and ductless air source heat pump (ASHP) systems are well suited for most U.S. climates (IECC climate zones 1-6). Central ducted systems are most common in new homes with sufficient attic space for ducting. Mini-split systems are commonly used in retrofits when ducting isn't practical.

The recommended HSPF and COP heat pump efficiencies increase as the climate zones become colder. Homes in climate zones 4-7 often need more significant backup heat sources when winter temperatures are consistently cold. In this case, mini-split systems can heat efficiently during shoulder or warmer winter days, and a resistance or fossil fuel central heating system can provide primary heat on colder days. Insulating a home well improves the efficacy of heating systems and can reduce reliance on a back-up heating system. Importantly, heat pumps can also provide summertime cooling without the addition of any other equipment. Notably, when a high-efficiency heat pump is installed, it provides energy savings benefits for both heating and cooling, which can result in significant annual energy savings. This was explored at length in Pecan Street's Electric Texas: Emissions and Grid Impacts of All Electric Residential Heating white paper.

A ground source heat pump is recommended by Energy Star in climate zones 7 and 8 because they are able to operate most efficiently at very low temperatures by exchanging heat underground rather than with the outside air. However, ground source heat pumps are significantly more expensive to purchase and install than air source heat pumps.

IECC Climate Zones



Energy Star Heat Pump Efficiency By Climate Zone

IECC Climate Zones	Efficiency	Type	Backup Heat
Zone 7	3.5 COP	GSHP	Electric or dual-fuel backup
Zone 6	9.5 HSPF	ASHP	Electric or dual-fuel backup
Zone 5	9.25 HSPF	ASHP	Electric or dual-fuel backup
Zone 4	8.5 HSPF	ASHP	Electric or dual-fuel backup
Zones 1-3	8.2 HSPF	ASHP	Electric or dual-fuel backup

Utility Rates

Though heat pumps use less energy to condition air than traditional furnaces measured by a Coefficient of Performance (COP), actual energy cost savings will depend on local utility rates.

In areas where electricity is relatively expensive and/or natural gas is relatively cheap, energy savings from a new heat pump could be smaller and are best assessed through an energy audit. If a gas utility has high fixed rates for service, a customer will realize more utility savings when they disconnect completely from gas service. This can be an incentive for electrifying all the systems in a home rather than just the HVAC system.

Home Size and Thermal Envelope

Homes with tight thermal envelopes make any heating and cooling system operate more efficiently. However, heat pumps benefit more from tighter envelopes than fossil fuel or electric resistance furnaces because heat pumps run longer at low power to continuously maintain temperature setpoints rather than quickly heating or cooling a home. Energy codes have greatly improved the standards of new construction across the country, but there are still millions of older homes without adequate insulation, windows and weatherstripping. These homes should upgrade their thermal envelope before or at the same time a heat pump is installed to ensure they can operate efficiently and comfortably. Generally, an energy audit is the best way to identify the most effective thermal envelope upgrades.

Examples of thermal envelope upgrades include:

- Insulation – Adding spray foam or high R-Value insulation to roofs, walls and floor.

- Windows – Windows with Energy Star certification, double-paned windows, and storm windows in the wintertime can all improve the thermal envelope.

- Weatherstripping and Repairs – covering small gaps in windows, doors and siding

Even before installing a heat pump, low- to moderate-income (LMI) families stand to realize the highest energy savings from improving their homes' thermal envelope – a tighter envelope is cheaper to heat or cool regardless of the technology. Moreover, it is important for LMI families to make such envelope improvements before installing a heat pump because a heat pump in a leaky home could increase electricity use and costs.

Sizing is another important aspect of heat pump performance. If a heat pump is not sized correctly to a home or is installed in a leaky thermal envelope, the efficiency of the heat pump decreases as it relies more heavily on backup heating sources. Electric resistance heating, the most common backup heat source, is much less efficient than heat pumps and natural gas furnaces. It's important to hire a reputable installer and understand a home's energy performance and utility rates before deciding on which heat pump system to install.

Navigating the Installation Market

Due to advances in refrigerant and compressor technology, heat pumps can be installed in IECC climate zones 1-6. Many contractors have been installing fossil fuel furnaces for decades and are reluctant to recommend or install heat pumps. Overcoming status quo bias among contractors will be key, because each new fossil fuel furnace locks in greenhouse gas emissions for another 15-20 years. Contractors also must learn to navigate the new rebate and incentive programs funded by the Inflation Reduction Act. Additionally, we need more contractors to handle the increased demand for heat pump installation. The demand for heat pump systems will grow as incentives are realized and a skilled workforce of HVAC installers will be crucial to deploying them at the required scale.

