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From Models to Reality: A Systematic Review on Simulated and Measured Residential Heat Pump Energy Savings

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21 Keywords
22 High-performance HVAC; Residential HVAC systems; Energy efficiency; Energy simulation;
23 Field measurement; Building retrofit.

24 Nomenclature

25 HP
26 Heat Pump
27 ASHP
28 Air-Source Heat Pump
29 ccASHP
30 Cold-Climate Air-Source Heat Pump
31 GSHP
32 Ground-Source Heat Pump
33 EUI
34 Energy Use Intensity
35 HVAC
36 Heating, Ventilation, and Air Conditioning
37 PV
38 Photovoltaic
39 TES
40 Thermal Energy Storage
41 TMY
42 Typical Meteorological Year
43 kWh
44 Kilowatt-hour
45 kBtu
46 Kilo British Thermal Units
47 MMBtu
48 Million British Thermal Units

Abstract

High-performance HVAC solutions are central to residential energy management. A substantial share of these are electric, reversible-cycle systems, with heat pumps representing the largest portion of current and near-term adoption. This review synthesizes peer-reviewed and grey literature on residential space heating and cooling heat pumps. The academic literature is dominated by modeling (73.8%), with limited field measurement (13.1%). Grey literature from United States serve as a supplemental resource providing measured savings. Conversions from electric-resistance heating consistently show the largest site energy reductions, while oil/propane baselines yield moderate savings, and gas baseline scenario often deliver small and region-dependent savings. This study cross-checks the grey literature measured data with simulation data filtered from the ResStock dataset. The comparison indicates a discrepancy between simulations and measured data: simulated site EUIs are typically lower than measured EUIs, but percentage energy savings fall in similar ranges, implying simulations capture directional effects while underestimating energy use. Factors associated with variability and model-measurement differences include system characterization and control representation (e.g., backup heat engagement, thermostat/setpoint strategies, commissioning/installation quality), occupant behavior, weather normalization, metering scope, and envelope characterization. This paper also outlines the proposed methodology for comparing simulation and measured data for heat pumps. It emphasizes the metrics used for comparison and units harmonization, building characteristics matching, and compact metadata are needed for simulations to match measured data. The proposed methodology is expected to improve the credibility of simulated savings as measured evidence grows.

1. Introduction

High-performance HVAC systems are a major focus of residential building energy research because they aim to reduce energy use, improve comfort, and support emerging load management needs. A longstanding challenge across all high-performance systems is that real-world performance often differs from expectations based on rated efficiency or modeled outcomes. Understanding these discrepancies is essential for both research and program planning.

Within this broad category, heat pumps (HPs) have received substantial attention in recent years. Their deployment across diverse climates and housing types has made a practical example for examining modeled-versus-measured savings. Market statistics reflect this broad presence. The International Energy Agency identifies HPs as one of the most widely adopted high-performance HVAC options globally [1]. In the United States, the world's second-largest market, AHRI (Air Conditioning, Heating and Refrigeration Institute) shipment data show consistent year-over-year growth between 2023 and 2025, with shipments exceeding other types by roughly four to one [2]. This prevalence is why HPs serve as a suitable case study for investigating performance gaps.

Persistent adoption barriers remain, which include high upfront costs, uncertainty in operation costs, consumer awareness limitations, and contractor availability [3, 4, 9]. These adoption challenges are compounded by uncertainty about energy performance and savings. In the United States, regional initiatives and utility programs are the primary drivers of adoptions [3, 4]. These programs recognize that addressing market barriers requires not only financial incentives but also reliable information about energy performance to build consumer confidence and justify program investments. To plan portfolios, set incentive levels, and forecast savings, many programs rely on Technical Reference Manuals (TRMs) and standardized evaluation protocols (e.g., the Uniform Methods Project) that document deemed values and engineering algorithms used for ex-ante savings and cost-effectiveness screening [4, 5]. Those savings estimates are typically grounded in engineering simulations run on “prototype” buildings [6, 7, 8]. Program administrators use these projections to establish rebate levels and set targets, while customers consider the savings estimates as part of their decision-making for heat pump installations. In this review we will not directly cover any of these cost-related issues.

These realities raise important questions about how well simulated savings translate to real-world outcomes. This literature review therefore focuses on three research questions critical for advancing heat pump energy analysis and supporting more effective market development strategies:

Research Question 1: What is the current state of knowledge on simulated and measured heat pump energy savings, beyond efficiency metrics?

Research Question 2: How do simulated energy savings compare to measured energy savings? What are the potential causal factors contributing to the discrepancies if they exist?

Research Question 3: What systematic methodology would be useful for comparing field energy savings to simulation data, and what key dimensions should be considered in such comparisons?

To answer these research questions, this literature review encompasses a systematic search of academic databases for peer-reviewed studies on energy use, complemented by analysis of U.S. utility program evaluations and field studies. This combined approach recognizes that academic research provides rigorous analysis while utility program evaluations offer insights into real-world performance under different operating conditions. The paper synthesizes academic knowledge on energy savings by system type, then analyzes U.S. utility program data to compare simulated versus measured performance across different regions and applications. The discussion identifies potential factors contributing to discrepancies and proposes a methodology for systematic comparison of simulated and measured savings.

2. Methodology

This literature review employed a systematic approach to identify and analyze both academic and grey literature sources addressing heat pump energy savings. The methodology was designed to capture evidence on energy performance from both simulated and measured studies to enable subsequent comparison analysis.

2.1 Academic Database Search

A systematic search was conducted across three major academic databases: Scopus, IEEE Xplore, and OSTI.GOV. These databases were selected to ensure comprehensive coverage of engineering, energy, and building science literature.

The search strategy employed a structured Boolean query designed to capture studies examining energy savings of this high-performance HVAC system in residential applications compared to conventional heating systems. The query targeted publications containing system technology terms (including various combinations of heat pump system descriptors), energy performance indicators ("energy savings," "efficiency," "energy reduction," "energy conservation," "energy performance"), residential building contexts ("residential," "home," "house," "dwelling," "domestic," "household," "apartment"), comparative analysis terms (e.g., "compare," "versus," "baseline," "retrofit"), and conventional heating system references ("gas," "furnace," "boiler," "electric resistance," "oil," "propane," "fossil fuel"). Studies focusing on water heating applications were excluded to maintain focus on space heating and cooling applications.

The search was limited to English-language publications to ensure consistent analysis and interpretation. A wide temporal restriction from 2000 - 2025 was applied to capture the evolution of research on this type of system.

2.2 Grey Literature Collection

Recognizing that utility program evaluations and field studies often contain valuable measured performance data not captured in academic publications, a targeted collection of grey literature was conducted. This approach was justified by several key factors that emerged during the initial academic database search.

The academic literature search revealed a limited number of studies reporting measured energy savings data from field installations, with most academic research focusing on laboratory testing, simulation studies, or efficiency metrics rather than field-measured energy consumption. This scarcity of measured performance data in peer-reviewed literature creates a significant knowledge gap for understanding actual energy savings in operational conditions.

Furthermore, utility programs serve as front-line implementers of installations and oftentimes possess first-hand data through their program evaluation requirements. These organizations are mandated by regulatory frameworks to conduct evaluations of their energy efficiency programs,

including measurement and verification of actual energy savings achieved by energy efficiency measures. Utility program evaluations therefore represent a critical source of empirical data that complements the academic literature by providing measured performance data from diverse building types, climate conditions, and baseline system scenarios.

The grey literature collection included utility program evaluation reports and industry field studies from the United States. Grey literature sources were identified through systematic searches of utility websites, state energy program databases, the Database of State Incentives for Renewables and Efficiency (DSIRE), and reports from organizations such as the American Council for an Energy-Efficient Economy (ACEEE), Rocky Mountain Institute, and U.S. Department of Energy National Laboratories.

2.3 Inclusion and Exclusion Criteria

Studies were included if they reported quantitative energy savings data for residential buildings, included comparison to baseline heating systems, provided sufficient methodological detail to assess data quality, and focused on space heating and cooling applications rather than water heating. For grey literature acceptability, documentation of evaluation methodology and data collection procedures is required.

Exclusion criteria eliminated studies focusing solely on efficiency metrics without energy consumption data, commercial or industrial applications, and studies lacking sufficient detail about baseline systems or measurement methodology. Conference abstracts and brief communications without full methodological descriptions were also excluded.

