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Energy innovation in the US buildings sector: Setting the stage and mapping the future

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Summary

Buildings are a critical resource for managing emerging challenges in global energy systems, including accelerating load growth and rapid changes in the energy generation mix. However, the diversity of building energy end uses and stakeholders suggests many possible strategic opportunities for decision makers to pursue, and a comprehensive framework for comparing buildings sector innovation pathways does not exist. Using the United States as a case study, we develop the basis for such a framework by estimating all current and expected future sources of US building energy use, energy costs, and greenhouse gas emissions through 2050 under multiple scenarios for buildings sector development. Pairing these data with expert feedback, we identify key technical innovation pathways for the buildings sector, discuss implementation barriers for these pathways, and identify the actions that could address such barriers. The analysis distills focus areas for buildings sector planning and sets a common foundation for assessing the role of buildings in the broader transformation of national energy systems.

Keywords

buildings, innovation, energy system transformation, electric load growth, energy efficiency, affordability

Buildings at the center of US energy system transformation

The US energy system is undergoing rapid change, spurred by improvements in technology cost and performance, new sources of load growth, and the implementation of federal, state, and local plans to meet economic and environmental goals. On the demand side of energy, electricity sales are accelerating after years of stagnation due to the emergence of new data center loads, new domestic manufacturing, and electrification of building and transportation services. On the supply side, new power generation capacity is overwhelmingly being met by variable renewable sources—primarily solar, wind, and battery storage—with generation from renewable sources surpassing that of coal-fired plants, while natural gas remains the largest overall source of generation.¹ Taken together, these recent developments suggest a dynamic and uncertain outlook for the energy system across the coming decades.

The buildings sector is a linchpin for US energy system futures by virtue of its operation at the intersection of energy demand and supply. Building heating and cooling loads drive peak demand and therefore determine the scale and cost of electricity infrastructure investments; buildings are where distributed energy resources (DERs) connect to the power grid; infrastructure sited in or around buildings enables the deployment of new transportation options; and building design and construction drives material manufacturing demand.² Moreover, the quality

of the built environment directly affects individuals and communities by influencing energy costs and affordability—a critical impact at a time when over 20 million U.S. households cannot afford to use all of the energy services they desire.³ Therefore, innovation in the management and use of energy in buildings could have widespread benefits for the US energy system, the broader economy, and people’s daily lives.

Buildings sector innovation is challenged foremost by the complexity of building energy end uses. Building end-use patterns arise from a combination of factors—consumer preferences, environmental, economic, and regulatory conditions, and physical infrastructure constraints, among others. For a given end use, there may be multiple pathways for technical innovation with merits and drawbacks that depend on the lens through which impact is viewed (e.g., energy, costs, emissions, etc.). In turn, each pathway may benefit from multiple avenues of support from decision makers (e.g., research and development (R&D) to expand product offerings and improve consumer choice, market transformation activities, legislative instruments). The field of actors is complex in its own right, ranging from federal and sub-federal decision makers, to grid planners and regulators, to industry service providers, manufacturers, and vendors. To coordinate actions in the face of such heterogeneity, a common understanding is needed about the opportunity space, how key end uses could change in ways that will challenge the future energy system, and which pathways for technical innovation have the greatest potential to benefit consumers and the US energy system as a whole. Modeling analysis is an essential tool for developing this shared understanding; yet, previous modeling research tends to focus on limited portions of the buildings sector and it is challenging to compare insights across studies given the use of different input datasets, scenario assumptions, and reporting conventions, as well as differing degrees of methodological transparency and data accessibility.

To address this information gap, we leverage existing buildings datasets and modeling capabilities to take stock of current and possible future buildings sector impacts on energy demand, energy costs, and the environment, including detailed segmentation of impacts down to the technology level. From these estimates, we identify the most important segments of buildings sector impacts and elicit expert feedback on key pathways for technical innovation in each priority segment, as well as implementation considerations for those pathways. Cross-cutting innovation opportunities that apply across multiple segments are also discussed. The work establishes a foundational, national-scale framework to map buildings sector innovation strategies from problem areas to solutions (Figure 1). This framework is adaptable to various stakeholder perspectives and can improve the consistency with which stakeholders assess the broader impacts of their plans on buildings and energy sector futures, both in the United States and in other countries that face similar challenges.

The future of US buildings without continued innovation

To frame key innovation pathways for buildings, we first segment the end-use drivers of US building energy demand, emissions, and costs today (see *Segmentation philosophy* in the *Supplemental information (SI)* for an outline of how segments are organized). We then assess how building end uses could change over the coming decades under two counterfactual scenarios: a) a business-as-usual case (“BAU”) that stems from the *2023 Annual Energy Outlook*⁴ Reference Case forecast, which carries forward historical buildings sector trends plus the effects of new federal and state policies that were enacted as of 2022, and b) an inefficient high electrification case (“Ineff. Elec.”) that adds widespread switching of fuel-fired equipment — constrained by plausible rates of technology turnover and fuel switching — to typical-efficiency electric alternatives, including a mix of resistance furnaces and heat pumps that rely on resistance elements to meet peak heating demands. The two scenarios are designed to illuminate key challenges that

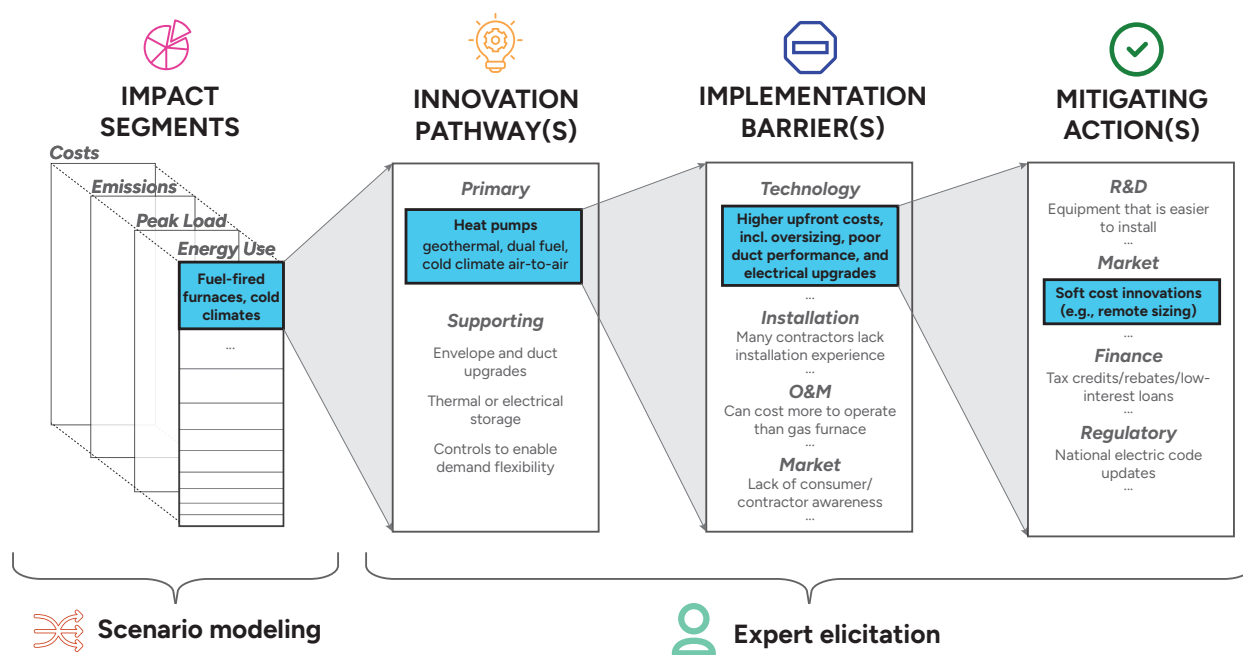


Figure 1: Mapping energy innovation pathways for the US buildings sector. The analysis approach proceeds from initial segmentation of buildings sector impacts across multiple metrics to the identification of innovation pathways for the most impactful segments, the barriers to deploying each pathway, and the actions that could address each barrier.

future buildings could present for the energy system and consumers — stubbornly high energy use and emissions, in the BAU, and rapid unmanaged growth in demand for electric services and associated costs, in the inefficient electrification case. Additional details on the data sources for end-use consumption estimates and scenario assumptions are available in the *Scenarios* section of the SI and in SI Table S1.

Figure 2 shows the resulting end-use segments across counterfactual scenarios and impact metrics. These summaries are aggregated from technology-level segments that readers may explore further through an interactive dashboard.⁵ Here we highlight key segments and trends at the end-use level.

Energy use and electricity demand

Fuel-fired space heating is currently the single largest segment of buildings sector energy use (Figure 2a). Under business-as-usual changes, fuel-fired heating remains the largest portion of overall energy use by 2050, even as heating consumption lessens with warming temperatures and consumption for cooling and miscellaneous electric loads grows. Overall, buildings sector energy use is 10% larger in the 2050 BAU than in 2024. The segmentation stack looks very different under inefficient electrification of fuel-fired end uses, as fuel-fired heating and water heating segments are substantially reduced, electric heating energy surpasses that of cooling, and other end uses make up the majority of the overall stack by 2050. Considered on this annual time scale, the performance advantages of even minimum efficiency electric vs. fuel-fired heating equipment result in overall decreases of total annual heating energy under inefficient electrification between 2024 and 2050.

On the hourly timescale, however, inefficient electrification could significantly increase peak electricity demand in the winter (Figure 2b). Buildings sector winter peak demand for the con-

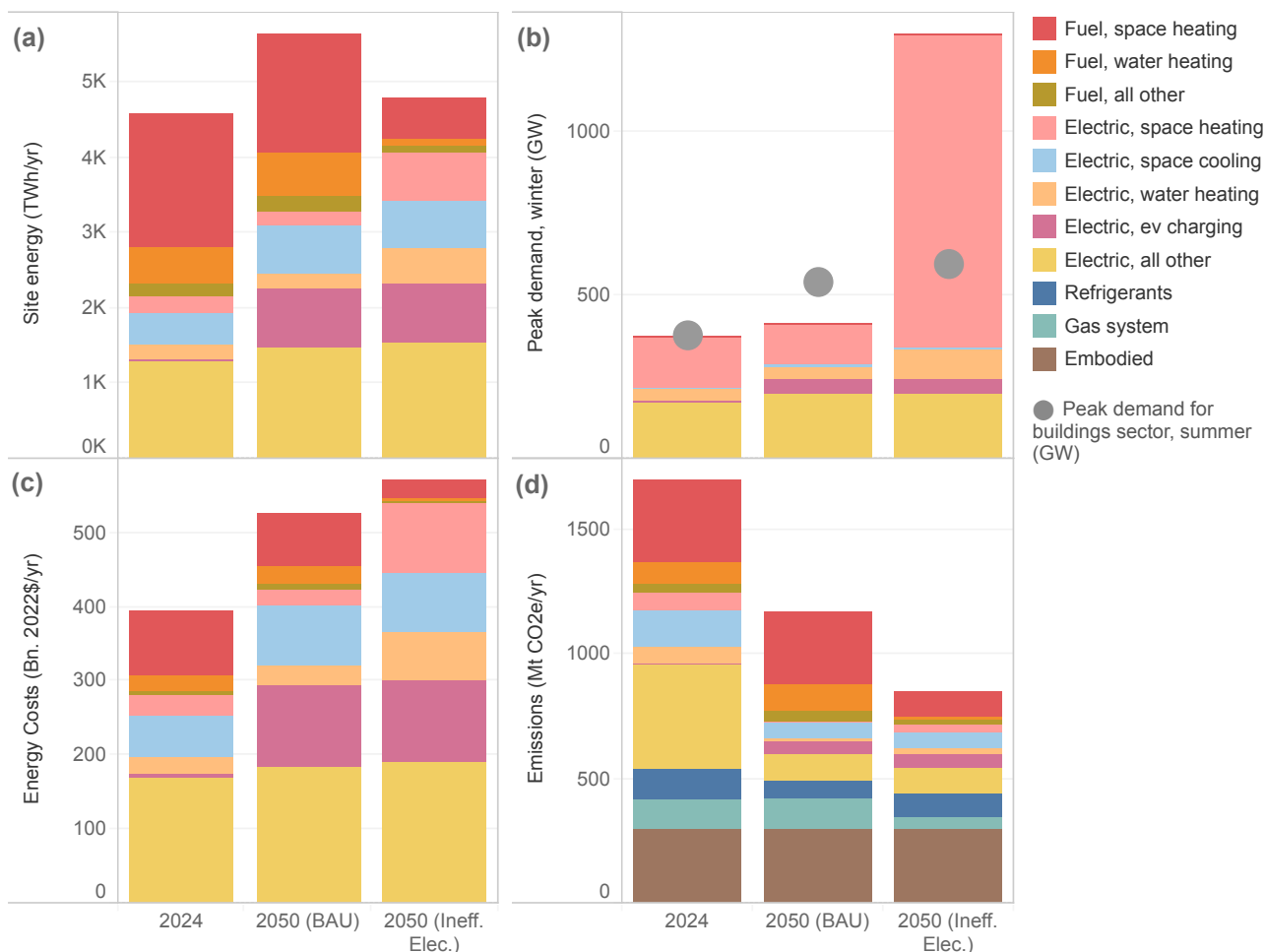


Figure 2: End-use segmentation of US buildings sector impacts. Segmentation of buildings sector impacts by: total site energy use (a), total peak electricity demand, winter (non-coincident across regions) (b), total consumer energy costs in 2022 dollars (c), and total greenhouse gas emissions (d). End-use segmentation excludes non-building loads (e.g., water pumps, manufacturing in commercial buildings, combined heat and power, etc.) and reflects only the contiguous United States.

contiguous US more than triples in this case from 2024 to 2050, driven by a sixfold increase in peak heating demand given the use of resistance-based heating to meet peak heating loads. This massive winter load growth, which would likely be large enough to switch peak demand days from summer to winter in many regional power systems,⁶ stands in stark contrast to the BAU trend. In the BAU, winter peak loads from buildings increase only slightly through 2050 as warming trends without widespread heating equipment electrification reinforce the current tendency for electricity demand to peak in the summer months.

Heat losses and gains through existing building envelopes—the physical barriers between inside and outside—are important determinants of both annual and peak energy demand from the heating and cooling segments in Figures 2a-b. Thermal loads from envelope heat transfer are especially important in residential buildings (see SI Figure S1), where envelope component heat losses and gains are responsible for 80% of annual residential heating and cooling energy use, along with 14% from duct losses. In commercial buildings (see SI Figure S2), ventilation air is the single most important source of commercial thermal loads (33% of annual commercial heating and cooling energy), though loads from envelope components are also substantial (50% of annual commercial heating and cooling energy across all envelope components).

Energy costs

Maintaining energy affordability for consumers under rapid transformation of the energy system is a critical challenge for the buildings sector. Figure 2c shows that under BAU conditions and AEO 2023 Reference Case retail price projections, total building energy costs are expected to increase 12% from 2024 to 2050 (all cost values are in 2022 dollars, so this increase is distinct from any inflation). These cost increases could nearly double under inefficient high electrification, assuming the same price projections (see the SI section *Analysis limitations* for discussion of this limitation).⁴ End-use sources of BAU cost increases mirror those for energy use (Figure 2a)—primarily, growth in cooling and other end-use energy costs. Under inefficient electrification, however, energy costs increase even as total energy use decreases. In this case, energy performance gains from switching to minimum efficiency electric equipment without further measures for energy efficiency fail to offset the relative price disadvantage of electricity. Residential and commercial electricity prices are more than three times natural gas prices today, a ratio which continues through the 2050 forecast.⁴ The stark growth that results in electric heating and water heating energy costs drives the overall energy cost increases through 2050.

Greenhouse gas emissions

Buildings sector greenhouse gas (GHG) emissions are expected to decrease by more than a third from 2024 to 2050 under BAU conditions (Figure 2d). This decrease is primarily due to the continued decline in the GHG intensity of electricity, which serves roughly half of US building site energy demand.⁷ The steepest declines in BAU end-use emissions are from operational end uses served by electricity—cooling, water heating, and other uses—while the emissions from fuel-fired end use segments remain flat across this time horizon. High electrification reduces the emissions of these fuel-fired end uses while lower-emissions electricity moderates the added emissions from converted equipment. This results in a steeper decline in total buildings sector emissions—roughly 60% from 2024 to 2050—even assuming switching to minimum efficiency electric equipment. Heating and water heating segments, which make up the vast majority of fuel-fired emissions from buildings, are the primary source of emissions reductions beyond the BAU under inefficient electrification.

Figure 2c shows that three additional sources of emissions will become more important as operational end use emissions decline: fugitive refrigerants and fluorinated gases; fugitive methane from the buildings natural gas supply chain; and life cycle emissions embodied in the manufacture, transport, construction, retrofit, and disposal of building materials. Fugitive refrigerant and methane emissions decrease over time across both counterfactual scenarios: in the BAU, increased use of low-GWP refrigerants reduces emissions, while under inefficient electrification, an increase in refrigerant emissions from greater use of electric heat pumps is more than offset by concurrent reductions in methane leakage. Embodied emissions comprise an estimated 18% of today's buildings sector emissions, which is lower in the United States relative to other countries.⁸ Yet, embodied sources could comprise more than one third of the sector's emissions by 2050 as the buildings stock continues to grow and many of today's buildings remain in place.

The 2050 buildings sector

The previous sections point to multiple challenges that the buildings sector could face by 2050 without further innovations to improve efficiency, lower the cost of building energy end uses for consumers, and reduce GHG emissions. On one hand, carrying forward BAU trends will keep annual energy use high, fail to blunt rising energy costs, and leave substantial emissions

unabated. On the other hand, encouraging further reductions in energy use and emissions through widespread switching of building end uses to run on lower-emissions electricity could dramatically increase peak demands on the power grid while exacerbating growth in energy costs.

Figure 3 decomposes these 2050 end points at the sector level into constituent end-use and technology segments to frame the potential impacts of segment-specific innovation pathways that could deliver more beneficial outcomes. The figure shows, for example, that residential fuel-fired furnaces in cold climates are on track to remain a top source of building energy use and emissions in 2050 (10% and 8% of the totals, respectively) but that innovations in this segment must weigh reductions in energy and emissions against adverse impacts on other outcomes — again, switching away from fuel-fired equipment could lead to unmanaged growth in electric heating demand that strains electricity supply and increases costs. The following sections elaborate on key innovation pathways for the largest segments of buildings sector impact shown in Figure 3.

Innovation pathways, barriers, and actions

We leverage structured feedback from buildings sector experts to highlight primary and supporting pathways for technical innovation in each group of buildings sector segments shown in Figure 3. Expert feedback was collected via a spreadsheet that presented respondents with a summary of the segments to assess and instructions about how to assess each segment (see the SI section *Expert elicitation and response synthesis* for additional details about the elicitation approach and common areas of focus in the responses). The experts identified key barriers to pathway implementation that relate to technology characteristics, installation, operation and maintenance, and markets. Additionally, the experts identified the actions needed to address each barrier; actions span the categories of R&D, market, finance, and policy. Full summaries of segment-specific innovation opportunities based on the expert responses are available in the SI section *Full assessments of building end-use and technology segments*.

Thermal loads in existing buildings

A building's thermal load is the amount of heat energy that needs to be added or removed to keep it at the desired temperature. Thermal loads are imposed by heat transfer through the building envelope—the physical barrier between inside and outside—including air leakage; by the introduction of outdoor air for ventilation; heat gain from solar radiation through windows, occupants, and other internal sources; and by heat losses and gains from the ducts and pipes that distribute heating and cooling. We include separate segment categories on thermal load reduction and end-use equipment to provide sufficient attention for each. In Figure 3, the impacts of heating and cooling end uses are shown under both the thermal load and fuel-fired/electric equipment segments.

In existing buildings, thermal loads are responsible for 39% of buildings sector energy use, 32% of energy costs, and 26% of emissions. Heat transfer through existing residential envelopes is by far the largest thermal load segment at 25% of BAU buildings sector energy and 17% of emissions. In commercial buildings, thermal loads from envelope components and conditioning ventilation air are both important sources of energy and emissions impacts. Thermal load segments also determine peak building heating and cooling service demands and thus the size and cost of both heating, ventilation, and air conditioning (HVAC) equipment and the electric grid infrastructure that is required meet these demands.



Figure 3: Sources of U.S. buildings sector impacts in 2050 without further innovation. Segment-specific impact (from left to right): site energy use, winter peak electricity demand, consumer energy costs in 2022 dollars, and GHG emissions, under two counterfactual scenarios (BAU = business-as-usual scenario, Ineff. Elec. = high inefficient electrification scenario). Metrics reflect only the contiguous United States. Heating and cooling impacts are shown under both thermal load and fuel-fired/electric equipment segments.

Key **technical innovation pathways** for reducing thermal load segments include:

- Primary:
 - *Residential and commercial envelope*: traditional air-sealing, insulation, and window upgrades; emerging components and approaches (aerosol-based air-sealing, cladding-integrated insulation, secondary glazing, window films, thin triple-pane windows, pre-fabricated wall/roof/window panel solutions).
 - *Residential duct losses*: traditional and novel (aerosol-based) duct sealing.
 - *Commercial ventilation*: energy recovery ventilation (ERV; packaged unit add-on and standalone systems).
- Supporting:
 - *Residential and commercial envelope*: novel diagnostic approaches (e.g., non-destructive testing, virtual sensing, autonomous platforms); higher-fidelity modeling of air, heat, and moisture flows in building design/retrofit software.
 - *Residential duct losses*: ductless HVAC solutions.
 - *Commercial ventilation*: sensors and controls to correct under- and over-ventilation (building automation systems, occupant sensing, demand-controlled ventilation, economizers, heat/smoke-sensing kitchen exhaust hoods); indoor air-treatment devices (traditional filtration, germicidal ultraviolet air treatment, portable or sorbent air cleaners).

Key **implementation barriers** identified in the structured feedback include:

- Technology: high up-front cost for existing and emerging envelope, duct, and ventilation upgrades; lack of widely available and low-cost energy recovery ventilation options for commercial packaged units.
- Installation: disruption to occupants; lack of trained workforce for installing ventilation upgrades and controls; outdated design and operation guidance.
- O&M: lack of trained workforce for maintaining ventilation systems and controls.
- Market: lack of consumer and utility awareness of options and benefits.

Key **stakeholder actions** identified in the structured feedback include:

- R&D: lower-cost, easier to install upgrades (i.e., prefabricated envelope solutions); quantify non-energy and grid-edge benefits to support incentive design; test effectiveness of air-treatment products; support updates to ASHRAE ventilation standards.
- Market: provide information about tradeoffs to promote benefits to homeowners and contractors; support valuation of energy efficiency in real estate transactions; promote insulation at time of re-siding; incentivize aerosol-based duct sealing in weatherization and other programs to expand trained workforce and availability; real-world case studies to demonstrate HVAC downsizing benefits of envelope upgrades; encourage manufacturers to include optional ERVs for major equipment types; training on right-sizing ventilation rates.
- Finance: utility, state, and federal incentives, tax credits, and financing mechanisms for upgrades; pre-weatherization remediation incentives.

- Policy: technical support for multifamily building performance standard development; incorporate less-marketable upgrades (walls, leakage, roofs) into building performance standards; support code/building performance standard requirements for ERV in major markets and more stringent ASHRAE 90.1 ERV requirements.

