Title

Technology Innovation Opportunities for the U.S. Buildings Sector

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***This is the landscape version of the report. For content in an accessible format, go to [Data and Analysis for Buildings Sector Innovation](). ***

BUILDINGS IMPACT OUR EVERYDAY LIVES IN MANY WAYS

- **90% of people's time** is spent in buildings, which provide shelter and keep us safe.[1]
- **75% of U.S. GDP** is from commercial and public companies operating in buildings.[2]
- **2.3 million people** are already employed in jobs related to energy efficiency.[3]
- **$374 billion** is spent annually on building energy costs and much of that energy is wasted.[4]
- **34 million households** have experienced energy insecurity from struggling to pay their bills.[5]
- **75% of U.S. electricity** and 40% of total energy is consumed by buildings.[6]

EXECUTIVE SUMMARY

Technology innovation can improve the competitiveness of American companies and the lives of American families.

This report identifies promising building technology innovation opportunities to:

- Make buildings more affordable, efficient, healthy, and resilient for all Americans.
- Increase the international competitiveness of U.S. businesses.
- Improve the integration of buildings with the electric grid to reduce consumer and grid system costs.

In this **Technology Innovation Opportunities for the U.S. Buildings Sector** report, the U.S. Department of Energy (DOE) identifies key opportunities to accelerate improvements in the efficiency and affordability of building end uses, with a particular focus on the performance of building envelopes, space conditioning—including dual-fuel systems—and water heating to reduce up-front cost and operational costs for all residential and commercial buildings.

APPROACH

1. Developed a detailed **segmentation of buildings-sector energy end uses** between now and 2050, including an interactive dashboard.
2. Identified the most likely **technology solutions** for **25 high-priority segments**, spanning thermal loads, fuel-fired equipment, electric equipment, and embodied and fugitive emissions categories.
3. Identified the key **barriers to realizing those technology solutions at scale** and **federal actions** that could accelerate innovation.
4. Investigated **6 key cross-cutting opportunities** that affect multiple segments of building energy use and emissions.

See Data Generation and Collection Approach for additional details on the methodology.

FINDINGS

Detailed insights about key technology solutions, barriers, and actions for each segment and cross-cutting opportunity are presented on each slide in a consistent, easy-to-digest format.

CAVEATS

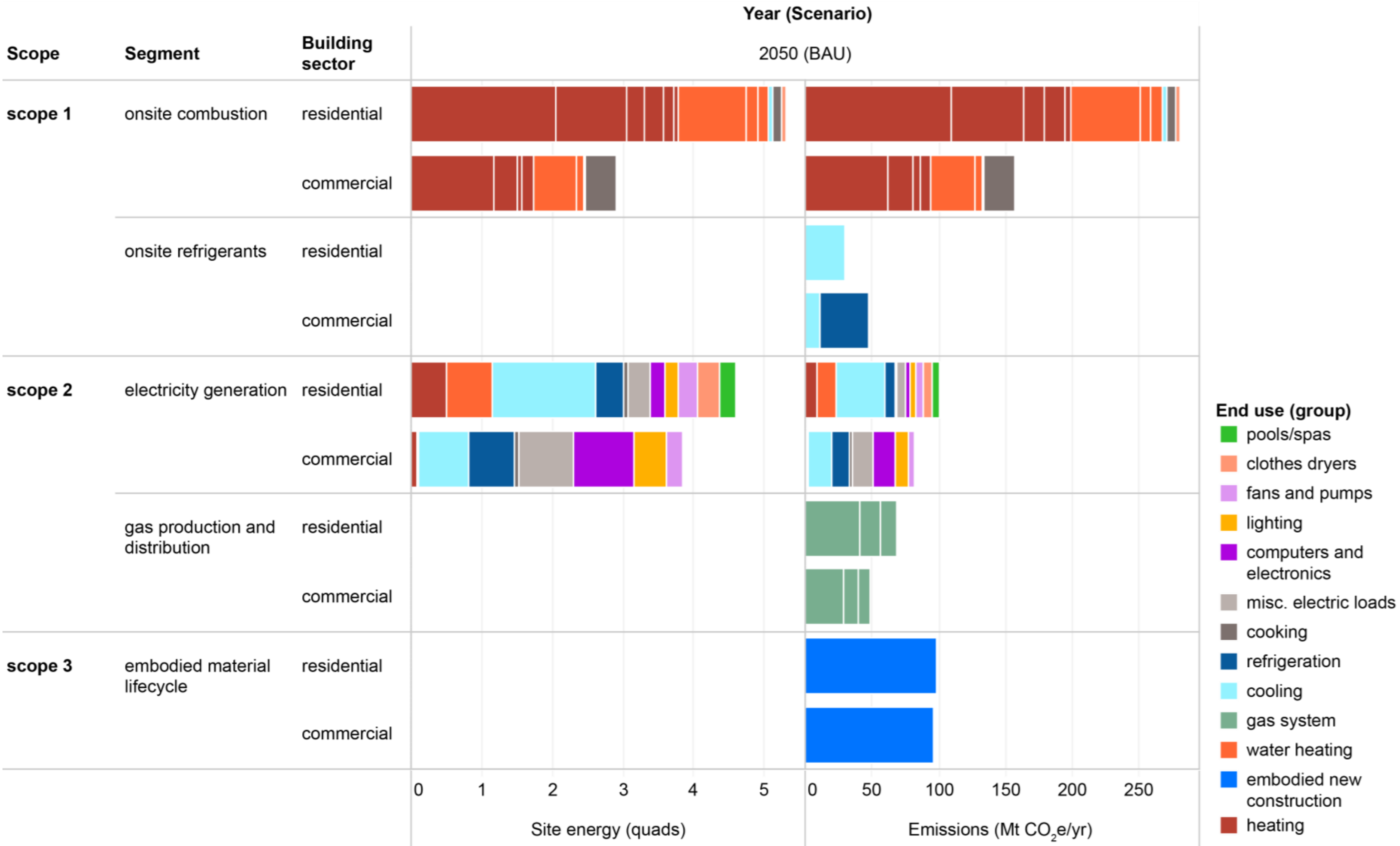
This report represents our current understanding of building technology innovation opportunities as a basis for further engaging key buildings industry stakeholders to accelerate progress. All of the suggested actions can be pursued through existing federal authority and available funding. We expect the content of this report to be updated as our understanding of buildings-sector energy end uses improves and as technology and markets continue to evolve.

25 BUILDING SEGMENTS ARE HIGHLIGHTED FOR FURTHER FOCUS

Segment category	Segment name	Energy Costs (Bn.$/yr), 2050 BAU	Site energy (quads/yr), 2050 BAU	GHG (Mt CO2e/yr), 2050 BAU	Peak demand, winter (GW), 2050 High Elec
Operational, existing bldgs, thermal loads	Residential, Thermal Loads, Envelope	91	19%	19%	
	Residential, Thermal Loads, Ducts	21	4%	3%	
	Commercial, Thermal Loads, Envelope	12	4%	6%	
	Commercial, Thermal Loads, Ventilation	10	3%	4%	
Operational, existing bldgs, fuel-fired end uses	Residential Fuel-Fired Furnaces Cold Climates (Zones 5–8)	23	8%	11%	
	Residential Fuel-Fired Furnaces Warm Climates (Zones 1–4)	10	4%	5%	
	Residential Fuel-Fired Water Heating (Single-unit, 40+ Gallon Tanks)	10	4%	5%	
	Residential Fuel-Fired Wall/Floor Space Heaters	6	1%	2%	
	Residential Fuel-Fired Boilers (Space Heating, Single-Unit)	3	1%	1%	
	Residential Fuel-Fired Boilers (Water Heating, Multi-Unit)	2	1%	1%	
	Residential Fuel-Fired Boilers (Space Heating, Multi-Unit)	1	0%	0%	
	Commercial Fuel-Fired Gas Rooftop Units	6	3%	4%	
	Commercial Fuel-Fired Large Boilers (Space Heating)	2	1%	1%	
	Commercial Fuel-Fired Centralized Water Heaters	3	1%	2%	
	Commercial Fuel-Fired Cooking	2	1%	2%	
Operational, existing bldgs, electric end uses	Residential Electric HVAC	67	8%	4%	597
	Residential Electric Water Heating	18	2%	1%	49
	Residential All Other Electricity	58	6%	3%	47
	Commercial Electric HVAC	17	2%	1%	132
	Commercial Refrigeration	11	2%	1%	10
	Commercial All Other Electricity	39	5%	2%	67
Operational, EV charging	Electric Vehicle Charging	217	24%	1%	89
Operational, new const.	New Building Operational Energy (Built 2024-2050)	130	25%	22%	350
Refrigerants	Refrigerants and Other Fluorinated Gases			8%	
Embodied	Embodied Construction Material Life Cycle Emissions			19%	