Data extraction captured study characteristics including system types, building characteristics, climate zone, measurement methodology, duration of monitoring, and reported energy savings with associated uncertainty measures where available.

2.4 Data Extraction and Metadata Schema

To enable structured synthesis across heterogeneous study designs, a standardized set of metadata and outcome variables was extracted from each academic study and grey literature and recorded in an extraction database. The schema was designed to (1) support transparent aggregation (e.g., by baseline heating type, system category, climate/region, and study type), (2) document reporting completeness and uncertainty, and (3) support evidence-weighted interpretation of factors that influence predicted savings and realized savings.

For each study, the following information was extracted where reported:

Study Descriptors: publication year, country/region (climate when available), study type (simulation-only, field measurement-only, mixed simulation + field), sample size (if field), monitoring duration (if field), and weather basis/normalization approach (e.g., TMY, actual weather, degree-day normalization, regression).

Building Characteristics: residential building type (single-family/multifamily), floor area, vintage/age band, distribution system (ducted/ductless; hydronic vs forced-air when available), and envelope characterization reporting level (e.g., insulation/air leakage/windows reported vs not reported).

System Characterization: heat pump type (air/ground/water source, other technology), baseline heating system type (electric resistance, gas, oil, propane, district, etc.), presence and type of backup/supplemental heating, and the level of operational/control description (e.g., setpoints/schedules, dual-fuel switching).

Outcomes: energy scope and metric definition (e.g., HVAC-only vs whole-home; heating-only vs space conditioning; site vs source/primary energy), baseline and post energy, reported savings (absolute and/or percent). When uncertainty information was reported (e.g., confidence intervals, standard errors, calibration statistics), it was recorded alongside the primary outcomes.

Factors affecting model-measurement differences: To understand the likely model-measurement discrepancies identified in the study, the data schema also includes evidence coding of factors. Because most studies are simulation-only or measurement-only (rather than direct model-measurement comparisons), three evidence categories were distinguished when synthesizing factors associated with differences and variability in reported savings: (1) measured-variability evidence from field studies; (2) modeled-sensitivity evidence from simulation scenario/sensitivity studies; and (3) model-measurement discrepancy evidence from the smaller subset of mixed-method studies that explicitly compare or calibrate simulations against measured data. A predefined factor taxonomy was applied, including: controls and operation; installation and commissioning; baseline displacement and hybrid operation; envelope and internal loads; weather and normalization; metering scope and attribution; and modeling assumptions and calibration. For each factor category, studies were coded using an evidence strength scale: 0 = not addressed; 1 = discussed qualitatively/hypothesized; 2 = evidence-supported through measurement, controlled comparison, sensitivity analysis, or formal attribution. For evidence-supported cases (code = 2), the evidence basis was recorded as direct measurement/experimental variation, or analytical attribution via calibration/sensitivity.

Missing information was recorded explicitly as “not reported” rather than inferred. Energy outcomes were recorded in original units and converted to common units and percentages during synthesis. This structured extraction supports reproducible aggregation and avoids over-interpreting studies with limited metadata.

2.5 Use of Extracted Data

All academic studies and grey literature collected contribute to descriptive evidence mapping (e.g., distributions by study type, geography, and system category) and to the literature synthesis tables/figures presented in section 3. Subsets contributed to specific analyses depending on reported variables: studies reporting energy outcomes informed savings-range

summaries; field and mixed-method studies informed synthesis of measured variability; and simulation studies with explicit scenario/sensitivity designs informed synthesis of modeled sensitivity to assumptions.

3. Literature Search Results

3.1 Academic Knowledge Base

The initial database search yielded 205 papers. A subsequent manual review was conducted to exclude studies that were inadequately filtered by the automated query or failed to meet the inclusion criteria outlined in Section 2.3. The filtered-out studies are (1) non-residential applications, including agricultural facilities that were misclassified due to titles containing terms such as "pig house"; (2) whole-building retrofit or zero-energy housing studies where the installations were integrated with multiple energy efficiency measures, making it hard to isolate individual system impacts; (3) studies comparing different HP technologies or performance enhancement methods (e.g., cold climate HPs versus conventional HPs) rather than evaluating them against alternative heating systems; and (4) studies that reported only efficiency metrics or environmental benefits without providing quantitative energy savings data. Following this screening process, 84 papers were retained for detailed review and analysis.

The remaining 84 studies compared the target systems against other heating and cooling systems in regards to energy usage. The literature demonstrates significant research acceleration in recent years (Figure 1), with 65% of studies published after 2020, reflecting growing interest and gradual technology maturation.

The geographic distribution spans multiple continents (Figure 1), with Canada (12 studies), China (11 studies), and the United Kingdom (10 studies) leading research output. This diversity provides insights across varied climatic conditions and residential building stock characteristics, enabling comprehensive understanding of the system performance across different contexts.

Methodologically, the literature is dominated by modeling approaches (62 studies, 73.8%), with field measurement studies (11 studies, 13.1%) and modeling combined with experimental validation (10 studies, 11.9%) representing smaller components (Figure 1). This distribution highlights a significant gap between predictions and validation, which forms a central theme of this review.

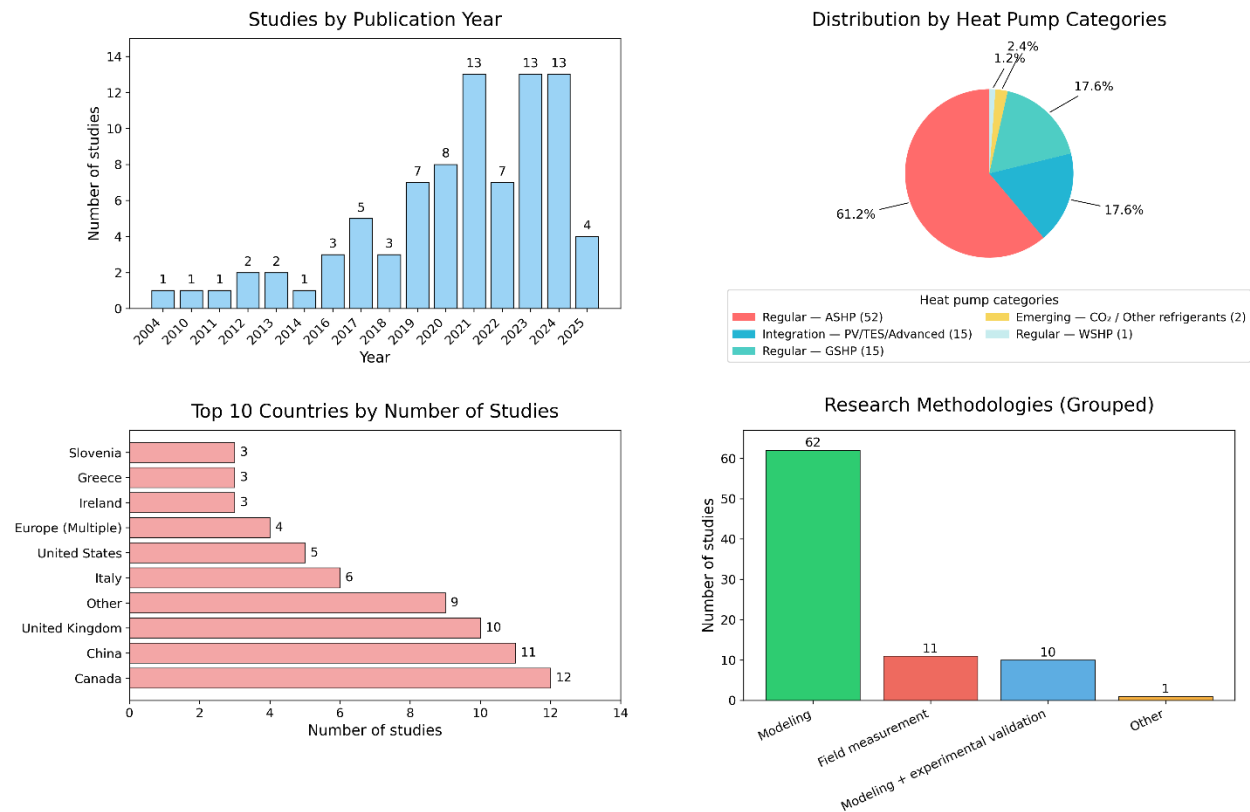


Figure 1. Academic Studies on Energy Savings (Top Left: Distribution by System Categories; Top Right: Distribution by Year; Bottom Left: Distribution by Countries; Bottom Right: Distribution by Research Methodologies.). Abbreviations: ASHP = Air-source Heat Pump; PV = Photovoltaic; TES = Thermal Energy Storage; GSHP = Ground-source Heat Pump; WSHP = Water-source Heat Pump.

