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Residential adoption and grid impacts of heat pumps depend on equipment efficiency and rebates

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Abstract

Heat pumps have become the fastest-growing residential heating and cooling technology in the United States, but their economics and grid impacts depend on location, fuel prices, and household characteristics. We quantify the county-level benefits of heat pumps in the U.S. through geospatial analysis, techno-economic analysis, and grid-impact analysis. Minimum- and high-efficiency heat pumps could be economically viable without subsidies for 19% (10.4 million) of modeled single-family homes, rising to 25.0-26.4 million with Inflation Reduction Act rebates, or 14.4–15.5 million under new guidance eliminating fuel-switching project eligibility. If every modeled home adopts, net annual residential electricity demand rises 35% with minimum-efficiency models but barely changes with high-efficiency systems. Incentives that offset the higher upfront cost of efficient equipment could therefore help reduce this demand increase. This study can inform infrastructure investment and policy programs by identifying areas with the highest heat pump adoption potential and quantifying the range of grid impacts.

Introduction

The electrification of residential heating and cooling through the deployment of heat pumps represents a key strategy for achieving deep decarbonization in the building sector [1–3]. Residential heat pump adoption is gaining momentum [4] and heat pump sales have outpaced the sale of natural gas furnaces in the United States (U.S.) for the past four years [5, 6]. However, the adoption of heat pumps remains uneven across the United States and is most common in the South [4] where the heating demands are lower and electric resistance heating is dominant. Regions with lower winter temperatures and greater heating demands often require a larger or more efficient system to meet their heating requirements year-round, leading to higher upfront capital costs. When it is time to replace an existing heating system, the higher upfront capital costs of heat pumps relative to incumbent technology [7], a higher price of electricity relative to other heating fuels [8], and the split incentives of landlords (installation cost) and their tenants (lower energy bills) can all hinder the adoption of residential heat pumps [9]. Adoption can be especially challenging in colder regions with relatively cheap natural gas availability, as the lower lifetime operational savings from the heat pump retrofit make it harder to justify the often higher upfront capital costs.

The widespread deployment of electric heating technologies is likely to increase peak electricity demands, posing challenges for existing generation, transmission, and distribution infrastructure [10–12]. We define beneficial or favorable electrification outcomes as instances where electrification leads to a positive NPV over the equipment lifetime (i.e., private benefit) or cases where retrofits lead to net reductions in electricity demand and peak load (i.e., an example of a public benefit). One strategy to address this challenge is limiting the addition of new electric loads or improving the efficiency of existing electric heating and cooling equipment by replacing legacy systems with heat pumps. In June 2026, the U.S. Department of Energy (DOE) issued a revised Program Notice (Program Notice 26 – 2) for the two Home Energy Rebates programs created by the Inflation Reduction Act, ending High-Efficiency Electric

Home Rebates (HEEHR) rebate funding for projects that remove an existing fossil-fuel heating system [13, 14]. However, past studies have shown that households with existing fuel oil and propane systems tend to have economically favorable electrification outcomes [1, 2, 15], and the new DOE rebate program policies will remove access to energy savings measures for millions of these delivered fuel homes. This paper uses the Tradeoff Analysis of Residential Energy (TARE) model to identify counties where electrifying home heating and cooling is most beneficial, from both a household-savings and a public-benefits (electricity demand and peak load) perspective [16].

One component of this analysis is a demonstration of how a publicly available heating fuel analysis toolkit can serve as a county-level screening metric for beneficial electrification, informing electricity infrastructure investment and utility incentive programs [17]. A recent study showed that natural gas is the dominant heating fuel in 55.2% of census tracts and electricity in 38.2%, with fuel oil (3.5%) and propane (2.7%) concentrated regionally [17]. According to data from the U.S. Census Bureau's American Community Survey, there has been a 4% decrease in the share of census tracts where natural gas is the dominant heating fuel type and a 5% increase in the prevalence of electric heating from 2011 to 2023 [18–20]. An important metric that determines the relative economic feasibility of electrifying space heating and the geographical distribution of primary heating fuel usage is the electricity-to-gas price ratio, also referred to as the "spark gap" [21]. However, the spark gap is an insufficient indicator of electrification viability, since it does not account for equipment efficiency, climate-driven performance variation, or whether operational savings outweigh incremental capital costs. In addition to comparing county-level visualizations of lifetime operational savings, adoption potential, and changes in electricity demand to the geographic distribution of dominant heating fuel types, we conduct a market potential case study and grid impact analysis for a county dominated by natural gas heating.

Here we assess the economic feasibility of electric heat pump adoption for residential heating and cooling at the local level across the United States and assess the extent of potential electrical grid impacts from heat pump adoption. We examine the unsubsidized adoption potential of residential heat pumps and also examine how existing and proposed rebate policies affect adoption system cost. We address several gaps identified in past work by: (1) developing and validating county-level screening metrics using publicly available data, (2) comparing adoption potential across two heat pump efficiency tiers under multiple economic assumptions, (3) estimating county-level peak and total electricity demand changes from technology-differentiated adoption scenarios, and (4) demonstrating an integrated case study framework that connects adoption potential, grid impacts, and heating fuel distribution at the utility planning scale. Heating fuel distributions are resolved at the census tract scale, the finest resolution at which the American Community Survey reports heating fuel. Adoption potential, operating costs, and grid impacts are resolved at the county scale, which matches the resolution of the building stock, energy price, and income data used in the model. We then evaluate how the December 2024 and June 2026 Home Energy Rebates policies change which homes can justify a retrofit, and what the resulting adoption implies for county-level electricity demand and peak load.

Results

We model the heat pump economic adoption potential under a base case of no purchase subsidies (rebates) availability, and then assess the impacts of rebates under the December 2024 eligibility rules (i.e., Inflation Reduction Act), and the home energy rebates program eligibility rules under the June 2026 Program Notice (see Methods). We define adoption potential as the ability for a household (an economic adopter) to recover the electrification premium, defined as the additional capital cost of a heat pump incremental to a like-for-like replacement of the existing equipment, via discounted lifetime operational savings. The system cost sensitivity varies the avoided cost of the equipment the household was already going to replace (i.e., heating, cooling, or both systems), included in the retrofit cash flow so that the incremental net present value reflects only the additional cost of choosing a heat pump instead of a like-for-like replacement. We chose the unsubsidized rebate policy because the degree to which funding has been allocated and implementation programs rolled out varies significantly by state and these policies are not finalized. Unless otherwise noted, results in the paper correspond to the unsubsidized rebate policy and the replacement cost offset of both systems, with additional sensitivities in the SI.