Fuel-fired equipment in existing buildings

Fuel-fired end uses in existing buildings make up an estimated 35% of BAU energy use, 18% of BAU energy costs, and 28% of BAU emissions in 2050, primarily from heating and water heating. At the technology level, impacts from residential furnaces are predominant, especially in colder climates. Residential single- and multi-unit boilers are less significant in terms of overall energy and emissions impacts, but the latter disproportionately serve renters.³ In commercial buildings, gas-fired packaged or rooftop units are the largest source of energy and emissions impacts, with additional impacts from large central boilers that serve a variety of hydronic system types including multi-zone variable-air-volume systems, zonal water-source heat pumps, and other zone-by-zone system types.

Key **technical innovation pathways** for these fuel-fired technology segments include:

- Primary: heat pumps for heating (types include air-to-air, air-to-water, geothermal, hybrid/dual-fuel, and thermally-driven/absorption; deployed at scales ranging from large central heat pump boilers to distributed micro heat pumps); combination heating/water heating heat pump boilers; domestic hot-water-only heat pump water heaters.
- Supporting: envelope upgrades, thermal energy storage, demand flexibility (DF), energy recovery ventilation. Cross-cutting innovations listed under *Building electrical infrastructure*, *Grid edge resource management*, *Dual-fuel and cogeneration systems*, *Thermal energy networks* are also highly relevant to this category.

Key **implementation barriers** identified in the structured feedback include:

- Technology: higher upfront costs compared with conventional fuel-fired equipment; limited availability of drop-in products for high-temperature radiator (180°F) applications; thermal storage products not widely available and high up front cost of HVAC- and envelope-integrated thermal storage.
- Installation: technology form factors limit deployment where there are space constraints.
- O&M: higher operating costs of electric systems compared with conventional gas equipment — particularly in colder regions with high electric rates.
- Market: lack of consumer and contractor awareness; heat pump products not well stocked for retail/distribution in new markets.

Key **stakeholder actions** identified in the structured feedback include:

- R&D: improve and validate product cold climate performance in more mature segments (e.g., single family residential); develop heat pump products with high cold climate performance for emerging markets (e.g., commercial heat pump RTUs, large hydronic systems); improve dual-fuel configurations and controls to maximize efficiency and emissions reductions; new form factors for space-constrained applications; increase availability and performance of plug-in and quick-connect solutions; develop new thermal energy storage products.

- Market: contractor training programs and resource development; consumer awareness campaigns; tools and design guides to avoid equipment oversizing; standardized quality installation guides; potential studies to understand emerging heat pump markets; business model innovations.
- Finance: utility, state, and federal equipment purchasing incentives; streamlined consumer guidance for accessing incentives.
- Policy: technical assistance for rate design; heat pump compliance pathways for energy codes/performance standards; national electric code updates; air conditioner-to-heat pump replacement policies.

Electric equipment in existing buildings

Electric end uses in existing buildings make up an estimated 33% of BAU energy use, 51% of BAU energy costs, and 11% of BAU emissions in 2050. Energy use and costs could grow to up to 55% and 65% of the 2050 totals, respectively, under high electrification (excluding EV charging). Figure 3 shows that under both a BAU and high electrification case, residential heating, ventilation and cooling (HVAC) and non-thermal loads across building types (“all other,” including lighting, plug loads, and other miscellaneous electric) are predominant electric end uses. Under high electrification, the large impacts of additional heating demand on peak loads is evident, and residential water heating also shows up prominently in the impact segmentation.

Key **technical innovation pathways** for these electric end use segments include:

- Primary: standard and cold-climate heat pumps (to replace electric resistance heating and meet new electric heating demands; see *Fuel-fired equipment in existing buildings* for types).
- Supporting: connected or device-integrated controls to enable heating and water heating demand flexibility (DF) and grid-responsiveness; minimal, low-power network communications; efficient envelopes, integrated thermal storage, and energy recovery to reduce thermal loads. Cross-cutting innovations listed under *Grid edge resource management* are also highly relevant to this category.

Key **implementation barriers** identified in the structured feedback for electric heat pumps are discussed in *Fuel-fired equipment in existing buildings*; additional innovation barriers identified for electric segments include:

- Technology: lack of easily configured product interfaces or control sequences for high performance commercial HVAC and lighting systems; plug loads designed for low-latency vs. efficiency.
- Installation: lack of workforce to configure commercial HVAC/lighting controls; challenge of deploying system-wide power management technologies.
- O&M: uncertain performance of control products/services; load-shedding service acceptability thresholds are poorly understood.
- Market: lack of valuation for envelope in reducing peak demand and increasing demand flexibility potential (see also: *Thermal loads in existing buildings*); lack of compensation mechanisms for load shifting and shedding; lack of common communication standards, metrics, and device compatibility for smart electrical devices across vendors and end uses; commercial miscellaneous electric loads (MELs) are diverse and poorly understood.

Key **stakeholder actions** identified in the structured feedback for electric heat pumps are discussed in *Fuel-fired equipment in existing buildings*; additional actions to address electric segment barriers include:

- **R&D**: plug-and-play software installations; efficient networking and onboard computation, predictive control for plug load devices; standardized designs/libraries of operating sequences; platforms for integrated MELs control.
- **Market**: development of commonly accepted smart device metrics and communication standards; encourage integration across end-use ecosystems; best practices for procurement and operation of power management technologies; guidelines for acceptable service reduction thresholds under different conditions.
- **Policy**: collect and share data on demand-side flexibility measure operation for utility distribution and resource planning; technical assistance to support design of consumer compensation, rates, and incentives to encourage flexibility; incorporate control sequences in technical standards; develop semantic modeling standards, consensus specifications, and testing capabilities/protocols to verify control sequences and load impacts.

Other operational energy

New building operational energy (built 2024–2050)

We group together all fuel-fired and electric operational energy for buildings that will be constructed between 2024 and 2050. Together, this segment is estimated to comprise 32% of BAU energy use, 31% of BAU energy costs, and 18% of BAU emissions in 2050.

Key **technical innovation pathways** for new building operational energy span a wide range of cost-effective technologies for thermal load reduction, all-electric/electric-ready construction, and management of behind-the-meter resources. Many of the key **implementation barriers** identified in the structured feedback for these innovations echo those already highlighted for existing buildings. Several *market* barriers are unique to new construction, however, including: lack of value proposition for efficiency; design decisions that are split across multiple professions; a shortage of new housing supply; and outdated energy codes in states and local jurisdictions. Key **stakeholder actions** identified in the structured feedback include: scaling up high-quality offsite housing construction (*market*); encouraging professional credentialing programs (*market*); and supporting state and local energy code adoption and compliance (*policy*).

Electric vehicle charging

Electric vehicle (EV) charging is a key area of coordination between buildings and transportation research planning given the potential synergy between EV charging and space heating—unmanaged EV charging could add up to 119 GW to evening peak loads, but has much lower impacts in the morning hours when space heating electrification is most likely to increase electricity demand.⁹ At the bulk power scale, this synergy could be exploited and further enhanced through coordinated management of EV charging and electric space heating loads.

Key **technical innovation pathways** for EV integration include coordination of charging with building loads and improved interoperability of vehicle and building controls to support flexibility and resilience. Key **implementation barriers** identified in the structured feedback include: potential for EV integration to prompt distribution grid upgrades (*technology*); lack of charger feasibility/accessibility in multifamily buildings (*market*); and lack of access to vehicle data for coordinated control of charging (*market*). Key **stakeholder actions** identified in the structured

feedback include: smart charge management to coordinate EV charging, other building loads, onsite generation, and grid signals (*R&D*); market adoption of standardized charging protocols (*market*); and code requirements for EV infrastructure in multifamily buildings and at workplaces (*policy*).

Embodied and fugitive sources

The final grouping of segments is unique to the emissions metric, spanning all three scopes of emissions—refrigerants (scope 1); gas system (scope 2); and embodied (scope 3). Collectively these segments are an estimated 32% of 2024 buildings sector emissions, but by 2050 this share could grow to between 44% (2050 BAU) and 55% (2050 high electrification).

Embodied construction material life cycle emissions

Embodied construction lifecycle emissions associated with producing, transporting, installing, and disposing of building materials are expected to be the largest single source of this group's emissions in 2050 at 27% to 38% of total emissions depending on the scenario (see Fig. 2).

Key **technical innovation pathways** span three categories:

- *Design*: repurpose existing buildings; salvage materials; design with low-carbon materials and material efficiency; design for deconstruction and reuse.
- *Construction*: reduce waste and construction equipment emissions.
- *Manufacturing*: reduce the carbon intensity of building materials, including concrete and steel.

Key **implementation barriers** identified in the structured feedback include: higher cost of low-embodied carbon products (*technology*); low-quality of environmental product declarations (*technology*); low product availability (*market*); and risk-aversion to new construction materials (*market*). Key **stakeholder actions** identified in the structured feedback include: field validation of new low-carbon materials to de-risk adoption (*R&D*); financing and incentivizing new material manufacturing (*finance*); educating builders on low-cost strategies (*market*); and establishing life cycle assessment standards and guidelines (*policy*).

Refrigerants and other fluorinated gases

The production and consumption of hydrofluorocarbons (HFC)—used in buildings as refrigerants, foam blowing agents, and some fire protection systems—comprise an estimated 7% of 2050 BAU buildings sector emissions. As of 2025, these emissions are required by law to be reduced by about 85% by 2036,¹⁰ which will reduce their relative share of emissions impacts in 2050. Note that while our scenario data represent increasing levels of low-GWP refrigerant adoption, the 85% target is not explicitly assumed in the modeling behind Figures 2 and 3.

Key **technical innovation pathways** for reducing HFC emissions include: reduced refrigerant usage; reduced leakage; improved end-of-life reclamation; and substitution with low/ultra-low global warming potential (GWP) alternatives. Key **implementation barriers** identified in the structured feedback include: lack of leak detection methods (*technology*); uncertainty about performance and safety (*technology*); lack of incentives for reclamation (*market*); and limited availability of ultra-low GWP refrigerant equipment (*market*). Key **stakeholder actions** identified in the structured feedback include: improve refrigerant sensing and management systems (*R&D*); develop and demonstrate ultra-low GWP options (*R&D*, *market*), and recycling and leak detection incentives or requirements (*market*, *policy*).

Gas production and distribution

The emissions associated with producing and distributing the piped natural gas used in buildings—which includes venting, flaring, and leaking of methane at various stages of the supply chain—comprise an estimated 10% of 2050 BAU buildings sector emissions. Emissions inventories often include methane leakage estimates as part of the emissions intensity of gas consumption;¹¹ however, we characterize this as a separate segment because pathways for addressing onsite consumption may differ in their implications for gas system emissions (e.g., reliance on dual-fuel equipment).

Key **technical innovation pathways** include: identifying and addressing leaks across the supply chain; reducing venting; improving flaring efficiency; and electrifying production operations. Key **implementation barriers** identified in the structured feedback include: lack of understanding about the fugitive emissions impacts of low-carbon fuels(*technology*); uncertainty in leakage estimates (*O&M, market*); and lack of coordination between gas and electricity system planning (*market*). Key **stakeholder actions** identified in the structured feedback include meta-analyses of leakage data at the national scale (*R&D*); GHG intensity assessments for low-carbon fuels (*R&D*); and support of integrated system planning across gas and electric utilities (*market*).

Cross-cutting opportunities

The preceding sections address innovations that affect particular segments of buildings sector impact. Here we highlight innovation opportunities that relate to multiple segments.

Building electrical infrastructure

Decisions to switch from fuel-fired to electric equipment may trigger costly and time-consuming upgrades to building electrical infrastructure (e.g., new circuit runs; electrical panels; service upgrades; transformers) that technical innovations can avoid. **Technical innovations** include: low-power end-use equipment (e.g., 120-volt heat pump water heaters); behind-the-meter load management (e.g., circuit sharing; smart breakers; digital load management, electrical storage); and supporting thermal load reductions to allow smaller equipment (e.g., envelope; ventilation; thermal storage). Key **implementation barriers** identified in the structured feedback include: lack of simple load management hardware (*technology*); lack of common protocols for controlling distributed storage and managing building loads (*technology*); and conservative determination of electrical capacity needs (*installation*). **Stakeholder actions** identified in the structured feedback include: development of a low-power product ecosystem (*R&D*); consensus standards on physical connections and software interoperability that supports native load balancing and storage integration (*R&D*); granular analyses of actual peak electrical use (*market*); and National Electric Code provisions that permit alternate peak load calculations (*policy*).

Grid edge resource management

As building electrical loads grow, grid edge resource management coordinates energy efficiency, load flexibility, solar, electrical/thermal storage, and EVs behind-the-meter to make more efficient use of distribution and bulk power system infrastructure. **Technical innovations** include: equipment and controls that enable automatic price-based and direct load control (e.g., connected thermostats, building automation systems, and water heaters; managed EV charging; thermal storage [HVAC- or envelope-integrated]; electrical storage [standalone, appliance-integrated]; and supporting innovations that enable valuation energy efficiency and demand flexibility resources in utility planning and power markets. Key **implementation barriers** identified in the

structured feedback include: higher costs for connected products and storage (*technology*); lack of required control capabilities and standards (*technology/market*); and lack of valuation and incentives to drive adoption of behind-the-meter grid resources (*market*). Supportive **stakeholder actions** identified in the structured feedback include: improving the ability of control algorithms to manage multiple loads against grid and occupant objectives (*R&D*); developing business models for stacking value across grid edge assets (*market*); offering incentives for connected equipment and storage (*finance*); adding or bolstering demand-side resource valuation requirements in integrated utility planning (*policy*); and industry-led standardization of communications protocols for distribution system management (*policy*).

On-site solar generation

Together with storage and other behind-the-meter resources, on-site solar generation can provide value at the grid edge and the bulk power system scale—particularly where there are power transmission and distribution constraints—and can improve electrical resilience for individual buildings and/or community microgrids. **Technical innovations** include integration of on-site solar with other grid edge resources, including storage (thermal and battery) and flexibility; and the integration of solar photovoltaics with building materials. Key **implementation barriers** identified in the structured feedback include: the high upfront costs of batteries and islanding controls (*technology*); lack of confidence among distribution planners in reliance on distributed generation (*O&M*); and the diminishing economic and environmental impact value of increasing amounts of mid-day distributed solar generation (*market*). **Stakeholder actions** identified in the structured feedback include: demonstrations of distributed solar plus storage technology and controls (*R&D*); development of affordable islanding technology and controls (*R&D*); technical assistance for distribution planners (*market*); programs to reduce permitting costs (*policy*); regulatory development of new ownership models for solar plus storage systems (*policy*); and new compensation requirements for distributed resources and virtual power plants (*policy*).

Dual-fuel and cogeneration systems

Continued use of existing on-site fuel infrastructure through dual-fuel and cogeneration solutions could also help manage the cost, grid reliability, and resilience impacts of adding new electric loads on the grid. **Technical innovations** include efficient dual-fuel heating configurations (e.g., heat pumps supplemented with fuel-fired furnaces) with switchover controls that optimize across multiple objectives; and adapting existing combined heat and power (CHP) systems to use low-carbon fuels and/or carbon capture to reduce environmental impacts. Key **implementation barriers** identified in the structured feedback include: uncertainties about the cost, availability, and environmental impact of low-carbon fuels (*technology*); conservative dual-fuel switchover temperatures that limit emissions reductions benefits (*O&M*); and concerns about the health impacts of fuel combustion (*market*). **Stakeholder actions** identified in the structured feedback include: analysis to further understand the availability and environmental/health impacts of low-carbon fuels (*R&D*); comprehensive characterization of the benefits and costs of dual-fuel systems (*R&D*); development of control systems to manage tradeoffs between fuel use, comfort, and cost savings in dual-fuel systems (*R&D*); and installer training and operational guidance to avoid overly conservative switchover defaults (*market*).

Thermal energy networks

Thermal energy networks (TENs) share heating and/or cooling services across multiple buildings to improve overall system efficiency and affordability, reduce environmental impacts, and

moderate the peak load profiles of thermal services on the power grid. **Technical innovations** for new TENs include: ambient-temperature water loop designs that use geothermal boreholes, bodies of water, and wastewater as heat sources and sinks. In the United States, existing TENs (typically high-temperature district steam or hot water systems that sometimes include CHP) serve about 8% of commercial building floor area.¹² Technical innovations for these existing systems include: low-carbon heat sources, transitioning to ambient-temperature loops, and decentralizing where networks are no longer feasible. Key **implementation barriers** identified in the structured feedback include: the high cost of drilling geothermal boreholes (*technology*); potential constraints from available land area, geological conditions, and existing infrastructure that raise uncertainty about technical and financial performance (*technology*); and the lack of a value proposition and regulatory certainty for TEN business models (*market*).¹³ **Stakeholder actions** identified in the structured feedback include: modeling, subsurface characterization, and system design validation tools (*R&D*); comprehensive valuation of grid benefits, including avoided peak loads (*R&D*); drilling and HVAC training and apprenticeships (*market*); incentives for new drilling businesses and water-well drillers (*finance*); capital and loan guarantees from government agencies (*finance*); legislation to allow thermal utilities (*policy*); integrated distribution system planning requirements for utilities (*policy*); utility pilots and knowledge sharing (*policy*).¹³

Energy modeling and analysis

Finally, energy modeling and analysis generates the data for exploring and evaluating all other innovations. At the individual project scale, modeling and analysis informs building and system designs, system selection and sizing, and code compliance. In stock-level assessments, modeling data inform R&D priorities, program planning, and code development. **Technical innovations** include: common open-source platforms for vendors to build custom products; accurate predictive modeling to support building performance standards (BPS) and performance-based codes; modeling of time-of-use dynamics and multi-building systems; and standardized stock-scale modeling scenarios and datasets. Key **implementation barriers** identified in the structured feedback include: outdated or limited modeling templates for advanced technologies (*technology*); high cost of performance-based modeling (*technology*); lack of valuation of uncertainty (*market*); and conflicting scenario modeling definitions, inputs, and tools (*market*). **Stakeholder actions** identified in the structured feedback include: update models, sizing methods, and templates for key innovations such as heat pumps and thermal energy storage (*R&D*); publish best practices for uncertainty quantification (*R&D*); harmonize and integrate buildings sector datasets and modeling tools to develop a robust and regularly updated set of common scenario inputs and projections (*R&D*); further integrate design, codes, and BPS software (*market*); support BPS and other use cases that require accurate predictive modeling (*policy*).

A crowded and evolving landscape

Our analysis addresses fundamental questions about how the buildings sector impacts people and the broader energy system—both today and in future decades—and identifies innovation pathways that can help avoid the most challenging impacts. While our findings highlight specific innovation opportunities and actions, we leave open the questions of who will act on this information and how, recognizing that buildings sector innovation is driven by the collective decision making of many different stakeholders, each with a unique purview, levers for influence, and set of internal priorities.

National governments around the world have a wide range of tools to use in supporting innovation, including R&D program support of early-stage technologies; demonstrations and techni-

cal assistance to support key technology markets; incentives for homeowners and businesses; and minimum requirements for product performance. However, many critical innovation levers depend on sub-national decision-making. The United States is similar to Canada, Australia, India, in that new building code adoption and electricity regulation occur at the state, provincial, or local levels. US states have significant latitude in designing financial incentives for building technologies from ratepayer funded utility programs and federal grants. State utility commissions and legislatures can also set policies that would advance several of the innovation pathways described above, including energy efficiency resource and clean heat standards, utility planning and rate reform, and utility business model innovations. The private sector is also strongly influential: national and sub-national policies must account for the availability of products and how likely industry professionals are to recommend those products to their customers.

Beyond stakeholder roles, timing is important. Strategic sequencing of actions can improve effectiveness—for example, actions to reduce the cost of higher-performance technologies bolster efforts to scale markets for these technologies, which in turn improve the economic justification for increasing minimum technology performance thresholds. Moreover, certain actions may warrant more near-term attention than others—e.g., actions addressing heating or cooling equipment, where turnover is slow and replacement decisions today could lock in legacy technologies for decades to come. In the case of fuel switching, deferred conversions to electric equipment prolong the emissions impacts of fossil-fired equipment and increase the cost of reducing emissions later; yet fuel switching to the lowest-cost, least efficient electric alternatives increases stress on the power grid and puts upward pressure on electricity rates. Such dynamics and tradeoffs are important to consider when determining near-term priorities for technology development and market-facing initiatives—priorities that deliver impacts within the next five years—versus priorities with longer-term horizons.

Many of the innovation pathways, barriers, and actions identified for the United States in this study are relevant to other countries, though each country's circumstances are unique. Canada, Australia, and New Zealand have similar building stocks with many detached homes. Northern and eastern Europe are similar to the United States in their use of fossil fuels for heating, though these regions use less air conditioning and rely more on boilers and district heating rather than individual furnaces. In recent years, high natural gas prices and carbon pricing have led to increasing shares of electric heat pumps in Europe, particularly in Scandinavia.¹⁴ The lower share of air conditioning means that much of Europe's power grid is already winter peaking with forecasted growth in summer peaks, which differs from the US grid and its majority of summer-peaking regions.¹⁵

We aim to regularly update the segmentation study and elicitation of innovation pathways to capture changes in buildings sector development. By leveraging public, regularly maintained datasets and a structured instrument for collecting expert feedback as the basis for this analysis, we reduce the burden of each update and lay the groundwork for future improvements. These include adding to the scope and resolution of the modeling outputs and incorporating the emerging technical breakthroughs, market conditions, and strategy adjustments that will continue to reshape the prospects for buildings sector innovation in the United States and globally.

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Declaration of Interests

The authors have no competing interests to declare.

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Supplemental information

Experimental procedures

Segmentation philosophy

Segmentation of buildings sector impacts is organized by sector (residential vs. commercial), end use (space heating, water heating, etc.) and by class of equipment (e.g., major types of HVAC systems), as allowed by the underlying data. The goal of this organization is to facilitate discussions of common technical solutions. The paper's segmentation approach stands in contrast to traditional building stock segmentation methods that divide up the building stock by physical characteristics like building activity type, climate zone, vintage, floor area, and ownership structures.^[1] With up to 15 commercial building use types and 8 or more climate zones,^[2] considering all combinations quickly expands the total number of segments to assess. Segmenting by end use and class of equipment reduces this number and simplifies the identification of key technology innovations, barriers, and actions for individual segments. We recognize that there are important differences in technology performance and deployment issues for different building types and climates. The flexible dashboard that accompanies this analysis allows one to explore how impacts are distributed across these additional parameters.^[3]

The approach that we use to determine segments of buildings sector impact is as follows:

1. Segment overall impacts into those related to *operational energy use* and *non-operational emissions sources* (embodied, refrigerants, gas system).
2. Further segment operational energy use segments by *existing* (built before 2024) and *new* (built 2024–2050) buildings. Electric vehicle charging (in both existing and new buildings) is split into its own unique segment.
3. Further segment existing building operational energy segments by delivered service (heating, water heating, etc.), *residential* vs. *commercial*^[1] context, and energy carrier type. The resulting end use segments are then divided into three sub-categories:
 - (a) *thermal loads*^[ii] — further split into categories of envelope, ducts, ventilation, and internal gains.
 - (b) *fuel-fired end uses* — further split into equipment type categories;^[iii] the largest of these categories (residential fuel-fired furnaces) is split into colder (zones 5–8) and warmer (zones 1–4) climates to capture the difference in relative difficulty and solution types in addressing furnace emissions (e.g., by replacing with heat pumps) in cold climates vs. warm climates.^[2]
 - (c) *electric end uses* — further split into end use categories (HVAC, water heating, refrigeration, all other)

ⁱIn the United States, the commercial building sector is comprised of all non-residential buildings, including those serving non-commercial public and institutional activities.