***Note**: Percentage values sum to more than 100% because heating and cooling emissions are counted under both loads and equipment segments. Percentages are relative to totals across all building segments, including those not highlighted in the table (the 11 segments not shown make up 2.8% of energy and 3.4% of emissions). BAU = business-as-usual scenario. High Elec. = high electrification without efficiency scenario. **Data sources**: Scout[7] (all segments except thermal loads and embodied), ResStock[8] (res. thermal loads), ComStock[9] (com. thermal loads), U.S. Buildings Decarbonization Blueprint[6] (embodied emissions).*

HIGHLIGHTS ARE BASED ON DETAILED CHARACTERIZATION OF BUILDINGS SECTOR EMISSIONS AND ENERGY END-USE SEGMENTS IN AN INTERACTIVE DASHBOARD



Dashboard link: https://bit.ly/innovatebuildings

THERMAL LOADS

Thermal loads are divided into four major segments:

1. Residential envelopes (heat transfer through windows, walls, ceilings/floors, air leakage).
2. Residential duct losses (air leakage between conditioned air in ducts and unconditioned spaces).
3. Commercial envelopes (see residential).
4. Commercial ventilation (conditioning outdoor air).

All four of these segments are focused on thermal loads in the existing building stock. Thermal loads in new construction are included in the New Building Operational Energy segment.

Note: Energy costs for thermal loads are estimated by applying the component load breakouts from citations 8 and 9 to the total heating and total cooling energy costs from citation 7.

Residential Thermal Loads: Envelope

HIGH IMPACT HIGH DIFFICULTY

KEY IMPACTS

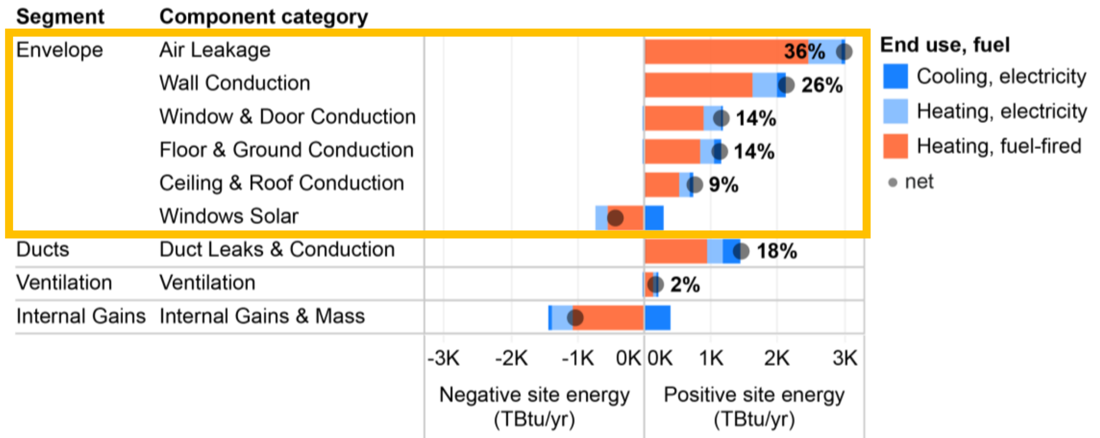
Energy Costs
$91 billion/year in 2050[7,8]

Safety
Determines thermal resilience

Technical Solutions

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

Concentration Areas[8]



Key Deployment Barriers	Key Federal Actions
High up-front cost for envelope upgrades	⚙ Lower cost, easier to install upgrades, including automated methods for detecting and sealing air leaks 🛒 Promote insulation at time of re-siding $ Decision support for utility, state, and federal incentives and tax credits
Lack of consumer demand	⚙ 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
Disruptive to occupants	⚙ Prefab solutions, especially for multifamily ⚙ Improved bio-based spray foams

⚙ = R&D 🛒 = market $ = finance ✍ = policy

Residential Thermal Loads: Duct Losses

HIGH IMPACT HIGH DIFFICULTY

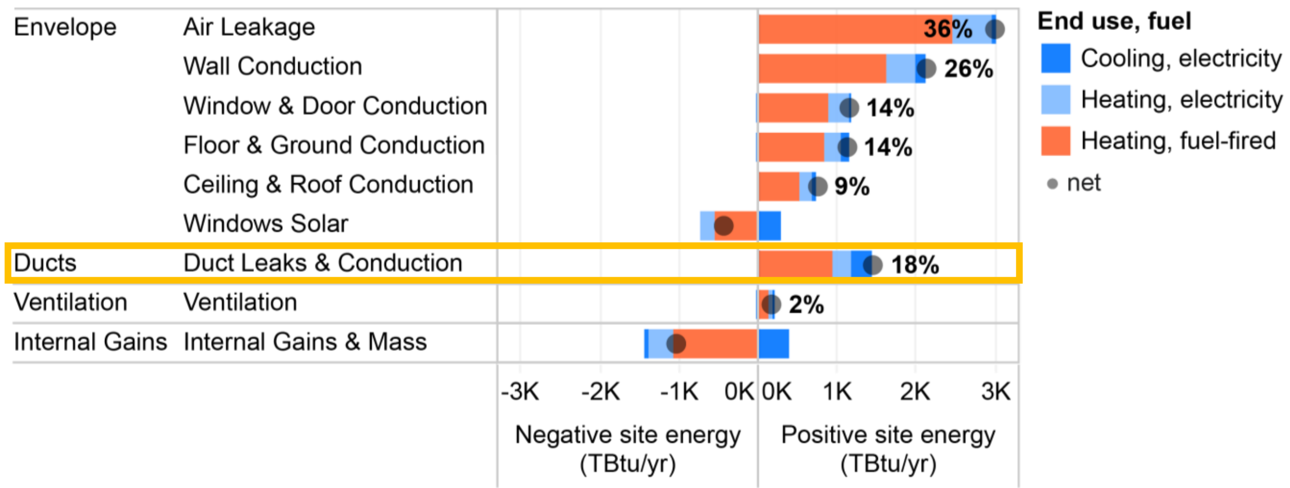
KEY IMPACTS

Energy Costs
$21 billion/year in 2050[7,8]

Technical Solutions

- Traditional and novel technology for duct sealing and insulating
- Ductless solutions

Concentration Areas[8]



Key Deployment Barriers	Key Federal Actions
Lack of demand and awareness for ductwork upgrades	Awareness campaign: 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
Aerosol-based duct sealing is expensive	Cost compression Include in weatherization and other programs to expand trained workforce and availability
Ductless solutions for every room may be expensive	Evaluate pros and cons of ductless heads in every room

= R&D = market = finance = policy

Commercial Thermal Loads: Envelope

HIGH IMPACT   HIGH DIFFICULTY

KEY IMPACTS

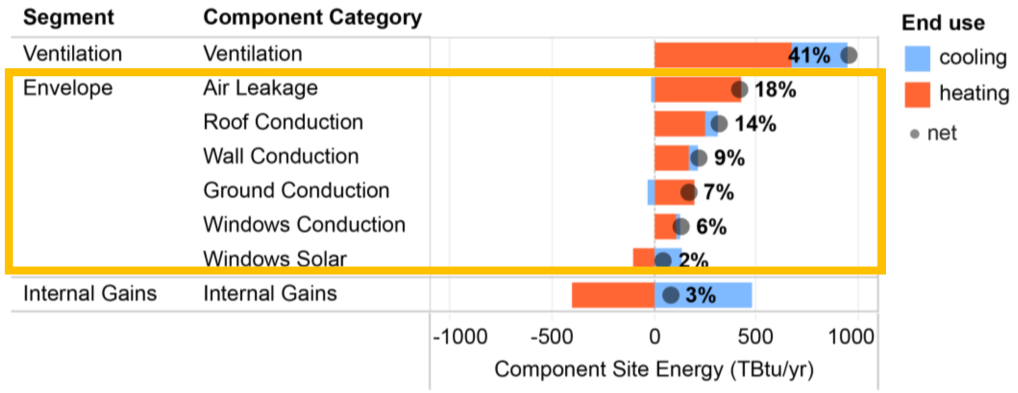
Energy Costs
$12 billion/year in 2050[7,9]