Heat Pump Insights from Our Participant Network

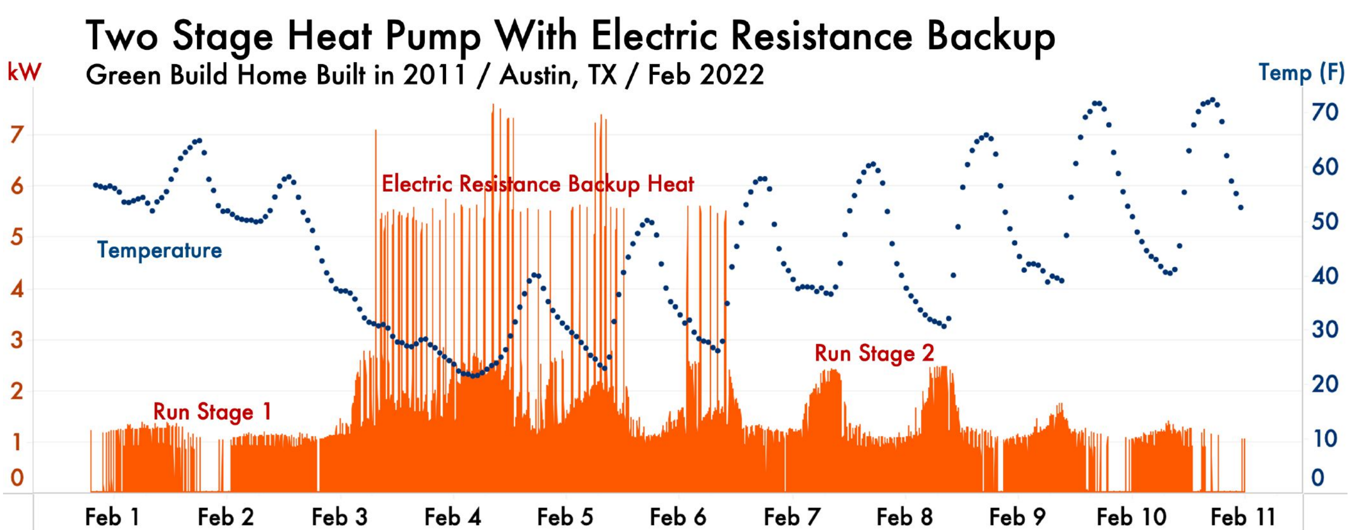
Pecan Street Inc. has created a unique network of volunteer research participants whose home energy data is collected 24/7 at ultra-high resolution. Our monitoring equipment allows our researchers to isolate individual circuits and energy uses, which can uncover insights about how various heating and cooling technologies perform. Over the past few years, we expanded our network into different parts of the country, which allows us to compare energy profiles across climate zones.

To demonstrate how heat pumps perform in different types of homes in different climate zones, we examined the heating energy used for select homes in Austin, TX, and Ithaca, NY.