ⁱⁱHeating and cooling energy use is a function of both these thermal loads and the mechanical heating or cooling equipment used to meet the load. Thus, we are intentionally double-counting heating and cooling operational energy to reflect both aspects.

ⁱⁱⁱResidential multi-unit boilers were split into space and water heating to preserve information about the end uses, despite often being the same piece of equipment. Some single-unit homes also use boilers that provide both space and water heating, though this is less common than in multifamily buildings, and the available data from the Residential Energy Consumption Survey 2020 does not make this distinction.

The resulting 37 segments of buildings sector impact underpin the quantitative analysis and expert elicitation steps described in the following sections. Note that individual buildings do not map into a single segment under this approach. For example, an existing school building may be related to the following segments:

- Commercial thermal loads, envelope;
- Commercial thermal loads, ventilation;
- Commercial fuel-fired large boilers (space heating);
- Commercial fuel-fired centralized water heaters;
- Commercial fuel-fired cooking;
- Commercial electric HVAC;
- Commercial refrigeration;
- Commercial all other electricity;
- Electric vehicle charging;
- Refrigerants and other fluorinated gases;
- Embodied construction materials (for potential renovations); and
- Gas production and distribution.

Development of segmentation data and metrics

Segment impacts are estimated using a combination of existing tools and datasets, scenarios, and metrics, which are listed here.

Scout. For segments related to buildings sector operational energy, data on energy use, electricity demand, GHG emissions, and costs are estimated for 2024–2050 using Scout,^{iv} a hybrid building stock modeling framework that combines a Q1 technological-econometric model of building and technology stock size and dynamics and a Q4 end-use distribution model of energy use per unit stock.^v

Scout's baseline forecast of operational building energy use is drawn from the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO), which utilizes the National Energy Modeling System (NEMS) Residential and Commercial Demand Modules (RDM and CDM)^{6,7} on the demand-side; the Electricity Market Module (EMM) to forecast grid conditions and electricity prices;⁸ and the Macroeconomic Activity Module to forecast economic conditions, building construction, and population changes.⁹ The AEO forecast for buildings is resolved by U.S. Census Division and reflects a changing menu of market-available building technology cost, performance, and lifetime characteristics,¹⁰ bottoms-up representations of existing technology turnover rates and consumer choice, and a future weather forecast that extrapolates 30-year historical trends in heating and cooling degree days.

^{iv}The specific version of Scout that was used to generate the data for the dashboard is available online: <https://github.com/trynthink/scout/releases/tag/pathways-v1.0.0>. The sequence of commands needed to produce the data are included in the data record that accompanies this article, which is available at: <https://data.mendeley.com/preview/6skfxh8w2m?a=eb3f6b37-657f-4003-8327-85a9d101a6b2>

The RDM and CDM feed-forward from base-year estimates of equipment and housing stock that are calibrated to the Residential Energy Consumption Survey (RECS) and Commercial Building Energy Consumption Survey (CBECS).^{[11][12]} Consumption estimates in the early years of the forecast are benchmarked against data from the State Energy Data System (SEDS),^[13] Monthly Energy Review (MER),^[14] and Short-Term Energy Outlook (STEO).^[15] Retrospective analysis of NEMS predictions of total consumption by sector from 1994-2022 demonstrates absolute relative prediction errors of between 1–16% for the RDM and of between 2–11% for the CDM.^[16] While over the full time frame both modules have tended to overpredict consumption in both modules, versions of the AEO and NEMS from the past ten years have tended to underpredict consumption, on average by 1-4% vs. surveyed consumption levels.

Scout integrates additional data sources and assumptions to further resolve the EIA buildings module data geographically down to the EMM resolution and temporally down to the hourly time scale. Scout also adds measures to the market competition that are not in the EIA forecast to develop alternate scenarios of operational energy use for the buildings sector through 2050. Details about these additions on top of the baseline operational energy forecast from EIA are covered at length elsewhere.^[17] Similarly, Scout projects fugitive emissions from building refrigerant and gas supply leakage by attaching additional assumptions about leakage rates and the emissions impacts of various refrigerants and methane to the operational energy forecast, as described in previous studies.^{[17][18]} Finally, Scout integrates several alternate forecasts of regional grid emissions intensity, drawing the majority from Cambium/ReEDS projections.^[19]

ResStock and ComStock. Thermal load component data and hourly end-use load shapes to estimate peak load impacts are drawn from ResStock^[20] and ComStock,^[21] which are classified as Q4 physics-simulation models.^[5] These models generate a large number—typically around 900,000—synthetic samples of dwelling units and commercial buildings, drawing characteristics from trees of conditional probability distributions. Each sample is simulated with a sub-hourly physics simulation using OpenStudio^[22] and OpenStudio-HPXML^[23] modeling workflows and EnergyPlus^[24] as the underlying simulation engine to perform a bottom-up characterization of the current US building stock.

Estimates of thermal load components from previous studies are multiplied against Scout estimates of annual heating and cooling energy use to develop final thermal load impacts.^{[25][26]} Additionally, the hourly end use load profiles from ResStock and ComStock were converted into hourly fractions of annual end-use loads, which are multiplied against Scout’s annual energy projections to develop hourly electric load and peak demand estimates, following an approach developed in earlier work.^[27] For this analysis, Scout used hourly end-use load profiles for the baseline building stock from ResStock data release 2024.2 (AMY 2018 weather)^[28] and ComStock data release 2024.1 (AMY 2018 weather).^[29] The ResStock and ComStock timeseries outputs were calibrated and validated under the End-Use Load Profiles for the U.S. Building Stock project and subsequent improvement efforts.^[30]

Embodied life cycle emissions. We developed an estimated range of 200–400 Mt CO₂/yr based on the following procedure. Berrill et al. estimate 89 Mt/yr for residential construction and

^vIn some cases, AEO segments are aggregated from RECS and CBECS segments and needed to be disaggregated again to map to this study’s 37 segments of buildings sector impact noted in the previous section. Specifically, this approach was used to further partition the following AEO segments: residential boiler consumption to shared vs. individual boilers; residential storage water heater consumption to consumption that serving a single unit with 40+ gallon tank, vs. serving a single unit with <30 gallon tank or tankless, vs. serving multiple units; commercial gas furnace consumption to rooftop units vs. residential-style furnaces; and commercial water heaters to central boilers vs. point-of use.

8.6 Mt/yr for residential renovations.^[31] Pauliuk et al. estimate 181.1 Mt/yr for the U.S. residential construction sector.^[32] Based on personal communication with an author contributing to both studies, the discrepancy is likely due to different assumptions about concrete usage. Thus, we assume a range of 100–200 Mt CO₂e/yr for the residential sector.

The commercial construction portion of this estimate (100–200 Mt CO₂e/yr) is based on data from the Carbon Leadership Forum's 2017 Embodied Carbon Benchmark Study V1.^[33] Our analysis of this dataset yields a mean embodied emissions intensity for North American commercial buildings of 469 kgCO₂e/m². Applying this factor to the 2.0–2.5 billion ft²/yr of annual commercial construction forecast for 2023 to 2050 by EIA's 2023 Annual Energy Outlook^[34] yields 87–109 Mt CO₂e/yr. However, this estimate does not account for renovations of commercial buildings. Given this uncertainty, we assume that commercial renovation emissions could be of a similar magnitude as commercial new construction emissions and assume a range of 100–200 Mt CO₂e/yr for commercial construction and renovation. Together, the residential and commercial estimates yield a the range of 200–400 Mt CO₂e/yr. The midpoint of this range (300 Mt CO₂e/yr) was used in the graphical results of this analysis. Both residential and commercial embodied estimates exclude furnishings and mechanical, electrical, and plumbing services because these categories are typically excluded from life cycle assessment datasets.^[35]

Other data sources: RECS, CBECS and GHGI. In addition to Scout, ResStock, and ComStock data, the U.S. Energy Information Administration (EIA) 2020 Residential Energy Consumption Survey (RECS) and 2018 Commercial Building Energy Consumption Survey (CBECS) microdata support more detailed disaggregation of how each end-use segment's impacts are distributed—for example, across different building types—for today's building stock.^{[11][12]} U.S. Environmental Protection Agency Greenhouse Gas Inventory (GHGI) data are also used to disaggregate current sources of emissions from refrigerants/fluorinated gases and from natural gas production and distribution.^[36] These data are presented in the section *Full assessments of building end-use and technology segments* to illustrate key concentration areas for each segment that innovations should target for maximum impact.

Scenarios. Counterfactual projections of buildings sector energy use through 2050 draw from previously published scenario assumptions. The Business-as-Usual (“BAU”) assumptions are consistent with the EIA Annual Energy Outlook (AEO) 2023 Reference Case.^[34] The general characteristics of the AEO forecast are described in the “Scout” section. The base year in the AEO23 forecast is calibrated to the 2015 and 2012 versions of RECS and CBECS, respectively, and the forecast from the base years reflects the effects of federal-level policies that were enacted by November 2022, including incentives for technology adoption in the Inflation Reduction Act (IRA) and federal appliance efficiency regulations that were posted to the Federal Register by that time.

The Inefficient Electrification (“Ineff. Elec.”) case uses similar assumptions from the scenario “Low benchmark without efficient electrification” in a previous Scout modeling study.^[17] Here, fossil-based equipment is converted to a mix of heat pumps and electric resistance heating and water heating, as well as electric resistance cooking. The share of heat pumps vs. resistance in the technology mix is consistent with that of the AEO 2023-forecasted electric equipment sales shares in 2023 — 53% air-source heat pump/4% ground-source heat pump/43% resistance (residential heating), 18% heat pump/82% resistance (residential water heating), 37% air-source heat pump/8% ground-source heat pump/55% resistance (commercial heating), and 5% heat pump%/95% resistance (commercial water heating).^{[37][38]} Each class of electric equipment is represented at a typical efficiency level.^[10] Cooking electrification is assumed to occur at the same rate as for the heating end use and carries an efficiency increase that is based on the ratio

of combined energy efficiency between typical gas and electric cooking units in the 2023 EIA building technology characteristics report—82% for residential cooking and 51% for commercial cooking.¹⁰

Both of the scenarios use the same assumptions about energy prices and grid emissions intensity, drawing from AEO23 projections of the former and Cambium23 Mid-case projections of the latter.^{34,19}

Key data sources and assumptions for the two counterfactual scenarios are summarized in Table S1.

Table S1: Summary of assumptions and data sources for the two counterfactual scenarios of buildings sector development through 2050.

Scenario	Energy Efficiency Level	Electrification Level	Energy Prices	Electricity Emissions
Business-as-Usual (BAU)	Annual Energy Outlook (AEO) 2023 Reference Case tech. performance and deployment ^{10,34}	AEO23 Reference Case fuel switching assumptions ^{6,7}	AEO23 Reference Case ⁸	Cambium 2023 Mid-case, ³⁹ average emissions rates of generation induced by a region's load (<i>aer_gen_co2e</i>)
Inefficient Electrification (Ineff. Elec.)	Conversion of fossil-fired equipment to sales-weighted shares of “typical” efficiency electric equipment from AEO23 Reference Case;* no additional efficiency deployment beyond AEO23	Consistent with highest rate of fuel-fired equipment conversion to electric in Langevin et al. ¹⁷ **		

* Sales shares are 53% air-source heat pump/4% ground-source heat pump/43% resistance (residential heating), 18% heat pump/82% resistance (residential water heating), 37% air-source heat pump/8% ground-source heat pump/55% resistance (commercial heating), and 5% heat pump%/95% resistance (commercial water heating). Gas-fired cooking is assumed to be converted at the same rates as heating equipment.

** See assumptions for the ‘Most Aggressive’ fuel switching rate in that analysis.

Metrics. Segment impact calculations begin with the annual site energy use metric, where applicable. Projections are initially generated for each of the 25 EMM grid regions and 14 AEO-based building types and are aggregated to the 11 regions and building types reported in Langevin et al.¹⁷ in the final output data. For building type breakouts, an additional dimension of vintage was added—new buildings and equipment, constructed or installed from 2024–2050, versus existing buildings and equipment, already constructed or installed as of 2024.

Hourly end-use load fractions, unit energy costs and CO₂e emissions intensities are then layered on top of annual energy use estimates to estimate total peak electricity demand, annual energy cost and annual GHG emissions impacts, respectively.

Estimating peak demand impacts requires an assumption about when the total system load peak occurs in each season, grid region, and modeling scenario. The days in the summer and winter in which the peak occurs align with the seasonal peak days observed in the underlying ResStock/ComStock aggregate load shape for the contiguous United States.^{vi} The summer peak

^{vi}The ResStock/ComStock load shape is based on an actual meteorological year (AMY) weather data from 2018. The load shape for this year peaks on July 2nd in the summer and January 1st in the winter. This assumption is appropriate because weather-dependent electric heating and air conditioning in buildings drive the timing of seasonal peaks.⁴⁰

demand hour in both the BAU and inefficient high electrification case is consistent with the AEO 2023 Electricity Market Module (EMM) peak day projections for each of the 25 EMM regions. While the assumed winter peak hour is consistent with the AEO EMM in the BAU as well, in the inefficient high electrification case, a generic winter peak hour of 8–9 AM (local standard time) is imposed across EMM regions. This assumes that heating electrification drives the timing of the overall peak hour in this scenario. For simplicity, we aggregate peak impacts across all grid regions into a single value for the contiguous United States, recognizing that in reality the US power system is comprised of multiple grids that are planned and operated at a variety of geographic scales.^{vii}

For costs, we use AEO 2023 Reference Case retail electricity and fossil fuel price projections for both scenarios.³⁴ We acknowledge that high electrification could result in price dynamics that depart from the Reference Case, and discuss this limitation further in *Analysis limitations*.

For GHG emissions, we map Cambium 2023 Mid-case scenario electricity GHG intensities^{viii} to the electricity consumption in each EMM region for both counterfactual scenarios.¹⁹

Data products. The segmentation data that were produced using the tools and assumptions documented above were compiled into a master spreadsheet, which is included in the data record associated with this study.^{ix} These compiled data serve as the basis for an interactive dashboard,³ where users can explore the segmentation results under different scenarios, projection years, and output metrics.^x

Downselection of highlight segments

With the quantitative segmentation data in hand, we established a process for selecting segments that warranted specific attention in the expert elicitation of innovations, barriers, and actions (see *Expert elicitation and response synthesis*). The process was as follows:

1. Identify metrics for evaluating potential impact:

- Percentage of 2050 BAU total GHG emissions (to mitigate overall GHG emissions).
- Percentage of 2050 inefficient high electrification total annual peak load (to mitigate the need for grid infrastructure investments to increase electricity affordability).

2. Identify high and medium impact segments:

- *High* impact:
 - 5% or more of total buildings GHG in 2050 under BAU, or
 - 10% or more of total buildings peak demand in 2050 under ineff. elec. (applies to electric segments only)
- *Medium* impact:

^{vii}The 8–9 AM window is the time of the hourly peak on the peak winter day in the ResStock/ComStock aggregate load shape for the contiguous United States.

^{viii}Specifically, the Cambium metric “average emission rates of generation induced by a region’s load”.

^{ix}Available: <https://data.mendeley.com/preview/6skfxh8w2m?a=eb3f6b37-657f-4003-8327-85a9d101a6b2>

^xThermal load components derive from separate datasets and thus are not included as segments in the main spreadsheet or dashboard.²⁵ This also helps to avoid double-counting of heating and cooling impacts. As they derive from ResStock and ComStock representations of the circa 2024 building stock, they are manually applied to the 2050 scenarios and assumed to maintain the same distribution across thermal load components while accounting for changes in heating fuels in the 2050 scenario. The thermal load components are included as secondary dashboards and in figures such as Figure 3.

- 1% or more of total buildings GHG in 2050 under BAU, or
 - 5% or more of total buildings peak demand in 2050 under ineff. elec. (applies to electric segments only)
 - All other segments were labeled as *Low* impact.
3. Based on feedback from the expert elicitation process, we included two additional segments that were of high policy interest and had potential spillover benefits despite smaller impacts:
- Residential Fuel-Fired Boilers (Water Heating, Multi-Unit)
 - Residential Fuel-Fired Boilers (Space Heating, Multi-Unit)

Expert elicitation and response synthesis

We drew from the expertise of U.S. Department of Energy (DOE) staff to identify key innovations, implementation barriers, and actions that address each of the highlight segments identified as described in the previous section. In total, the analysis reflects the responses of 22 experts. Each of the experts managed and/or provided technical input to projects or initiatives that relate to the buildings sector and span early-stage research, market-facing and deployment-related activities, and policy/regulatory work. In some cases, respondents reached out to supporting technical consultants outside of DOE for additional input on their responses.

Expert feedback was collected using a structured spreadsheet instrument between June and August 2024. Respondents were presented with a list of highlight segments to assess, where each row in the spreadsheet represented an assessment of a unique segment and the columns of the spreadsheet guided respondents through the items to assess (see Table S2). Some of these items were tagged with instructions to improve the consistency with which each expert interpreted a given item, and these instructions are included in the Table. Where an item required a categorical response, experts were able to choose from a drop down menu of pre-populated options. The fully compiled and de-identified spreadsheet responses are separately available via a data record associated with this paper.^{xi}

Respondent engagement was conducted in the following stages:

1. initial distribution of spreadsheet instrument with instructions about how to fill out key items, where needed;
2. follow-up group discussions after an initial read through of the spreadsheet to address any questions respondents had about how to fill out information;
3. a second round of follow-up group discussions after responses were received to review initial summaries of results (see subsequent description of these summaries), fill in any missing information, clarify ambiguous responses, and ensure that any corrections we made to apparent errors or omissions in their responses were warranted;
4. final distribution of fully corrected and compiled spreadsheet version; and
5. opportunity to review content in the highlight slide deck developed from individual spreadsheet responses (described further in the section *Highlight slides and content iteration*).

Quantitative summaries of expert responses were developed using three metrics:

^{xi}Available: <https://data.mendeley.com/preview/6skfxh8w2m?a=eb3f6b37-657f-4003-8327-85a9d101a6b2>

Table S2: Expert elicitation frame. The “Notes” column includes the instructions or context given to expert respondents, where applicable, and otherwise describes the possible responses for a given item.

Item	Notes
Category	Fuel-fired equipment; electric equipment; fuel-fired and electric equipment; embodied and fugitive emissions; commercial heating/cooling loads; residential heating/cooling loads; all operational; all
Sector	Commercial; residential; all
Segment	Maps to segment types shown in Figure 3.
Solution type	Include one solution type and solution per row in the spreadsheet. <i>technical-primary</i> directly replaces the service of an incumbent technology; <i>technical-supporting</i> enables/facilitates the replacement of the incumbent technology service. ¹
Solution name	Name of proposed solution.
Barrier type	Technology-retail cost; technology-performance; technology-physical constraints; technology-other; installation-installation cost; installation-electrical upgrades; installation-workforce; installation-other; operation and maintenance (O&M)-operational cost; O&M-maintenance cost; O&M-workforce; O&M-other; market-consumer perception/awareness; market-distributor/installer perception/awareness; market-access to technology/distributor; market-other.
Barrier name	Name of identified barrier to implementing proposed solution.
Barrier description	Description of identified barrier to implementing proposed solution.
Barrier significance	Identify specific barriers to innovation in each segment via the specific solution in this row in the spreadsheet and rate the significance of each barrier. <i>Low</i> is limited impact on the ability to achieve program objectives; <i>medium</i> could limit the achievement of some office objectives; <i>high</i> is impossible or very difficult to achieve office objectives without addressing.
Action type	<i>R&D</i> includes foundational science, early-stage R&D funding, solutions for hard-to-decarbonize segments, pilot demonstrations; <i>market</i> ² includes enabling tools, partnerships, and market-facing resources, contractor/consumer outreach, workforce development, technical assistance/validation; direct funding via rebates, tax credits/deductions, and innovative financing approaches; <i>regulatory</i> includes appliance efficiency standards, support for building energy code development and adoption, and support for other state/local regulatory actions.
Action	Name of identified action to address specific barrier to implementing proposed solution.
Action description	Description of identified action to address specific barrier to implementing proposed solution.
Action difficulty	Rate the difficulty of carrying out each action using the rating system below. ³ <i>Low</i> is within federal programs’ traditional purview and/or areas of expertise or coordination and requires at most a moderate amount of federal resources to achieve; <i>medium</i> is somewhat outside federal programs’ traditional areas of focus, expertise, and/or coordination and/or requires a moderate to high amount of federal resources to achieve; <i>high</i> is largely outside federal programs’ traditional areas of focus, expertise, and/or coordination and/or requires heavy federal resources to achieve.

¹ The spreadsheet also included a third category, *market and policy*, which includes solutions that operate downstream from technology development and demonstration. This category was dropped because many of the solutions given were not technical in nature and instead aligned strongly with the actions item.

² Finance was subsequently broken out as a separate category from market that specifically refers to direct funding/financing.

³ Given that the experts are federal program staff, actions were initially framed from the federal perspective; however, many could be pursued by non-federal stakeholders.

1. The count of responses for a given segment and barrier type (technology, installation, O&M, market) or action type (R&D, market/finance, policy/regulatory)
2. The count-weighted average rating of barrier significance by type or action difficulty by type for a given segment (possible ratings of 1=low significance barrier or low difficulty action to 3=high significance barrier or high difficulty action).
3. A count-weighted average composite rating of barriers/actions that multiplied each barrier rating by each associated action rating (possible range of 1=low significance, low difficulty to 9=high significance, high difficulty).

These calculations produced heat maps of response counts and average scores for each segment that is included in the compiled spreadsheet and is accessible via the data record associated with this paper.^{xii} The heat map of response counts revealed areas of focus for the experts as well as notable gaps in the data. Areas of focus include:

- market barriers and market-related actions for deploying envelope upgrades in existing buildings;
- technology barriers and R&D and market transformation actions for fuel-fired residential space and water heating and both fuel-fired and electric commercial water heating segments in existing buildings; and
- market barriers and transformation actions for commercial lighting, ventilation, cooking, and miscellaneous electric loads in existing buildings.

There tend to be fewer expert scores for:

- district energy systems.^{xiii}
- residential electric segments in existing buildings; and
- operational energy in new buildings (built 2024–2050).

The heat maps of composite expert ratings for barrier significance and action difficulty are less informative than those for count data—most average ratings are in the 4.5 to 5.5 range (moderate significance and action difficulty). Residential space heating segments are a notable exception across technology type (e.g., furnaces in cold and warm climates, individual and multi-unit boilers, and wall and floor space heaters), with composite ratings that are one half to a full point higher than those of other segments and in the 6 to 7 range, suggesting moderate-high significance and difficulty of action.

Highlight slides and content iteration

Following the synthesis of expert data, a slide was developed for each highlight segment. The slide format organizes collected information as follows:

- **Segment name.** Includes indication of applicable building sector (residential/commercial), end use, and technology type. In some cases, region is also indicated (e.g., residential furnaces in cold vs. warm climates).

^{xii} Available: <https://data.mendeley.com/preview/6skfxh8w2m?a=eb3f6b37-657f-4003-8327-85a9d101a6b2>

^{xiii} District energy systems were initially included as a segment for expert assessment, but were subsequently removed and incorporated into the cross-cutting discussion on thermal energy networks.