Comfort
Regulates indoor temperature

Technical Solutions

- 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

Concentration Areas[9]



Key Deployment Barriers	Key Federal Actions
Potential tenant disruption and aesthetic and moisture concerns	⚙ Modeling to identify low-cost/disruption envelope retrofit packages; characterize moisture impacts
Lack of consumer access, awareness, and value proposition	🛒 Holistic cost-benefit analyses and real-world case studies that demonstrate HVAC downsizing and comfort/resilience benefits of envelope ✍ Incorporate less-marketable upgrades (walls, leakage, roofs) into building performance standards
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

⚙ = R&D   🛒 = market $ = finance   ✍ = policy

Commercial Thermal Loads: Ventilation

HIGH IMPACT HIGH DIFFICULTY

KEY IMPACTS

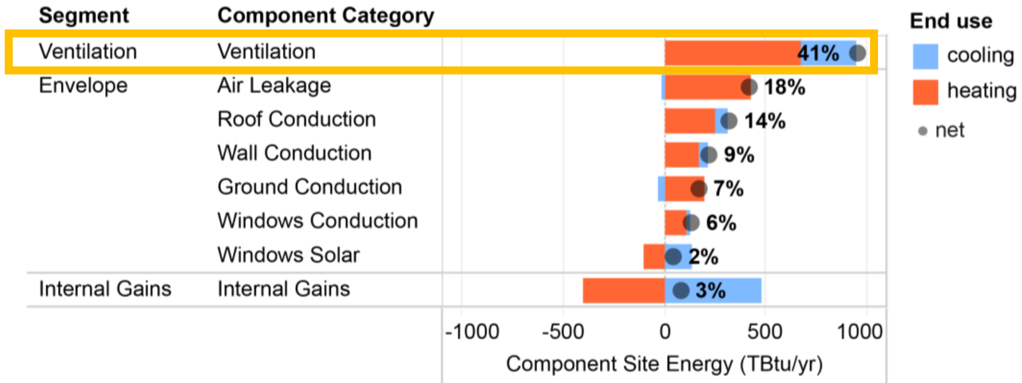
Energy Costs
$10 billion/year in 2050[7,9]

Public Health
Many buildings under-ventilated

Technical Solutions

- Energy recovery ventilation (ERV)
- Correct under- and over-ventilation via:
  - Building automation systems (BAS)/energy management and information systems (EMIS), occupant sensing, demand-controlled ventilation, and economizers
  - Heat/smoke-sensing exhaust hoods (food service)
- Indoor air-treatment devices (traditional filtration, germicidal ultraviolet air treatment, portable or sorbent air cleaners)

Concentration Areas[9]



Key Deployment Barriers	Key Federal Actions
Lack of available ERVs in new packaged air-source heat pumps (ASHPs); limited options are high cost	(R&D) Reduce ERV product costs, particularly in retrofits (market) Encourage manufacturers to include optional ERVs for major equipment types (rooftop units, air handling units, dedicated outdoor air systems) (policy) Support code/building performance standard requirements for ERV in major markets and more stringent ASHRAE 90.1 ERV requirements
Lack of qualified workforce to install and operate ventilation measures	(market) Training on right-sizing ventilation rates in fields like commissioning and testing/balancing (R&D) BAS/EMIS and automated fault detection and diagnosis that automates ventilation operation checks
Lack of information on performance/safety	(R&D) Test germicidal ultraviolet and other air-treatment products
Outdated design and operation guidance	(R&D) Research to support updates to outdated ASHRAE ventilation standards

(R&D icon) = R&D (market icon) = market (finance icon) = finance (policy icon) = policy

FUEL-FIRED END USES

- Includes all on-site combustion of fuels in existing buildings. Fuel-fired end uses in new construction are included in the New Building Operational Energy segment. The segments are divided based on the type of fuel-fired equipment, which in large part determines the types of solution pathways that are available.

- Detail in commercial equipment types is intentionally simplified to the type of main heating equipment, without further differentiating HVAC system type details.

- Equipment with relatively minor energy/emissions contributions is excluded here, as are non-building end uses, such as manufacturing that occurs in commercial buildings.

Residential Fuel-Fired Furnaces, Cold Climates (Zones 5–8)

HIGH IMPACT | HIGH DIFFICULTY

KEY IMPACTS

Energy Costs
$23 billion/year in 2050[7]

Public Health
Criteria air pollutant source

Comfort
Uneven temperature

Technical Solutions

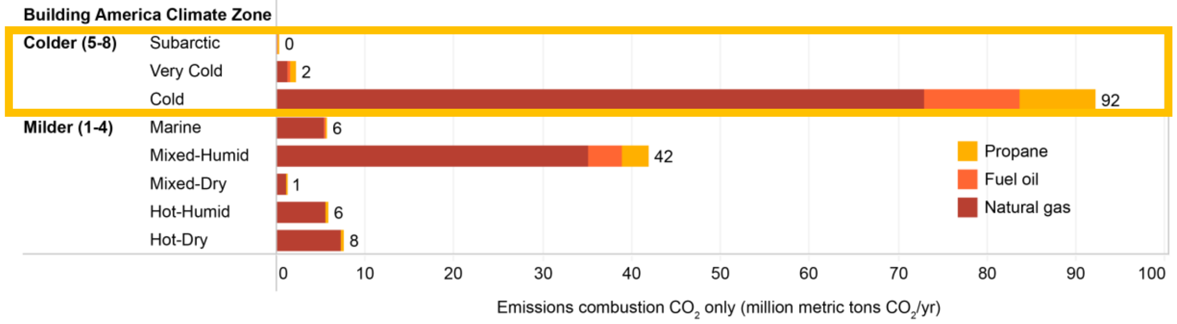
- Cold-climate air-source heat pumps (ccASHPs)
- Dual-fuel ASHPs, geothermal heat pumps (GHPs)
- Duct, envelope upgrades, thermal storage

Up-Front Cost

$8–35K per home (ccASHP) (vs. $4–5K for furnace, $4–9K for air conditioning)[11]

Equipment	Labor/Soft	Elec.

Concentration Areas[10]



Key Deployment Barriers	Key Federal Actions
High up-front costs, including oversizing and poor duct performance	R&D: Solutions to avoid duct size issues (higher discharge temperature [temp.]) and equipment size issues (closet) R&D: Validate and improve performance of plug-in and quick-connect solutions (switch to ductless) R&D: Improve dual-fuel ASHP configurations/controls Market: Support business model innovations like remote sizing, demand aggregation, and quote generation Market: Guidance for consumers on incentives Finance: Promote benefits of incentivizing peak load reduction (e.g., GHPs and envelope upgrades) Policy: Support national electric code updates (see also Cross-Cutting Opportunity: Building Electrical Infrastructure)
Lack of consumer and contractor awareness	Market: Contractor training and resource development Policy: Support AC-to-heat pump replacement policies
High operating cost when compared to gas in most areas	R&D: Improve cold-climate performance R&D: Thermostat demand response compatibility and interface Policy: Technical assistance for utility program and rate design Market: Promote standardized quality installations and workforce training/recognition
Sizing ASHPs for full heating load may lead to poor dehumidification	R&D: Improve dehumidification, e.g., separate sensible and latent control

= R&D = market = finance = policy

Residential Fuel-Fired Furnaces, Warm Climates (Zones 1–4)

⚠ MEDIUM IMPACT ⚠ MEDIUM DIFFICULTY

KEY IMPACTS

Energy Costs
$10 billion/year in 2050[11]

Public Health
Criteria air pollutant source

Comfort
Uneven temperature

Technical Solutions

See also: Residential Fuel-Fired Furnaces, Cold Climates

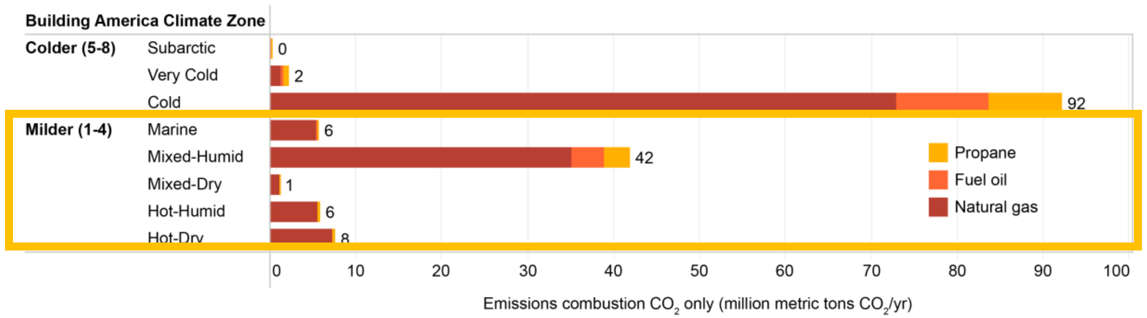
- Air-source heat pumps (ASHPs), dual-fuel ASHPs
- Duct upgrades