Geographic distribution of heating fuels and expected outcomes for adoption potential and grid impacts

Figure 1 shows the dominant heating fuel type in each county, produced using a publicly available heating fuel analysis toolkit [22]. The type of home heating equipment varies widely across the country: electric heating dominates the South and Pacific Northwest, delivered heating fuel usage is concentrated regionally (i.e., fuel oil in the Northeast, propane in the rural Midwest), and natural gas dominates the remainder of U.S. counties. At the county level, natural gas is the dominant heating fuel in 40% of counties (46% of homes), and electricity is the dominant heating fuel in 49% of counties (41% of homes) because gas is more common in higher-density areas where natural gas infrastructure exists. Fuel economics (i.e., the relative price of fossil fuels and electricity) plays a vital role in the benefits of electrification retrofits, both for households and the electric grid. We hypothesize that regions where delivered fuels are a dominant heating source will show favorable operating-cost outcomes, despite increased electricity usage, and higher adoption potential. Replacing the less efficient electric resistance heating with a heat pump provides immediate efficiency gains, resulting in favorable electrification outcomes for households adopting the technology and for the public via avoided grid upgrades due to net electricity-demand reductions. Natural-gas-dominated areas are expected to be the least favorable, often leading to bill increases or marginal savings insufficient to recover incremental costs. Natural gas is also the most common heating fuel across the U.S. and is particularly prevalent in colder regions. Thus, significant increases in electricity demand and peak demand during the coldest hours of the year are most likely to occur in these areas. The sections that follow test this hypothesis against county-level results, returning to the fuel map as the screening layer.

Each census tract is colored by its single most common primary heating fuel from ACS 2020–2024 five-year estimates. We classify a fuel source as dominant when it is used by the majority of homes in each county. The corresponding color code for each county's dominant heating fuel source is provided in the legend. Produced using a publicly available heating fuel analysis toolkit [22], as outlined in this peer-reviewed study [17].

County-level unsubsidized adoption potential for minimum-efficiency and high-efficiency heat pumps

We find that the overall unsubsidized adoption potential (the share of homes that would recover the incremental cost over the equipment lifetime) is about 19% (10.4 million single-family homes) for both the U.S. federal minimum-efficiency heat pump and higher-efficiency variable-speed system. Figure 2 reveals geographic clusters of unsubsidized county-level adoption potential that are not visible in national or state-level aggregates. Across 3,079 analyzed counties, the median county-level adoption potential for the minimum-efficiency heat pump is 24% (mean 27%), and about 17% of counties are at or above 50% adoption potential (Fig. 2A). The high-efficiency heat pump shows a slightly lower county median adoption potential of 22% (mean 24%), with about 10% of counties at or above 50% (Fig. 2B).

Without a subsidy, the most favorable counties for heat pump adoption are those where more households heat with electric resistance. For example, counties in the South and Pacific Northwest where electric resistance heating is dominant have the highest county-level adoption potential (median 43% for the minimum-efficiency and 33% for the high-efficiency system). These areas have an already-electric heating baseline and mild heating loads. Homes heated with natural gas are the least favorable anywhere in the country, with only 6% of homes adopting a high-efficiency heat pump (Fig. 4B) and 5% adopting a less efficient single-stage system (Fig. 4A).

The percentage of total adopters is defined as the share of the county sample that would recover either total or net capital expenses without rebates. Deeper green indicates a higher adoption potential rate. Panel (A) shows the minimum-efficiency air source heat pump single-stage option (16 SEER1, 9.5 HSPF1), and panel (B) shows the high-efficiency, variable-speed option (24-29.3 SEER1, 13–14 HSPF1). The national sample size is 3,079 counties. Gray counties have no modeled homes in the study sample.

Changes in annual electricity demand if all homes replace existing heating and cooling systems with different heat pump technologies

We present changes in electricity demand under a case in which all eligible single-family homes replace their existing heating and cooling systems with a heat pump, establishing an upper bound of grid impact independent of economic constraints (referred to as 100% adoption). Figure 3 shows the county-level change in the annual residential electricity demand resulting from replacing existing heating and cooling systems in 53.6 million modeled single-family homes (about two-thirds of the 80.3 million occupied single-family homes represented in ResStock) with either a minimum-efficiency or high-efficiency heat pump. The total annual residential electricity demand for the existing housing stock is referred to as the baseline scenario. Replacing the existing heating and cooling systems in the modeled 53.6 million single-family homes increases the annual residential electricity demand by 278,000 GWh for the min-efficiency system (about a 35% increase relative to the modeled baseline), representing about 18% of total current U.S. annual residential electricity sales [23]. However, replacing the existing heating and cooling systems in these modeled homes with high-efficiency variable-speed heat pumps increases residential electricity demand by only 1,280 GWh (about a 0.2% increase relative to the modeled baseline, representing less than 0.1% of total current U.S. annual residential electricity sales [23]). Both systems

add electricity for heating in homes that currently burn natural gas, propane or fuel oil (378,000 GWh for the minimum-efficiency system and 222,000 GWh for the high-efficiency system). However, the high-efficiency system offsets nearly all this increase by replacing less efficient electric resistance heaters and AC units, reducing heating electricity consumption by 113,000 GWh (against 83,300 GWh for the minimum-efficiency system) and cooling electricity by 108,000 GWh (against 16,100 GWh).

At the county level, we find that 64% of the 3,079 modeled counties that conduct minimum-efficiency heat pump retrofits would have a net increase in electricity demand, with an 18% median county-level increase (Fig. 3A). Opting for the more efficient heat pump option cuts the share of counties with increasing demand from 64% to 42% and turns the median county-level change into a net decrease of 12%. In the Supplementary Materials, we include a map for the magnitude of the annual electricity demand change. **Fig S1** supplements Fig. 3 by including the relative magnitude, which is particularly important for rural counties and much of the Midwest where there are fewer representative dwelling units in the sample size.

County-level percentage change in total residential electricity demand under 100% heat pump adoption. Panel (A) shows the minimum-efficiency air source heat pump single-stage option (16 SEER1, 9.5 HSPF1), and panel (B) shows the high-efficiency, variable-speed option (24-29.3 SEER1, 13–14 HSPF1). The national sample size is 3,079 counties. Gray counties have no modeled homes in the study sample. Please see **Fig S1** in the Supplementary Materials for a choropleth map displaying the magnitude of change in GWh.

Sensitivity of heat pump adoption potential to different rebate program policies

The degree to which a heat pump is economically justified is highly sensitive to rebate eligibility and which piece(s) of equipment the household was due to replace anyway. Figure 4 fixes the replacement offset at its base case (household replacing both heating and cooling equipment) and varies the rebate policy scenario assumptions. For the minimum-efficiency heat pump (Fig. 4A), the December 2024 eligibility rules raise national adoption potential from 19% of single-family homes without any subsidy (10.4 million) to 47% (25 million). The June 2026 rules reduce this to 27% (14.4 million), eliminating 10.6 million homes from the rebate program's original benefit. The high-efficiency system has similar directional results (Fig. 4B), with an unsubsidized adoption potential of 19%, 49% under December 2024 rebate eligibility rules, and 29% under June 2026 eligibility rules. This reduction falls entirely on homes that heat with fossil fuels because a home replacing a gas, oil, or propane system with a heat pump (i.e., removing the fossil system) no longer qualifies for a rebate. Natural-gas adoption potential falls from 34% under December 2024 to its unsubsidized level of 5%, with fuel oil (34% to 15%) and propane (69% to 41%) falling to their unsubsidized levels in the same way. Electrically heated homes are not affected by the policy change, since an electric-to-electric swap still qualifies. Their adoption potential holds at 71% for the minimum-efficiency system, and 72% for the high-efficiency system under both rule sets — well above the 45% and 40% they would reach without any subsidy.