To better understand the evolving development of heat pumps, the reviewed papers are split into three categories:

- Common system types: Air-source, Ground-source, and Water-source heat pumps;
- Emerging technologies such as systems that use alternative refrigerants;
- Integrated with other advanced technologies such as PV and thermal energy storage techniques.

Based on Figure 1, air-source heat pumps (ASHPs) dominate the reviewed literature (61.9%), followed by ground-source heat pumps (GSHPs) (16.7%). The overwhelming focus on air-source systems can be attributed to its broader market applicability because of simpler installation requirements and lower costs. The representation of ground-source systems reflects this type's superior efficiency potential, which make it an attractive subject for academic investigation despite its higher installation costs and site-specific requirements. The growing interest in integration studies (17.9%) indicates the research community's recognition that future energy systems will likely require hybrid approaches combining multiple technologies for optimal

303 performance. The limited research on emerging technologies such as new refrigerants (2.4%)
304 can be explained by limited commercial availability. Additionally, academic research on new
305 refrigerants is currently limited to efficiency metrics and oftentimes compared to regular HP
306 baseline, resulting in exclusion from this review work.

307 3.1.1 Regular Air-source Systems

308 Air source systems represent the most extensively studied technology in the literature, with
309 research spanning diverse applications including residential retrofits and new construction. The
310 studies reveal energy savings ranging from 15% to over 60% compared to other systems, with
311 significant variation based on baseline system type, climate conditions, and building
312 characteristics.

313

314 Table 1: Air-source Systems Studies Analysis

Baseline Heating System	Energy Savings Range	Key Context & Findings	Common Limitations
Gas heating (furnaces or boilers) [10-20, 22-35]	30-55% site energy reduction	ASHP or ccASHP retrofits in gas-heated homes deliver moderate-to-high heating energy savings. Savings rise when weather-compensated control or envelope improvements are added.	Limited field data: Most results come from modeling; Limited field datasets reporting both simulated and measured savings; Various energy metrics: Several studies only focus on heating rather than annual energy use; Economic sensitivity: Several studies look at energy cost and note that the outcomes depend on energy prices.
Electric resistance heating (Electric furnace or baseboard) [21, 36-45]	50-75% site energy use reduction in moderate climates when electric resistance heating is retired completely. Cold-climate	ASHP consistently yields large heating energy savings. Studies in Europe and North America document seasonal performance: even in sub-freezing conditions, modern ASHPs maintain high COPs.	Backup heat and behavior hard to capture: Field studies indicate some homes retain electric resistance backup or do not fully utilize the new system for all heating needs. These operation variations are hard to capture; Various energy metrics: Most studies only focus on heating rather than annual energy use;

	observes 40-55% heating energy reduction.		Short monitoring periods: Several studies cover only one winter, limiting insight into multi-year performance and reliability.
Oil heating (fuel oil furnaces) [46]	25-45% reduction in site energy use.	The literature shows moderate energy savings and significant pollution reduction, improved comfort and moisture control.	Sparse data: Limited academic studies that have looked at oil heating baseline.
Other baselines (Propane or wood) [46]	30% savings with propane baseline. Mixed systems (e.g. dual-fuel furnace + resistance supplemental heat) see 20-50% savings, depending on the fraction of resistant heating offset.	Propane baseline cases indicate energy savings on par with oil baseline cases, which is notable for rural homes. For propane/wood baseline realized savings depend on control strategy and continued use of the original equipment.	Scattered focus: Very few studies, often with context-specific results; Backup heat and behavior hard to capture: The operation variations of hybrid systems are hard to capture.

3.1.2 Regular Ground-source Systems

Studies on ground-source systems focus primarily on their superior efficiency potential and consistent performance across varying climatic conditions. The literature emphasizes the importance of ground loop design and soil thermal properties.

Table 2: Ground-source System Studies Analysis

Baseline Heating System	Energy Savings Range	Key Context & Findings	Common Limitations
Gas heating (furnace or boiler) [50-52]	30-50% heating energy savings.	Studies highlight that ground-source systems' efficiencies (COP 3-5) outperform baseline systems	Limitation of the systems themselves: Many papers note that adoption is limited by the cost and site requirements of drilling

		especially for homes with significant heating loads.	boreholes. Limited field studies: Few studies involve measured data; most rely on simulations or short experiments, leaving uncertainty about long-term ground thermal effects.
Electric resistance heating (Electric furnace or baseboard) [53-56, 58]	50-75% heating energy savings when replacing electric resistance	Ground-source systems offer large energy savings in electric resistance heating baseline cases.	Small sample of contexts: The literature here is dominated by idealized cases. Thermal interactions: Few studies consider long-term soil temperature changes or proximity of multiple ground-source system installations.
Other baselines (Oil, propane, district heating) [50,59-60]	30-40% heating energy savings	A few studies compare ground-source systems' performance to oil-fired heating, noting moderate energy reduction.	Sparse research: Propane and oil baseline cases are not widely covered in academic literature.

3.1.3 Integration with Advanced Technologies

This section reviewed the studies that focus on integration with photovoltaic systems, thermal energy storage, and other advanced technologies. These studies represent an emerging research area with significant potential for enhanced energy savings and system optimization. Note that in the manual filtering process, this is the category where a significant number of studies are comparing the integrated scenario against heat pump baseline, thus excluded from this review.

Table 3: Integration Studies Analysis

Integration Scenario	Baseline System	Reported Energy Impact	Notable Insights	Common Gaps
Integration with Solar PV [61-75]	Typically electric resistance; A few studies assume a gas boiler baseline	PV can directly offset 10-20% of a home's HVAC energy consumption in simple configurations, or up	Integration with solar generation can reduce grid energy use and improve sustainability.	Optimization needed: Many papers note that without intelligent control or storage, PV output may

	for comparison.	to ~40% with optimized controls and larger PV arrays. When coupled with smart controls or batteries, net energy savings of 40-65% have been demonstrated in simulations.	These studies highlight the importance of controls: timing the HVAC operation to coincide with PV output (or storing PV energy for later use) vastly increases self-consumption.	not coincide with heating demand, limiting its benefit. Few real-world pilots: Most results are theoretical or from lab homes; practical issues (like variability of solar, storage losses, and costs) are insufficiently addressed.
Integration with Thermal Energy Storage (TES) [68, 70, 77, 78, 80]	Electric resistance heating baseline; A few gas/oil systems. For cooling TES (ice storage), baseline is conventional AC.	Enhanced energy savings (~30-70%) are reported when adding storage to a heat pump system, due to load shifting and heat reuse. For example, a heat pump with phase change material (PCM) storage achieved ~25-45% annual energy savings compared to conventional heating. Seasonal underground TES in a ground-source system showed ~45-70% savings vs. baseline by storing summer heat for winter use. An ice storage coupled with an ASHP cut cooling electricity by ~30-50% in peak	Thermal storage allows heat pumps to operate more efficiently or during off-peak times. Key insights include the ability to maintain high COPs by avoiding extreme outdoor temperatures. Also, ice storage can shift cooling load to nighttime. Collectively, these studies demonstrate the potential of HP+TES to reduce peak grid load and improve overall system COP.	Complexity and cost: Integrating TES increases system complexity. Authors note that control strategies must be sophisticated to realize benefits, and economic analysis is often limited or missing. Limited field demos: Almost all findings are simulation-based. Real installations aside from a few small pilot projects are rare.

summer conditions.				
Hybrid System (Coupled with dry cooler, hybrid control rules, Thermally Activated Building Systems) [84-91]	Electric resistance heating.	Scenario-specific; 20-30% reductions in energy use if reported.	Energy use benefit depends on dispatch rules: hybrids can reduce energy consumption during low-ambient periods; results are system- and climate-specific.	Limited methodologies: Many studies in this category are techno-economic simulations.