Up-Front Cost

$7–19K per home (compared to $4–5K for furnace, $4–9K for air conditioning)[11]

Equipment	Labor/Soft

Concentration Areas[10]



Key Deployment Barriers	Key Federal Actions

Same barriers and actions as:
Residential Fuel-Fired Furnaces, Cold Climates

Caveats:

- Potentially less need for cold-climate, dual-fuel, and geothermal solutions in warmer climates
- Up front and operating cost barriers are likely less significant in warmer climates, although high electricity rates can still be a barrier

= R&D = market = finance = policy

Residential Fuel-Fired Water Heating (Single-Unit, 40+ Gallon Tanks)

MEDIUM IMPACT **MEDIUM DIFFICULTY**

KEY IMPACTS

Energy Costs
$10 billion/year in 2050[7]

Public Health
Criteria air pollutant source

Technical Solutions

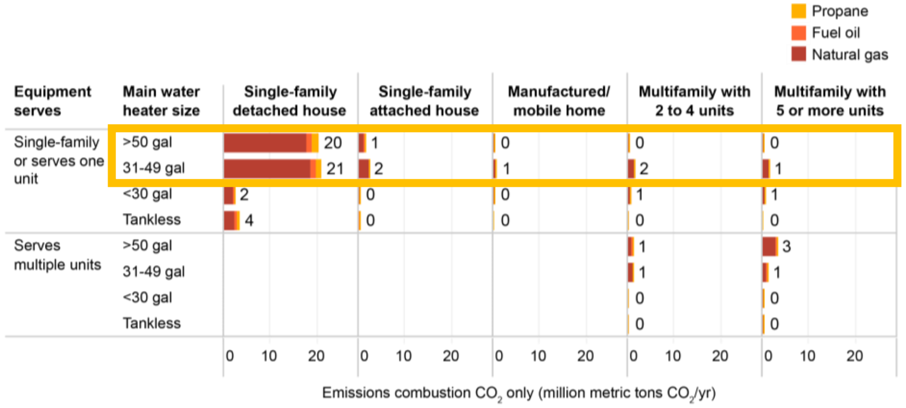
- Heat pump water heaters (HPWHs), single-home
  - 120V HPWH, split systems, form factor, combi systems
- Circuit splitters/smart panels

Up-Front Cost

$2–5K per unit (compared to $1–2K for a gas unit)[11]

Equipment	Labor/Soft	Elec.

Concentration Areas[10]



Key Deployment Barriers	Key Federal Actions
High up-front costs	Improve 120V HPWH solutions (cost, recovery, times, smaller form factors) Support for utility, state, and federal incentives
Possible increased monthly cost vs. gas	Technical assistance on rate design and utility revenue potential
Availability; HPWHs not “on truck” or stocked in retail/dist.	Marketing/consumer education Contractor training 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

= R&D = market = finance = policy

Residential Fuel-Fired Wall/Floor Space Heaters

MEDIUM IMPACT   LOW DIFFICULTY

KEY IMPACTS

Energy Costs
$6 billion/year in 2050[7]

Public Health
Criteria air pollutant source

Technical Solutions

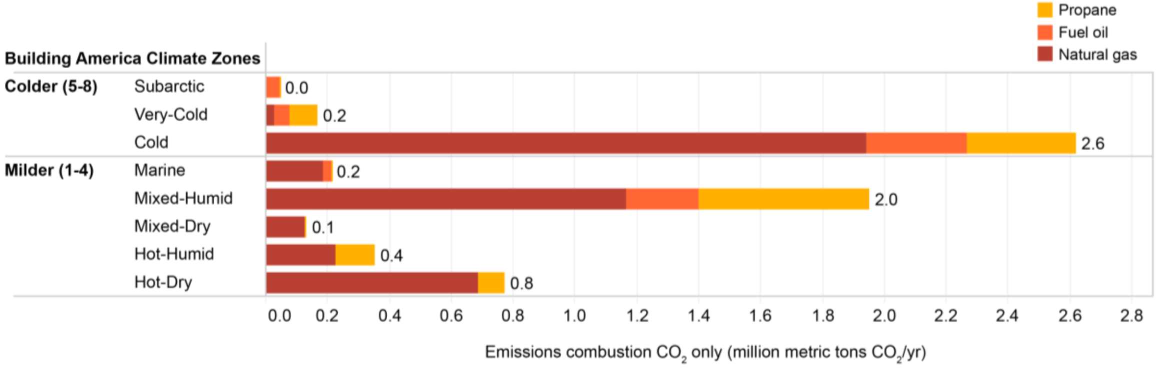
- Ductless heat pumps (DHPs)
- Window, through-wall, and quick-connect heat pumps (HPs)

Up-Front Cost

$4–10K per unit[11,12]

Equipment	Labor/Soft	Elec.

Concentration Areas[10]



Key Deployment Barriers	Key Federal Actions
Solutions have higher up-front cost than fuel-fired and window air conditioning alternatives	(R&D) Window/saddle, through-wall, and quick-connect HP validation, development and cost reduction (finance) Support for utility, state, and federal incentives
DHPs can be DIY, but often still require specialized tools and skills	(R&D) Simpler do-it-yourself retrofit solution development (market) Training and resource development for DIY installs
Safe removal of defrost meltwater in multifamily contexts (window and through-wall heat pumps)	(R&D) Solutions to manage defrost meltwater (water melted off the coil during defrost cycles)

(gear icon) = R&D (cart icon) = market (dollar icon) = finance (pen icon) = policy

Residential Fuel-Fired Boilers (Space Heating, Single-Unit)

MEDIUM IMPACT   HIGH DIFFICULTY

KEY IMPACTS

Energy Costs
$3 billion/year in 2050[7]

Public Health
Criteria air pollutant source

Comfort
Uneven temperature

Technical Solutions

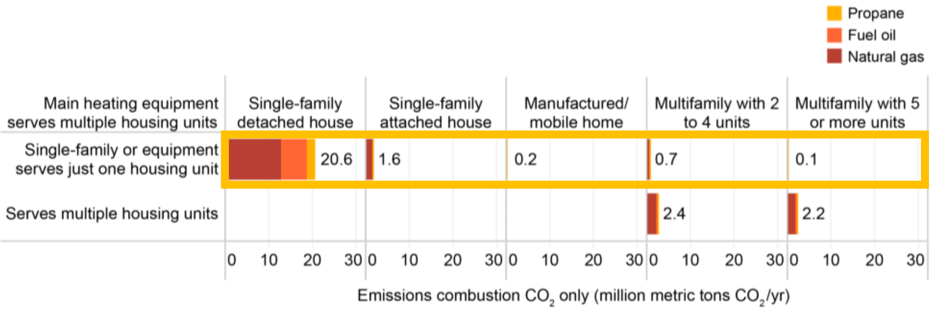
- Ductless air-source heat pumps (DHPs)
- Air-to-water heat pumps (AWHPs), geothermal heat pumps (GHPs)
- Envelope upgrades, thermal energy storage (TES)

Up-Front Cost

- **DHP:** $16–38K[11]
- **AWHP:** $15–40K[13]
- **GHP:** $30–60K[11]

Equip.	Labor/Soft	Elec.

Concentration Areas[10]



Key Deployment Barriers	Key Federal Actions
Building owners may opt for air-based DHP solutions to gain air conditioning. For DHP barriers, see Residential Fuel-Fired Wall/Floor Space Heaters Hydronic solutions share barriers with Residential Fuel-Fired Furnaces, Cold Climates; additional barriers unique to hydronic solutions are below.	
Hydronic AWHPs/GHPs 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 too low for existing radiators	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.)