In the Supplementary Materials, we include another dot plot visual for the replacement cost offset sensitivities. **Fig S2** assumes the unsubsidized case for the rebate policy sensitivity and shows the sensitivity of adoption potential to changes in the incremental cost, assuming replacement cost offsets for cooling, heating, or both systems (the sensitivity included in Fig. 4).

Horizontal dot plots of national adoption potential (%) by baseline heating fuel type, offsetting the planned replacement cost of both heating and cooling systems, for the minimum-efficiency (top) and high-efficiency (bottom) heat pump. Markers denote the rebate policy scenario, and the modeled base case is unsubsidized (circle).

Sensitivity of county-level grid impacts from equipment efficiency and heat pump penetration levels

Figure 5 illustrates the impact of heat pump adoption on residential peak load in Allegheny County, Pennsylvania, where nearly all existing homes are heated with natural gas. The residential electricity demand for the existing housing stock (referred to as baseline) is drawn as a red line in Fig. 5, with a peak of 715 MW shown by the dashed horizontal red line. The existing housing stock has a peak that occurs in early July (hour 4433 of the year), and this represents the summer cooling peak. Under 100% adoption, heat pumps in Allegheny County lead to a net increase in peak demand and shift the summer cooling peak to a winter heating peak (dashed blue line). Under 100% adoption of minimum-efficiency heat pumps (Fig. 5B), the aggregate household peak reaches 4,900 MW (hour 152), nearly 7 times the baseline. Simultaneously replacing all heating systems with high-efficiency, variable-speed heat pumps (Fig. 5D) results in a peak electric load that is roughly 17% lower than the minimum-efficiency bound (Fig. 5B), highlighting the importance of incentivizing more efficient equipment. The large increases in both bounding scenarios are driven by the electrification of natural-gas-heated homes, which make up 92% of the county's representative homes. A variable-speed heat pump can operate efficiently under colder temperatures, while a typical single-stage system needs to supply backup electric resistance heating (strip heat) more often to meet the heating load. The backup heating that turns on during the coldest days of the year is several times less efficient than typical heat pump operation, and this results in a higher peak relative to the variable-speed system. In the case where only the households considered potential adopters replace their existing heating and cooling systems with a heat pump (Fig. 5A and Fig. 5C), the change in peak load is negligible because few homes in the county are economic adopters (45 and 68 of 1,146 modeled representative dwelling units for the minimum and high-efficiency systems, respectively).

Peak aggregate household electricity demand for Allegheny County, PA, with different assumptions for heat pump efficiency (rows) and different degrees of heat pump penetration (columns). The red line represents the load for the existing housing stock (peak is the horizontal dashed line) and is consistent in each panel. The blue line represents the load after the heat pump retrofit, and the dashed horizontal blue line represents the post-retrofit peak load. A black open circle marks the exact hour where the peak occurs. The top row is for the minimum-efficiency, single-stage heat pump, with panel (A) representing only economic adopters of the heat pump, with the remainder retaining their existing equipment, and

panel (B) representing the case where all homes replace their existing heating and cooling system regardless of their modeled adoption decision. The bottom shows the same adoption assumption sensitivities for the high-efficiency, variable-speed heat pump.

Limitations of this analysis and opportunities for future work

Several sources of uncertainty should be considered when interpreting our results. First, we will discuss the limitations inherent in the data sources used in our modeling. Energy price projections are drawn from the EIA Annual Energy Outlook 2026 [24] and grid emissions intensity from the National Laboratory of the Rockies (NLR)'s Cambium 2024 dataset [25]. These are annual projections meant to represent the current policy landscape, but they do not capture potential rate restructuring or time-of-use pricing changes. Equipment capital costs are national-average estimates from the National Residential Efficiency Measures Database (REMDB v4), using the recommended NLR mid-point estimate, and are inflated using the Consumer Price Index to be expressed in inflation-adjusted 2025 dollars [26, 27]. REMDB v4 has no data for an electric furnace or electric boiler, so the avoided replacement cost of these systems is estimated with the electric baseboard formula. The ResStock database and TARE model include a simplified representation of the rebate programs, exclude household electric service upgrade costs, and use state-average fuel prices [2, 28, 29]. ResStock also models the housing stock circa 2018, and it is likely that the equipment present in these homes has since changed. Future work could explore alternative methods for representing the rising cost of appliances beyond the consumer price index and apply state and local cost adjustment factors.

Next, we will discuss sources of uncertainty tied to our modeling assumptions and methods. Our modeled adoption potential framework does not account for behavioral barriers, split incentives in rental housing, or workforce availability constraints. At the time of this analysis, the finalized rebate program guidance and state-specific information for the weatherization required before homes can access heat pump rebates were not available. Consequently, the modeled June 2026 rebate scenario omits the new weatherization prerequisite, and we assume no homes with existing fossil fuel systems qualify for a rebate (dual fuel systems are not included in this analysis). The grid impact analysis includes estimates for county-level electricity demand and peak load changes, but does not model distribution-level power flow or transformer capacity. Both modeled technology options satisfy the rebate programs' efficiency requirements because we adjust the specifications of the minimum-efficiency option to meet ENERGY STAR requirements. While the adjusted efficiency is used for cost estimation, the modeled energy use from ResStock still represents the original technical specifications, and this leads to a conservative treatment of its savings (see Methods). Lastly, adoption potential estimates throughout this analysis should be interpreted as indicative upper bounds under the stated assumptions, not as forecasts of realized adoption.

Additional details on the limitations of this study can be found in the documentation for the ResStock 2022 Dataset Release [29] and past studies using the TARE model [1, 2]. Future work could further improve the resolution of technology, policy, and household characteristics, including decision drivers. In

our analysis, rebate-eligible projects are now limited to electric-to-electric upgrades (we do not model dual fuel at this time). Extending the framework to dual-fuel systems remains a priority for future work, particularly for colder climates with access to relatively cheap natural gas.

Discussion

This analysis identifies areas where electrifying home heating and cooling can be beneficial in the U.S., in terms of household savings and public grid benefits. We also investigate how recent changes in federal rebate programs reshape the distribution of benefits. Overall unsubsidized adoption potential is about 19% (10.4 million) for both the federal minimum-efficiency heat pump and higher-efficiency variable-speed system. We find that removing rebates for fuel-switching decreases overall adoption potential by 10.6–11.0 million single-family homes, which includes a 28–29% drop for homes with natural gas systems and a 20–36% decrease for homes using fuel oil and propane. We analyze 3,079 counties and visualize county-level adoption potential and resulting changes in residential electricity demand across the nation. We also conduct a detailed grid impact analysis for a county in Pennsylvania to show the impacts of heat pump adoption under different penetration levels and for the modeled least and most efficient systems available on the market today. In gas-dominated counties (e.g., Allegheny County), more homes choosing an inefficient heat pump could result in up to a 7-fold increase in residential electricity peak load. However, our results show that higher-efficiency systems can help mitigate increases in peak residential load and the need for grid upgrades. In other words, incentives favoring efficient equipment could align household and grid outcomes by reducing the higher upfront cost barrier.