3.1.3 Emerging Technologies

Systems with alternative refrigerants represent a small but noteworthy segment of recent literature (~2.4% of studies). These technologies are in early development. Only two academic studies in the review fell into this category:

- CO₂ HPs for High-Temperature Applications [92]: This study examined this innovative system providing high-temperature hot water for heating. It found 35-55% energy savings compared to an electric resistance baseline when delivering 60-80°C supply temperatures. This suggests this type of system can retrofit into systems designed for boilers, achieving significant savings even at high output temperatures. The authors noted the technology's promise for cold climates and older homes, while also citing limited field data and higher cost as current barriers.
- Systems with Other Natural Refrigerants (Hydrocarbons, Ammonia, etc.) [93]: This study evaluated a prototype system using natural refrigerants in a residential home. It reported 25-45% energy savings relative to conventional electric heating, along with improved environmental metrics due to the refrigerant choice. The paper emphasized that while performance was encouraging, safety standards and lack of familiarity with new refrigerants bring challenges. Again, the scale of research is very limited.

The literature analysis reveals several critical research gaps that limit the translation of theoretical energy savings into practical results. The predominance of modeling studies (73.8%) compared to field measurements (13.1%) represents a fundamental challenge for validating predicted performance under real-world conditions. Among the small portion of studies that applies both modeling and field measurement (11.9%), the field measurement process is often used for refining the inputs to finetune the models, rather than accounting for the real-world operation factors or understanding the potential discrepancies [35, 81, 83, 91]. The references

listed in the tables above reveal pervasive concerns about "limited field validation" across all technology categories, with studies repeatedly identifying this as a critical limitation.

Most field studies span only 1-2 heating seasons, creating gaps in understanding long-term performance trends and seasonal variation impacts. The references list in the tables consistently identify "limited long-term performance data" and "short monitoring period" as critical limitations across all technology categories.

The evidence base is also biased toward single-family homes and/or idealized new constructions, with comparatively few studies on multifamily buildings or older existing stock. Many studies focus on single-family detached dwellings or new construction with favorable envelopes and controls [23, 25, 27, 38, 39, 43], whereas multifamily buildings appear only sporadically [49]. Similarly, older housing with poor insulation and legacy systems is underrepresented.

In regards to cost savings, energy price volatility and changing utility rate structures create ongoing challenges for economic analysis validity. The references listed "economical sensitivity" as critical gaps.

3.1.4 Evidence-coding Results

To understand factors associated with savings variability and model–measurement differences, evidence-coding is applied. Because most studies are simulation-only or measurement-only rather than direct model-measurement comparisons, coded results are summarized by evidence type (modeled sensitivity, measured variability, and model–measurement discrepancy) and by whether a factor is evidence-supported versus discussed qualitatively. This synthesis is reported descriptively and is used to weight interpretation in the discussion involving grey literature results rather than to infer causality.

Table 4: Evidence Type Coverage

Evidence Type	Interpretation	No. of Studies
Modeled sensitivity	Factors tested via scenarios/sensitivity analyses in simulations	36
Measured variability	Factors supported by field observations or evaluator attribution in measured studies	17
Model-measurement discrepancy	Factors supported by studies explicitly comparing/calibrating models to measured data	9
Not specified	Studies that report energy outcomes but do not provide factor attribution content	22

What's summarized in Table 4 is consistent with the broader study-type distribution reported earlier where simulation is dominating the academic literature, direct evidence for attributing model-measurement discrepancies appears in only a small subset of the academic evidence base, while modeled sensitivity evidence is more common.

The coded results in Table 5 indicate that the strongest evidence base in the academic literature relates to modeled sensitivity and modeling assumptions, with fewer studies providing evidence-supported attribution related to controls/operation, weather normalization, or metering scope. Evidence-supported treatment of installation/commissioning and envelope characterization appears relatively infrequently in the academic studies.

Table 5: Evidence-supported Factor Categories

Factor Category	Evidence Supported	Discussion Only
Modeling assumptions / calibration / sensitivity	18	15
Controls & operation (setpoints, schedules, backup heat logic)	10	5
Weather basis & normalization	9	8
Baseline displacement / hybrid operation	4	6
Metering scope & attribution	3	2
Installation & commissioning	1	3
Envelope / internal loads characterization	1	5

3.2 Supplementary Evidence - Grey Literature (Utility Programs and Field Studies)

Given the gaps identified in academic research - especially the limited field performance data - this review incorporates a grey literature analysis focusing on U.S. utility program evaluations and field studies. These sources include program impact evaluation reports, pilot studies, and other industry research that provide measured energy savings from installations. Although not peer-reviewed in the traditional sense, such reports are invaluable for assessing the energy savings under everyday conditions, across diverse homes and climates.

3.2.1 Scope of Collected Grey Literature

A total of 21 entries from grey literature were reviewed [95-115], encompassing programs in over 10 states (e.g. New York, Massachusetts, Maine, Minnesota, California, Oregon, Washington, etc.). These programs primarily cover residential retrofits where existing heating

systems (gas furnaces, oil boilers, electric baseboards, etc.) were retired or supplemented by heat pumps. Key characteristics of the collected studies include:

Geographical diversity: Shown in Figure 2, many evaluations come from the Northeast, Pacific Northwest, Midwest, and California, capturing a range of climate zones from cold (Minnesota, Maine) to marine (Washington/Oregon) to warm temperate (California).

Baseline heating fuels: The programs cover baseline systems including fuel oil, propane, natural gas, electric resistance, and wood.

Methodologies: Utility evaluations use a mix of methods. Many employ pre and post utility billing analysis. Others use submetering in homes to directly measure heating and cooling end uses. Baseline energy use is determined either from pre-installation data or via modeled baselines when pre-data is unavailable.

Metrics considered: Most grey literature report site energy savings. Many also translate savings into bill impacts for customers and realization rates - the ratio of measured savings to the program's initial predicted savings.

This grey literature complements the academic review by providing empirical answers to some questions the papers raised. In particular, it offers data on longer-term performance - several evaluations track one year or more.

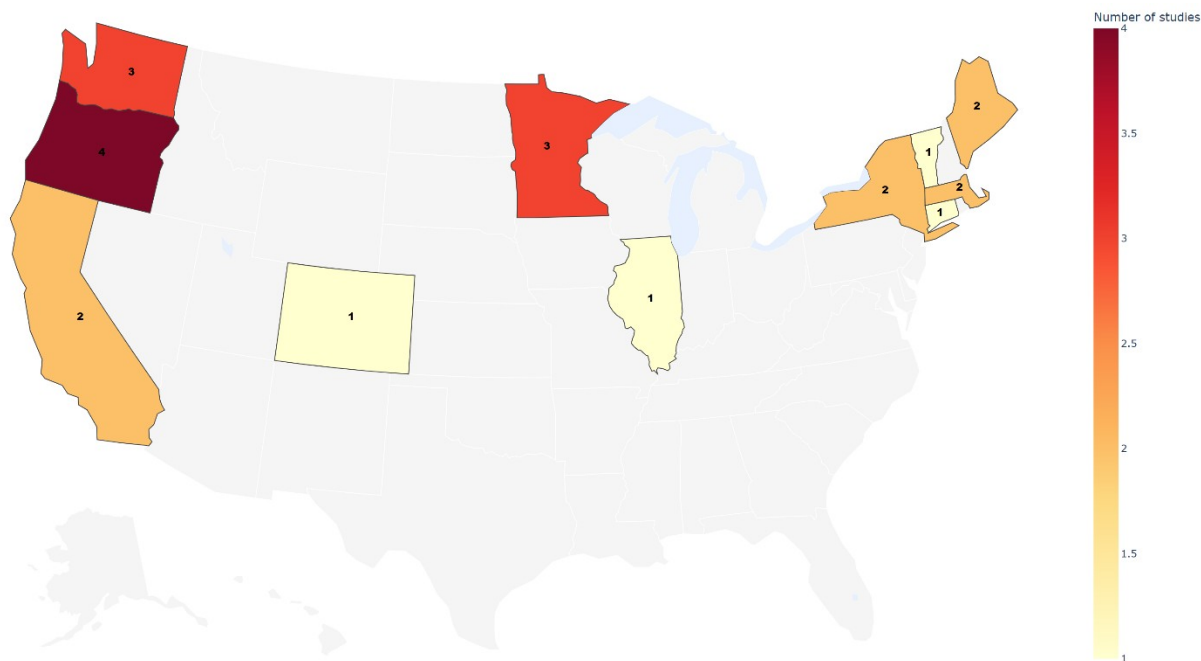


Figure 2. Number of grey literature (utility program impact evaluation report, case studies, etc.) by U.S. states.