= R&D   = market   = finance   = policy

Residential Fuel-Fired Boilers (Water Heating, Multi-Unit)

LOW IMPACT HIGH DIFFICULTY

KEY IMPACTS

Energy Costs
$2 billion/year in 2050[7]

Public Health
Criteria air pollutant source

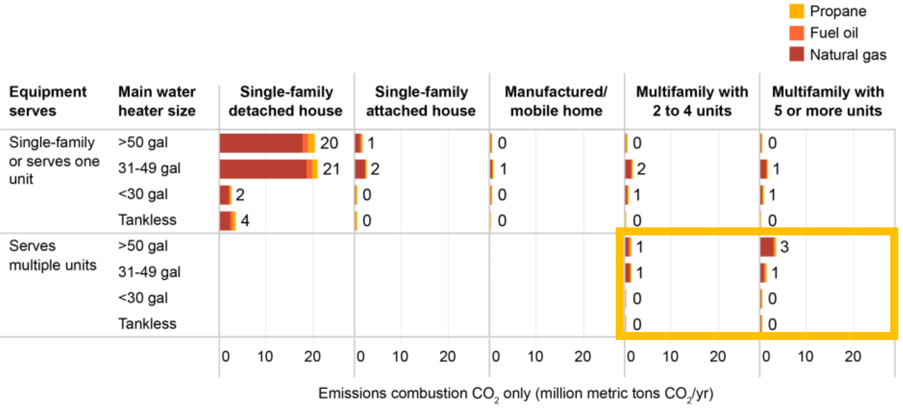
Technical Solutions

- Centralized solutions
  - Large combination (heating/water heating) heat pump boilers; dual-fuel boilers
  - Domestic hot-water-only heat pump water heaters (HPWHs) in series
- Decentralized compact HPWHs
- High-performance fixtures, drain water-heat recovery

Up-Front Cost

- Centralized: $200K (compared to $100K for an 800,000 Btu/hour boiler)[14]
- Decentralized: $2–5K per unit (compared to $1–2K for a gas unit)[11]

Concentration Areas[10]



Key Deployment Barriers	Key Federal 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
Performance issues and lack of facility manager experience	Improve system performance Training for facility managers

= R&D = market = finance = policy

Residential Fuel-Fired Boilers (Space Heating, Multi-Unit)

LOW IMPACT   HIGH DIFFICULTY

KEY IMPACTS

Energy Costs
$1 billion/year in 2050[7]

Public Health
Criteria air pollutant source

Comfort
Uneven temperature

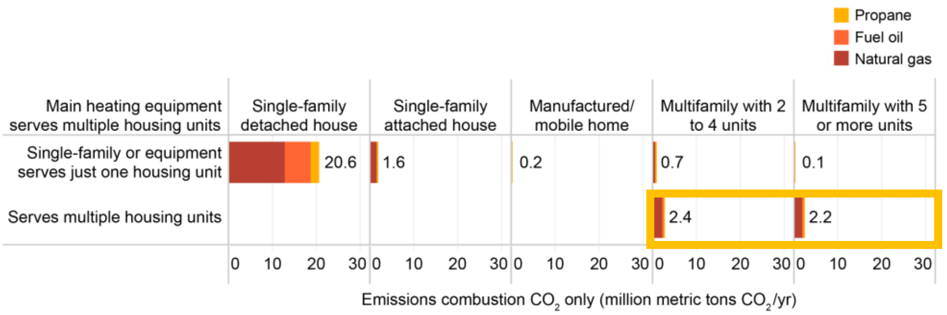
Technical Solutions

- Centralized (large heat-pump boilers, including dual-fuel)
  - Low-temperature boiler serving water-source heat pumps
  - High-temperature boiler serving steam or hydronic radiators
- Decentralized (micro heat pumps)
- Envelope upgrades (including integrated HVAC)

Up-Front Cost

- Centralized: $200K (compared to $100K for an 800,000 Btu/hour boiler)[14]
- Decentralized: $4K per window-saddle HP[12]

Concentration Areas[10]



Key Deployment Barriers	Key Federal Actions
Centralized – see Residential Fuel-Fired Boilers (Water-Heating, Multi-Unit) **Decentralized –** see Residential Fuel-Fired Wall/Floor Space Heaters	
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)

= R&D   = market   = finance   = policy

Commercial Fuel-Fired Gas Rooftop Units

MEDIUM IMPACT MEDIUM DIFFICULTY

KEY IMPACTS

Energy Costs
$6 billion/year in 2050[7]

Public Health
Criteria air pollutant source

Technical Solutions

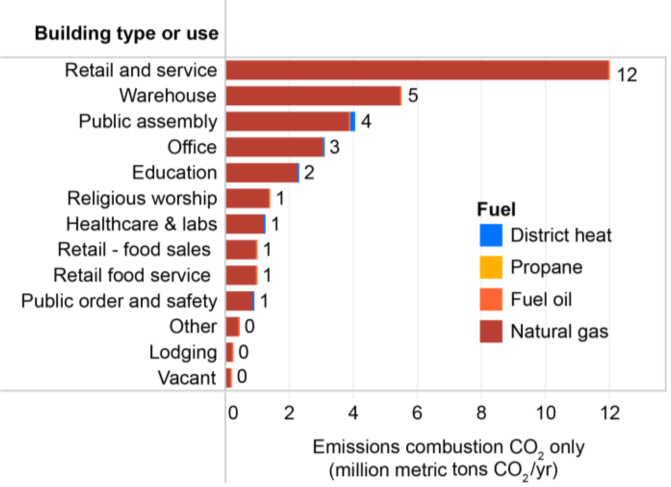
- Standard, cold climate, dual-fuel, and geothermal heat pump rooftop units (HP RTUs) with frost protection and defrost capabilities
- Integrated or external advanced controls and add-on energy recovery ventilators (ERVs)

Up-Front Cost[14]

(compared to $15K rooftop air conditioner + gas furnace)

- Cold-climate HP RTU: $21K per unit
- Warm-climate HP RTU: $15K per unit

Concentration Areas[15]



Key Deployment Barriers	Key Federal Actions
Lack of product availability	New HP RTU products with high performance in cold climates
Uncertain cold-climate performance	Improve defrost, including with thermal energy storage management HP RTU test facilities and field studies in cold-climate conditions
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 section 179D tax credit
Size/weight/noise issues for high efficiency	Component and system optimization to minimize retrofit issues with form factor

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Commercial Fuel-Fired Large Boilers (Space Heating)

MEDIUM IMPACT MEDIUM DIFFICULTY

KEY IMPACTS

Energy Costs
$2 billion/year in 2050[7]

Public Health
Criteria air pollutant source

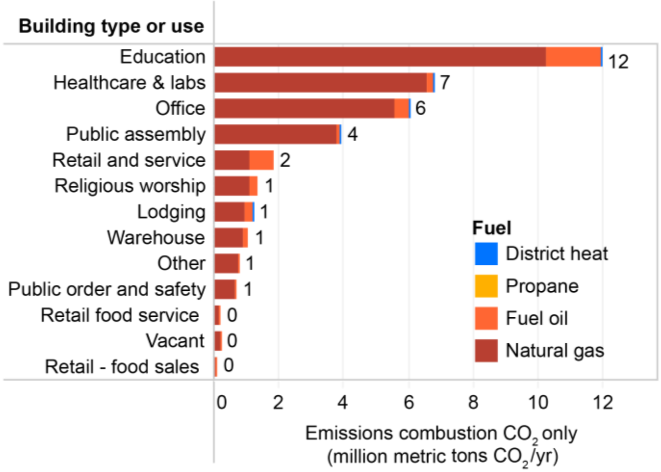
Technical Solutions

- Centralized large heat pumps (HPs) for heating and domestic hot water (including dual-fuel and geothermal) or decentralized micro HPs
- Envelope upgrades, thermal storage
- Energy recovery and demand-controlled ventilation

Up-Front Cost

- Centralized: $200K (vs. $100K for an 800,000 Btu/hour boiler)[14]
- Decentralized: $4–10K per unit[11,12]

Concentration Areas[15]



Key Deployment Barriers	Key Federal Actions
Drop-in alternatives to gas/steam-fired hydronic heating systems are limited, inefficient, and expensive	[R&D] New hydronic/steam HP equipment that efficiently functions in cold climates with improved capacity [market] Increase awareness of wastewater heat recovery, high-temperature HPs, and heat recovery chiller solutions
Lack of viable technologies to meet large heating loads and need for electrical upgrades	[market] Increase envelope retrofits and strategies to reduce ventilation loads [market] Simple sizing tools/design guides for thermal energy storage systems [market] Increase awareness of dual-fuel HPs as hybrid solution; workforce training on combining HPs with thermal storage
Lack of lab and field performance data and stakeholder risk aversion	[market] Pilots and field demonstrations to de-risk new technologies (e.g., demonstrate high delivery temperature, particularly in applications serving critical loads)