- **Potential impact and difficulty** of implementing relevant innovations (low, medium, high). We assigned impact ratings based on the thresholds described in the section concerning identification of highlight segments. We assigned initial difficulty ratings by referring to the composite barrier significance/action difficulty ratings described in the previous section and layering on our own judgment where composite ratings were ambiguous and/or based on less than five responses. These difficulty ratings were subject to further review and iteration as described subsequently in this section.
- **Key segment impacts.** Impacts are both quantitative—drawing estimates of energy, demand, emissions, and costs from the segmentation analysis—or qualitative—e.g., directional effects on comfort, resilience, and/or public health measures that we do not have specific estimates for.
- **Technical solutions.** Primary and supporting technical innovation pathways for addressing the impacts of a given segment. This section also lists the current up-front costs of innovations for which lack of parity with business-as-usual technology costs is a key issue.
- **Concentration areas.** Further breakouts of the current snapshot of a segment by region, building type, fuel type, end use, and/or component (for thermal loads). These breakouts are based on data from: ResStock and Comstock (thermal load components);^{25,26} EIA RECS and CBECS (fuel-fired segments);^{11,12} Scout segmentation data (electric segments, new operational energy segments);³ EPA GHGI (refrigerants);³⁶ EVI-Pro Lite Load Profile Tool⁴² (electric vehicle charging).
- **Key deployment barriers and mitigating actions.** A table with two columns: 1) the most significant barriers identified from the expert responses, listed one per row, and 2) the action(s) available to address each barrier/row.

Translating the individual spreadsheet responses on technical solutions, barriers, and actions into summaries for these highlight slides involved a high degree of editorial judgment. In general, we sought to ensure that segment-specific responses that were repeated by multiple respondents or were otherwise assigned a high degree of importance by respondents were well represented in the highlight slide for that segment. We also sought to fill in key gaps and make responses more concise where we felt it was needed to improve legibility. As with the spreadsheet, we offered the expert respondents an opportunity to review the slide content before it was shared beyond the expert group.

At this stage in the development process, it became apparent that certain innovation opportunities raised in expert responses or in other studies of energy system innovation are relevant to multiple buildings segments. A cross-cutting category was added to highlight such issues alongside segment-specific content. Innovations to avoid electrical infrastructure upgrades when converting fuel-fired to electric equipment is an example of one such cross-cutting opportunity that was frequently raised in expert responses. Other cross-cutting opportunities were not widely discussed in the segment-specific responses but are highlighted because we believe they are important issues for buildings innovation—notably, dual fuel and cogeneration systems, on-site solar generation, and thermal energy networks.

The first full draft of the highlight slide deck was distributed in September 2024 for further review by other staff across DOE who were not involved in the initial expert elicitation. Comments were received and addressed over the course of the Fall and a revised draft of the slide deck was published in early 2025.⁴³

In parallel with the distribution to additional DOE staff for review, an invitation-only technical feedback session on the draft slides was held at the Building Technologies Office Peer Review

(October 2024).^{xiv} In this session, several dozen energy researchers—mostly from the national laboratories and academia—reviewed poster-sized printouts of each highlight slide and posted written feedback on the printouts that was collected and digitized.^{xv} This feedback has been reflected in an updated version of the highlight slide content⁴³ that is included in the section *Full assessments of building end-use and technology segments*.

Analysis limitations

We acknowledge several limitations with our data collection and generation approach, which underscore opportunities for future improvement. The first set of limitations relates to the segmentation analysis:

- **Data lack the spatial resolution needed to assess state or local impacts.** Rather, the data were prepared for 25 electricity market regions that cover the contiguous United States. Ongoing work seeks to combine the capabilities of the tools used for this analysis (e.g., Scout, ResStock and ComStock) to enable county-level scenario projections that could inform more spatially granular updates to the current set of results.
- **Winter peak demand impacts under high inefficient electrification may be overstated.** Underlying hourly load shapes are based on a 2018 weather year, which resulted in higher winter peak loads than weather from other years.⁴⁴ Moreover, the inefficient electrification case assumes that all fuel-fired equipment conversions are to a mix of resistance furnaces and typical efficiency heat pumps that require full resistance backup during peak hour, though utilities and policy makers may provide incentives to switch to more efficient electric alternatives that avoid the need for new power system infrastructure investment and address consumer affordability concerns. Furthermore, the peak hour definition is aligned with the morning hour in which building heating load is expected to be at its highest. Future work could explore sensitivities to the use of alternate weather years in the load shapes, less pessimistic resistance backup assumptions, and coupling with grid modeling to ensure assumed peak hours match system-level conditions under high electrification.
- **Energy costs under inefficient electrification are based on reference case prices.** Reference case price scenarios may not be reflective of the impacts of high load growth on electric rates. High load growth increases the need for new electricity infrastructure, while also adding a new source of revenue for utilities. The net result of these countervailing effects on electric rates is uncertain and beyond the scope of this study to assess. Given the significance of this issue to estimating energy affordability, it could be a fruitful topic for investigation in future grid modeling studies.
- **Gas system segmentation assumes correlation between consumption and leakage.** Previous work has demonstrated that there is a correlation between gas consumption and system leakage,⁴⁵ but it is likely not one-to-one as was assumed in our modeling. Previous work has also demonstrated the sensitivity of gas system emissions estimates to changes in assumed methane leakage rates,¹⁸ and future work could develop better estimates of the portion of gas system leakage that is directly tied to consumption levels.

^{xiv}A total of 180 Peer Review registrants were invited, spanning participants from the national labs, government, and academia.

^{xv}The digitized feedback is included with this paper's data record, which is available at: <https://data.mendeley.com/preview/6skfxh8w2m?a=eb3f6b37-657f-4003-8327-85a9d101a6b2>

- **Segmentation base year data require recalibration against more recent historical datasets.** The baseline estimates from Scout are drawn from AEO 2023, for which base historical year consumption estimates are calibrated against older versions of RECS, CBECS, and EIA State Energy Data System survey data.^{46 47 48} The latest AEO 2025 data have been recalibrated against more recent datasets, which should in turn be incorporated into this work's estimates.
- **Quantitative impact analysis does not currently extend to non-energy metrics.** Public health, resilience, comfort, and other non-energy metrics are possible to model quantitatively—at least at the single building level—but are more challenging to estimate at the scale of the full buildings sector, which is the focus of this study. Future work could attempt to devise quantitative metrics for these types of impacts that could be communicated alongside stock-scale energy, environment, and cost impact segments.

Another set of limitations relates to the expert elicitation process:

- **The perspective of the expert pool is limited.** Expert respondents all bring a federal agency perspective. While the actions suggested by their responses are not exclusively the purview of federal agencies, collecting additional responses from state and local policy makers and/or industry professionals could improve the breadth of the insights that this framework delivers.
- **Response gaps are evident in emerging technical areas.** Key examples of this include innovations that enable residential demand flexibility and lowering the environmental impact of district energy systems. Future elicitation efforts could specifically target respondents with technical expertise in newer technical areas of interest to ensure that innovation strategies for such areas are not underrepresented in the response data.
- **Limitations with the segment-by-segment structure of the elicitation frame.** Such framing makes it challenging to highlight innovations such as controls that apply to many different segments. While cross-cutting tags were added to the spreadsheet after initial feedback from respondents, this special case could be more strongly emphasized in the elicitation guidance from the start. Similarly, clearer guidance could be added on how to characterize fuel switching innovations, which could conceptually apply to both fuel-fired and electric segments (e.g., electrification lowers the impact of the former and increases the impact of the latter).

Full assessments of building end-use and technology segments

Residential thermal loads: Envelope (existing buildings)

This is a **high impact** segment that will be **highly difficult** to address. Key **impacts** include:

- emissions (estimated 232 Mt CO₂/yr. in 2050 under BAU); and
- energy costs (estimated \$145B/yr. in 2050 under inefficient electrification); and
- safety (determines thermal resilience).

Key **technical innovation pathways** to address this segment's impacts include:

- Traditional air-sealing, insulation, and windows upgrades
- Emerging components and approaches:
 - Aerosol-based air-sealing
 - Insulation integrated with wall cladding or roofing materials
 - Minimally invasive insulation
 - Secondary glazing systems, window films, and thin triple-pane windows
 - Prefabricated wall/roof/window solutions for multifamily buildings

Key **concentration areas** for these innovations are the specific building components that contribute the most to residential thermal loads (Figure **S1**): air leakage (through all envelope components including ceilings, walls, and windows), heat conduction losses through walls, windows, ceilings, floors, and foundations. Figure **S1** shows that site energy from thermal loads is dominated by heating energy; cooling electricity is less significant because of smaller temperature differences and higher average equipment efficiencies for cooling. Notably, thermal loads contribute both positively and negatively to heating and cooling energy. For example, solar heat gain through windows provides “free” heat that reduces annual residential heating and cooling energy use by 7%. Further details can be found in Speake et al., which shows that residential envelope thermal loads for heating are greater in colder climates, older housing stocks, and single-family detached housing.

Table **S3** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

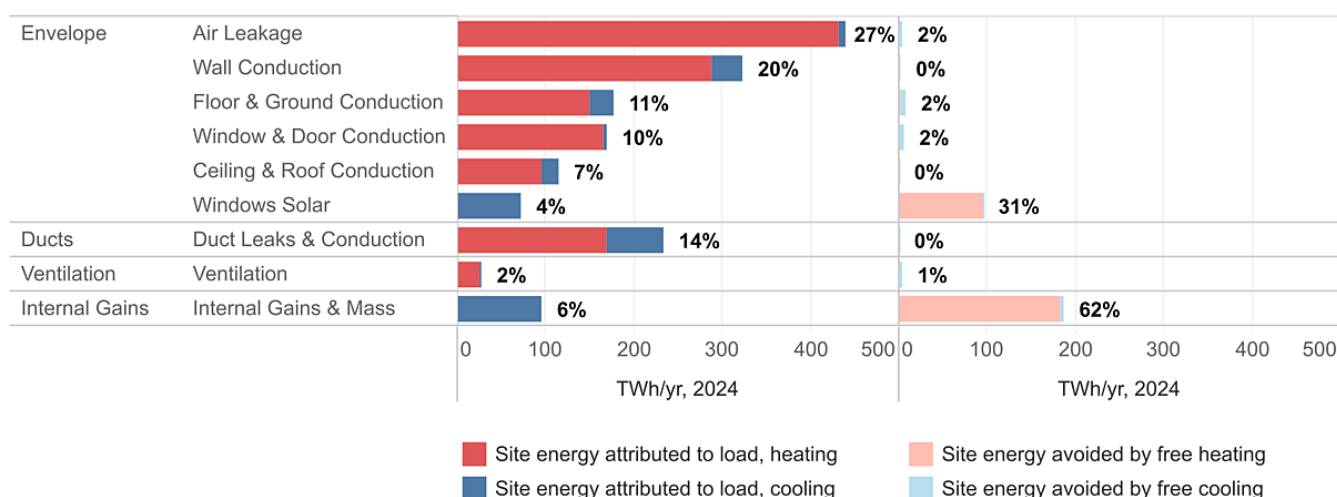


Figure S1: Residential site heating and cooling energy use breakout by thermal load component and fuel type. The percentages indicate the share of total residential sector heating and cooling energy use associated with each component. Based on data from Speake et al.²⁵

Table S3: Key implementation barriers and mitigating actions for innovations to address the residential envelope segment.

Key Barriers	Key Actions
High up-front cost for envelope upgrades	• Lower cost, easier to install upgrades (e.g., automated design of retrofit insulation panels; automated detection and sealing of air leaks) • Promote insulation at time of re-siding • Decision support for utility, state, federal incentives and tax credits
Lack of consumer demand and contractor awareness of solutions	• Quantify non-energy and grid edge benefits to support incentivization • Awareness campaign: fact sheets, webinars, etc. to promote benefits to homeowners and contractors • Consumer enabling/informing tool (e.g., Home Energy Score) to raise awareness • Support value of energy efficiency in real estate transactions • Technical support for multifamily building performance standard development • Quality installation guidelines for contractors
Disruptive to occupants	• Prefabricated solutions, especially for multifamily • Improved bio-based spray foams
Structural and other remediation issues may hinder ability to upgrade	• Integrate resilience (wind, fire, flood) features alongside envelope efficiency upgrades • Decision guidance for envelope retrofits in buildings with significant health, safety, or durability concerns

Residential thermal loads: Duct losses (existing buildings)

This is a **high impact** segment that will be **highly difficult** to address. Key **impacts** include:

- emissions (estimated 43 Mt CO₂/yr. in 2050 under BAU); and
- energy costs (estimated \$34B/yr. in 2050 under inefficient electrification).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary: Traditional and novel technology for duct sealing and insulating
- Supporting: Ductless solutions; encapsulating attics and crawlspaces

As with residential envelopes, key **concentration areas** for these innovations to address are heating loads from duct losses in colder climates, older housing stocks, and single-family detached housing.²⁵ Duct losses are concentrated in homes that have ductwork outside of the conditioned living area, which is more common in single-story homes without basements, where HVAC equipment and some portion of the ductwork is located in an unconditioned attic or crawlspace.

Table S4 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S4: Key implementation barriers and mitigating actions for innovations to address the residential duct losses segment.

Key Barriers	Key Actions
Lack of demand and awareness for ductwork upgrades	• Awareness campaign: survey research-informed fact sheets, webinars, etc. to promote importance of duct losses to homeowners, contractors, and grid operators • Consumer enabling/informing tool (e.g., Home Energy Score) to raise awareness • Develop improved workforce training on duct sealing, insulating, and leakage testing
Aerosol-based duct sealing is expensive	• Cost compression • Include in weatherization and other programs to expand trained workforce and availability development
Ductless solutions for every room may be expensive	• Evaluate pros and cons of ductless heads in every room

Commercial thermal loads: Envelope (existing buildings)

This is a **high impact** segment that will be **highly difficult** to address. Key **impacts** include:

- emissions (estimated 82 Mt CO₂/yr. in 2050 under BAU); and
- energy costs (estimated \$21B/yr. in 2050 under inefficient electrification); and
- comfort (regulates indoor temperature).

Key **technical innovation pathways** to address this segment’s impacts include:

- Traditional wall and roof insulation upgrades
- Emerging components and approaches:
 - Secondary glazing systems, window films, and thin triple-pane windows
 - Novel diagnostic approaches (e.g., non-destructive testing, virtual sensing, autonomous platforms)
 - Higher-fidelity modeling of air, heat, and moisture flows in building design/retrofit software

Key **concentration areas** for these innovations are the specific building components that contribute the most to commercial thermal loads (Figure S2): air leakage (through all envelope components including ceilings, walls, and windows), heat conduction losses through ceilings, walls, ground contact, and windows. Figure S2 shows that site energy from thermal loads is dominated by heating energy; cooling electricity is less significant because of smaller temperature differences and higher average equipment efficiencies for cooling. Solar heat gain through windows provides “free” heat that reduces annual commercial heating and cooling energy use by 3% while “free” cooling from ground conduction and air leakage contribute reductions of 2% and 1%.

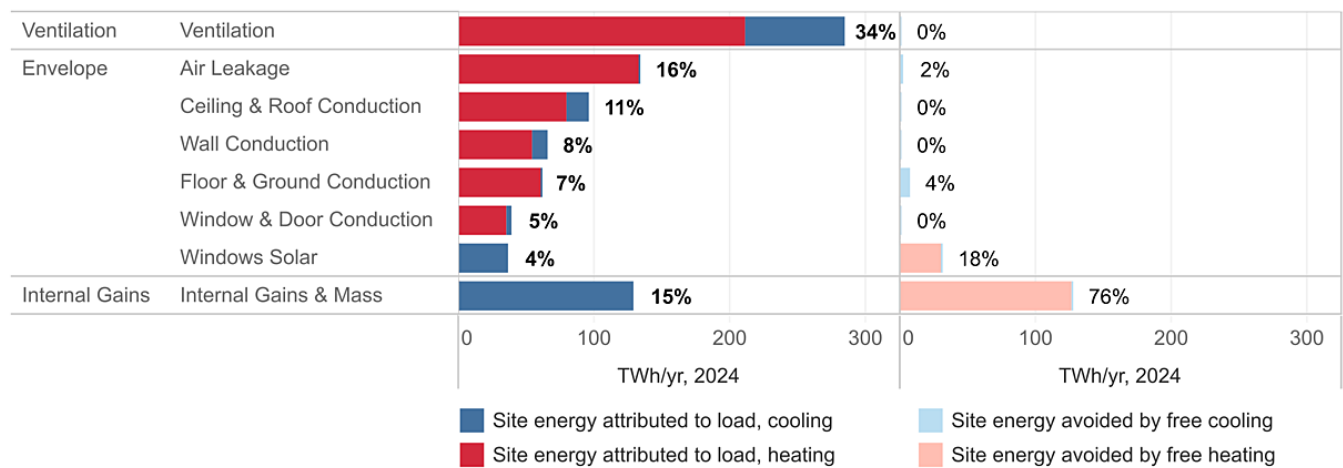


Figure S2: Commercial site heating and cooling energy use breakout by thermal load component and fuel type. The percentages indicate the share of total commercial sector heating and cooling energy use associated with each component. Based on data from Eric Ringold.²⁶

Table S5 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S5: Key implementation barriers and mitigating actions for innovations to address the commercial envelope segment.

Key Barriers	Key Actions
Potential tenant disruption and aesthetic and moisture concerns	• Modeling to identify low-cost/disruption envelope retrofit packages; characterize moisture impacts • Develop contractor training on emerging retrofit methods that minimize disruption to occupants
Lack of consumer access, awareness, and value proposition	• Holistic cost-benefit analyses and real-world case studies that demonstrate HVAC downsizing and comfort, productivity, and resilience benefits of envelope • Incorporate less-marketable upgrades (walls, leakage, roofs) into building performance standards • Support incentives for manufacturers to develop higher performance commercial envelope products
Complexity of air leakage testing	• Simple, low-cost air leakage testing methods • Modeling to identify major commercial leakage contributors
Structural issues in small commercial	• Support for utility, state, and federal incentives, including pre-weatherization remediation efforts

Commercial thermal loads: Ventilation (existing buildings)

This is a **high impact** segment that will be **highly difficult** to address. Key **impacts** include:

- emissions (estimated 55 Mt CO₂/yr. in 2050 under BAU); and
- energy costs (estimated \$18B/yr. in 2050 under inefficient electrification); and
- public health (many buildings under-ventilated).

Key **technical innovation pathways** to address this segment's impacts include:

- Energy recovery ventilation (ERV)
- Correct under- and over-ventilation via:
 - Building Automation Systems (BAS)/Energy Management and Information Systems (EMIS), occupant sensing, and demand-controlled ventilation
 - Heat/smoke-sensing exhaust hoods (food service)
 - Indoor air treatment devices (traditional filtration, germicidal UV air treatment, portable or sorbent air cleaners)

In terms of key **concentration areas**, previous work has shown that ventilation loads are the most significant load component for both heating and cooling across all most building types. Ventilation thermal loads are particularly important in food service buildings with kitchen ventilation and are less significant in warehouses, which have lower heating and cooling loads in general.⁴⁹

Table S5 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S6: Key implementation barriers and mitigating actions for innovations to address the commercial ventilation segment.

Key Barriers	Key Actions
Lack of available ERVs in new packaged air-source heat pumps (ASHPs); limited options are high cost	• Reduce ERV product costs, particularly in retrofits • Encourage manufacturers to include optional ERVs for major equipment types (rooftop units, air handling units, dedicated outdoor air systems) • Support code/building performance standard requirements for ERV in major markets and more stringent ASHRAE 90.1 ERV requirements
Lack of facility manager access, awareness, and value proposition	• Training on right-sizing ventilation rates in fields like commissioning and testing/balancing • BAS/EMIS and automated fault detection and diagnosis that automates ventilation operation checks • Facility manager education on proper valuation of comfort, productivity, and health benefits of better ventilation systems • Explore additional value streams, such as use of ventilation as a short-term demand response resource
Lack of information on performance/safety	• Test germicidal UV and other air-treatment products
Outdated design and operation guidance	• Research to support updates to ASHRAE ventilation standards based on latest evidence — particularly in cases where ERV is not a good fit, to limit over-conditioning of outdoor air

Residential fuel-fired furnaces, cold climates (zones 5–8, existing buildings)

This is a **high impact** segment that will be **highly difficult** to address. Key **impacts** include:

- emissions (estimated up to 91 Mt CO₂/yr. in 2050 (BAU));
- energy costs (estimated up to \$23B/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants);⁵⁰ and
- comfort (uneven air temperature across larger spaces).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - cold-climate air-source heat pumps (ccASHPs); and
 - dual-fuel ASHPs, geothermal heat pumps (GSHPs).
- Supporting:
 - duct, envelope upgrades, and thermal storage.

The **up-front cost** of these innovations tends to be higher than typical fuel-fired equipment. For example, a ccASHP can cost \$8-35K per home, vs. \$4-5K for a gas furnace and \$4-9K for central air conditioning.⁵¹ Labor and soft costs comprise the majority of the overall cost of ccASHPs.

Key **concentration areas** for these innovations to address include natural gas-fired units in the Cold US climate region, which generates by far the largest share of this segment's overall emissions impacts (Figure S3).

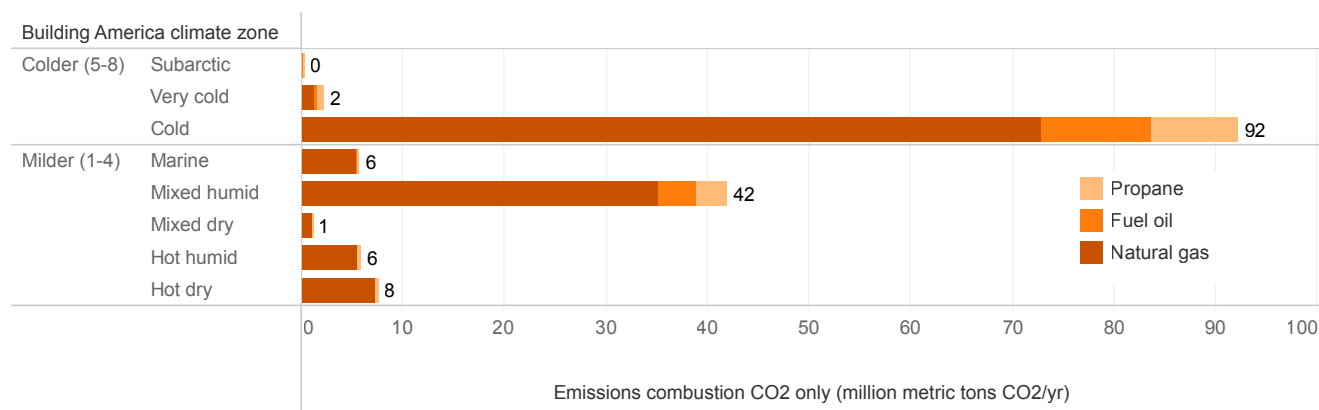


Figure S3: Building America climate zone concentration and fuel type breakout of residential fuel-fired furnace emissions impacts as of 2021-2022, based on data from Residential Energy Consumption Survey (RECS)¹¹ and application of national average emissions factors: natural gas (0.053 Mt/TBtu), propane (0.063 Mt/TBtu), fuel oil (0.073 Mt/TBtu) and electricity (0.088 Mt/TBtu).^{52,39}

Table S7 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S7: Key implementation barriers and mitigating actions for innovations to address the cold climate residential fuel-fired furnace segment.