The degree to which incentive funding has been allocated and implemented varies significantly by state. Since these policies are not finalized, we treat the December 2024 and June 2026 rules as bounding policy scenarios rather than forecasts. The HEEHR rebate program (December 2024 and earlier) was intentionally designed to promote the adoption of efficient electric appliances in low-to-moderate income households, and the HOMES program makes incentives available to all homes, so long as these homes meet modeled or measured savings requirements. The rebates reduced the upfront cost of a heat pump retrofit by up to $8000 and made it possible for more families to cut their energy bills, while improving health outcomes and reducing greenhouse gas emissions. The One Big Beautiful Bill Act of 2025 primarily affected the clean-energy tax credits rather than the rebates [30]. However, the Homeowner Energy Freedom Act, which passed the House in early 2026, would rescind any unobligated rebate balances and repealed the electrification rebate program, state-based contractor training grants, and building energy code adoption assistance [31]. The June 2026 Program Notice effectively ended rebate funding for projects that remove a fossil-fuel heating system, alongside other administrative changes that affect program operation [13, 14]. The June 2026 Program Notice allows for a transition period through the end of August, during which states can continue running their programs as previously approved. Our rebate scenarios follow the June 2026 Program Notice (Program Notice 26 – 2). In our June 2026 scenario, only homes with existing electric heating receive a rebate: up to $8,000 through HEEHR for households at or below 150% of area median income, and up to $4,000 through HOMES above that (see Methods). Each home receives at most one rebate, and homes in South Dakota receive

no rebates because the state did not take part in the federal rebate programs. Lastly, we do not apply a state-level funding cap, so the modeled rebate totals represent uncapped modeled potential and exceed the combined appropriation of roughly $9 billion.

As the policy landscape evolves and state rebate programs are established, county-level screening tools that can inform state and utility program design become increasingly useful for targeting funding allocation. The remaining subsidized market for existing electric resistance systems is concentrated in the South, where heating loads are modest, cooling dominates, and a variable-speed system offers more capability than most homes require at a higher upfront cost. Variable-speed and two-stage systems nonetheless remain important for colder regions, where they maintain heating capacity and efficiency at low outdoor temperatures, improve occupant thermal comfort, and reduce reliance on electric-resistance backup during winter peaks.

Methods

An integrated modeling framework was developed to estimate the adoption potential of residential heat pumps across the United States, considering household equipment purchase and operational costs and county-level grid impacts. The approach combines primary heating fuel analysis, detailed building energy simulation, cost-based adoption modeling, and grid impact analysis. In this study, we extend the functionality of the TARE model in several important ways: (1) developing and validating useful screening metrics using publicly available data, (2) updating equipment capital cost data from the National Residential Efficiency Measures Database [26], (3) improving cost estimation methods with a novel approach validated with external industry cost data, (4) including additional technology options, and (5) incorporating grid impact analysis.

For the TARE model, projections (2025 through 2039, representing a 15-year equipment lifetime) for fuel prices are obtained directly from the EIA Annual Energy Outlook 2026 and grid emissions intensity projections come from the Cambium 2024 dataset (latest available at the time of the analysis) [24, 25]. The area median income thresholds and rebate program parameters reflect current data, and all costs are expressed in inflation-adjusted 2025 dollars. The model now accounts for cooling operational and capital costs alongside heating, where earlier versions considered heating costs only. We also model the new guidance for the DOE Home Energy Rebates program, using the June 2026 Program Notice (Program Notice 26 – 2) [13, 14]. Households at or below 150% of area median income (AMI) are eligible for HEEHR, which covers 100% (at or below 80% AMI) or 50% (80–150% AMI) of the heat pump cost up to $8,000. For households above 150% AMI, they are eligible for HOMES, which covers 50% of the project cost up to $2,000 or $4,000 for modeled whole-home energy savings of at least 20% or 35%. The December 2024 rules make both programs available regardless of the existing heating fuel, while the June 2026 scenario removes eligibility for fuel-switching projects. Overall, these improvements and extensive documentation significantly lower the barrier to entry for residential energy systems modeling and expand access to a wider audience.

ResStock data and the TARE model

The ResStock dataset has been widely used to provide metadata on housing characteristics and occupants and to model annual and time-series household energy consumption [1, 2, 10, 11]. The 2022.1.1 release of the ResStock dataset (also known as End-Use Savings Shapes or EUSS) combined a building characteristics database, physics-based computer modeling (accounting for climatic impacts on heating load and system performance), and high-performance computing to statistically represent the characteristics and consumption of the residential housing stock and potential retrofit upgrades (referred to as measure packages) [28, 29]. The TARE model accounts for the dynamic influence of climate change on heating and cooling demand by multiplying the 2018 energy consumption (AMY2018 and housing stock circa 2018) by projection factors derived from the regional EIA Annual Energy Outlook Heating Degree Day (HDD) and Cooling Degree Day (CDD) projections [2, 24]. Like preceding studies, this analysis is focused on single-family homes due to these housing types being more representative of available capital cost data [2]. Single-family homes are also the most common residential building type in the U.S., account for most residential thermal energy use, and have the highest thermal energy use intensity of any building type except mobile homes [32]. After filtering for occupied single-family homes with heating and cooling technologies for which cost data was available, the original ~ 550,000 dwelling unit sample (1 unit for approximately every 240 homes that exist in the U.S.) was reduced to ~ 221,000 dwelling units or ~ 53.6 million homes. We restrict the analysis to occupied single-family homes with both an existing heating system and an existing cooling system of their own, so that every modeled retrofit replaces equipment the household already operates rather than adding heating or cooling as a new service. The housing-type and heating-technology filters, and the exclusion of homes with a shared cooling system, reflect the equipment and building types for which installed-cost data are available (Table 1). Table 2 describes the technology included in our analysis, and additional information regarding ResStock data can be found in their technical documentation [28, 29, 33].

Table 1

Table of representative dwelling units after each filtering step. The final row of the table indicates the number of representative dwelling units and homes included in the study.