Central Air Source Heat Pump in Austin, TX

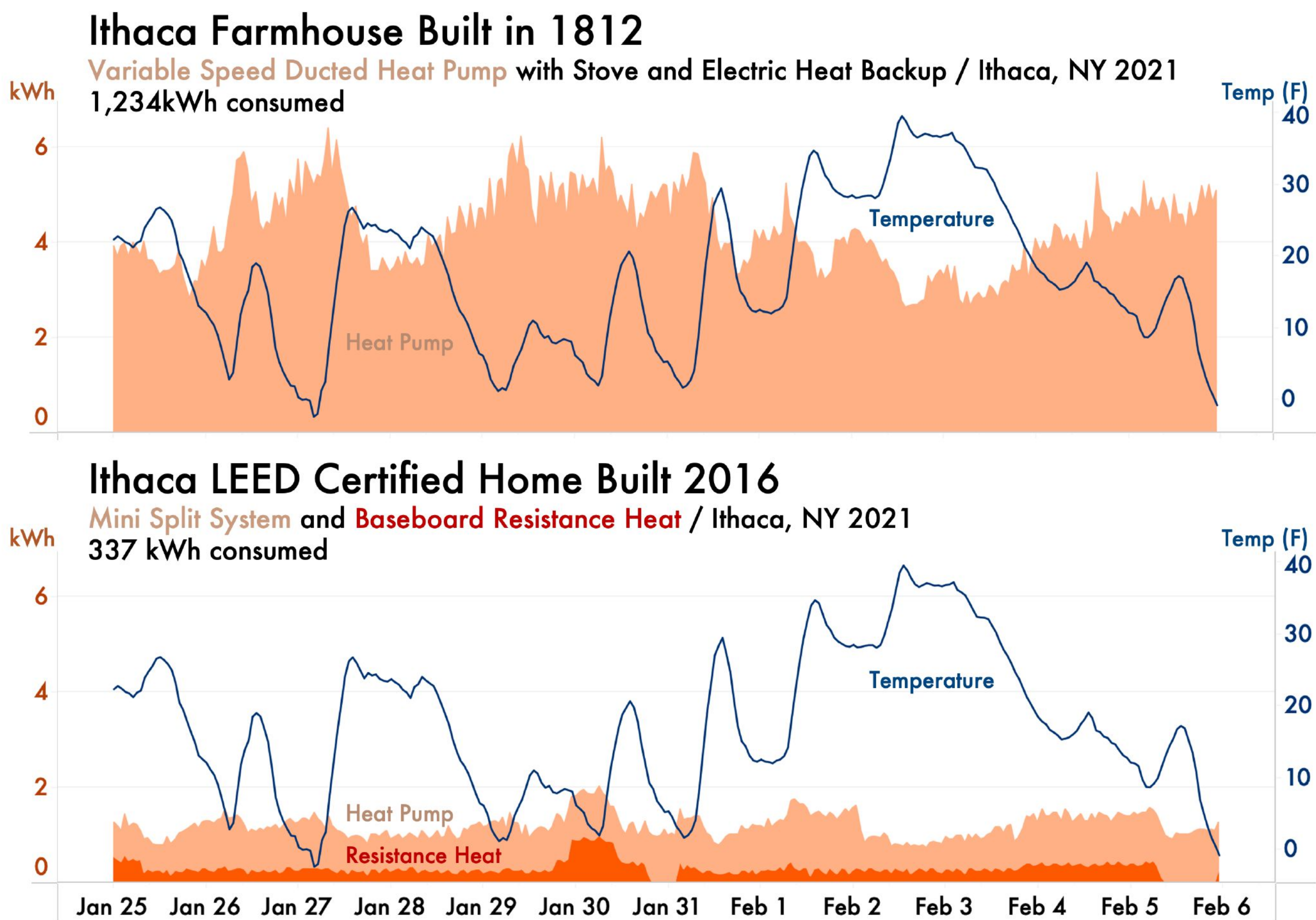
For Austin, we examined heating data for a home built in 2011 with a central ducted heat pump system. The chart below shows minute-by-minute energy use from the heat pump system over a ten-day period overlayed with the hourly outside temperature.

When outside temperatures are mild, the heat pump cycles at its low power stage – just above 1kW – and the resistance heat is not needed. When the temperature is between 30-40F, the system operates at the high power stage – around 2.5kW. At temperatures around and above freezing, the resistance heat is not needed. When the temperature drops below 30F, the system engages its electric resistance backup during some cycles, which uses between 5-8kW to reach the temperature setpoint. Such a system works well in temperate climates like Austin. It provides the overall efficiency and emission advantages of heat pump systems with the convenience of more powerful heating during infrequent cold snaps.