= R&D = market = finance = policy

Commercial Fuel-Fired Centralized Water Heaters

MEDIUM IMPACT MEDIUM DIFFICULTY

KEY IMPACTS

Energy Costs
$3 billion/year in 2050[7]

Public Health
Criteria air pollutant source

Technical Solutions

See also: Commercial Fuel-Fired Large Boilers (Space Heating)

- Centralized large hydronic heat pumps (including dual-fuel), residential-style heat pump water heaters (HPWHs), or decentralized small HPWHs
- Thermal storage, chiller heat recovery
- High-performance fixtures, drain water heat recovery

Up-Front Cost

- Centralized: $200K (vs. $100K for an 800,000 Btu/hour boiler)[14]
- Residential-style HPWH: $2–5K per unit (vs. $1–2K for a gas unit)[11]

Key Deployment Barriers	Key Federal Actions
Similar barriers (lack of drop-in alternatives to meet large loads, lack of performance data, risk aversion) and actions as: Commercial Fuel-Fired Large Boilers (Space Heating)	

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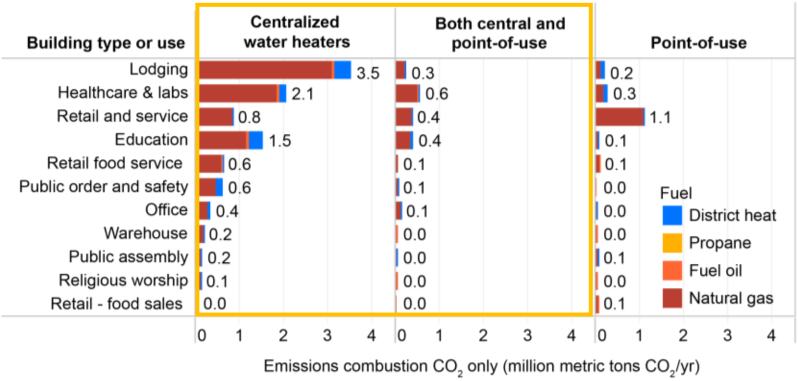
Concentration Areas[15]



Commercial Fuel-Fired Cooking

MEDIUM IMPACT HIGH DIFFICULTY

KEY IMPACTS

Energy Costs
$2 billion/year in 2050[7]

Public Health
Criteria air pollutant source

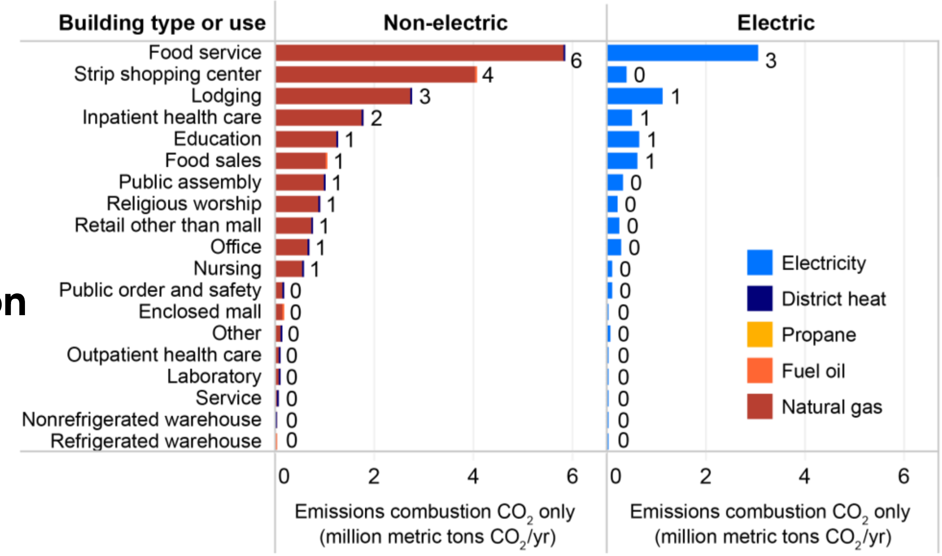
Technical Solutions

- Induction stoves and woks
- Low-power equipment with load-limiting controls
- Energy storage-enabled cooking equipment

Up-Front Cost

- Costs vary widely but induction equipment and electrical upgrades could cost thousands more

Concentration Areas[15]



Key Deployment Barriers	Key Federal 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
Insufficient electrical capacity	Low-power induction cooking options with integrated storage and controls to limit capacity needs

= R&D = market = finance = policy

ELECTRIC END USES

- Electric HVAC (heating, ventilation, and air conditioning) includes both existing electric HVAC as well as newly electrified HVAC systems in existing buildings and is split into residential and commercial contexts. Electric end uses in new construction are included in the New Building Operational Energy segment.
- Both residential electric water heating and commercial refrigeration systems have significant annual electricity demand impacts, but their contributions to peak demand are much smaller than HVAC.
- Two remaining segments capture all remaining residential and commercial electricity use.

Residential Electric HVAC (Existing and Newly Electric)

HIGH IMPACT MEDIUM DIFFICULTY

KEY IMPACTS

Up to 597 GW[7]
U.S. winter peak in 2050 without efficiency

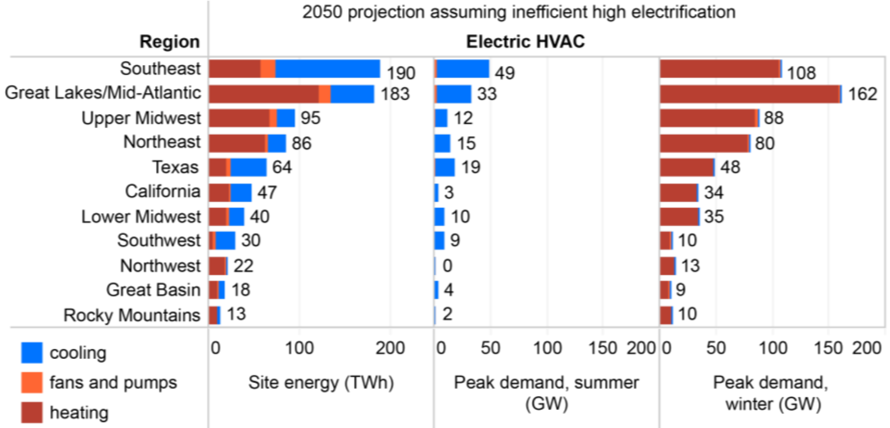
Energy Costs
$67 billion/year in 2050[7]

Technical Solutions

See also: Residential Envelope and Fuel-Fired Space Heating

- Standard and cold-climate heat pumps (HPs)
  - Envelope/duct upgrades
  - Improve cold-climate air-source HP (ASHP) performance
  - Dual-fuel ASHPs and geothermal HPs
- Demand flexibility (DF) to shift peaks
  - Connected thermostats for pre-heating/coasting
  - Envelope to increase time constants
  - Thermal energy storage (TES; HVAC/envelope integration)

Concentration Areas[16]



Key Deployment Barriers	Key Federal Actions
Similar barriers (up-front cost and awareness) and actions as: Residential Thermal Loads, Envelope; Residential Fuel-Fired Space Heating	
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 in reducing peak and increasing flexibility is not accounted for in utility planning	Support utility distribution and resource planning with data and analysis

= R&D = market = finance = policy

Residential Electric Water Heating (Existing and Newly Electric)