3.2.2 Field Performance Results and Trends

Results from utility programs confirm the trend observed in the academic literature: the magnitude of energy savings is strongly tied to the heating system being retired or supplemented. Below, the major findings from these field studies are organized by baseline fuel type and regions.

Electric Resistance Heating Baseline: Homes with electric resistance heating baseline see the largest energy savings. Field studies in cold climates (e.g. Vermont, Maine) [101][102] and moderate climates (Oregon, Washington) [95][96][99] all report on the order of 40-60% reduction in heating energy use, translating to up to 15 MMBtu (15.8 GJ)/year of site energy saved per home.

Fuel Oil/Propane Baseline: Fuel oil and propane baselines also yield substantial savings, though not as significant as electric resistance heating baseline. Fuel oil furnace baselines show 20-30% heating energy savings, equating to 10 MMBtu (10.6 GJ)/year saved per home. A Maine pilot program [100][101] observed 10-15% site energy savings for oil-heated baselines - some home saved significantly while others realize modest site savings, depending on displacement level of the systems. Vermont's metering study [102] documented fuel oil use reduction by 200-400 gallons (760-1,510L) /year, resulting in more than 20% site energy savings. Propane results are similar to fuel oil: a Minnesota program [108][109] recorded 30% heating energy savings with new systems installed.

Natural Gas Baseline: The net change in total site energy use for homes with natural gas furnaces or boilers baselines varies with displacement level and controls. The metering studies for Massachusetts and Connecticut show 10-16 MMBtu (10.6-16.9 GJ)/year savings per home [104] [112]. California studies found modest site energy savings when aggregated across mixed displacement scenarios [106][114].

Mixed or Partial Heating Scenarios: When ductless mini-split systems are added to just supplement existing central systems, average savings are smaller because the new equipment typically serves small portions of the home or narrower temperature ranges. On average, such partial change yield 5-20% of heating energy savings. For instance, a Connecticut program [112] found that in homes where a single ductless air-source system was added to supplement a fuel oil system, the oil usage drop was modest (only 10% reduction) as many homeowners used the new system for shoulder seasons and the oil furnace for winter peaks.

4. Comparison Analysis - Simulation vs Measured Savings

4.1 Methods for Integrating Simulated and Measured Data

National Renewable Energy Laboratory's Restock Annual Impacts from Residential Energy Efficiency Measures dataset [116] is used to obtain the simulated predictions for each scenario. This dataset development effort generated models to statistically represent the residential building stock of United States, and then modeled the energy consumption of those dwelling

unit models [117]. From this database, baseline energy use (with the original heating system) and post-retrofit energy use (Measure Category 5: Heat pumps With Electric Backup & Measure Category 6: Heat Pumps With Existing System as Backup) were extracted for homes comparable to those examined in the field studies. The heat pumps are all ASHPs. Because the grey literature encompassed a range of climates and building types, the simulation data were filtered by key attributes—state, building vintage, and heating system type—in order to replicate the conditions of each field study. For instance, when a utility report documented measured savings for oil-heated homes in Vermont, the subset of ResStock models representing Vermont with oil furnaces as the baseline system was selected. In cases where the field study homes included central air conditioning prior to the retrofit, the corresponding simulation subset also incorporated models with an equivalent cooling system in the baseline. This targeted filtering process produced a set of simulated homes that approximated the real homes represented in the grey literature.

After filtering, representative statistics were calculated from the simulation results to compare with the field data. In each scenario (defined by a specific state and baseline HVAC type), the median energy use for the baseline and for the HVAC upgrade was used. The comparisons were made in terms of annual site energy consumption for both the pre-retrofit and post-retrofit periods, as well as the percentage savings achieved. The range of simulated outputs within the filtered subset was also examined to assess variability.

It should be noted that perfectly matching each field study to the simulation data was challenging. The grey literature report does not always report very detailed information about building characteristics. This challenge was addressed by focusing on broad groupings (state, climate, house type, HVAC type) and acknowledging uncertainties. By synthesizing the data in this manner, patterns could be identified where simulated performance diverges from reality.

4.2 Comparisons by Region and Baseline System Type

Using the above methodology, the simulation-based predictions from Restock dataset are compared to the measured outcomes from grey literature across multiple U.S. states and for different original heating systems. Note that some of the utility program evaluations report stock level results rather than for single homes. They are excluded from this comparative analysis. The figures (Fig 3-6) are organized by baseline heating system. In each figure, the top panel shows pre-retrofit vs post-retrofit site EUI, and the bottom panel shows savings. For non-electric baselines, the bars are stacked (fuel + electricity). Pre vs post are distinguished by transparency; simulation vs field are grouped side-by-side.

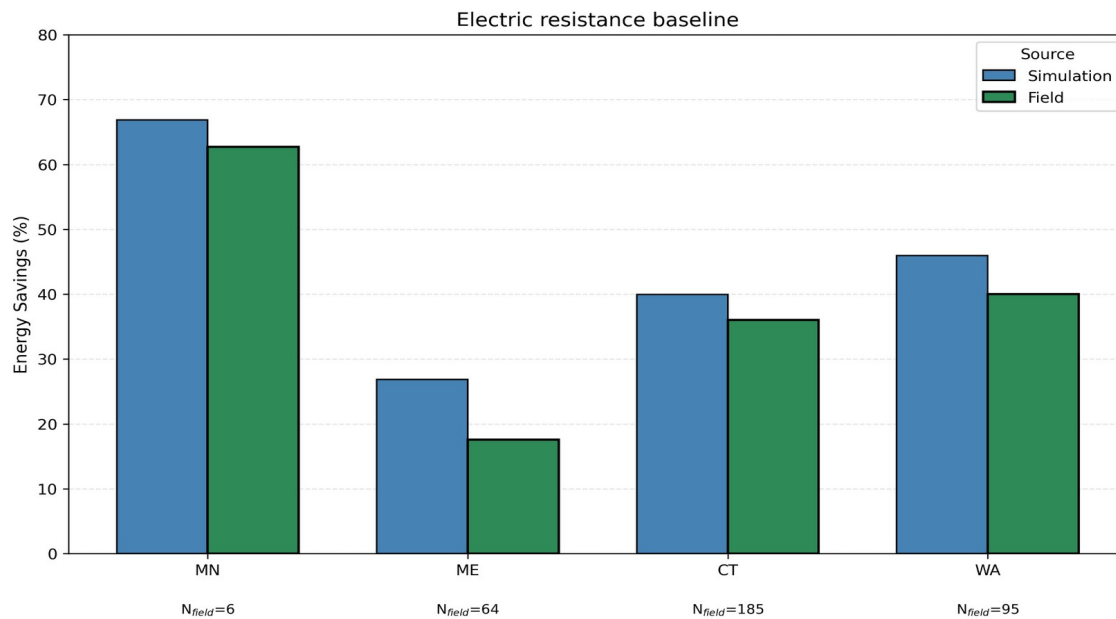
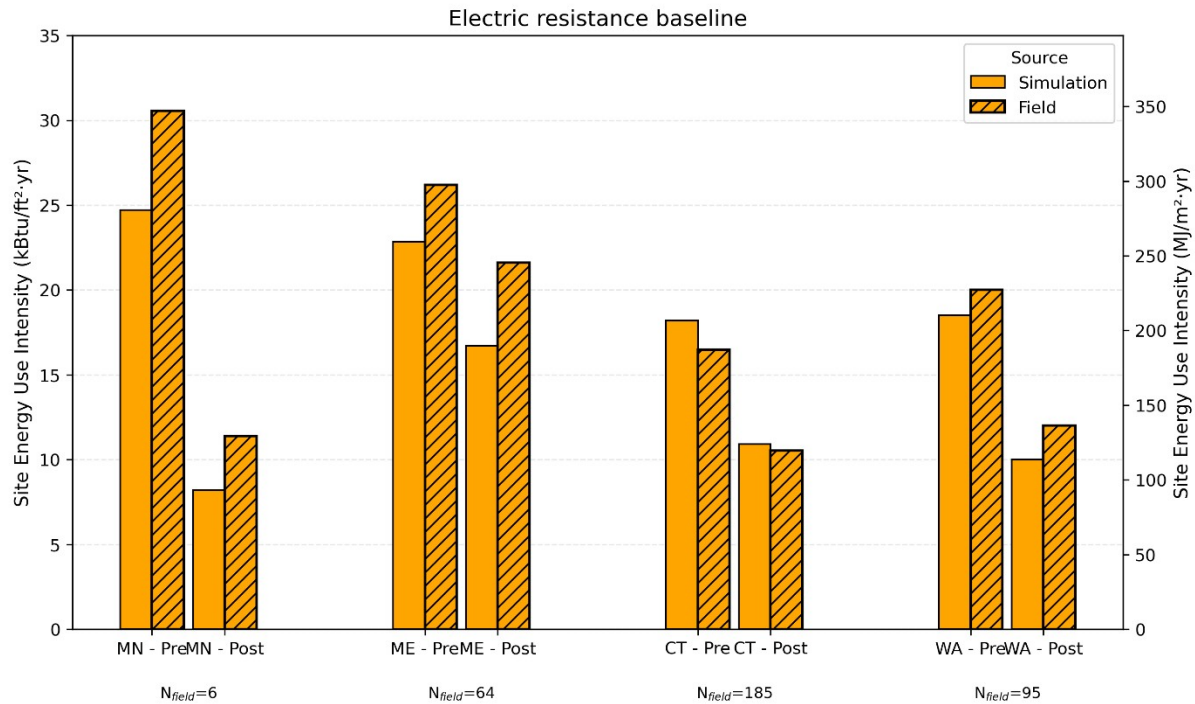