Filter	Representative dwelling units (rdu) remaining	Homes remaining (M)	Removed (rdu)	Removed homes (M)
ResStock 2022.1.1 stock	548,916	132.91	—	—
Upgrade applicable	548,260	132.75	656	0.16
Occupied	482,050	116.72	66,210	16.03
Single-family (attached, detached)	331,526	80.27	150,524	36.45
Heating fuel: electricity, natural gas, propane, fuel oil	321,352	77.81	10,174	2.46
No existing heat pump	290,005	70.22	31,347	7.59
Heating system with cost data	260,211	63.01	29,794	7.21
Existing cooling system (central or room AC)	221,301	53.58	38,910	9.42
Cooling system not shared	221,205	53.56	96	0.02

The TARE model was used for the techno-economic analysis of single-family homes, providing an indicative assessment of retrofit feasibility relative to a like-for-like replacement at the end of the existing equipment's useful life [2]. After projecting future space heating and cooling demand using HDD and CDD projections, the TARE model used annual energy consumption and household metadata (for both baseline and post-retrofit packages) to calculate household lifetime operational savings, emissions reductions, and incremental capital costs with and without incentives. Heating and cooling energy use includes the primary equipment, fans and pumps, and electric-resistance backup heat, each priced at its fuel’s price. We defined adoption potential as the share of homes for which heat pump replacement is economically justified under modeled market conditions. We then evaluated county-level adoption rates, changes in electricity demand, and peak load impacts for each technology option. The enhancements made to the TARE model in this analysis allow for a more comprehensive electrification feasibility assessment by using updated data sources, improving past capital cost estimation methods, covering a wider variety of technology options and economic assumptions, and incorporating grid impacts. Additional information regarding the data used in our analysis, as well as the underlying assumptions and methodologies of the TARE model, can be found in the past studies using version 1 and version 2 of the model [1, 2].

Table 2

ResStock Data Description. Both datasets include a baseline scenario. In all cases, the 2018 housing stock and actual meteorological year 2018 (AMY2018) are modeled.

ResStock Release 2022.1.1 ***Measure Package Name***	**Description**
MP0: Baseline Counterfactual	Like-for-like replacement with minimum-efficiency floors adjustment. Used for replacement cost estimate.
MP3: **Heat Pumps, Min-Efficiency**, *Electric Backup*	Ducted: Centrally-ducted heat pump 15 SEER1, 9 HSPF1*, sized with ACCA Manual S Non-Ducted: Ductless mini-split heat pump 15 SEER1, 9 HSPF1*, sized to max load
MP4: **Heat Pumps, High-Efficiency**, *Electric Backup*	Ducted: Centrally ducted variable-speed heat pump (ducted mini-split): SEER 24, 13 HSPF, sized with ACCA Manual S Non-Ducted: Ductless variable-speed mini-split heat pump: SEER 29.3, 14 HSPF, sized to max load

* Minimum-efficiency single-stage heat pump technical specifications were adjusted to clear the ENERGY STAR minimum requirement (16 SEER1, 9.5 HSPF1 converted from SEER2 and HSPF2) and be eligible for the home energy rebates. Please see the Methods section for details.

Capital cost estimation and validation

Equipment capital costs were estimated using deterministic regression formulas from the National Residential Efficiency Measures Database (REMDB v4.0.0), which represents 2023 technology and practice in USD2023 [26]. Two regression cost formulas are used to obtain the installed cost, $C_{installed}$ **(See Eq. 1 and Eq. 2)**. First, the material price is estimated by multiplying the equipment performance metrics by a coefficient $\left(pm \times pm_{coefficient}\right)$, the products of each metric are summed, and then an intercept value is added. The second step multiplies the material price, $C_{material}$, by a retrofit or new construction multiplier and applies an adder to the product. Capital costs are national-average estimates; state and local cost adjustment factors identified in the REMDB documentation were not applied in this analysis and are left to future work, so the reported results are directly comparable to past work using unadjusted capital costs [1, 2].

$$C_{material} = \left[\left(pm_1 \times pm_{1,\ coefficient}\right) + \left(pm_2 \times pm_{2,\ coefficient}\right)\right] + intercept \textbf{ (Eq. 1)}$$

$$C_{installed} = \left[C_{material} \times multiplier\right] + adder \textbf{ (Eq. 2)}$$

One of the primary issues we observed in the cost validation process was a misalignment of equipment specifications. The EUSS models a housing stock circa 2018 with equipment from the late 1990s and early 2000s, resulting in legacy efficiencies like 8–10 SEER central ACs and 60–76% AFUE furnaces. These are well below the REMDB v4 regression bounds, which are calibrated to equipment available in 2023 and beyond. When these legacy systems fail, homeowners do not replace them with identical

1990s-era equipment. They purchase what is currently available on the market, which must meet current federal minimum standards. Applying these changes brought the efficiency of central ACs, furnaces, and boilers in the ResStock data within the NLR regression bounds (equipment sizes outside a formula's range are priced by extending the regression line), and led to more reasonable estimates validated by proprietary data from an HVAC equipment manufacturer.

When estimating the capital cost of the minimum-efficiency equipment and rebate eligibility, we adjusted the equipment specifications to barely clear the eligibility threshold. In other words, the costs for the minimum-efficiency option were estimated at the ENERGY STAR-equivalent specification (16 SEER1, 9.5 HSPF1) rather than the ResStock system (15 SEER1, 9 HSPF1). The associated energy consumption remains that of the minimum-efficiency measure package (MP3), so the modeled savings for this option are conservative. There are several reasons for this adjustment. First, the two technology options in the 2022 ResStock release represent the least efficient and most efficient systems available on the market, and the ENERGY STAR threshold is much closer to the minimum-efficiency heat pump technical specifications. Second, homeowners replacing a failed system tend to purchase equipment meeting current federal minimum standards or what is readily available (often the same system). Lastly, households with existing electric resistance systems (those eligible for the rebates) are concentrated in the South, where the higher-efficiency variable-speed system far exceeds what is required.

Modeling grid impacts from heat pump adoption

The first way we model grid impacts from heat pump adoption is by determining the changes in annual residential electricity demand. ResStock includes baseline and post-retrofit electricity consumption for each building in the database, indexed by unique building IDs. We assigned each building in the sample to either its baseline (non-adopter) or post-retrofit (adopter) electricity consumption based on the adoption potential determined by the TARE model. For a given geographic region, we aggregated the assigned consumption values to estimate the change in total residential electricity demand. A 100% adoption bounding scenario was modeled by assigning all homes in the study sample to their post-retrofit consumption, representing the upper bound of grid impact from simultaneous replacement of all their heating and cooling systems.

The second way we model grid impacts is by determining changes in peak load through a detailed analysis of the time-series data for building energy consumption. Building IDs from each adoption scenario were used to query hourly electricity consumption from the AWS-hosted ResStock time-series data. For each county, we constructed aggregate load profiles by summing the hourly consumption of adopter households (post-retrofit) and non-adopter households (baseline). Peak load changes were identified from these scenario-specific aggregate profiles. We used the county level as the geographic unit of analysis because county-level census data, fuel price data, and building stock metadata are readily available, and county boundaries provide a reasonable approximation for utility and regional planning purposes.

Analyzing the geographic distribution of primary heating fuels

The geographic distribution of dominant heating fuels comes from a publicly available census-tract dataset and toolkit [17, 22]. That resource derives tract-level counts of occupied housing units using each of nine heating fuel types from American Community Survey five-year estimates (accessed through the National Historical Geographic Information System) for three periods — 2011–2015, 2016–2020, and 2019–2023. The toolkit then identifies the dominant fuel in each tract and generates the maps used here through a documented, publicly available workflow with data deposited on Zenodo [22]. We re-ran the toolkit using the most recently available 5-year period data (2020–2024) at the county-level, as this is the resolution of this study's results [34]. The limitations of this data source are documented in the paper and the data repository.