Key Barriers	Key Actions
High up-front costs, including oversizing and poor duct performance	• Equipment that is faster and easier to install • Validate and improve performance of plug-in and quick-connect solutions (switch to ductless) • Improve dual-fuel ASHP configurations/controls • Support business model innovations like remote sizing, demand aggregation, and quote generation • Guidance for consumers on incentives • Promote benefits of incentivizing peak load reduction (e.g., GHPs and envelope upgrades) • Incentives for new drilling businesses and geothermal well drillers • Support national electric code updates (see also Cross-Cutting Opportunity: Building Electrical Infrastructure)
Lack of consumer and contractor awareness	• Contractor training and resource development • Support AC-to-heat pump replacement policies • Research to further understand homeowner motivations regarding heating system choice
High operating cost when compared to gas in most areas	• Improve cold-climate performance • Thermostat demand response compatibility and interface • Technical assistance for utility program and rate design • Promote standardized quality installations and workforce training/recognition
Sizing ASHPs for full heating load may lead to poor dehumidification	• Improve dehumidification, e.g., separate sensible and latent control

Residential fuel-fired furnaces, warm climates (zones 1–4, existing buildings)

This is a **medium impact** segment that will be **moderately difficult** to address. Key **impacts** include:

- emissions (estimated up to 41 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$10B/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants);⁵⁰ and
- comfort (uneven air temperature across larger spaces).

Key **technical innovation pathways** to address this segment's impacts include (see also *Residential fuel-fired furnaces, cold climates (zones 5–8, existing buildings)*):

- Primary:
 - air-source heat pumps.
- Supporting:
 - duct upgrades.

The **up-front cost** of these innovations tends to be higher than typical fuel-fired equipment. For example, a ccASHP can cost \$7-19K per home, vs. \$4-5K for a gas furnace and \$4-9K for central air conditioning.⁵¹ Labor and soft costs comprise the majority of the overall cost of ccASHPs.

Key **concentration areas** for these innovations to address include natural gas-fired units in the Mixed-Humid US climate region, which generates the largest share of this segment's overall emissions impacts (Figure **S3**).

Key barriers and mitigating actions for deploying the technical innovations for this segment are the same as those listed for *Residential fuel-fired furnaces, cold climates (zones 5–8, existing buildings)* in Table **S7**, with the following caveats:

- Potentially less need for cold-climate, dual-fuel, and geothermal solutions in warmer climates, as well as greater need for research on low load modulation strategies (e.g., using multiple smaller heat pumps instead of one larger unit).
- Up-front and operating cost barriers are likely less significant in warmer climates, although high electricity rates can still be a barrier.

Residential fuel-fired water heating (single-unit, 40+ gallon tank, existing buildings)

This is a **medium impact** segment that will be **moderately difficult** to address. Key **impacts** include:

- emissions (estimated up to 41 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$10B/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants);⁵⁰

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - heat pump water heaters (HPWHs), including 120-volt HPWHs, split systems, and combination heating/water heating systems.
- Supporting:
 - circuit splitters and smart panels.

The **up-front cost** of these innovations tends to be higher than typical fuel-fired equipment. A typically-sized residential HPWH can cost \$2-5K per home, vs. \$1-2K for a gas unit.⁵¹

Key **concentration areas** for these innovations to address include natural gas-fired units of over 30 gallons that serve single family detached houses, which generate the largest share of this segment's overall emissions impacts (Figure S4).

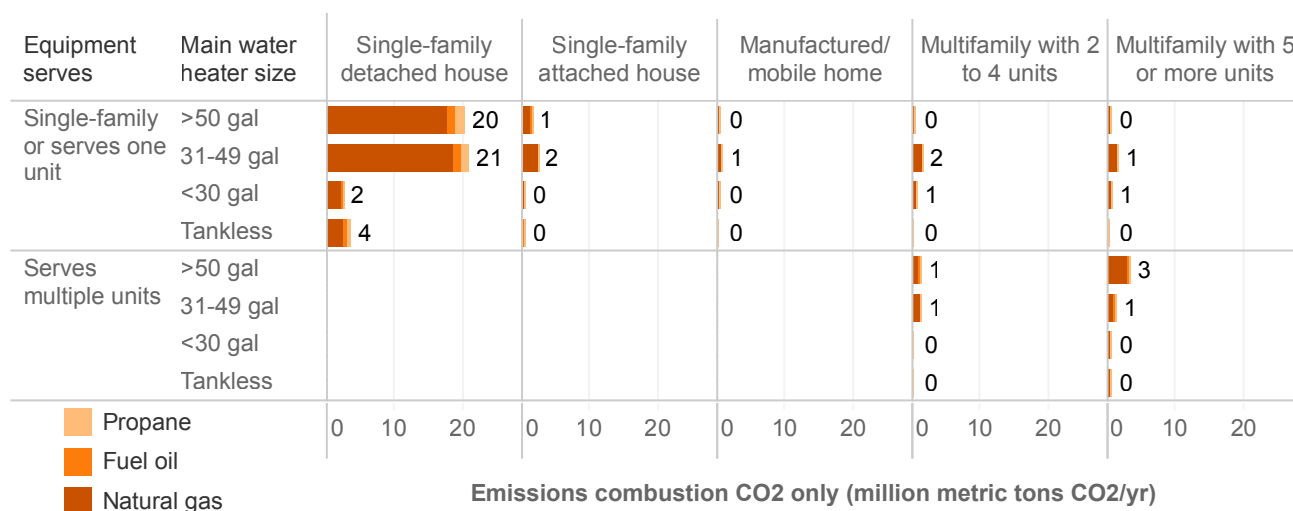


Figure S4: Building type and fuel type breakout of residential fuel-fired water heating emissions impacts as of 2021-2022, based on data from Residential Energy Consumption Survey (RECS)¹¹ and application of national average emissions factors: natural gas (0.053 Mt/TBtu), propane (0.063 Mt/TBtu), fuel oil (0.073 Mt/TBtu) and electricity (0.088 Mt/TBtu).^{52,39}

Table S8 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S8: Key implementation barriers and mitigating actions for innovations to address the residential fuel-fired water heating segment for single units.

Key Barriers	Key Actions
High up-front costs	• Technology improvements to enable simplified, plug and play installations (e.g., low-cost 120-volt HPWH solutions with good recovery times and smaller form factors) • Support for utility, state, and federal incentives • Incentives to increase stocks of HPWHs in retail/distribution
Possible increased monthly cost vs. gas	• Technical assistance on rate design and utility revenue potential
Lack of contractor and consumer awareness; existing business models hinder deployment	• Marketing/consumer education • Contractor training to improve familiarity and confidence with HPWH installs and business model development
HPWH form factor issues for high efficiency (size, weight, noise)	• Alternative form factors • Smaller tanks using phase change materials • R&D/validation for split systems and combination systems

Residential fuel-fired wall/floor space heaters (existing buildings)

This is a **medium impact** segment that will be **moderately difficult** to address. Key **impacts** include:

- emissions (estimated up to 12 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$6B/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants);⁵⁰

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - ductless air-source heat pumps (DHPs); and
 - window, through-wall, and quick-connect HPs.
- Supporting:
 - envelope upgrades.

The **up-front cost** of these innovations is typically \$4-10K per unit.^{51 53}

Key **concentration areas** for these innovations to address include natural gas-fired built-in room heaters in Cold and Mixed-Humid climates, which generate the largest share of this segment's overall emissions impacts (Figure **S5**).

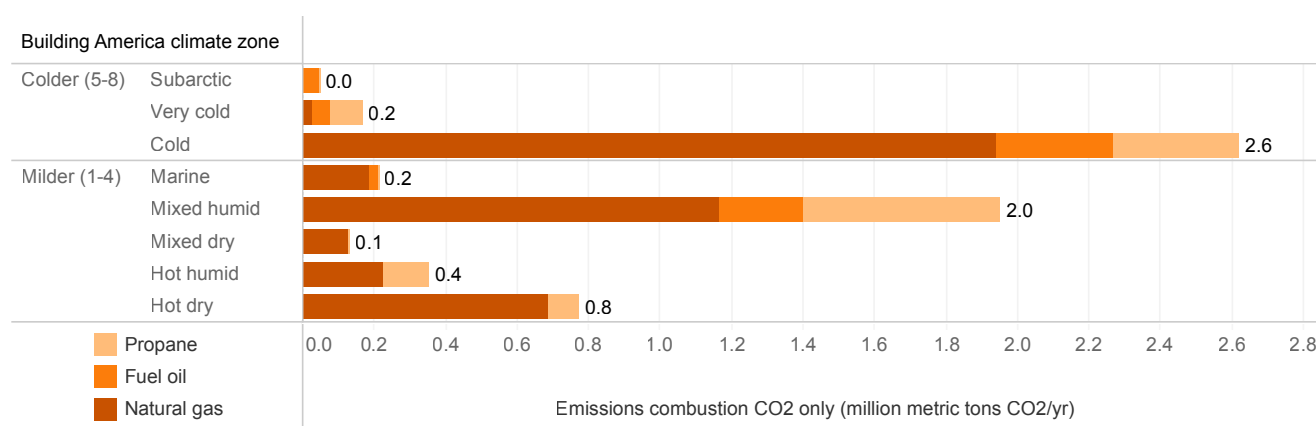


Figure S5: Building America climate region and fuel type breakout of residential fuel-fired built-in room heater emissions impacts as of 2021-2022, based on data from Residential Energy Consumption Survey (RECS)¹¹ and application of national average emissions factors: natural gas (0.053 Mt/TBtu), propane (0.063 Mt/TBtu), fuel oil (0.073 Mt/TBtu) and electricity (0.088 Mt/TBtu).^{52 39}

Table **S9** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S9: Key implementation barriers and mitigating actions for innovations to address the residential fuel-fired wall/floor space heater segment.

Key Barriers	Key Actions
Solutions have higher up-front cost than fuel-fired and window AC alternatives	• Window/saddle, through-wall, and quick-connect HP validation, development and cost reduction • Support for utility, state, and federal incentives
DHPs can be DIY, but often still require specialized tools and skills	• Simpler do-it-yourself retrofit solution development, including form factors to fit in the space of existing systems, such as packaged terminal air conditioners (PTACs) • Training and resource development for DIY installs
Safe removal of defrost meltwater in multifamily contexts (window and through-wall heat pumps)	• Solutions to manage defrost meltwater (water melted off the coil during defrost cycles)

Residential fuel-fired boilers (space heating, single-unit, existing buildings)

This is a **medium impact** segment that will be **highly difficult** to address. Key **impacts** include:

- emissions (estimated up to 12 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$3B/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants);⁵⁰ and
- comfort (uneven air temperature across larger spaces).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - ductless air-source heat pumps (DHPs); and
 - air-to-water heat pumps (AWHPs), geothermal heat pumps (GHPs).
- Supporting:
 - envelope upgrades, thermal energy storage (TES).

The **up-front cost** of these innovations varies by equipment type:

- DHP: \$16-38K⁵¹
- AWHP: \$15-40K⁵⁴
- GHP: \$30-60K⁵¹

Labor and soft costs comprise the majority of the overall cost of residential boilers.

Key **concentration areas** for these innovations to address include natural gas-fired boilers that serve single-family detached houses, which generate the largest share of this segment's overall emissions impacts (Figure S6).

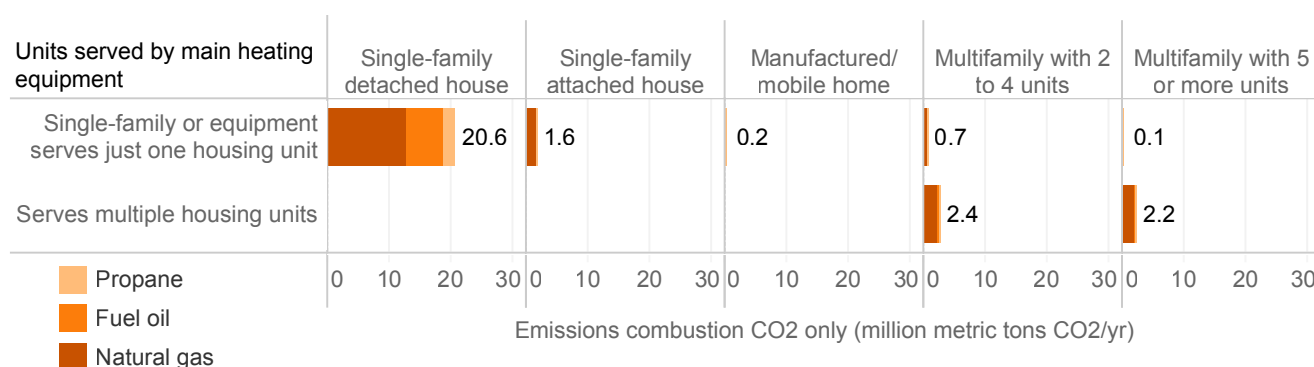


Figure S6: Building America climate zone concentration and fuel type breakout of emissions impacts from residential fuel-fired boilers for space heating as of 2021-2022, based on data from Residential Energy Consumption Survey (RECS)¹¹ and application of national average emissions factors: natural gas (0.053 Mt/TBtu), propane (0.063 Mt/TBtu), fuel oil (0.073 Mt/TBtu) and electricity (0.088 Mt/TBtu).^{52,39}

Building owners may opt for air-based DHP solutions to gain air conditioning. For DHP barriers, see Residential fuel-fired wall/floor space heaters (existing buildings). Hydronic solutions also share barriers with Residential fuel-fired furnaces, cold climates (zones 5–8, existing buildings); additional barriers unique to deploying hydronic solutions and the actions that address these barriers are listed in Table S10.

Table S10: Key implementation barriers and mitigating actions for innovations to address the residential single-unit, fuel-fired boilers for space heating segment.

Key Barriers	Key Actions
Hydronic AWHPs/GHPs typically don't provide cooling	• Evaluate market size and affordability potential of AWHPs that don't provide cooling • Understand potential market overlap with A3 refrigerant monobloc ducted (fan coil) solutions
AWHP/GHP outlet temperature may be too low for existing radiators	• Field validation to determine if this issue is significant • Research, development, and demonstration and field validation of high-temperature refrigerant AWHP/GHPs
High up-front cost	• Technology solutions that avoid need for custom hydronic system designs • Contractor training and resource development on unique challenges of hydronic heat pumps (radiator upgrades, freeze protection, buffer tanks, etc.)

Residential fuel-fired boilers (water heating, multi-unit, existing buildings)

This is a **low impact** segment that will be **highly difficult** to address. We highlight it because it disproportionately affects renters and innovations to address it have potential spillover benefits.

^{xvi}

Key **impacts** include:

- emissions (estimated up to 7 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$2B/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants).⁵⁰

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - centralized solutions:
 - * large combination (heating/water heating) heat pump boilers; dual-fuel boilers; and
 - * domestic hot-water-only heat pump water heaters (HPWHs) in series.
 - decentralized compact HPWHs.
- Supporting:
 - high-performance fixtures, drain water-heat recovery.

The **up-front cost** of these innovations varies by equipment type, but is generally more expensive than typical fuel-fired equipment:

- centralized: \$200K (compared to \$100K for an 800 kBtu/h boiler);⁵¹
- decentralized: \$2-5K per unit (compared to \$1-2K for a gas unit).⁵¹

Key **concentration areas** for these innovations to address include large (>50 gallon) natural gas-fired water heaters that serve multiple units within multifamily buildings that have 5 or more units, which generate the largest share of this segment's overall emissions impacts (Figure **S4**).

Table **S11** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

^{xvi}A good example of this is window saddle or other plug-in micro heat pumps. While these types of heat pumps are particularly well-suited for serving heating and cooling needs in multifamily buildings, successful deployment there with cost reductions could make them attractive as a local space conditioning solution for single-family and other housing types as well.

Table S11: Key implementation barriers and mitigating actions for innovations to address residential fuel-fired boilers for water heating that serve multiple units.

Key Barriers	Key Actions
Lack of awareness of solutions (for both central and decentralized)	• Tech validation for conversion • Decentralized compact HPWHs (in unit) tech development and piloting • Building owner guidance • Contractor training and resource development
High up-front cost and operational cost	• Promote efficiency (fixtures, heat recovery) and storage to reduce needed capacity • Support utility, state, and federal incentives • Technical assistance for rate design and building performance standards
Electric upgrades may increase up-front cost	• Demonstrate replicable ways to minimize costs of electrical upgrades • Support national electric code update standards
Performance issues and lack of facility manager experience	• Improve system performance • Training for facility managers

Residential fuel-fired boilers (space heating, multi-unit, existing buildings)

This is a **low impact** segment that will be **highly difficult** to address. We highlight it because it disproportionately affects renters and innovations to address it have potential spillover benefits.

Key **impacts** include:

- emissions (estimated up to 3 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$1B/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants),⁵⁰ and
- comfort (uneven air temperature across larger spaces).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - centralized solutions:
 - * low-temperature boiler service water-source heat pumps; and
 - * high-temperature boiler serving steam or hydronic radiators.
 - decentralized micro heat pumps.
- Supporting:
 - envelope upgrades (including integrated HVAC).

The **up-front cost** of these innovations varies by equipment type, but is generally more expensive than typical fuel-fired equipment:

- centralized: \$200K (compared to \$100K for an 800 kBtu/h boiler),⁵¹
- decentralized: \$2-5K per unit (compared to \$1-2K for a gas unit)⁵¹

Key **concentration areas** for these innovations to address include natural gas-fired boilers that serve multiple units within multifamily buildings, which generate the largest share of this segment's overall emissions impacts (Figure S6).

Barriers and mitigating actions for deploying centralized solutions are shared with the Residential fuel-fired boilers (water heating, multi-unit, existing buildings) segment, while barriers and actions for deploying decentralized solutions are shared with the Residential fuel-fired wall/floor space heaters (existing buildings) segment. Additional barriers and actions that are unique to the technical innovations for this segment are summarized in Table S12.

Table S12: Key implementation barriers and mitigating actions for innovations to address the residential fuel-fired boilers for space heating that serve multiple units.

Key Barriers	Key Actions
AWHP/GHP boiler outlet temperature too low for existing radiators	• High-temperature refrigerant air-to-water and geothermal heat pumps • Prefab envelope-integrated HVAC distribution solutions for multifamily buildings
Safe removal of defrost meltwater in multifamily contexts (window and through-wall heat pumps)	• Solutions to manage defrost meltwater (water melted off the coil during defrost cycles)

Commercial fuel-fired rooftop units (existing buildings)

This is a **medium impact** segment that will be **moderately difficult** to address.

Key **impacts** include:

- emissions (estimated up to 32 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$23/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants)⁵⁰

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - standard, cold climate, dual-fuel, and geothermal heat pump rooftop units (HP RTUs) with frost protection and defrost capabilities; and
- Supporting:
 - integrated or external advanced controls; and
 - add-on energy recovery ventilators (ERVs).

The **up-front cost** of these innovations varies by heating service needs; cold-climate solutions are generally more expensive than typical fuel-fired equipment (\$15K per unit), while warm-climate solutions are similar in cost to gas-fired units:

- cold-climate HP RTU: \$21K per unit⁵¹
- warm-climate HP RTU: \$15K per unit⁵¹

Key **concentration areas** for these innovations to address include natural gas-fired RTUs serving retail and service buildings, which generate the largest share of this segment's overall emissions impacts (Figure **S8**).

Table **S13** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

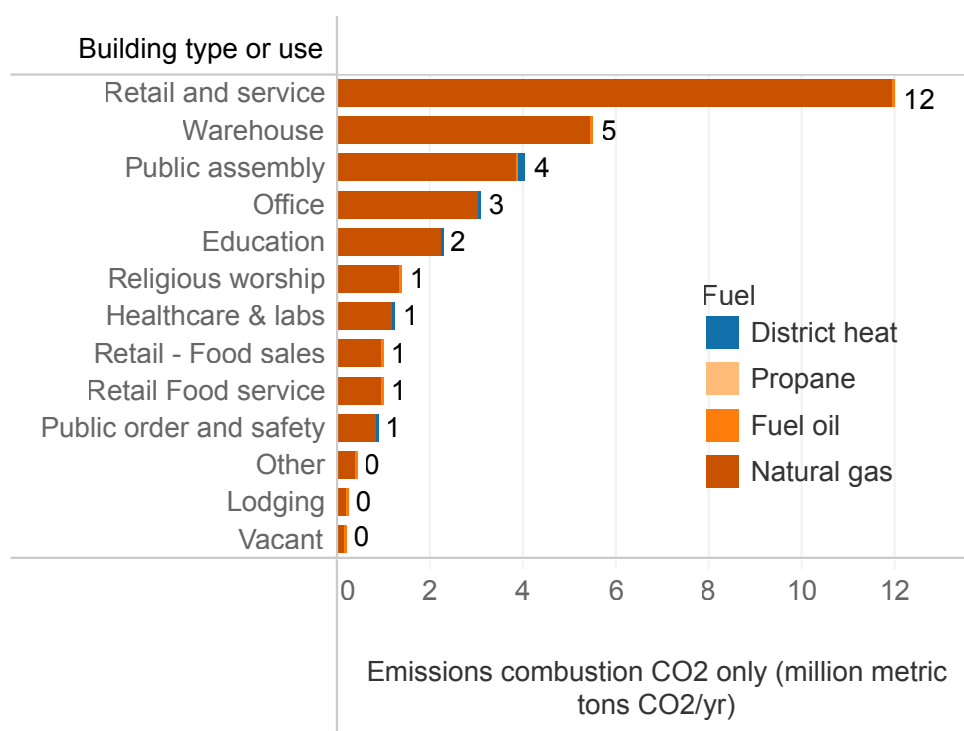


Figure S7: Building and fuel type breakout of emissions impacts from commercial fuel-fired rooftop units for space heating as of 2021-2022, based on data from Commercial Building Energy Consumption Survey (CBECS)¹² and application of national average emissions factors: natural gas (0.053 Mt/TBtu), propane (0.063 Mt/TBtu), fuel oil (0.073 Mt/TBtu) and electricity (0.088 Mt/TBtu).^{52,39}

Table S13: Key implementation barriers and mitigating actions for innovations to address the commercial fuel-fired RTU segment.

Key Barriers	Key Actions
Lack of product availability	• New HP RTU products with high performance in cold climates • Develop tools to enable rapid visibility into market suppliers and product inventory to inform at-failure replacement decisions
Uncertain cold-climate performance and peak demand impacts	• Improve defrost, including with thermal energy storage management • HP RTU test facilities and field studies in cold-climate conditions • Controls to optimize coordination across RTUs to moderate peaks in electricity demand
Limited workforce awareness and design skills	• HP RTU awareness campaign • HP-specific training curricula • Develop guidance on HP RTU compliance pathways for codes/standards
High up-front cost	• Develop guidance on how HP RTUs could qualify for financial incentives (e.g., section 179D tax credit) • Design and broadly advertise more affordable financing options and cash incentives for replacement (e.g., cash rebates/discounts for replacing existing equipment)
Size/weight/noise issues for high efficiency	• Component and system optimization to minimize retrofit issues with form factor

Commercial fuel-fired large boilers (space heating, existing buildings)

This is a **medium impact** segment that will be **moderately difficult** to address.

Key **impacts** include:

- emissions (estimated up to 10 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$2/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants);⁵⁰

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - centralized large heat pumps (HPs) for heating and domestic hot water (including dual-fuel and geothermal) or decentralized micro HPs.
- Supporting:
 - envelope upgrades, thermal storage; and
 - energy recovery and demand-controlled ventilation.

The **up-front cost** of these innovations varies by equipment type, but is generally more expensive than typical fuel-fired equipment:

- centralized: \$200K (compared to \$100K for an 800 kBtu/h boiler);⁵¹
- decentralized: \$2-5K per unit (compared to \$1-2K for a gas unit)⁵¹

Key **concentration areas** for these innovations to address include natural gas-fired boilers serving education buildings, which generate the largest share of this segment's overall emissions impacts (Figure S8).