Figure 3. Comparison of simulation results to measured data for electric resistance heat baseline. Top: site energy use intensity; Bottom: energy use savings. Abbreviations: MN = Minnesota; ME = Maine; CT = Connecticut; WA = Washington.

For the electric-resistance baseline, all data sources indicate significant reductions in energy use after retrofit. In every data source across different states, the simulated pre- and post-retrofit EULs sit below the measured data levels, while the pre-to-post reductions are broadly

comparable. Across the sources in four states, the simulated savings span from 27% to 67%, while measured savings span from 18% to 63%.

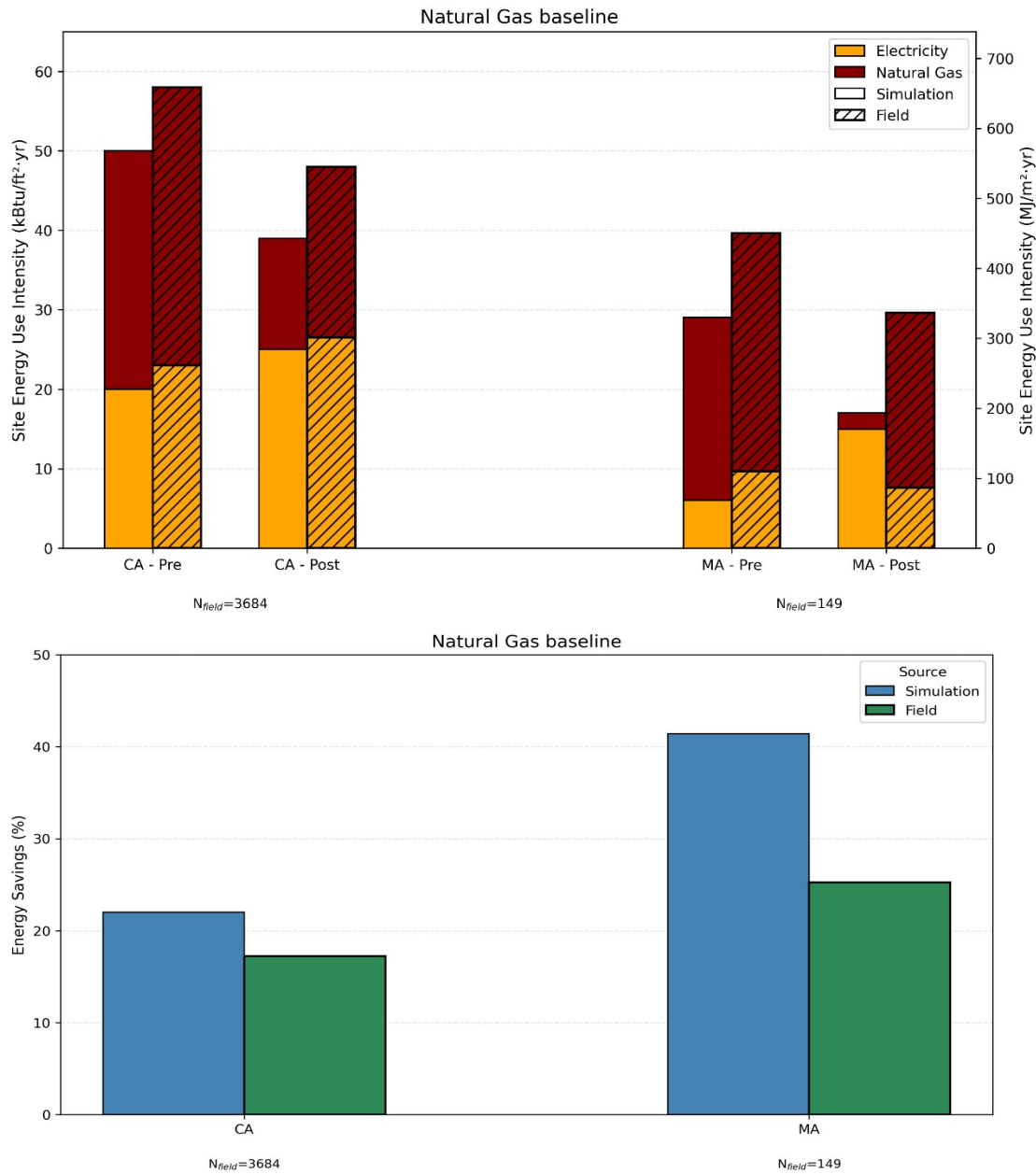


Figure 4. Comparison of simulation results to measured data for natural gas baseline. Top: site energy use intensity; Bottom: energy use savings. (Note: California study reports whole-home use data rather than end-use, and normalized with assumption of average house size of 1,500 ft² (139 m²).). Abbreviations: CA = California; MA = Massachusetts.

The natural gas baseline results show larger divergence in simulated and measured energy use. California presents whole-home electricity and gas, and the simulation was expressed on a whole-home basis to match that scope; even so, the measured pre- and post-retrofit EUIs

remain above the simulated values, while the reductions are of more comparable scale. Minnesota shows significant differences not only in total site energy use, but also in the ratio of electricity use to natural gas use in pre- and post-retrofit scenarios. In the cases where original system is kept, it's hard to capture how much load is handled by the original system versus the new system. The operation decisions between systems depends on either user behavior or control setup, which is challenging to match in the simulation models.