MEDIUM IMPACT   LOW DIFFICULTY

KEY IMPACTS

Up to 49 GW[7]
U.S. winter peak in 2050 without efficiency

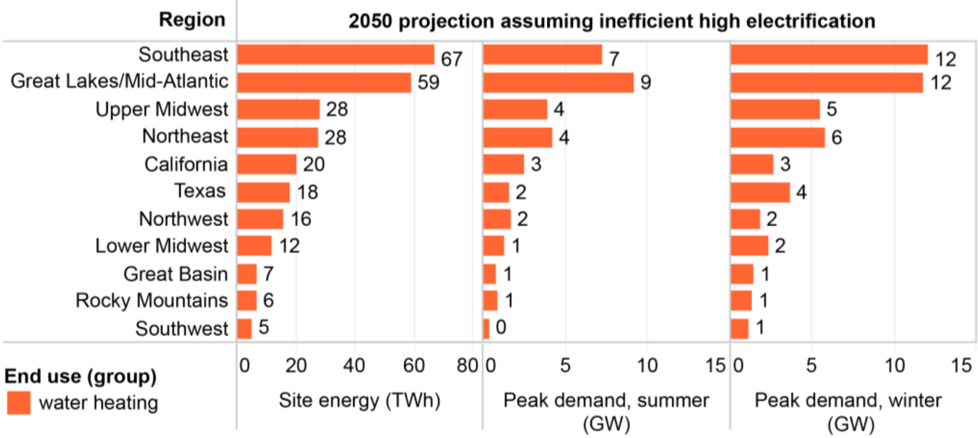
Energy Costs
$18 billion/year in 2050[7]

Technical Solutions

See also: *Residential Fuel-Fired Water Heating (Single Unit, 40+ Gallon)*

- Heat pump water heaters (HPWHs)
- Connected demand flexibility (e.g., enabled by integrated or add-on controls) to leverage water storage tank for load shifting

Concentration Areas[16]



Key Deployment Barriers	Key Federal Actions
Similar barriers (up-front cost, availability, form factor) and actions as: Residential Fuel-Fired Water Heating (Single Unit, 40+ Gallon)	
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

= R&D   = market   = finance   = policy

Residential All Other Electricity Use

MEDIUM IMPACT HIGH DIFFICULTY

KEY IMPACTS

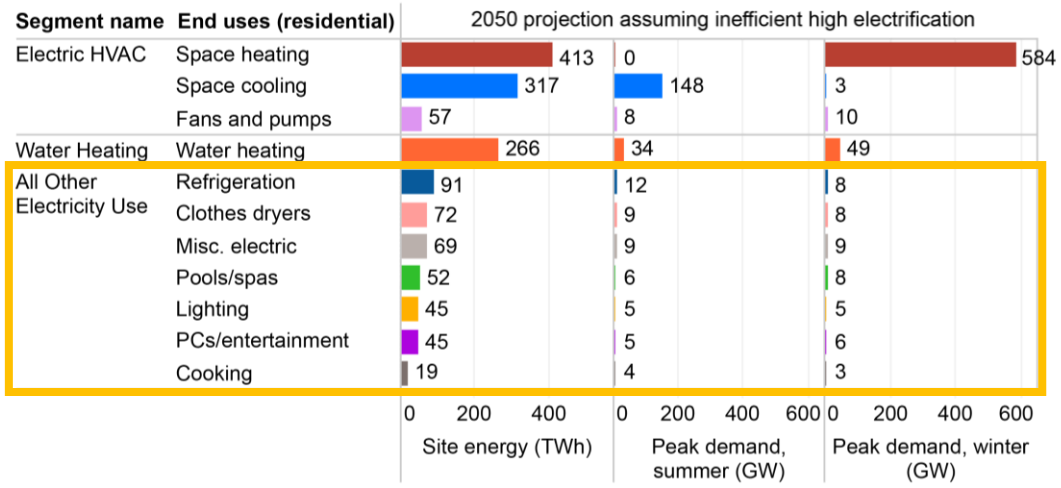
Up to 47 GW[7]
U.S. winter peak in 2050 without efficiency

Energy Costs
$58 billion/year in 2050[7]

Technical Solutions

- Low-power network communication
- Natively direct current devices
- Connected sensors and controls to support HVAC demand flexibility

Concentration Areas[16]



Key Deployment Barriers	Key Federal Actions
Lacking smart electrical device metrics	Support development of smart device metrics
Plug loads are designed for low-latency, not efficiency	Efficient networking and onboard computation 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

= R&D = market = finance = policy

Commercial Electric HVAC (Existing and Newly Electric)

HIGH IMPACT   HIGH DIFFICULTY

KEY IMPACTS

Up to 132 GW[7]
U.S. winter peak in 2050 without efficiency

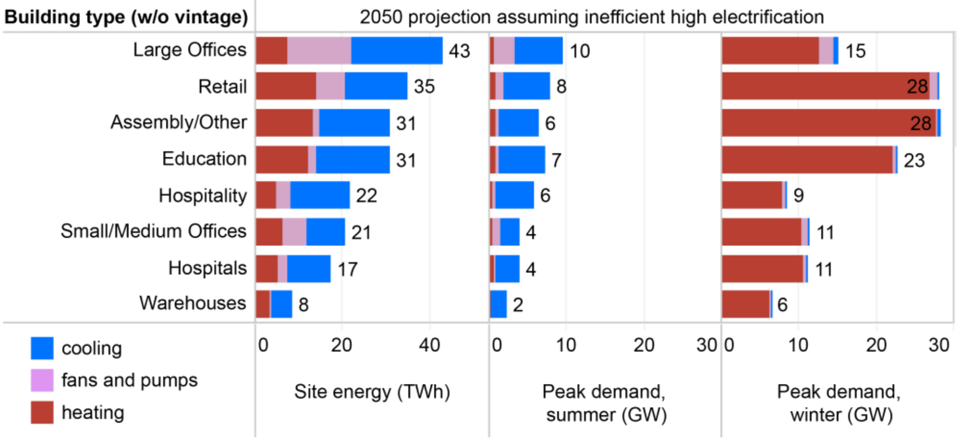
Energy Costs
$17 billion/year in 2050[7]

Technical Solutions

See also: Commercial Envelope and Ventilation; Commercial Fuel-fired RTUs, Furnaces, and Boilers

- Standard, cold-climate, dual-fuel, and geothermal heat pumps (residential-type, rooftop, packaged terminal, hydronic); energy recovery ventilation
- Building automation systems/connected thermostat controls for energy management and demand flexibility via preconditioning; high-efficiency envelope, integrated thermal storage

Concentration Areas[16]



Key Deployment Barriers	Key Federal Actions
Similar barriers (product availability/form factor, cost, awareness, and workforce) as: Commercial Envelope, Ventilation Commercial Fuel-Fired RTUs, Furnaces, and Boilers	
Lack of standard, easily configured product interfaces or control sequences for key low-carbon heating systems	(R&D) Standard designs and libraries of equipment operating sequences (R&D) Plug-and-play software installations (policy) Incorporate control sequences in technical standards (e.g., ASHRAE G36) and codes (policy) Semantic modeling standards, consensus specifications, testing capabilities, and protocols
Uncertain performance of products/services	(policy) Performance benchmarks/testing protocols to verify control sequences and load impacts
Lack of workforce to configure controls	(market) Training infrastructure (e.g., virtual buildings)

(R&D) = R&D   (market) = market $ = finance   (policy) = policy

Commercial Refrigeration

MEDIUM IMPACT HIGH DIFFICULTY

KEY IMPACTS

Up to 10 GW[7]
U.S. winter peak in 2050 without efficiency

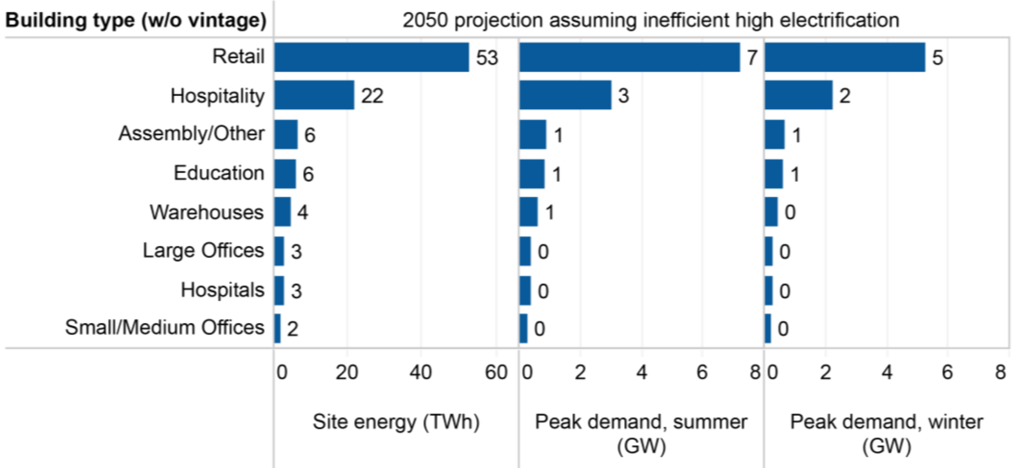
Energy Costs
$11 billion/year in 2050[7]