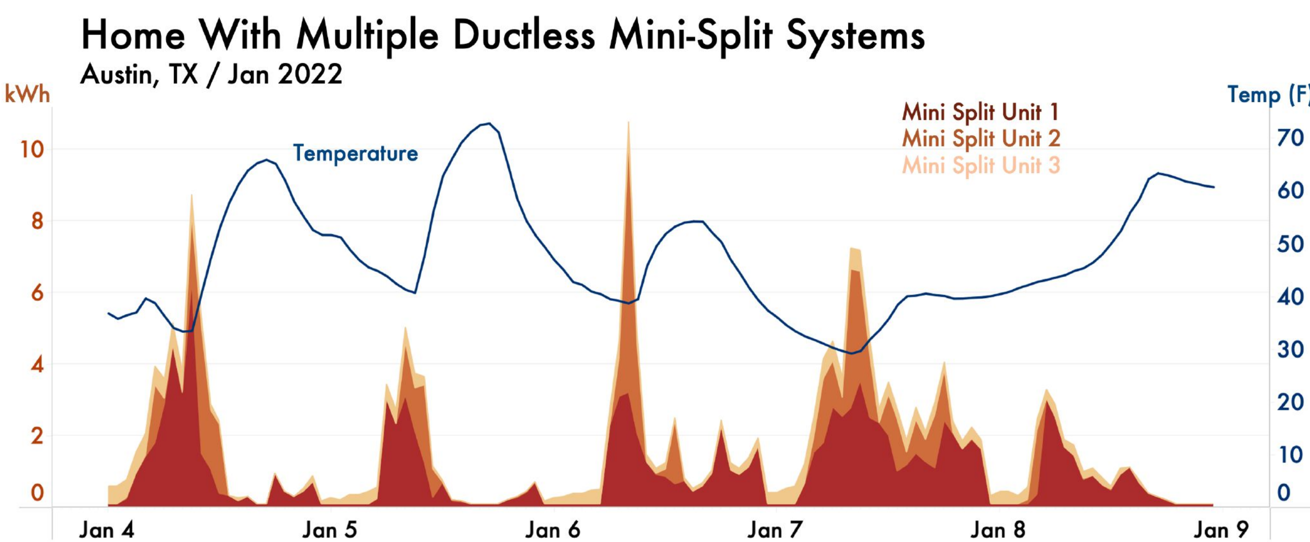
New and Old Homes in New York

Unsurprisingly, heating profiles are different among our participants in Ithaca, which experiences very cold winters. The figure below compares two similarly sized Ithaca homes. One is an old farmhouse with an average thermal envelope and multiple sources of backup heating. The other is a LEED-certified new construction home with an extremely tight thermal envelope. Both homes are between 2,200-2,300 square feet. Because its thermal envelope is leakier, the farmhouse requires multiple forms of backup heat from a wood stove and electric resistance heaters whose energy data are not included in the chart. The LEED-certified home, however, has a ductless mini-split heat pump system with supplemental resistance baseboard heaters. The overall electricity required to heat the LEED-certified home over this period is more than three times lower, despite it being a similar size and in the same city. This example clearly shows the impact of a tight thermal envelope on heat pump performance.



Multiple Mini Split Systems in Austin

Although central ducted heat pump systems are common in warmer climates, there are many reasons why people use multiple mini-split systems throughout a home. When retrofitting a home, for example, there may not be available space for ducting due to prior construction or for aesthetic reasons like vaulted ceilings. In this case, mini-split heat pump systems can condition different zones of a home, which can provide inherent efficiency and operational cost savings when only the parts of a home in use are heated or cooled. The figure below profiles a home with two mini-split systems in the main house (Units 1 and 2) and a third unit in an adjacent guest apartment (Unit 3). This configuration also offers flexibility when programming thermostats in each zone – they can be conditioned to turn on or off independently of each other. Areas that are not in use can have their thermostat adjusted to save energy and the system's cycling can also potentially be staggered to avoid all of them pulling a maximum load at the same time. This is particularly important when the backup resistance heating elements are engaged during cold weather.



Conclusion

The myriad of heat pump systems available can be configured to suit the needs of homes in any climate. Contractors and homeowners need to familiarize themselves with heat pump systems and their implementation to accelerate the adoption of this critical technology. Similarly, we recommend households discuss operational costs with their HVAC contractor to understand how these technologies will impact their household utility bills. Since HVAC systems are often purchased when a current system fails, understanding heat pump upgrades proactively is key to maximizing their adoption. Additionally, weatherizing homes will improve the energy efficiency of homes and increase heat pump readiness. Heat pump systems can be installed in almost any home, but they have the best performance and payback when homes are sufficiently insulated and weatherized. Low-income households should be the focus for these upgrades through streamlining rebates and incentive programs, particularly those in the High Efficiency Electric Home Rebate Act and tax rebates in the IRA.

Citations

1. U.S. Energy Information Administration - EIA - Independent Statistics And Analysis. www.eia.gov/consumption/residential/data/2020/index.php?view=state.

2. Stone, Laurie. "It's Time To Incentivize Residential Heat Pumps." RMI, 2 Mar. 2022, www.rmi.org/its-time-to-incentivize-residential-heat-pumps.

3. "National Program Requirements ENERGY STAR Certified Homes." Energy Start, www.energystar.gov/sites/default/files/ES%20NPR%20v85%202018-05-16_clean.pdf.