Declarations

Data availability

All data supporting this study's findings were sourced from publicly available datasets and are available on Zenodo [35]. Data repository DOI: https://doi.org/10.5281/zenodo.23399051

Code availability

The analysis code and visualization tools are publicly available in the GitHub repository under the GNU GPLv3 license [36]. Code repository DOI: https://doi.org/10.5281/zenodo.23461999

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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AI-assisted tools (e.g., Grammarly) were used as part of the proofreading and editing process to strengthen the quality of this work. As further described in the codebase documentation, Claude and GitHub Copilot were used for troubleshooting and debugging. The original text was written by the

authors, and all suggestions (both written and for coding) were reviewed by the authors and then accepted, rejected, or modified. The words and ideas expressed here are those of the authors.

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Figures

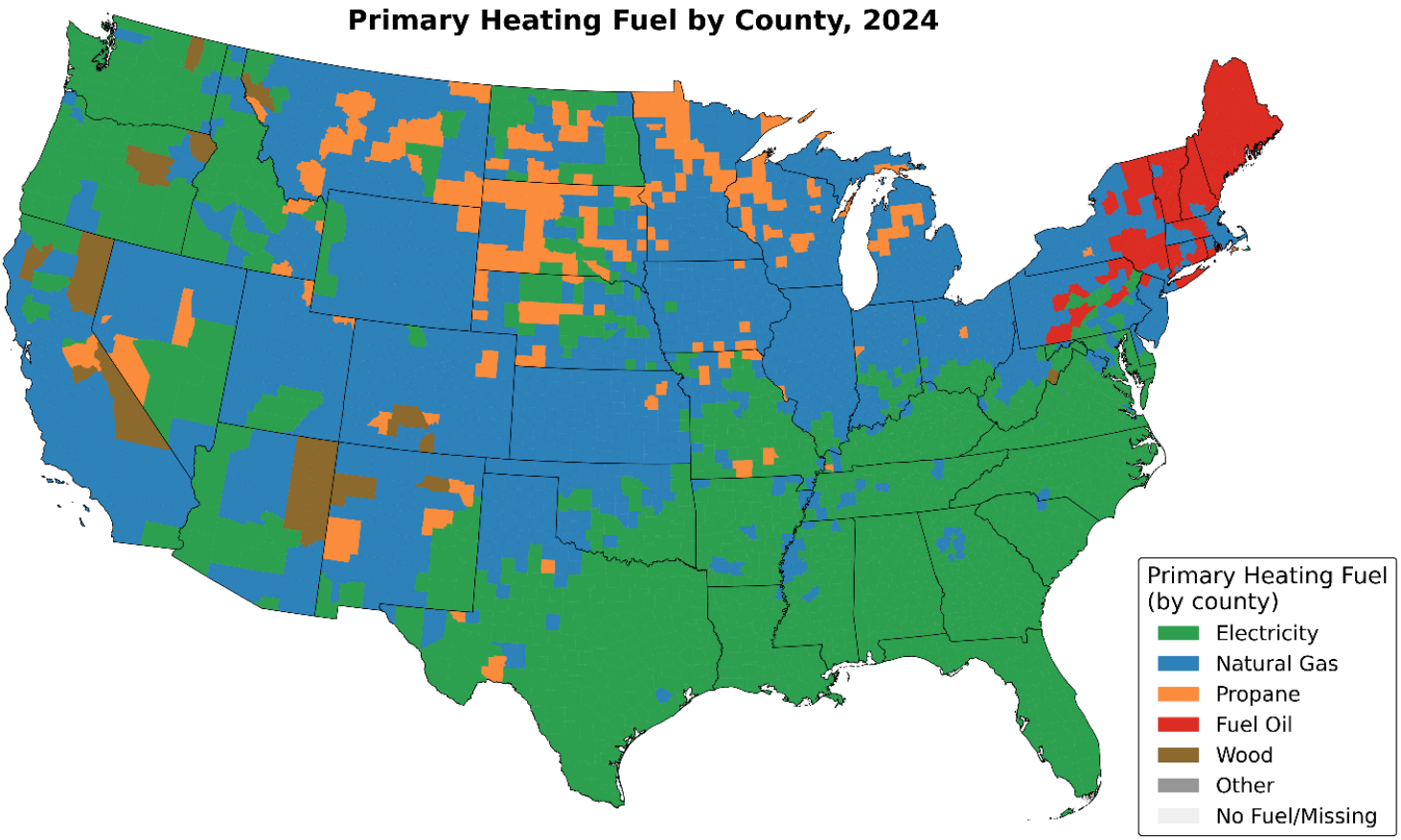


Figure 1

Map of U.S. primary heating fuel by county. Data from ACS 5-year averages for the time period 2020-2024.

Each census tract is colored by its single most common primary heating fuel from ACS 2020–2024 five-year estimates. We classify a fuel source as dominant when it is used by the majority of homes in each county. The corresponding color code for each county's dominant heating fuel source is provided in the legend. Produced using a publicly available heating fuel analysis toolkit [22], as outlined in this peer-reviewed study [17].