Table S14 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

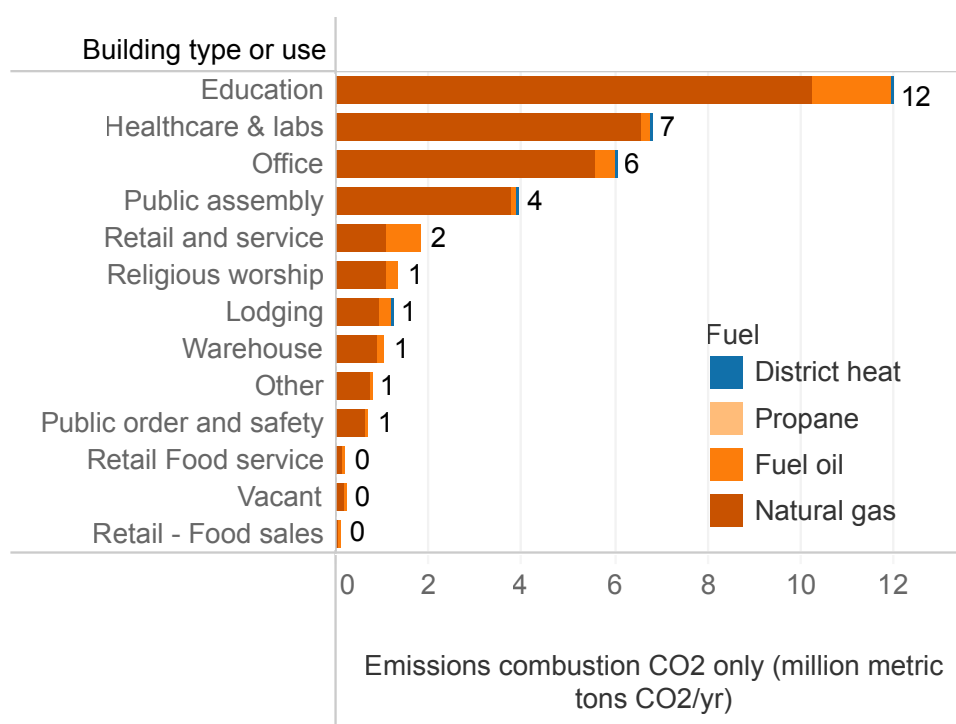


Figure S8: Building and fuel type breakout of emissions impacts from commercial fuel-fired boilers for space heating as of 2021-2022, based on data from Commercial Building Energy Consumption Survey (CBECS)¹² and application of national average emissions factors: natural gas (0.053 Mt/TBtu), propane (0.063 Mt/TBtu), fuel oil (0.073 Mt/TBtu) and electricity (0.088 Mt/TBtu).^{52,39}

Table S14: Key implementation barriers and mitigating actions for innovations to address the commercial fuel-fired boiler heating segment.

Key Barriers	Key Actions
Drop-in alternatives to gas/steam-fired hydronic heating systems are limited, inefficient, and expensive	• New hydronic/steam HP equipment that efficiently functions in cold climates with improved capacity • Increase awareness of wastewater heat recovery, high-temperature HPs, and heat recovery chiller solutions • Develop archetype large HP systems that integrate with scalable design-build workflows
Lack of viable technologies to meet large heating loads and need for electrical upgrades	• Increase envelope retrofits and strategies to reduce ventilation loads • Simple sizing tools/design guides for thermal energy storage systems • Increase awareness of dual-fuel HPs as hybrid solution; workforce training on combining HPs with thermal storage • Controls development and testing to ensure successful and efficient operation of large HP plants, including with thermal storage, energy recovery, and grid integration
Lack of lab and field performance data and stakeholder risk aversion	• Pilots and field demonstrations to de-risk new technologies (e.g., demonstrate high delivery temperature, particularly in applications serving critical loads) • Draw from industrial sector demonstrations given overlaps in operational challenges

Commercial fuel-fired centralized water heating (existing buildings)

This is a **medium impact** segment that will be **moderately difficult** to address.

Key **impacts** include:

- emissions (estimated up to 16 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$3/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants)⁵⁰

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - Centralized large hydronic heat pumps (including dual-fuel), residential-style heat pump water heaters (HPWHs), or decentralized small HPWHs.
- Supporting:
 - thermal storage, chiller heat recovery
 - high-performance fixtures, drain water heat recovery.

The **up-front cost** of these innovations varies by equipment type, but is generally more expensive than typical fuel-fired equipment:

- centralized: \$200K (compared to \$100K for an 800 kBtu/h boiler)⁵¹
- decentralized: \$2-5K per unit (compared to \$1-2K for a gas unit)⁵¹

Key **concentration areas** for these innovations to address include centralized natural gas-fired water heaters serving lodging buildings, which generate the largest share of this segment's overall emissions impacts (Figure S9).

Barriers and actions for this segment overlap with those of Commercial fuel-fired large boilers (space heating, existing buildings) (lack of drop-in alternatives to meet large loads; lack of performance data; stakeholder risk aversion).

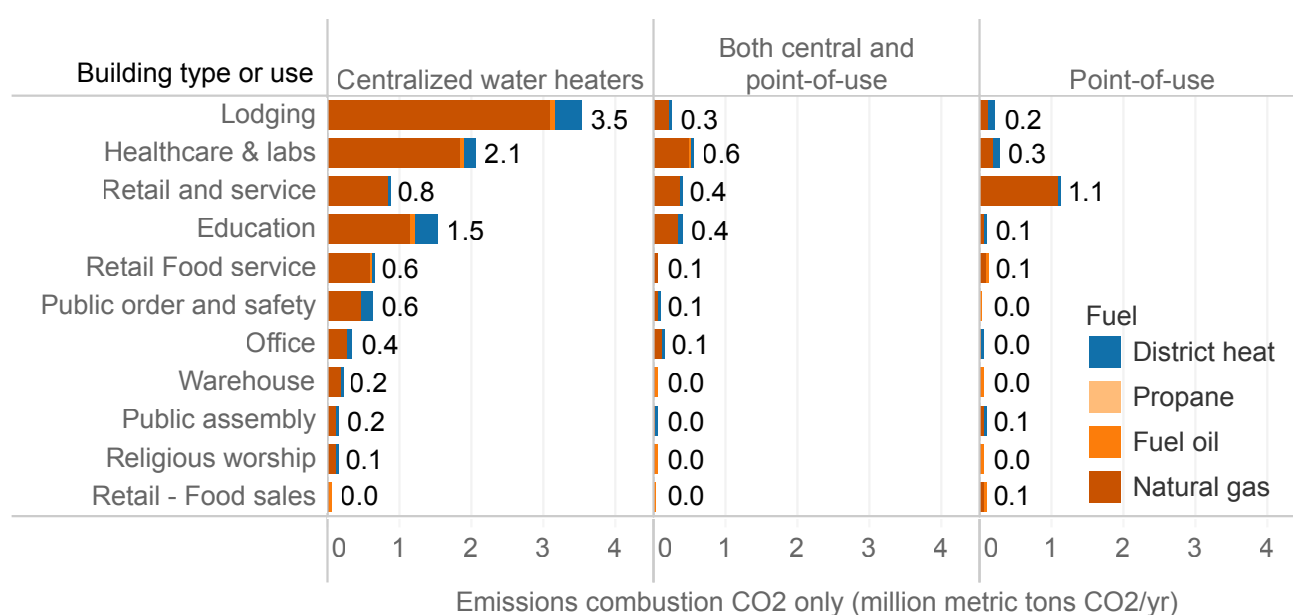


Figure S9: Building and fuel type breakout of emissions impacts from commercial fuel-fired boilers for space heating as of 2019, based on data from Commercial Building Energy Consumption Survey (CBECS)¹² and application of national average emissions factors: natural gas (0.053 Mt/TBtu), propane (0.063 Mt/TBtu), fuel oil (0.073 Mt/TBtu) and electricity (0.088 Mt/TBtu).^{52,39}

Commercial fuel-fired cooking (existing buildings)

This is a **medium impact** segment that will be **highly difficult** to address.

Key **impacts** include:

- emissions (estimated up to 12 Mt CO₂/yr. in 2050 (BAU)); and
- energy costs (estimated up to \$2/yr. in 2050 (BAU)); and
- public health (source of criteria air pollutants)⁵⁰

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - induction stoves and woks.
- Supporting:
 - low-power equipment with load-limiting controls; and
 - energy storage-enabled cooking equipment.

The **up-front cost** of these innovations varies widely, but induction equipment and electrical upgrades could cost thousands more than typical gas-fired options.

Key **concentration areas** for these innovations to address include natural gas-fired cooking equipment in food service buildings, which generate the largest share of this segment's overall emissions impacts (Figure **S10**).

Table **S15** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S15: Key implementation barriers and mitigating actions for innovations to address the commercial fuel-fired cooking segment.

Key Barriers	Key Actions
Lack of product availability	• New commercial induction cooking products
High up-front cost	• Support incentives/rebates for businesses and distributors • Quantify bottom-line and non-energy lifetime benefits
Consumer distrust/lack of awareness	• Consumer awareness campaigns that use field study data to address misconceptions about quality and performance • Leverage celebrity tie-ins/social media to demonstrate success with commercial electric cooking equipment and spread awareness on potential health benefits
Insufficient electrical capacity	• Low-power induction cooking options with integrated storage and controls to limit capacity needs

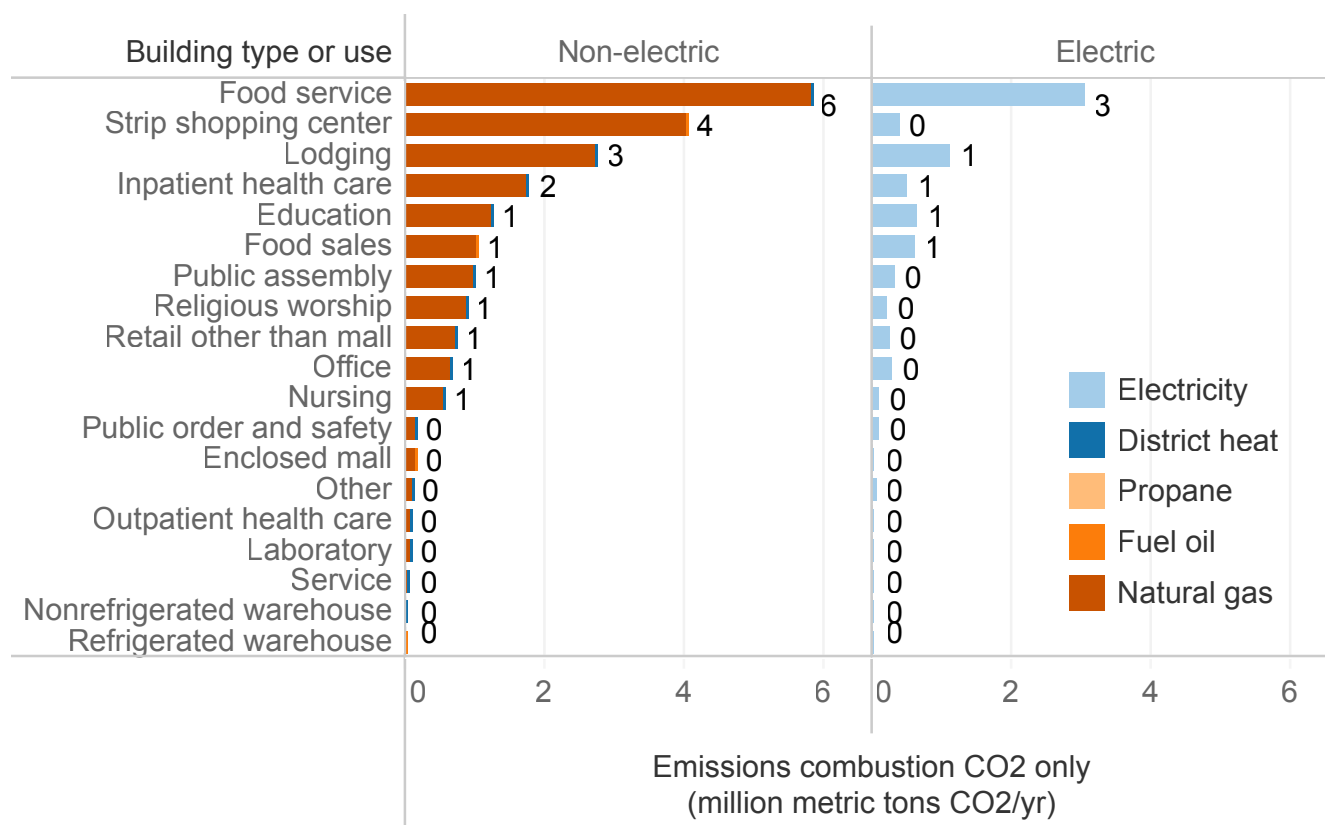


Figure S10: Building and fuel type breakout of emissions impacts from commercial fuel-fired cooking as of 2019, based on data from Commercial Building Energy Consumption Survey (CBECS)^[12] and application of national average emissions factors: natural gas (0.053 Mt/TBtu), propane (0.063 Mt/TBtu), fuel oil (0.073 Mt/TBtu) and electricity (0.088 Mt/TBtu).^{[52][39]}

Residential electric HVAC (existing buildings)

This is a **high impact** segment that will be **moderately difficult** to address. Key **impacts** include:

- peak demand (estimated up to 597 GW in the winter season of 2050 (Ineff. Elec.)); and
- energy costs (estimated up to \$117B/yr. in 2050 (Ineff. Elec.)).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - standard and cold-climate air source heat pumps (HPs), dual-fuel air source heat pumps, geothermal heat pumps
- Supporting:
 - connected thermostats for demand flexibility through pre-conditioning
 - envelope and duct upgrades;
 - thermal energy storage (TES; HVAC/envelope integration)

Key **concentration areas** for these innovations to address include heating in the Great Lakes/Mid-Atlantic region and cooling in the Southeast region and Lakes/Mid-Atlantic grid regions, which are expected to generate the largest share of this segment's peak winter and summer demand, respectively, in 2050 under high inefficient electrification (Figure S11).

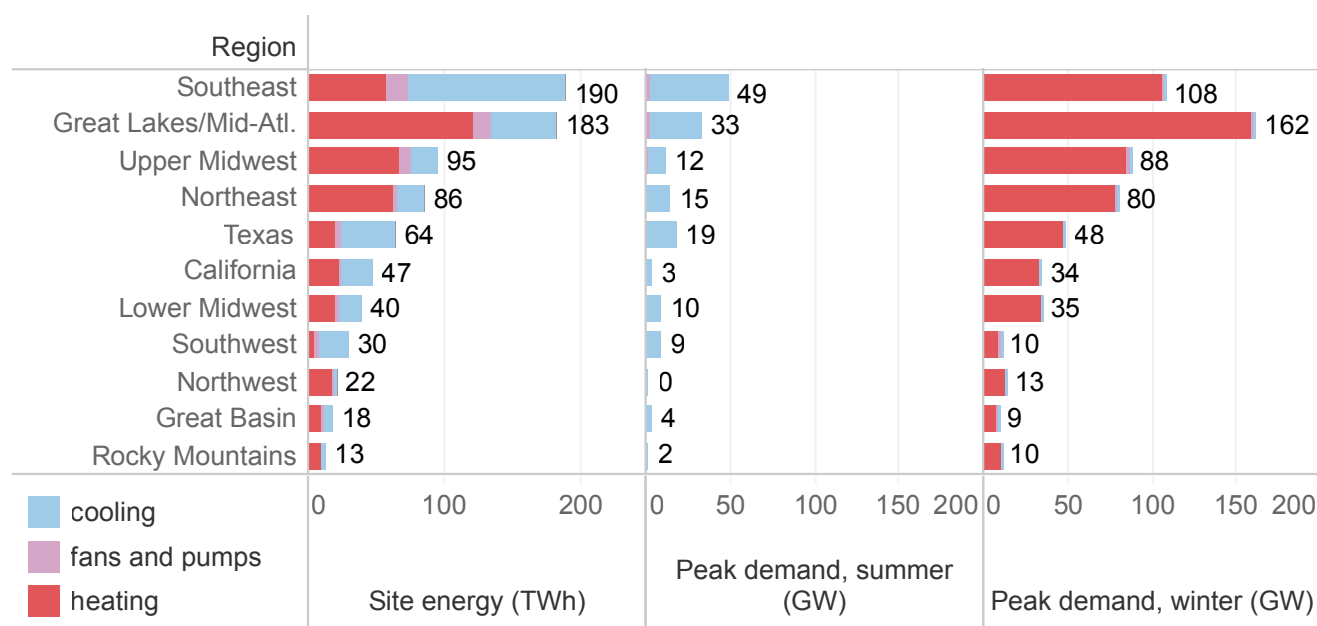


Figure S11: Grid region and end use concentration of residential electric HVAC site energy use and peak summer and winter demand in 2050 under high inefficient electrification of fuel-fired heating segments.³

Key barriers and mitigating actions for deploying the technical innovations for this segment overlap with those listed for *Residential thermal loads: Duct losses (existing buildings)* and *Residential fuel-fired furnaces, cold climates (zones 5–8, existing buildings)* (up-front cost and awareness). Table S16 lists additional barriers and actions that are unique to the innovations that address this segment.

Table S16: Key implementation barriers and mitigating actions for innovations to address the residential electric HVAC segment.

Key Barriers	Key Actions
Competition with cooling-only AC units slows adoption of efficient HPs	• Provide equipment manufacturer incentives to produce units with reversing valves to enable two-way operation (heating and cooling)
TES products not widely available	• RD&D on new thermal energy storage (TES) products • Case studies and technical assistance
Higher up-front cost of TES (HVAC- and envelope-integrated)	• RD&D on TES cost compression • Case studies and technical assistance
Value of envelope and other innovations for reducing peak HVAC loads and increasing flexibility is not accounted for in utility planning	• Support utility distribution and resource planning with data and analysis

Residential electric water heating (existing buildings)

This is a **medium impact** segment that will be **less difficult** to address than other segments. Key **impacts** include:

- peak demand (estimated up to 49 GW in the winter season of 2050 (Ineff. Elec.)); and
- energy costs (estimated up to \$40B/yr. in 2050 (Ineff. Elec.)).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - heat pump water heaters (HPWH), including combination air and water systems
- Supporting:
 - integrated or add-on controls for demand flexibility.

Key **concentration areas** for these innovations to address include the Southeast and Great Lakes/Mid-Atlantic grid regions, which are expected to generate the largest share of this segment's peak demand and site electricity impacts in 2050 under high inefficient electrification (Figure S12).

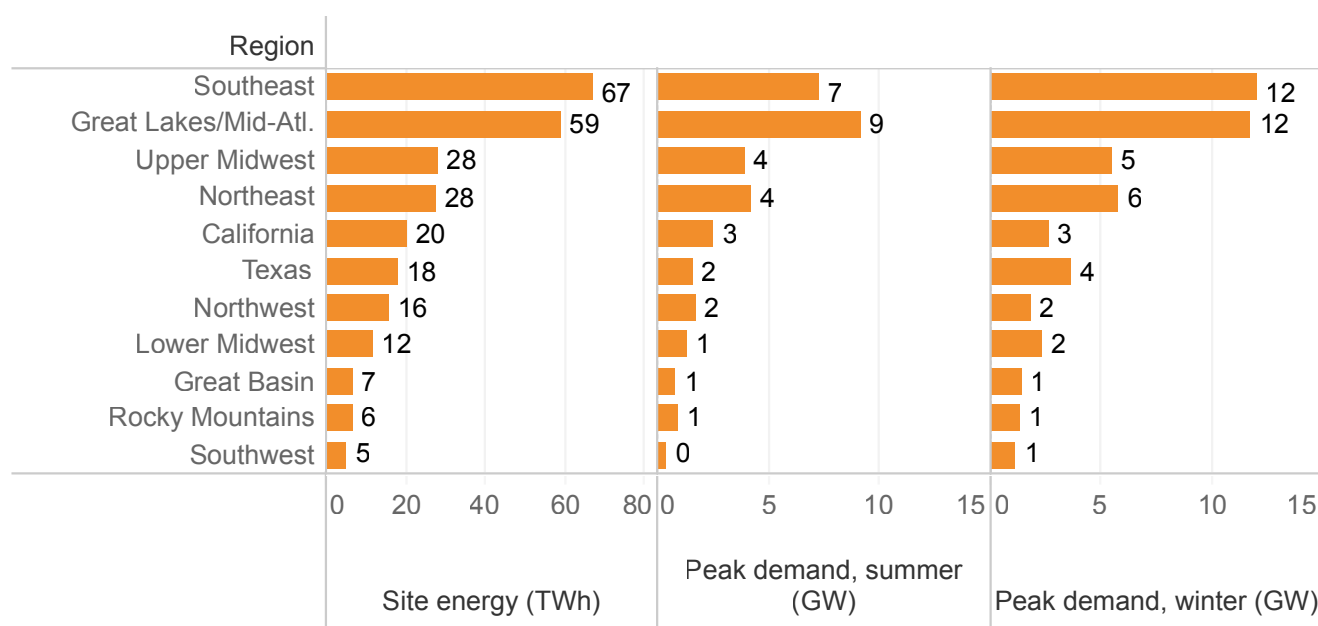


Figure S12: Grid region concentration of residential electric water heating site energy use and peak summer and winter demand in 2050 under high inefficient electrification of fuel-fired water heating segments.³

Key barriers and mitigating actions for deploying the technical innovations for this segment overlap with those listed for *Residential fuel-fired water heating (single-unit, 40+ gallon tank, existing buildings)* (up-front cost, availability, and form factor). Table S17 lists additional barriers and actions that are unique to the innovations that address this segment.

Table S17: Key implementation barriers and mitigating actions for innovations to address the residential electric water heating segment.

Key Barriers	Key Actions
HPWH form factor and noise concerns, especially in small dwelling units	• Lowboy replacement options (heat recovery, high delivery temp., thermal storage, and split systems) • Component and system optimization to minimize retrofit issues
Lack of widely available compensation mechanisms for water heater flexibility	• Support utility and regulator decision making on consumer compensation, rate design, and incentive programs

Residential all other electricity

This is a **medium impact** segment that will be **highly difficult** to address. Key **impacts** include:

- peak demand (estimated up to 47 GW in the winter season of 2050 (Ineff. Elec.)); and
- energy costs (estimated up to \$58B/yr. in 2050 (Ineff. Elec.)).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - low-power network communication, including power over Ethernet or communication over power line; and
 - natively direct current devices.
- Supporting:
 - sensors and controls to improve scheduling efficiency and enable demand flexibility.

Key **concentration areas** for these innovations to address include a wide range of end-uses within the broader other category, including refrigeration, clothes drying, and miscellaneous electric loads, which are expected to be the top three sources of site energy use by 2050 in high inefficient electrification scenario (Figure S13).