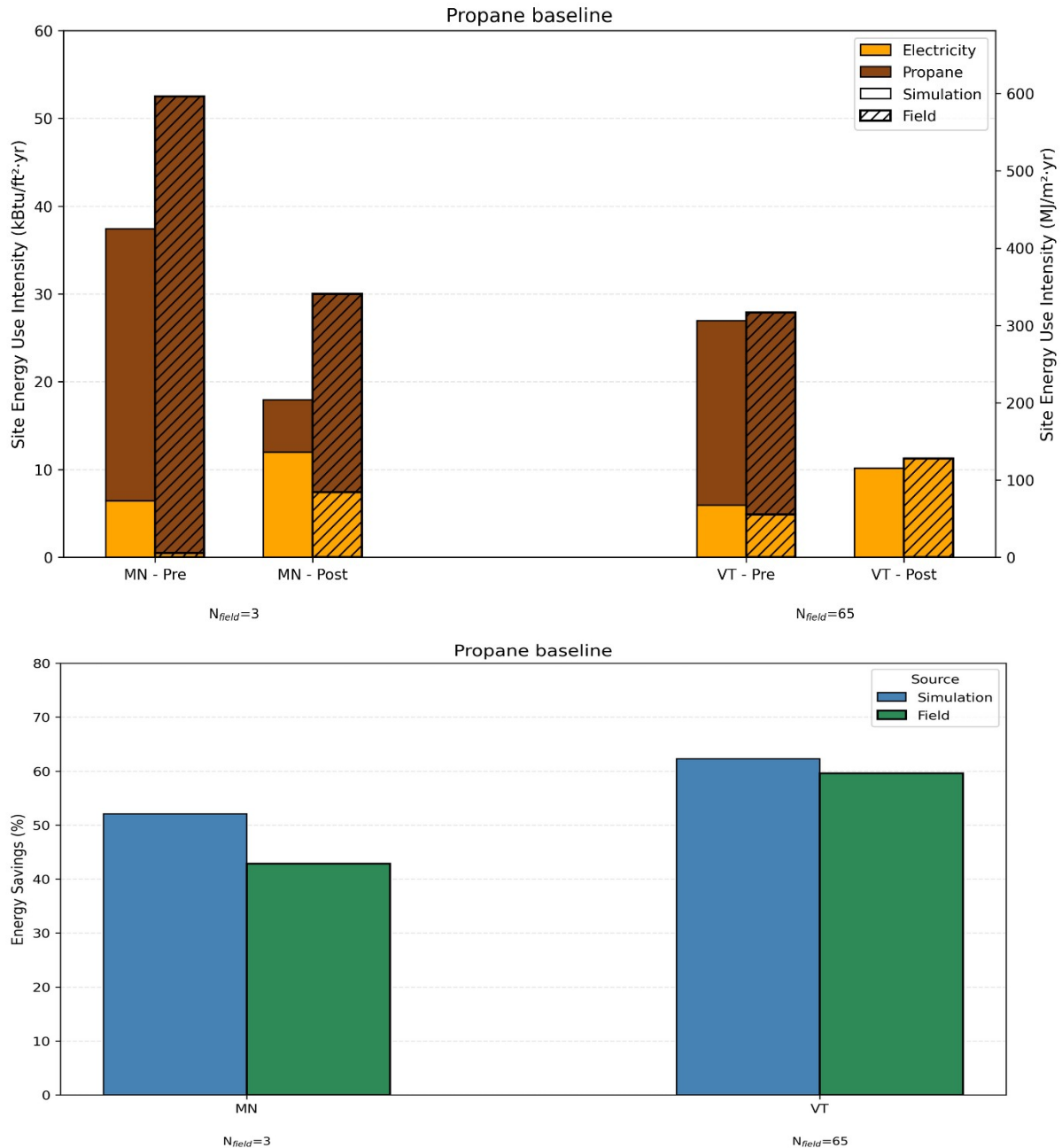


Figure 5. Comparison of simulation results to measured data for propane baseline. Top: site energy use intensity; Bottom: energy use savings. Abbreviations: MN = Minnesota; VT = Vermont.

For propane, the Vermont case shows similar reduction scales in simulated and measured results. Minnesota simulation results have more significant differences in simulated and measured EUIs. It's worth noting that the ratio of propane use to electricity use drastically differs between simulation and measured data in both pre- and post-retrofit scenarios. This also suggests that it's challenging to capture the actual operations in cases where the original system is kept and in use with the added system.

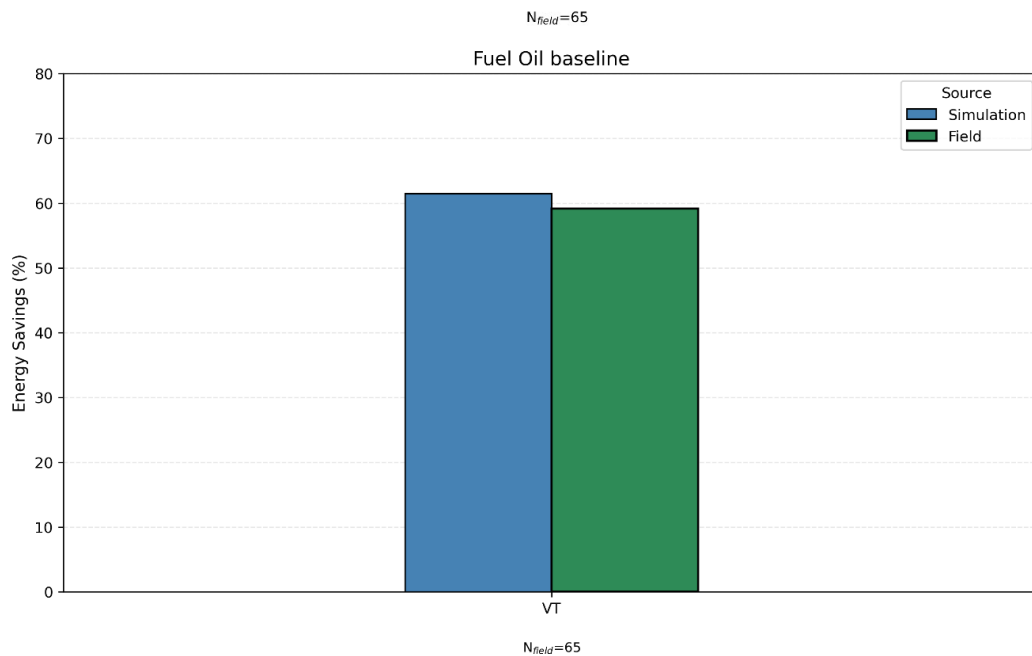
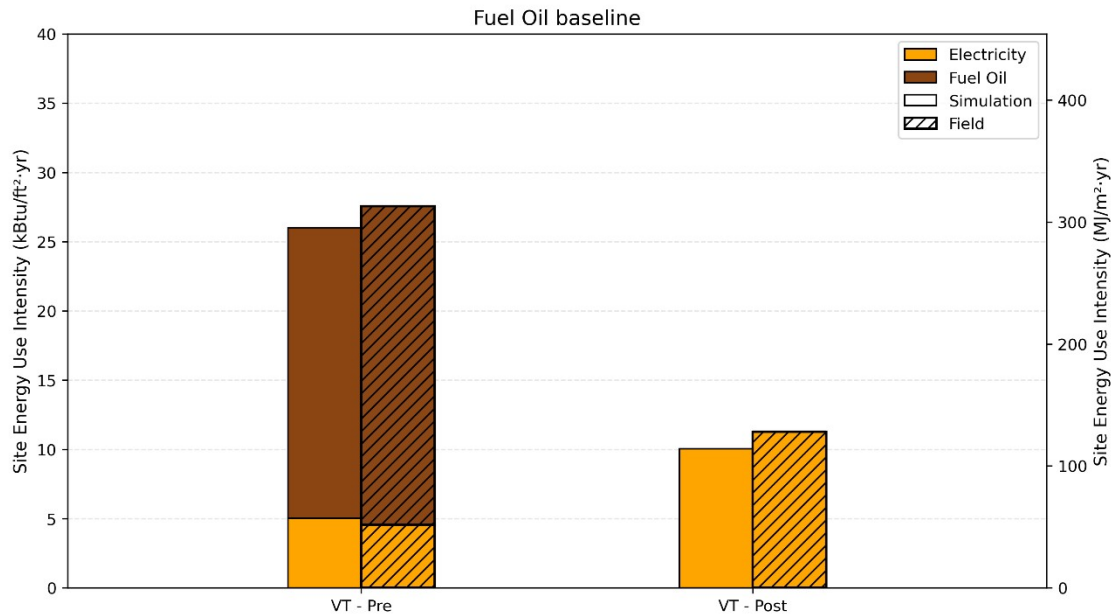


Figure 6. Comparison of simulation results to measured data for fuel oil baseline. Top: site energy use intensity; Bottom: energy use savings. Abbreviations: VT = Vermont.

The fuel-oil baseline rests on fewer studies. The Vermont results show most agreements in both energy use and savings between simulation and measured data.

Across all baselines, the figures point to a consistent pattern: modeled site EUIs are usually lower than those inferred from measured studies, whereas the simulated and measured savings are generally in the same ballpark. This suggests that the direction of the effect are captured by the stock simulations, but the absolute energy use is off from the measured data.

5. Discussion

5.1 Research gaps and challenges

The synthesis of academic literature and utility program evaluations has revealed several critical gaps that limit our understanding of heat pump performance and the reliability of energy savings projections.

The most significant challenge identified across all analyzed studies is the limited availability of measured data. Academic studies heavily rely on simulations. The limited field studies in academic literature frequently focus on controlled conditions and limited time span, that may not reflect the diverse operations in practice. Three utility programs in the United States have obtained substantial field data. However, the number of programs that have implemented field data collection and analysis are still limited. Besides, these field data collected often lack detailed documentation necessary for systematic analysis.