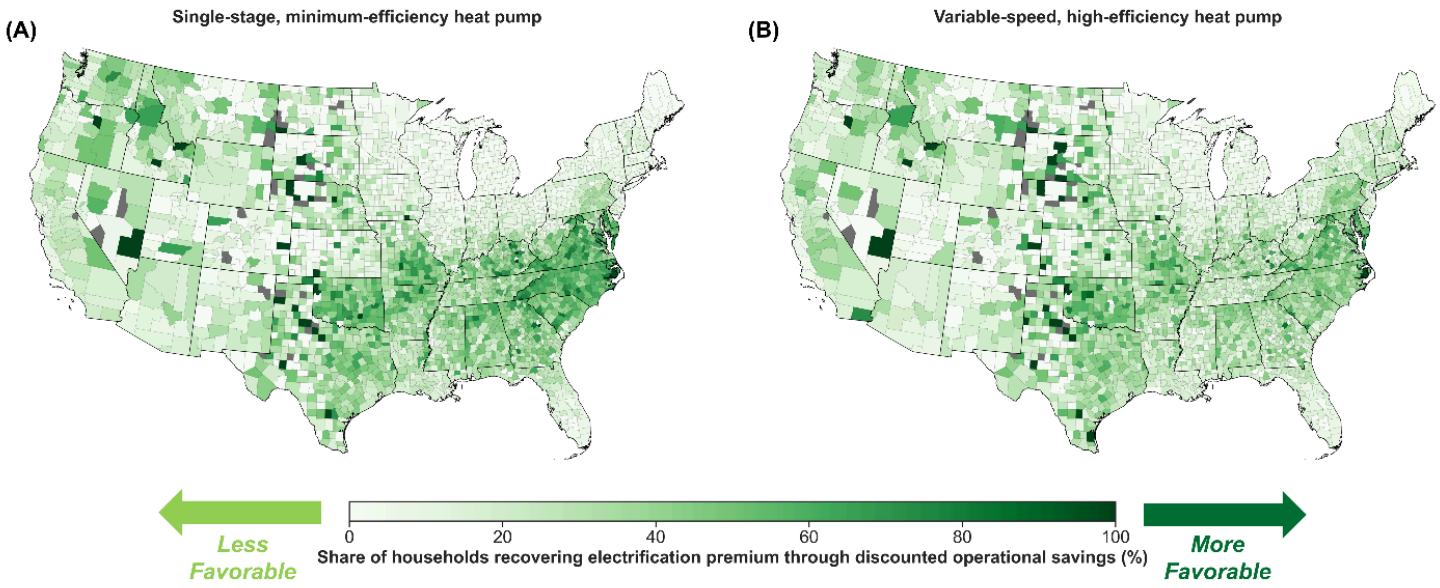


Figure 2

County-level adoption potential for standard and high-efficiency heat pumps reveals geographic clusters not visible in state-level aggregates.

The percentage of total adopters is defined as the share of the county sample that would recover either total or net capital expenses without rebates. Deeper green indicates a higher adoption potential rate. Panel (A) shows the minimum-efficiency air source heat pump single-stage option (16 SEER1, 9.5 HSPF1), and panel (B) shows the high-efficiency, variable-speed option (24-29.3 SEER1, 13-14 HSPF1). The national sample size is 3,079 counties. Gray counties have no modeled homes in the study sample.

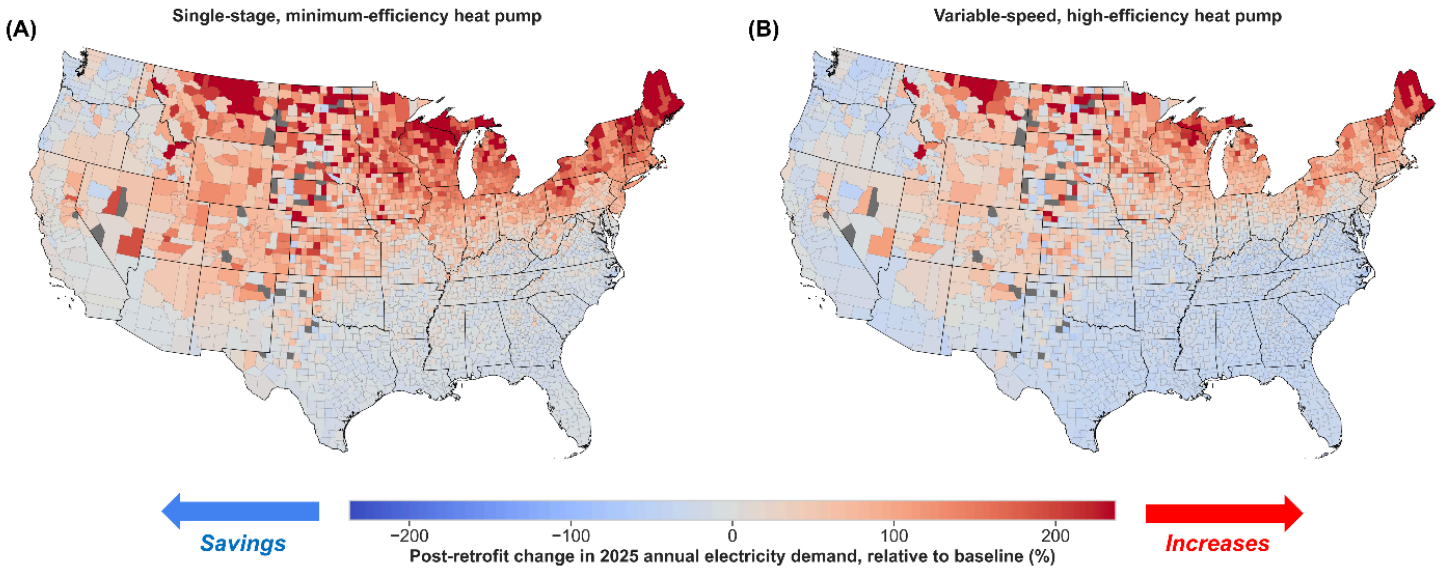


Figure 3

The change in electricity demand is highly dependent on the efficiency of the heat pump retrofit.

County-level percentage change in total residential electricity demand under 100% heat pump adoption. Panel (A) shows the minimum-efficiency air source heat pump single-stage option (16 SEER1, 9.5 HSPF1), and panel (B) shows the high-efficiency, variable-speed option (24-29.3 SEER1, 13-14 HSPF1). The national sample size is 3,079 counties. Gray counties have no modeled homes in the study sample. Please see **Fig S1** in the Supplementary Materials for a choropleth map displaying the magnitude of change in GWh.