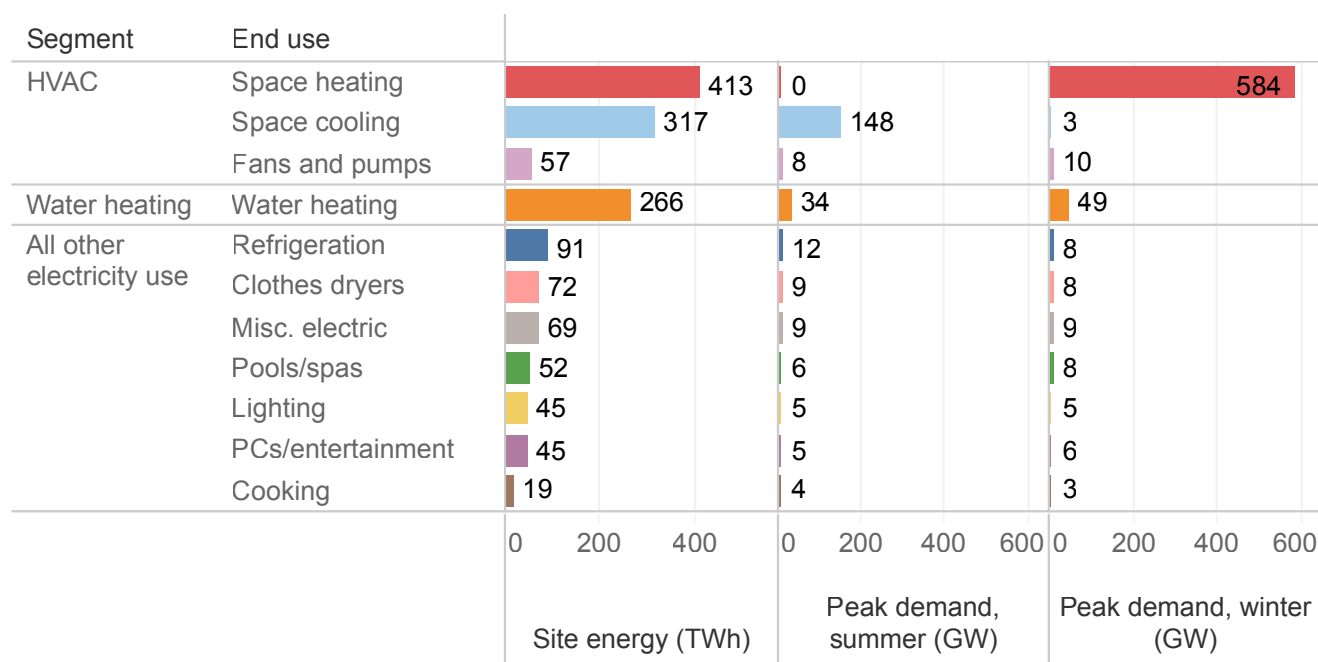


Figure S13: Grid region concentration of residential electric all other (non-HVAC, non-water heating) site energy use and peak summer and winter demand in 2050 under high inefficient electrification of fuel-fired segments.⁸ Residential electric HVAC and water heating segment data are also shown for context.

Table S18 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S18: Key implementation barriers and mitigating actions for innovations to address the residential electric all other (non-HVAC, non-water heating) end use segment.

Key Barriers	Key Actions
Lacking smart electrical device metrics	• Support development of smart device metrics
Plug loads are designed for low-latency, not efficiency	• Efficient networking, onboard sensing, computation, and actuation • Predictive control algorithms that "wake up" devices preemptively
Multi-vendor/multi-tech integration	• Common standards for communication and energy reporting such as Matter • Encourage connected products to work across building end-use ecosystems, i.e., connected lighting/HVAC/plug loads

Commercial electric HVAC

This is a **high impact** segment that will be **highly difficult** to address. Key **impacts** include:

- peak demand (estimated up to 132 GW in the winter season of 2050 (Ineff. Elec.)); and
- energy costs (estimated up to \$22B/yr. in 2050 (Ineff. Elec.)).

Key **technical innovation pathways** to address this segment's impacts include (see also:

Commercial thermal loads: Envelope (existing buildings), *Commercial thermal loads: Ventilation (existing buildings)*, *Commercial fuel-fired rooftop units (existing buildings)*, *Residential fuel-fired furnaces, cold climates (zones 5–8, existing buildings)*, *Commercial fuel-fired large boilers (space heating, existing buildings)*):

- Primary:
 - standard, cold-climate, dual-fuel, and geothermal heat pumps (classes include residential-type, rooftop, packaged terminal, hydronic).
- Supporting:
 - building automation systems/connected thermostat controls for energy management and demand flexibility via preconditioning; and
 - envelope upgrades; and
 - integrated thermal storage; and
 - energy recovery ventilation.

Key **concentration areas** for these innovations to address include retail, assembly, and education building types, which are expected to generate the largest share of this segment's winter peak demand and site electricity impacts in 2050 under high inefficient electrification (Figure S14). Large offices are also an important focus as the largest source of summer peak demand and site energy use from HVAC of any commercial building type.

Key barriers and mitigating actions for deploying the technical innovations for this segment overlap with those listed for *Commercial thermal loads: Envelope (existing buildings)*, *Commercial thermal loads: Ventilation (existing buildings)*, *Commercial fuel-fired rooftop units (existing buildings)*, *Residential fuel-fired furnaces, cold climates (zones 5–8, existing buildings)*, and *Commercial fuel-fired large boilers (space heating, existing buildings)* (product availability, form factor, cost, awareness, and workforce). Table S19 lists additional barriers and actions that are unique to the innovations that address this segment.

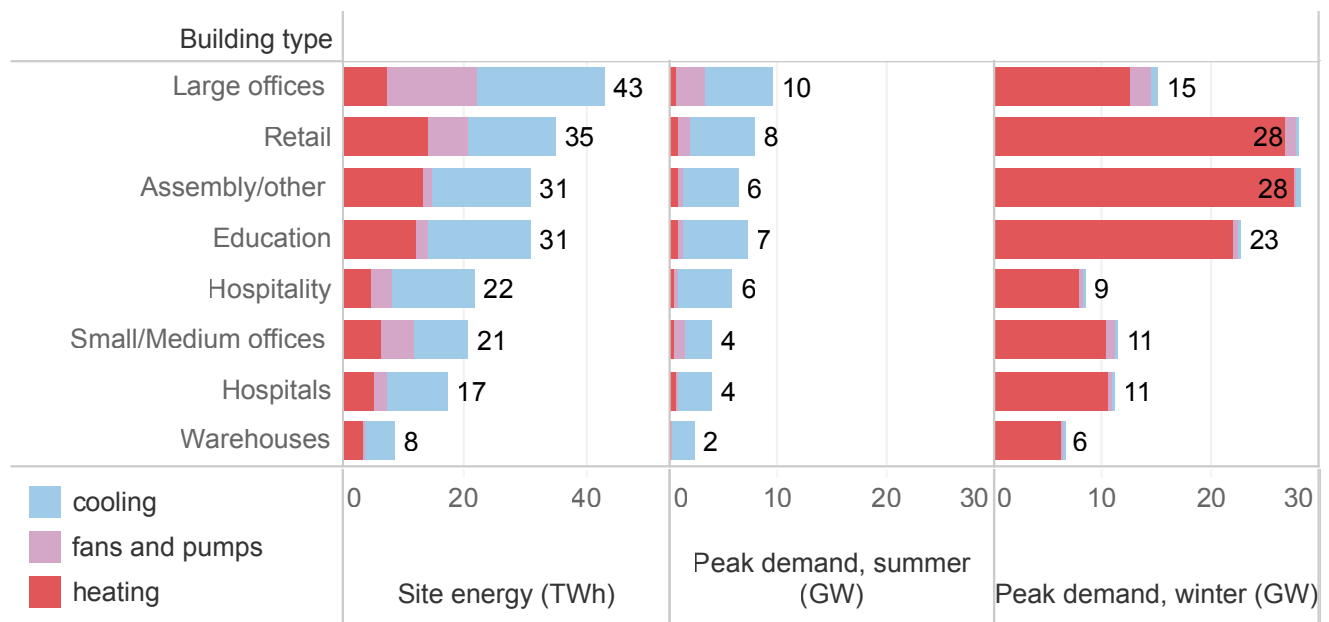


Figure S14: Grid region concentration of commercial electric HVAC site energy use and peak summer and winter demand in 2050 under high inefficient electrification of fuel-fired heating segments.³

Table S19: Key implementation barriers and mitigating actions for innovations to address the commercial electric HVAC end use segment.

Key Barriers	Key Actions
Lack of standard, easily configured product interfaces or control sequences for key low-carbon heating systems	- Standard designs and libraries of equipment operating sequences - Plug-and-play software installations - Incorporate control sequences in technical standards (e.g., ASHRAE G36) and codes - Semantic modeling standards, consensus specifications, testing capabilities, and protocols
Small/medium buildings lack control infrastructure needed to enable HVAC flexibility	Develop and demonstrate low-cost strategies for HVAC control in small-medium buildings (e.g., cloud-based approaches)
Uncertain performance of products/services	Performance benchmarks/testing protocols to verify control sequences and load impacts
Lack of workforce to configure controls	Training infrastructure (e.g., virtual buildings)

Commercial refrigeration

This is a **medium impact** segment that will be **highly difficult** to address. Note that this segment is focused on operational electricity use of commercial refrigeration in existing buildings. Impacts of refrigerant emissions are found under the **Refrigerants and other fluorinated gases** segment. Key **impacts** include:

- peak demand (estimated up to 10 GW in the winter season of 2050 (BAU and Ineff. Elec.)); and
- energy costs (estimated up to \$11B/yr. in 2050 (BAU and Ineff. Elec.)).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - efficient refrigeration case designs and high-performance supermarket systems in hot climates; and
 - distributed system designs with localized compressors; and
 - advanced defrost controls.
- Supporting:
 - connected refrigeration control systems for demand flexibility; and
 - heat recovery (for HVAC reheat and water heating).

Key **concentration areas** for these innovations to address include retail building types, which are expected to generate the largest share of this segment's peak demand and site electricity impacts in 2050 under both the BAU and high inefficient electrification (Figure S15).

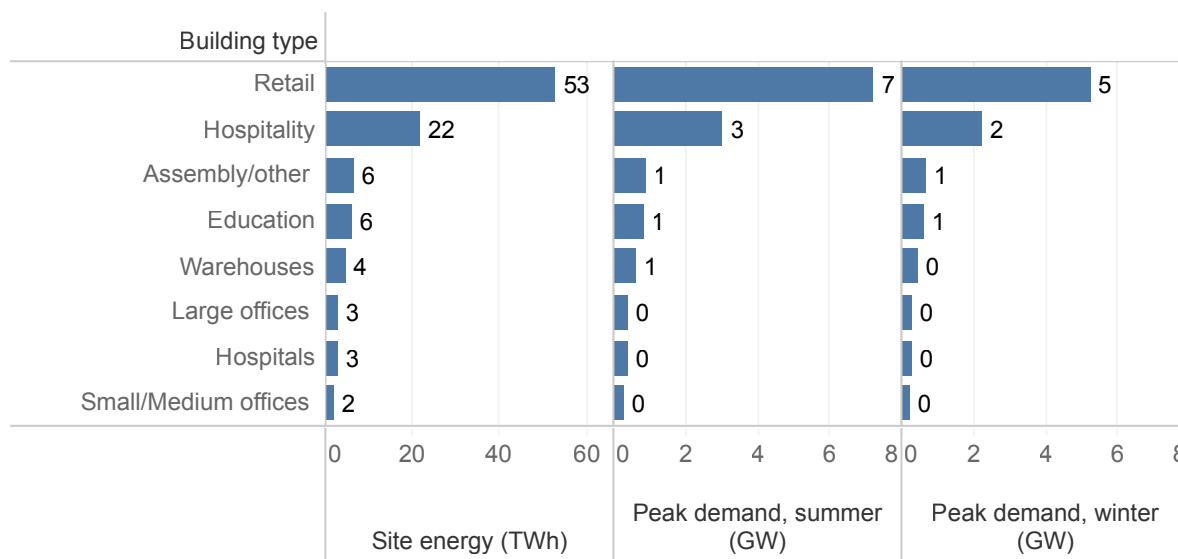


Figure S15: Grid region concentration of commercial refrigeration site energy use and peak summer and winter demand in 2050 under high inefficient electrification of fuel-fired heating segments.³

Key barriers and mitigating actions for deploying the technical innovations for this segment overlap with those listed for **Refrigerants and other fluorinated gases**. Table S20 lists additional barriers and actions that are unique to the innovations that address this segment.

Table S20: Key implementation barriers and mitigating actions for innovations to address the commercial refrigeration end use segment.

Key Barriers	Key Actions
Inefficient refrigerated case designs	• Support market adoption of doors/coverings on refrigerated cases
Supermarket system performance degrades in hot climates	• Improve performance in high temperatures, including by integrating thermal storage • Improve defrost controls
Integrated HVAC-and-refrigeration systems have increased complexity/costs	• Analyses of equipment materials/components to identify cost reduction opportunities • Installer training/skills recognition programs to increase system familiarity
Lack of confidence in flexible performance or user acceptability	• Facilitate demand response demonstrations for mission-critical commercial refrigeration systems

Commercial all other electricity

This is a **medium impact** segment that will be **highly difficult** to address. Key **impacts** include:

- peak demand (estimated up to 67 GW in the winter season of 2050 (BAU and Ineff. Elec.)); and
- energy costs (estimated up to \$50B/yr. in 2050 (BAU and Ineff. Elec.)).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - connected luminaires interoperable with building automation systems and responsive to grid signals; and
 - connected or device-integrated plug load controls that are simple and cost-effective (e.g., automatic receptacle control).
- Supporting:
 - vacancy detection and predictive controls; and
 - enterprise-wide power management software.

Key **concentration areas** for these innovations to address include miscellaneous electric end uses and PCs/office equipment, which are expected to generate the largest share of this segment's peak demand and site electricity impacts in 2050 under both the BAU and high inefficient electrification (Figure S16).

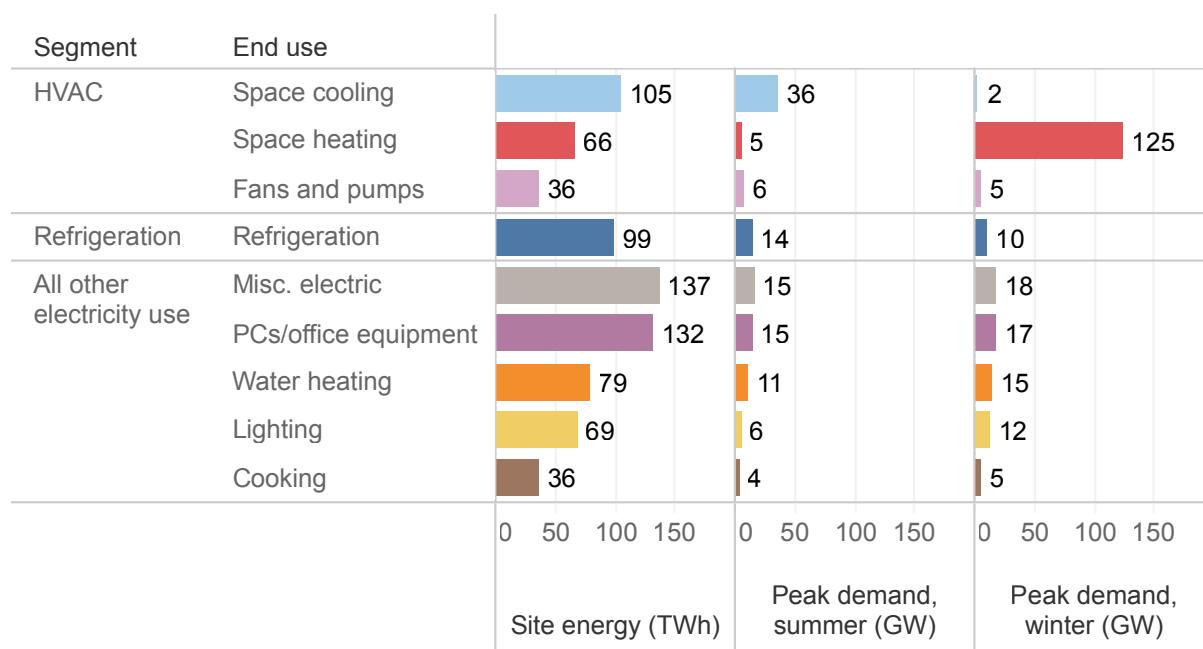


Figure S16: Grid region concentration of commercial electric all other (non-HVAC, non-refrigeration) site energy use and peak summer and winter demand in 2050 under high inefficient electrification of fuel-fired segments.³ Commercial electric HVAC and refrigeration data are also shown for context.

Table S21 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S21: Key implementation barriers and mitigating actions for innovations to address the commercial electric all other (non-HVAC, non-refrigeration) electric end uses segment.

Key Barriers	Key Actions
Complexity of available lighting retrofit and control options	• Context-specific guidance on retrofit options • Simplify lighting control platforms
Challenge of deploying system-wide power management and device-agnostic plug load controls	• Best practices for coordinated procurement and operation of power management technologies • Develop device-specific definitions and user acceptance guidelines
Commercial miscellaneous electric loads (MELs) are diverse and poorly understood	• Further characterize individual MELs and energy-use profiles • Platforms for integrated MEL control
Load-shedding acceptability thresholds are poorly understood	• Guidance for acceptable levels of lighting service reduction during peak load hours on the grid

New building operational energy (built 2024-2050)

This is a **high impact** segment that will be **moderately difficult** to address. This segment includes all fuel-fired and electric operational energy for all buildings to be constructed between 2024 and 2050. These form their own segment because of the unique challenges and opportunities of new construction. Key **impacts** include:

- emissions (estimated 196 Mt CO₂/yr. in 2050 under BAU); and
- energy costs (estimated \$140B/yr. in 2050 under inefficient electrification); and
- safety (highly efficient envelopes provide thermal resilience).

Key **technical innovation pathways** to address this segment's impacts include:

- Primary:
 - cost-effective technologies for thermal load reduction and all-electric/electric-ready construction
- Supporting:
 - controls infrastructure for grid edge resource management, including in small-to-medium buildings; and
 - prefabrication techniques, automation, and robotics that improve new construction productivity and efficiency

The **up-front cost** premium of highly efficient construction varies on factors such as the experience level of the designer and builder with such construction. Examples of cost premiums include a range of 0–3% for multifamily passive house construction and 3–5% for single-family passive house construction.⁵⁵ For commercial construction, studies have found that all-electric construction can be lower cost than mixed-fuel construction.^{56,57}

Key **concentration areas** for new building operational energy are fuel-fired space and water heating, fuel-fired cooking in commercial buildings, cooling, and computing in commercial buildings, where data centers are expected to drive future growth (Figure S17). The commercial building stock is projected to see more turnover and growth than the residential stock, with 75% of projected homes and 51% of projected commercial square feet in 2050 having already been constructed.³⁴

Table S3 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

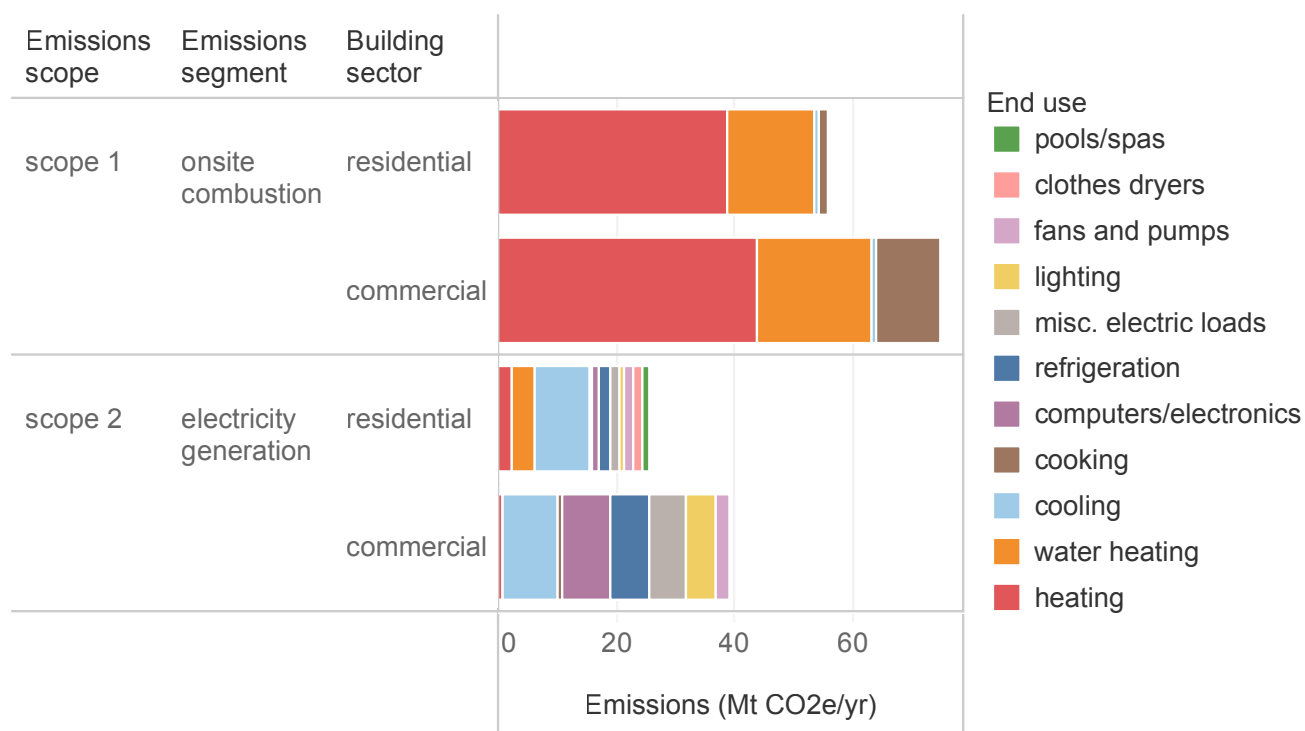


Figure S17: Breakout of 2050 business-as-usual scenario (BAU) emissions for buildings constructed 2024–2050, by emissions scope, sector, and end use.³

Table S22: Key implementation barriers and mitigating actions for innovations to address the new building operational energy segment.

Key Barriers	Key Actions
Lack of value proposition for greater efficiency	• Evaluate energy, cost, and greenhouse gas benefits of code adoption; expand quantification of health, life-safety, and resilience benefits • Increase performance and feasibility while reducing cost and associated risks • Demonstrate opportunities for low- and no-cost beyond-code improvements, particularly for manufactured homes
States and local governments remain on outdated building codes and standards	• Align federal programs to support model code adoption and compliance across the United States • Technical assistance around zero-energy and emissions standards, leveraging Bipartisan Infrastructure Law/Inflation Reduction Act • Develop and encourage adoption of advanced and stretch codes and standards • Update and align above code programs, including Zero Energy Ready Homes and ENERGY STAR for Homes
Segmented industry and workforce	• Expand workforce development and training—including of designers/mechanical, electrical, and plumbing professionals—to be more accessible and include the latest technologies and construction practices • Encourage professional credentialing through licensure and certification programs • Develop and disseminate a common definition for electric-ready construction
Shortage of housing in many areas	• Scale up quality housing by integrating efficiency features in offsite construction • Technical support for offsite construction cost compression and productivity • Demand consolidation by state/local governments to facilitate local production facility investment

Electric vehicle charging

This is a **medium impact** segment that will be **moderately difficult** to address. Key **impacts** include:

- peak demand (estimated up to 46 GW unmanaged demand on peak winter morning of 2050);⁵⁸
- energy costs (estimated up to \$112B/yr. in 2050); and
- affordability (puts downward pressure on rates).