By comparing the limited utility program measured data to Restock simulation dataset that represents the US building stock, gaps were found in both EUIs and fuel consumption changes. The utility program reports provide the primary evidence base for measured energy savings under real-world deployment conditions. However, they often vary in metering scope, normalization, and reporting completeness, and they rarely provide the full set of metadata needed for direct alignment with the modeling dataset. To avoid over-interpreting heterogeneous program results, interpretation in this section is guided by the evidence-coding results summarized for the academic literature in Section 3.1.

System characterization and operational controls. Many program outcomes depend on whether auxiliary heat is present, how it is configured, and how it is engaged in operation. Where reports provide evidence on backup heat use variability in measured savings can be linked to control strategies and operational behavior rather than equipment efficiency alone.

Installation quality and commissioning. Grey literature frequently documents implementation issues (incorrect configuration, sizing mismatches, missing commissioning steps) that materially affect measured performance. These observations provide a concrete mechanism for variability that is difficult to infer from simulation.

Envelope characterization and interactive effects. Although envelope conditions (air leakage, insulation, window performance) influence heating loads and therefore potential savings, many program reports do not provide sufficient envelope metadata to isolate envelope-equipment interactions. This mirrors the academic evidence-coding result that envelope reporting is not consistently detailed in a way that supports cross-study reconciliation, even if envelope is frequently mentioned as a contributor.

Occupant behavior and schedule changes. Occupant-driven changes are plausible and sometimes noted qualitatively, but they are rarely quantified in a way that enables consistent cross-program comparison. When behavioral changes are not measured or modeled explicitly, attribution should remain cautious.

Equipment performance rating versus installed performance. Nameplate efficiencies (HSPF/SEER/COP) are often reported, but installed performance may diverge due to control settings, auxiliary heat, and installation quality. Without operational data, these differences are difficult to separate.

Weather basis and normalization. Evaluations vary in whether they use degree-day normalization, regression-based normalization, or simple pre/post comparisons. Differences in normalization method and weather exposure can change reported savings materially.

Metering scope and attribution. Program reports differ in whether outcomes represent whole-home energy, HVAC-only energy, or billing-based estimates. Where submetering is available, attribution is clearer; where it is not, savings estimates can include confounding changes unrelated to HVAC.

5.2 Proposed Methodology for comparison of simulated and measured savings

To address the identified research gaps and improve the reliability of energy savings analysis, a methodology for systematic comparison of simulated and measured performance data is needed. It should standardize the methodology used for comparison methodologies and provide reference for further work when more measured studies and data become available.

Section 4 demonstrated a proof-of-concept comparison that aligns field-reported savings from grey-literature sources with ResStock-based predictions for comparable buildings. The objective was not to draw definitive conclusions but to demonstrate how heterogeneous field reports can be made commensurable with simulation outputs under clear alignment for scope, normalization, and attribution.

Scope and units. Comparisons are limited to site energy use in this work, which matters most when translating to energy cost or bills. Reported quantities are converted to common units and a common basis (e.g., kBtu or kWh per home or per floor area). If the measured data supports, weather normalization should be applied where inputs allow. Baselines are defined consistently,

distinguishing each fuel type, and noting the presence or absence of existing air-conditioning and heating systems.

Building characteristics matching. For field study, a ResStock building group is selected by matching climate zone or geography, building vintage and type, floor-area band, baseline fuel and system, and ducting and cooling if data is available. Predicted savings are drawn from the filtered groups.

Dimensions to emphasize. The following dimensions are most likely to influence differences between simulated and measured outcomes and should be recorded wherever sources permit: building envelope (insulation level, infiltration, window performance), equipment (baseline system type and efficiency, heat pump type and efficiency), control (setpoints and schedules), measurement and study design (monitoring duration, whole-home vs end-use metering, pre- and post- definitions). Each study entry should include a concise metadata record. It will enable transparent building group matching and reproducible comparisons.

Synthesis. With the above information standardized, future analyses can summarize the distribution of results within each stratum and assess systematic bias (e.g., consistent over-prediction where auxiliary heat engages frequently or envelope insulations are poor). Weighting by study quality (e.g., monitoring length, end-use resolution, baseline clarity) helps prevent over-interpretation of short or sparsely documented studies.

5.3 Future directions

The analysis of current research and program evaluation practices reveals several critical directions for advancing heat pump energy savings analysis and improving the alignment between simulated projections and measured performance. These future directions address both immediate research needs and longer-term strategic priorities for the industry and research community.

The expansion of high-performance HVAC systems program implementation coupled with comprehensive long-term monitoring represents the most immediate priority for advancing our understanding of real-world performance. Current utility programs provide valuable insights but are often limited in scope, duration, or geographic coverage. Future programs should incorporate more comprehensive monitoring protocols that capture not only energy consumption data but also detailed information about system operation, occupant behavior, and building performance. This expanded monitoring should extend beyond the typical one to two-year evaluation periods to capture long-term performance trends, seasonal variations, and equipment degradation patterns. Long-term monitoring efforts should also incorporate more sophisticated data collection technologies and analytical approaches. The integration of smart meter data, building automation systems, and Internet of Things sensors can provide unprecedented insights into heat pump operation and performance optimization opportunities.

Accurate modeling of heat-pump performance remains one of the key challenges in reconciling simulated and measured energy savings. Future modeling efforts should focus on improving how heat-pump controls and performance are represented in simulation tools. Key priorities include accurately capturing the operation of auxiliary and backup resistance heat, integrating dual-fuel control strategies, and refining variable-speed compressor performance maps using high-resolution laboratory and field data. Advancing these aspects of control and performance modeling will significantly improve the reliability of simulated energy savings compared with observed field results.

These enhanced simulation models must also better account for real-world variables and regional differences that significantly influence performance. This includes developing more accurate representations of occupant behavior, building envelope performance variations, and climate-specific operating conditions. The models should incorporate uncertainty analysis capabilities that can provide probabilistic rather than deterministic savings projections, better reflecting the inherent variability in real-world applications.

The advancement of energy analysis for this type of high-performance HVAC system also requires improved integration between research communities, utility programs, and industry stakeholders. This includes developing standardized data sharing protocols, establishing collaborative research platforms, and creating mechanisms for translating research findings into practical program improvements. Industry partnerships can facilitate access to performance data and provide insights into real-world installation and operational practices that influence performance.

6. Conclusion

This extensive literature review has examined the current state of knowledge regarding energy savings from heat pump retrofits, comparing simulated estimates with measured performance from utility program evaluations. The analysis reveals both significant progress in technology and persistent challenges in understanding energy performance in the field.

The review's findings demonstrate that significant discrepancies persist between simulated energy savings estimates and measured field performance. Academic literature provides strong evidence of efficiency advantages through simulations and a limited number of long-term field testings, with studies consistently demonstrating significant energy savings compared to conventional heating and cooling systems. The utility program evaluations reveal measured savings often differing from simulation-based projections.

A proof-of-concept comparison methodology was demonstrated in the paper by aligning measured savings with ResStock predictions for matched building characteristics. The approach emphasizes scope and unit standardization, cohort matching on climate, building and system attributes, simple discrepancy metrics, and transparent documentation of assumptions. Given the limited availability of measured datasets with consistent metadata, the current results should

be regarded as illustrative; the approach is intended to provide a methodology with initial data points for future reference as evidence grows.

The analysis also reveals several critical directions for future research and development efforts. Expanding heat pump program implementation with comprehensive long-term monitoring can provide the data foundation necessary for advancing our understanding of real-world performance. Developing simulation models specifically designed for heat pump applications, with enhanced representation of variable-speed operation, control system interactions, and regional operating conditions, represents a critical technical priority.

By addressing the evidence gaps and applying a standardized comparison approach, subsequent studies can improve the credibility of projected savings, inform program design, and support effective deployment of heat pumps across varied buildings and climates.

CRediT Authorship Contribution Statement

Lili Yu: Writing – original draft, review and editing; Methodology; Resources; Data curation; Formal analysis; Visualization; Validation.

Jingjing Liu: Writing – review and editing; Methodology; Conceptualization; Validation; Project administration; Supervision.

Iain Walker: Writing – review and editing; Project administration; Supervision; Funding acquisition.

Jessica Granderson: Conceptualization; Supervision; Funding acquisition.

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