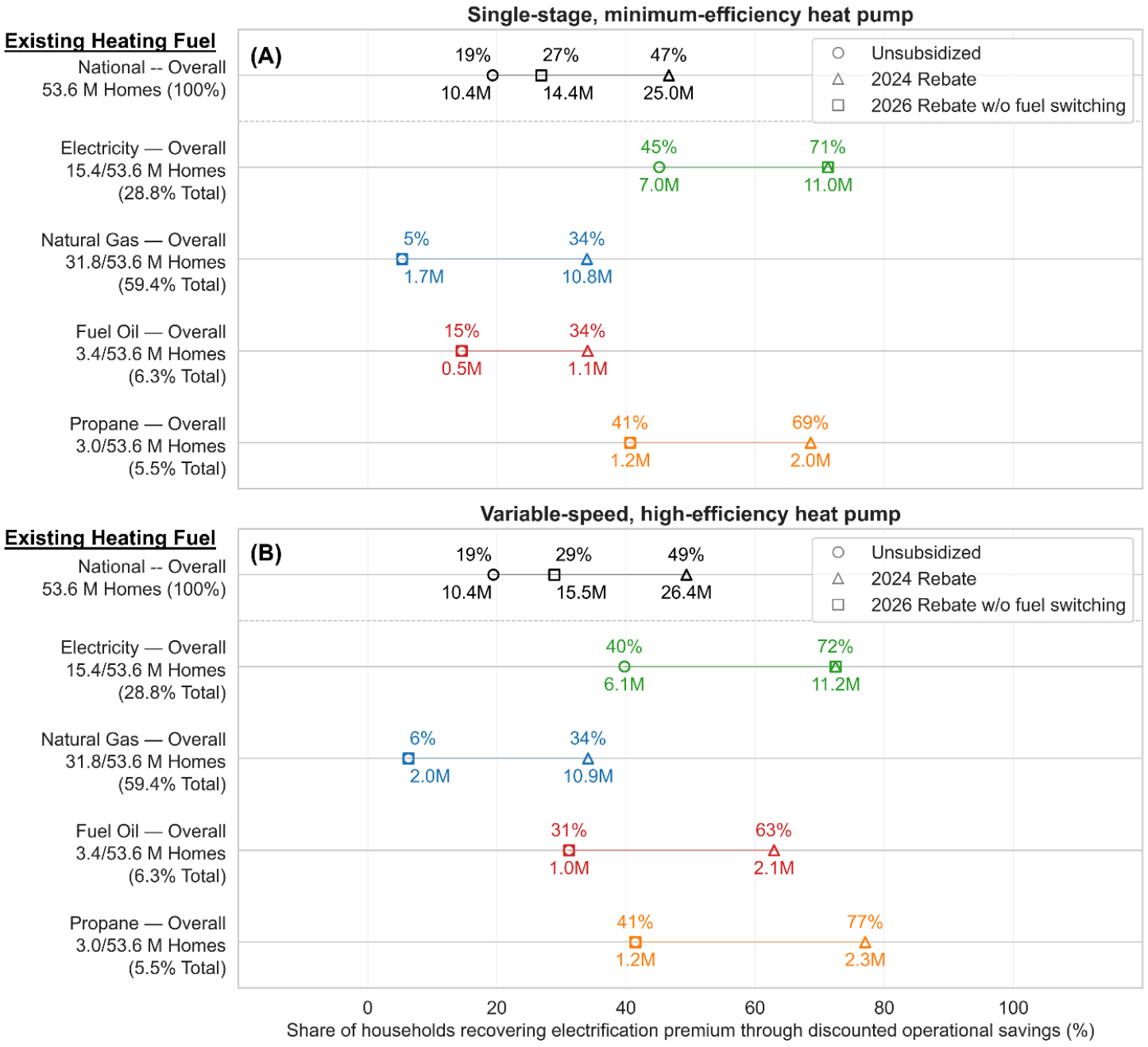


Figure 4

Rebate eligibility changes in the June 2026 Program Notice sharply reduce adoption potential for homes with existing fossil-fuel systems relative to the December 2024 guidance.

Horizontal dot plots of national adoption potential (%) by baseline heating fuel type, offsetting the planned replacement cost of both heating and cooling systems, for the minimum-efficiency (top) and high-efficiency (bottom) heat pump. Markers denote the rebate policy scenario, and the modeled base case is unsubsidized (circle).

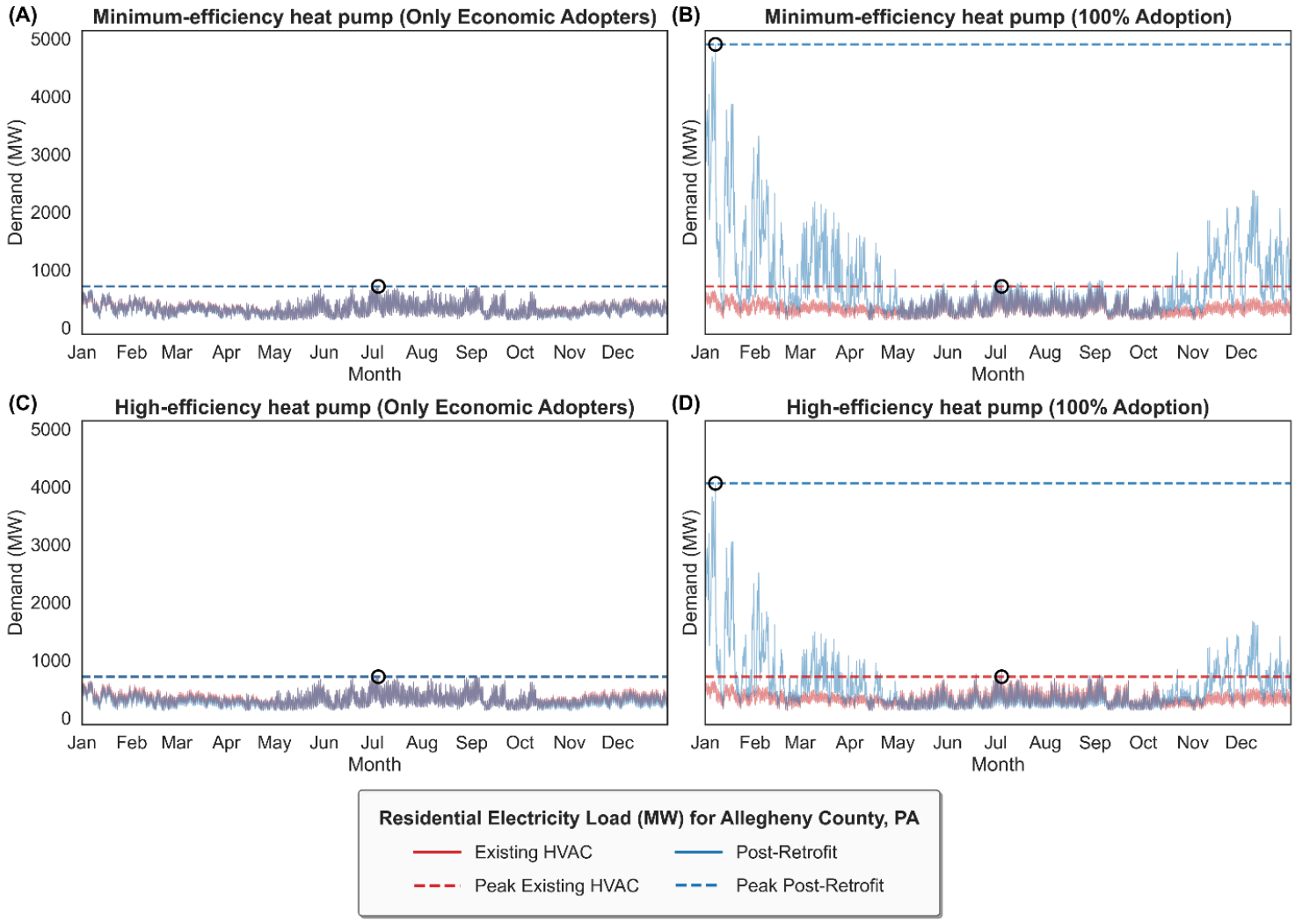


Figure 5

Impacts of heat pump adoption in a gas-dominated region on residential peak load, with sensitivities for equipment efficiency (rows) and adoption assumptions (columns).

Peak aggregate household electricity demand for Allegheny County, PA, with different assumptions for heat pump efficiency (rows) and different degrees of heat pump penetration (columns). The red line represents the load for the existing housing stock (peak is the horizontal dashed line) and is consistent in each panel. The blue line represents the load after the heat pump retrofit, and the dashed horizontal blue line represents the post-retrofit peak load. A black open circle marks the exact hour where the peak

occurs. The top row is for the minimum-efficiency, single-stage heat pump, with panel (A) representing only economic adopters of the heat pump, with the remainder retaining their existing equipment, and panel (B) representing the case where all homes replace their existing heating and cooling system regardless of their modeled adoption decision. The bottom shows the same adoption assumption sensitivities for the high-efficiency, variable-speed heat pump.

Supplementary Files

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