Key **technical innovation pathways** to address this segment's impacts include:

- Coordinate electric vehicle (EV) charging with building loads
- Improved interoperability of vehicle and building controls to support flexibility and resilience

The **up-front cost** of electric vehicle charging equipment varies from \$0–1,000 for level 1 (120-volt, plug-in), \$400–6,000 for level 2 (240-volt, dedicated circuit), and \$180,000—285,000 for DC fast charging equipment based on Wood et al.⁵⁹

To understand key **concentration areas** for this segment, we provide illustrative examples weekday load profiles for one million vehicles in an unmanaged scenario and in a scenario where charging is managed to minimize aggregate EV charging peak demand (Figure S18). One can see the importance of workplace and public charging options to shift part of the charging load into the middle of the day. In this example, the unmanaged EV charging scenario has lower demand in the early morning when building heating loads peak; illustrating that coordinating EV charging with building loads has the potential to reduce overall peak demand and reduce energy costs for all ratepayers.

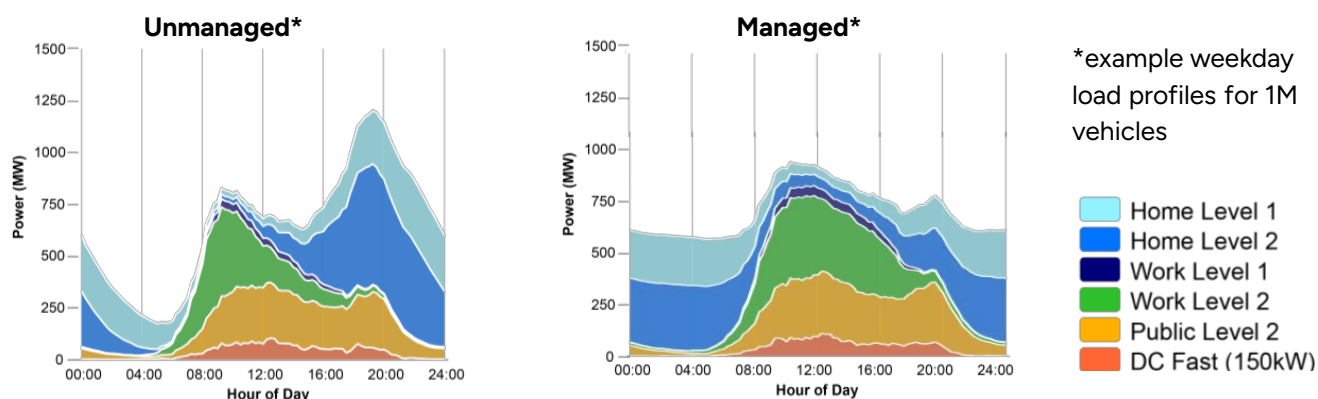


Figure S18: Example weekday load profiles for one million vehicles in an unmanaged scenario and in a scenario where charging is managed to minimize aggregate EV charging peak demand.⁶⁰ Managed charging reduces peak demand while supporting drivers' needs.

Table S23 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S23: Key implementation barriers and mitigating actions for innovations to address the electric vehicle charging segment.

Key Barriers	Key Actions
Transportation electrification exacerbates need for distribution grid upgrades	• Smart charge management to coordinate EV charging with other building loads, on-site distributed energy resources, and grid signals; vehicle-to-building/grid (V2B/V2G) • Promote workplace charging and support development of EV rates that support distribution grid planning and operation • Improve value stream for non-resilience V2B/V2G; reduce utility constraints and improve equipment readiness for V2G participation
Lack of vehicle data (e.g., state of charge) access impedes coordinated control	• Support market adoption of standardized protocols (e.g., ISO 15118 and Open Charge Point Protocols)
EV charging less accessible for multifamily occupants	• Innovation on charging designs and business models to increase access • Lower total cost of charging by supporting building codes for electric vehicle standard supply equipment in multifamily buildings and workplaces • Support multifamily-specific electric rates that reflect the lower cost-of-service for multifamily dwelling unit customers

Refrigerants and other fluorinated gases

This is a **high impact** segment that will be **moderately difficult** to address. Key **impacts** include:

- emissions (estimated up to 92 Mt CO₂/yr in 2050 under inefficient electrification); and
- manufacturer competitiveness in global markets.

Key **technical innovation pathways** to address this segment's impacts include:

- Reduce refrigerant usage; reduce in-service leakage; increase end-of-life reclamation and recycling;
- Substitute refrigerants with low and ultra-low global warming potential (GWP) alternatives;
 - Nearer-term: <750 GWP A2L (low toxicity and flammability) refrigerants (R-32, R-454B);
 - Longer-term: <10 GWP CO₂ (R-744), propane (R-290), etc.; and
- Reduce use of high-GWP foam blowing agents
 - Substitute non-foam insulation
 - Substitute blowing agents with hydrofluoroolefins, hydrocarbons, water.
 - Alternative foam manufacturing methods that reduce or avoid the need for blowing agents

Within the buildings sector, key **concentration areas** for fluorinated gas emissions are primarily fugitive emissions of refrigerants used for residential air conditioning (42%) and commercial refrigeration (37%), with smaller contributions attributed to commercial air conditioning (7%).³⁶ Notably, contributions from residential refrigeration are small because the most common refrigerant used in these appliances is isobutane, which has a low GWP of 3. Smaller contributions come from foam insulation blowing agents (11%) and some specialized types of fire protection systems (2%).³⁶

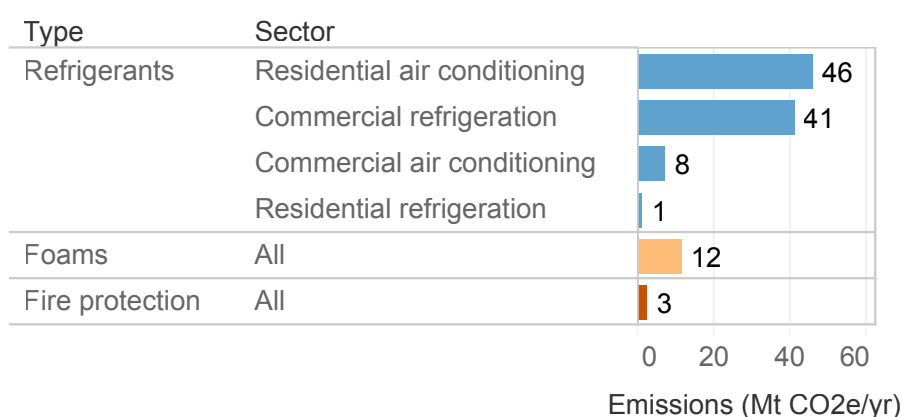


Figure S19: Buildings sector fluorinated gas emissions are primarily fugitive refrigerant emissions (87%) with smaller contributions from foam insulation blowing agents (11%) and some specialized types of fire protection systems (2%).³⁶

Table **S24** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S24: Key implementation barriers and mitigating actions for innovations to address the refrigerants and fluorinated gases segment.

Key Barriers	Key Actions
Lack of in-service leak detection and motivation for reclamation	• Improve sensors and management systems • Guidance on proper installation and reclamation/recycling approaches • Include fugitive refrigerant emissions in building code and standard provisions
Low availability of ultra-low GWP refrigerants	• Ultra-low GWP compatible equipment development
Uncertainty about performance of ultra-low GWP refrigerant systems	• Demonstrations to improve understanding of ultra-low GWP performance characteristics and the factors that most influence performance • R&D on equipment configurations and supporting measures (e.g., leak detection, ventilation) that allow for the use of CO₂ and propane refrigerants • Development of higher-performance ultra-low GWP refrigerants
Flammability and safety concerns	• Risk assessments for ultra-low GWP refrigerants

Embodied construction material lifecycle emissions

This is a **high impact** segment that will be **moderately difficult** to address. Key **impacts** include:

- emissions (estimated 200–400 Mt CO₂/yr in 2050 under both scenarios); and
- manufacturer competitiveness in global markets.

Key **technical innovation pathways** to address this segment's impacts include:

- Building design:
 - Repurpose existing buildings or parts of buildings (e.g., foundation reuse with partial teardown) and salvage materials
 - Design with low-carbon materials and material efficiency
 - Design for deconstruction and reuse
- Construction: methods that reduce waste and equipment emissions
- Manufacturing: reduce carbon intensity of materials

Key **concentration areas** for residential embodied construction emissions include concrete, insulation, and cladding, which together are estimated to comprise 70% of a typical new home's embodied emissions.⁶¹ For commercial, one study estimated contributors to U.S. office building material emissions between 2013 and 2018 as 37% from steel, 29% from concrete, and 1% from wood.⁶²

Table **S25** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S25: Key implementation barriers and mitigating actions for innovations to address the embodied construction material lifecycle emissions segment.

Key Barriers	Key Actions
Inconsistent methodologies for life cycle assessments (LCAs); high costs/low quality of environmental product declarations (EPDs)	• Provide market incentives/direct funding for EPD creation; develop common framework and underlying LCA dataset that facilitates development and updating of EPDs • Support Product Category Rule development for all building components • Establish U.S. whole-building LCA guidelines to improve consistency across LCA tools • Develop framework reference building models for embodied carbon and baseline embodied carbon data • Support state and local procurement policies
Builders and other key stakeholders don't measure or consider emissions	• Support industry efforts and tools; integrate energy and LCA modeling tools • Educate builders on no-cost and cost-savings strategies
Validation of low embodied carbon (LEC) materials	• Field-validate new low-carbon materials to derisk market adoption; certify new materials in building codes • Develop accelerated tests to predict durability/lifetime of new materials
LEC space is dense and difficult to understand	• Create an LEC working group with DOE, the American Center for Life Cycle Assessment Product Category Rules Committee, labs, practitioners
LEC products often more expensive	• Improve incentives for LEC materials via grants and awards • Design/select LEC materials that deliver demonstrable additional benefits (e.g., that improve building quality and occupant productivity); emphasize these benefits in marketing products
Limits from existing material production guidelines and lack of regional or local LEC manufacturing capacity	• Support/encourage updating of engineering standards for cementitious materials that may dictate use of specific material formulation to allow low-carbon alternatives • Provide support/financing for updates to material manufacturing facilities to produce low-carbon alternatives (concrete, mass timber, etc.)

Gas production and distribution

This is a **high impact** segment that will be **highly difficult** to address. Key **impacts** include:

- emissions (estimated 117 Mt CO₂/yr. in 2050 under BAU, using 100-year GWP for methane).

Key **technical innovation pathways** to address this segment's impacts include:

- Production, processing, transmission:
 - Identify and address leaks; and
 - Reduce venting; improve flaring efficiency; electrify operations.
- Distribution and post-meter:
 - Replace leaky pipes and repair acute leaks.

Key **concentration areas** are shown in Figure S20). We estimate that 29% of production, processing, transmission, and storage emissions (proportion of consumption) and 99% of distribution and post-meter emissions (proportion of customers) are attributable to the buildings sector. In our scenario analysis, methane leakage is assumed to be proportional to consumption; in reality, leakage may be a function of other characteristics, such as surface area of pipe, pipe material, and pressure levels—although some evidence suggests that leakage is partially proportional to consumption.⁴⁵

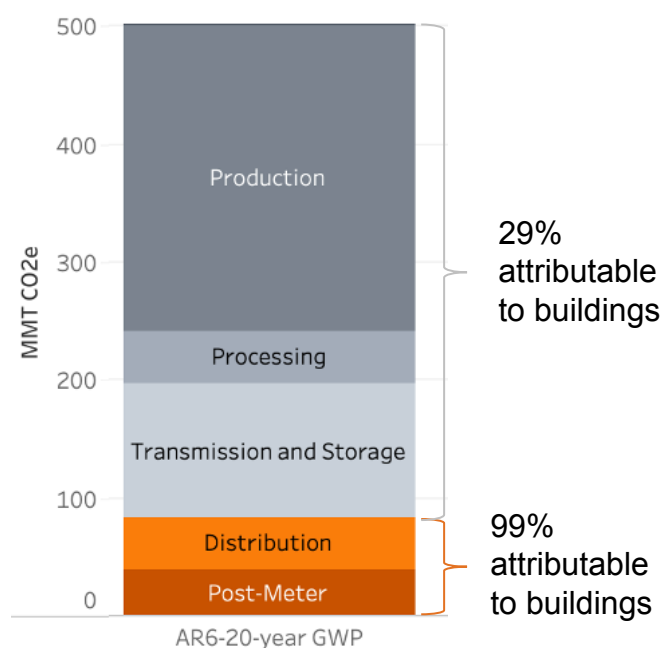


Figure S20: Gas production and distribution emissions are primarily methane and are attributed to various stages of production and distribution based on the U.S. Environmental Protection Agency Greenhouse Gas Inventory (GHGI). Figure shows equivalent CO₂/yr emissions using 20-year GWP.³⁶

Table S26 summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S26: Key implementation barriers and mitigating actions for innovations to address the gas production and distribution segment.

Key Barriers	Key Actions
Uncertainty in leakage estimates and sources	• National aggregation of existing utility reporting on leakage • EPA-led regulations on measurement and reporting
Implications of retaining gas lines for supplemental heat are not well understood	• Evaluate distribution pipe and post-meter leakage characteristics related to pressure and throughput
Fugitive emissions impacts of low-carbon fuels (e.g., bio/synthetic gas, blending hydrogen into gas systems) are not well understood	• Evaluate leakage rates and emissions impacts for new, low-carbon fuels in real-world conditions
Gas and electric system planning is not coordinated	• Support integrated gas and electric planning with technical assistance and resource sharing

Cross-cutting: Building electrical infrastructure

Electrification may trigger costly/time-consuming electrical infrastructure investments for customers (new circuit runs, rewiring, electrical panels, service upgrades, transformers). In many cases, technology solutions can avoid these upgrades.

Key **impacts** include:

- affordability: avoiding infrastructure oversizing makes electrification faster and less costly while making electricity more affordable for all.

Key **technical innovation pathways** to address this segment’s impacts include:

- Thermal load reduction enabling smaller equipment (envelope, ventilation, equipment efficiency, thermal and electrical energy storage)
- Low-power end-use alternatives
- Behind-the-meter load management (circuit sharing, smart breakers, digital load management, etc.)

Table **S27** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S27: Key implementation barriers and mitigating actions for innovations to address the cross-cutting building electrical infrastructure segment.

Key Barriers	Key Actions
Lack of low-power and simple load management hardware	• Low-power electrification ecosystem of products/appliances
Conservative determinations of electrical service capacity needs	• Analysis on actual peak electrical use for distinct building types and climate zones • Support National Electric Code 2023 provisions that permit alternative peak-load calculations
Lack of control protocols for distributed storage/load management	• Consensus standards on physical connections and software interoperability that support local load management and novel storage integration solutions to reduce peak load

Cross-cutting: Grid edge resource management

The cost of delivering electricity is increasing and may soon surpass the cost of producing it.⁶³ This cross-cutting segment is focused on managing energy efficiency, load flexibility, and other distributed energy resources such as solar, electrical/thermal storage, and EVs at the customer edge of the grid, to enable more efficient use of both distribution and bulk grid infrastructure.

Key **impacts** include:

- affordability: generates revenue for customers and increases affordability for all
- safety: supports resilience for buildings and communities

Key **technical innovation pathways** to address this segment's impacts include:

- Valuing efficiency and flexibility in utility resource and distribution planning and power markets
- Building equipment and controls that enable automatic price-based and direct load control, e.g.:
 - Connected thermostats, building automation systems, and water heaters
 - Managed electric vehicle charging
 - Thermal storage (HVAC- and envelope-integrated)
 - Electrical storage (standalone, appliance-integrated)

Table **S28** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S28: Key implementation barriers and mitigating actions for innovations to address the cross-cutting grid edge resource management segment.

Key Barriers	Key Actions
Lack of valuation and incentives to drive adoption and utilization of behind-the-meter grid resources	• Support utility and regulator decision-making on consumer compensation, rate design, and incentive programs • Support state requirements for demand-side resource valuation in integrated utility planning and performance-based utility regulation • Support new business models for stacking value across grid-edge assets • Develop improved ability to model cross-sector control and cybersecurity strategies across the building and power sectors • Use metered data that support predictive, optimization-based controls to improve understanding of the durability of energy efficiency, demand flexibility, and other BTM DERs across grid planning horizons
Higher cost and potential security vulnerabilities for connected products and storage	• Support utility program rebates for connected equipment and storage, particularly in low-to-moderate income homes and under-resourced communities • Develop low-cost, high-performance onboard device computing capabilities to reduce reliance on internet-connected equipment for grid edge management • Develop guidelines on cybersecurity responsibilities and management of the lifespan of cybersecurity vulnerabilities alongside equipment lifespans
Lack of control capabilities and standards	• Support industry-led standardization of communications protocols for distribution management • Controls to manage multiple loads against grid and occupant objectives

Cross-cutting: On-site solar generation

This cross-cutting segment is focused on on-site solar generation. Context for this segment includes:

- On-site solar photovoltaic (PV) power currently costs three times more than utility-scale PV but uses less land.⁶⁴
- States with high solar adoption are transitioning from net metering to other compensation structures.
- With storage, on-site generation can provide value at grid edge and bulk power scales, especially where there are transmission and distribution constraints. It can also provide electrical resilience to individual buildings and community microgrids

Key **impacts** include:

- affordability: can impact rates positively or negatively
- safety: supports resilience for buildings and communities

Key **technical innovation pathways** to address this segment’s impacts include:

- Combining on-site solar with storage (thermal and battery) and flexibility; and
- Integration of PVs with building materials.

Table **S29** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S29: Key implementation barriers and mitigating actions for innovations to address the cross-cutting on-site solar generation segment.

Key Barriers	Key Actions
Economic and greenhouse gas value of mid-day solar generation diminish as deployment increases	• Support state regulation that provides compensation mechanisms for distributed energy resources and virtual power plants
Distribution planners may not have confidence to rely on distributed energy resource solutions	• Technology and controls demonstrations • Technical assistance for distribution planners
Batteries and islanding controls have high up-front costs	• Affordable islanding technology and controls (e.g., vehicle-to-everything) • Programs to reduce permitting costs • Policies and incentives to increase affordability • Support of state regulation exploring new ownership models

Cross-cutting: Dual-fuel and cogeneration systems

This cross-cutting segment is focused on dual-fuel systems (e.g., air-source heat pumps with supplemental fuel-fired furnaces or boilers) and cogeneration (combined heat and power) systems. Context for this segment includes:

- Near-term use of existing on-site fuel infrastructure to supplement clean electric equipment (e.g., dual-fuel heating; cogeneration or combined heat and power [CHP]) may help manage the cost, grid, and resilience impacts of high electrification
- However, such configurations risk prolonging and increasing on-site emissions from buildings

Key **impacts** include:

- peak demand: can moderate peak impacts of electrification
- affordability: can avoid peak charges

Key **technical innovation pathways** to address this segment's impacts include:

- Dual-fuel heating configurations (e.g., residential HPs with fuel-fired furnace backup) with switchover controls that minimize fuel use
- Existing CHP systems transition to low-carbon fuel use and/or on-site carbon capture to reduce remaining combustion emissions

Table [S30](#) summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S30: Key implementation barriers and mitigating actions for innovations to address the cross-cutting dual-fuel and cogeneration systems segment.

Key Barriers	Key Actions
High switchover temperatures in dual-fuel heating configurations limit emissions reduction benefits	• Sensing and controls to minimize fuel use while maximizing comfort/cost savings • Incorporate switchover defaults that balance economic with environmental objectives into installer training; develop operational guidance and automated solutions for consumers
Uncertain impact on emissions and affordability	• Prioritize efficiency and electrification to limit residual fuel needs for buildings • Understand dual-fuel benefits, costs, and lock-in consequences • Understand availability of low-carbon fuels and carbon capture • Improve efficiency of CHP using low-carbon fuels in hard-to-decarbonize contexts (e.g., large commercial districts)
Health impacts of fuel combustion	• Support community-driven project prioritization and deployment

Cross-cutting: Thermal energy networks

This cross-cutting segment is focused on thermal energy networks (TENs), which use pipes to provide heating and/or cooling to multiple buildings. Context for this segment includes:

- Existing TENs include district energy systems that serve about 8% of commercial building floor area¹²
- TENs offer increased efficiency (by capturing waste heat from HVAC, refrigeration, and data centers) and flexibility (e.g., seasonal storage via geothermal boreholes)

Key **impacts** include:

- affordability: can be paid for through rates
- peak demand: can moderate peak impacts and thus system costs of electrification

Key **technical innovation pathways** to address this segment's impacts include:

- Network type:
 - New TENs are commonly designed as ambient-temperature water loops;
 - existing TENs can retain steam/hot water distribution using lowcarbon heat sources, transition to ambient-temperature loops, or fully decentralize heating
- Thermal sources and sinks:
 - Ambient loops can use geothermal boreholes, bodies of water, and wastewater as heat sources and sinks
 - Both ambient- and higher-temperature systems can use existing or new CHP with low-carbon fuels, heat pumps, boilers, etc.

Table **S31** summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S31: Key implementation barriers and mitigating actions for innovations to address the cross-cutting thermal energy network segment.

Key Barriers	Key Actions
Uncertainty in technical and financial performance	• Support of utility pilots, community input, and knowledge sharing • Modeling, subsurface characterization, and system design validation tools • Capital and loan guarantees from federal and state agencies
Lack of value proposition and regulatory certainty for TEN business models	• Comprehensive valuation of benefits, including system-wide/peak-load savings • Integrated distribution system planning requirements for utilities • Data collection to support utility and thirdparty ownership model decisions • Best practices for state and local regulation, including allowing deeper drilling
High cost of drilling geothermal boreholes	• Training and apprenticeships in drilling, HVAC installation • Incentives for new drilling businesses and water-well drillers • Explore potential for innovations such as deeper boreholes or dual-source (air and ground) GHP systems to reduce required number of boreholes and land area

Cross-cutting: Energy modeling and analysis

This cross-cutting segment is focused on energy modeling and analysis. This includes:

- Individual projects: informing design, HVAC selection/sizing, energy service provider companies, code compliance and calculations
- Stock-level assessments: informing R&D priorities and program planning, policy design, code development

Key **impacts** include:

- energy, emissions, and cost assessments: used to estimate and measure savings, determine code compliance, and explore policy effects

Key **technical innovation pathways** to address this segment's impacts include:

- Common open-source platforms upon which industry vendors can build custom products
- Increased focus on predictive modeling to support building performance standard (BPS) or performance-based codes
- Improved modeling of time-of-use dynamics, operational resilience, and multi-building thermal energy networks
- Digital twins of buildings/building clusters to support operational performance
- Standardized and regularly updated stock modeling scenarios and input datasets

Table [S32](#) summarizes the key barriers to deploying the technical innovations for this segment, as well as the actions that address each barrier.

Table S32: Key implementation barriers and mitigating actions for innovations for the cross-cutting energy modeling and analysis segment.

Key Barriers	Key Actions
Models of key low-carbon technologies may not be up to date or are limited	• Update models for heat pumps and thermal energy storage (TES) to derisk development of new product lines and reduce the cost of system integration • Improve sizing methods for heat pumps, TES, and other DERs • Standard templates for other common low-carbon systems
Calibration, validation, and uncertainty analysis not highly valued	• Encourage building system digitization; improve data integration and calibration/validation methods; best practices for uncertainty quantification • Support BPS/other use cases that require accurate predictive modeling
Performance-based modeling is costly	• Further integrate design, codes, and BPS software
Lack of under-resourced community metrics in stock models	• Update model inputs/outputs to delineate under-resourced communities
Lack of standard decarbonization scenario assumptions	• Publish standardized building scenario definitions, supporting datasets, and measure definitions

SI References

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