Technical Solutions

See also: Refrigerants and Other Fluorinated Gases

- Efficient refrigeration case designs and high-performance supermarket systems in hot climates
- Heat recovery (for HVAC reheat and water heating)
- Advanced defrost controls
- Connected refrigeration control systems for demand response and distributed energy resource (DER) integration

Concentration Areas[16]



Key Deployment Barriers	Key Federal Actions
Related barriers/actions in: Refrigerants and Other Fluorinated Gases	
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 DER performance or user acceptability	Facilitate demand response demonstrations for mission-critical commercial refrigeration systems

= R&D = market = finance = policy

Commercial All Other Electricity Use

MEDIUM IMPACT   HIGH DIFFICULTY

KEY IMPACTS

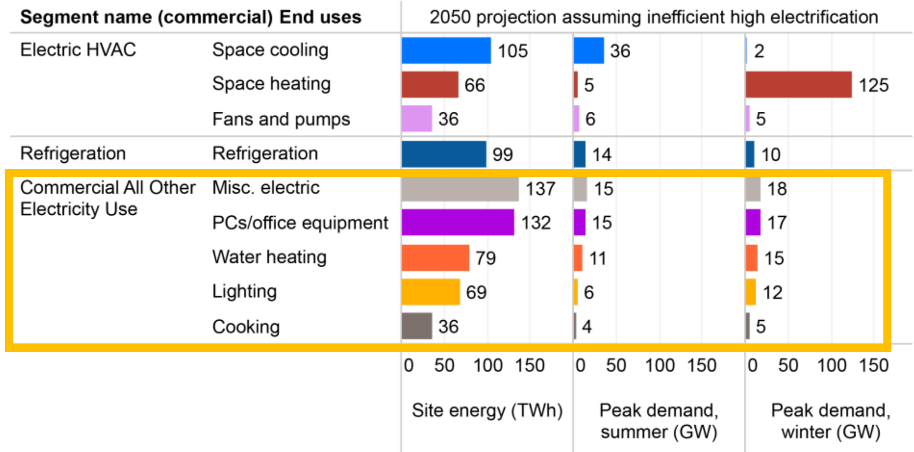
Up to 67 GW[7]
U.S. winter peak in 2050 without efficiency

Energy Costs
$39 billion/year in 2050[7]

Technical Solutions

- Connected luminaires interoperable with building automation systems and responsive to grid signals
- Connected or device-integrated plug load controls that are simple and cost-effective (e.g., automatic receptacle control)
- Vacancy detection and predictive controls
- Enterprise-wide power management software

Concentration Areas[16]



Key Deployment Barriers	Key Federal 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	🛒 Best practices for coordinated procurement and operation of power management technologies
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

⚙ = R&D   🛒 = market $ = finance   ✍ = policy

OTHER OPERATIONAL ENERGY

Two other segments of operational energy are:

1. **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.

2. **Electric vehicle charging**—which is often sited behind-the-meter within buildings and can be coordinated with other building loads.

New Building Operational Energy (Built 2024–2050)

HIGH IMPACT MEDIUM DIFFICULTY

KEY IMPACTS

Energy Costs[7]
$130 billion/year spent in 2024

Safety
Highly efficient envelopes provide thermal resilience

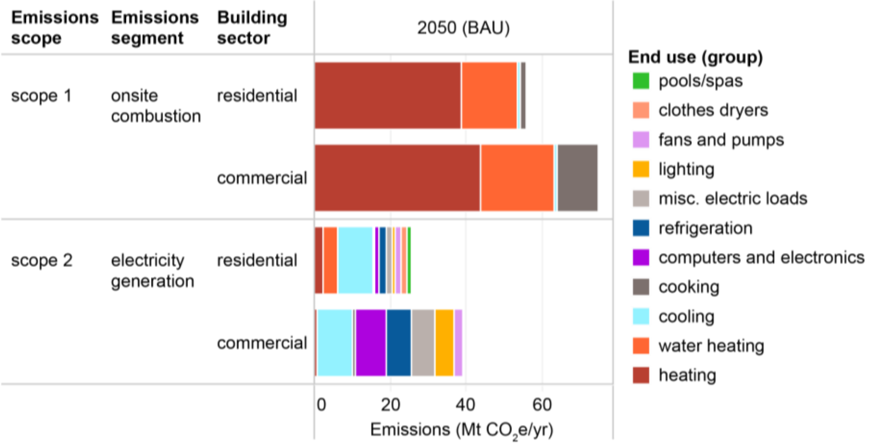
Technical Solutions

- Cost-effective technologies for thermal load reduction, all-electric/electric-ready construction, and grid edge resource management

Up-Front Cost Premium Examples

- 0–3% for multifamily passive house[17]
- 3–5% for single-family passive house[17]
- For commercial buildings, all-electric can be lower cost than mixed fuel[18]

Concentration Areas[16]



Key Deployment Barriers	Key Federal 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
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
Shortage of housing in many areas	Scale up quality housing by integrating efficiency features in offsite construction

= R&D = market = finance = policy

Electric Vehicle Charging (Integration with Buildings)

MEDIUM IMPACT MEDIUM DIFFICULTY

KEY IMPACTS

89 GW[21]
Unmanaged winter AM peak in 2050

Affordability
Puts downward pressure on rates

Technical Solutions

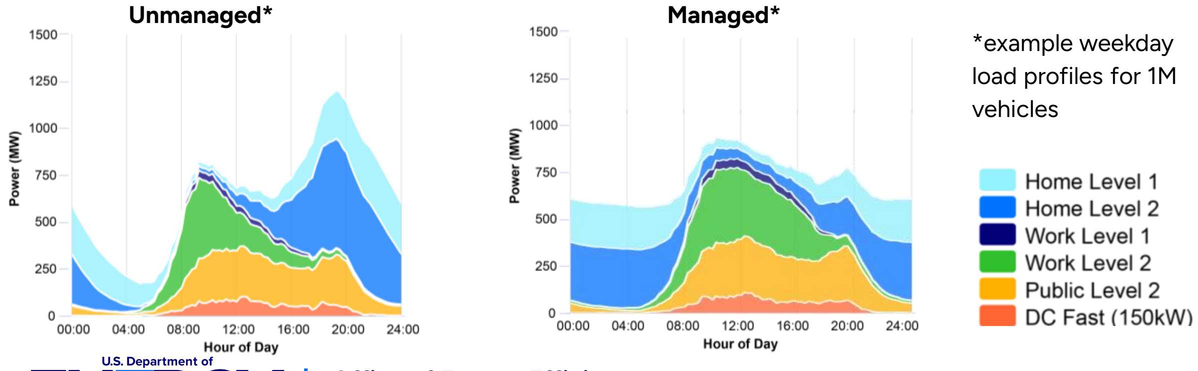
- Coordinate electric vehicle (EV) charging with building loads
- Improved interoperability of vehicle and building controls to support flexibility and resilience

Up-Front Cost[19]

- Level 1: $0–1,000
- Level 2: $400–6,000
- DC Fast: $180,000–285,000

Concentration Areas[20]

Managed charging reduces peak demand while supporting drivers' needs



Key Deployment Barriers	Key Federal Actions
Transportation electrification exacerbates need for distribution grid upgrades	(R&D) Smart charge management to coordinate EV charging with other building loads, on-site distributed energy resources, and grid signals; vehicle-to-home/grid (V2H/V2G) (market) Promote workplace charging
Lack of vehicle data (e.g., state of charge) access impedes coordinated control	(market) Support market adoption of standardized protocols (e.g., ISO 15118 and Open Charge Point Protocols)
EV charging less accessible for multifamily occupants	(market) Innovation on charging designs and business models to increase access (policy) Lower total cost of charging by supporting building codes for electric vehicle standard supply equipment in multifamily buildings and workplaces

= R&D = market = finance = policy

EMBODIED AND FUGITIVE SOURCES

- Because they are not associated with building operational energy use, embodied life cycle and fugitive refrigerant leakage emissions sources from buildings have historically received less attention.
- Together, they represent almost 40% of buildings sector 2050 business-as-usual emissions and span scope 1 (refrigerant leakage) and scope 3 (embodied life cycle) emissions categories.

Refrigerants and Other Fluorinated Gases

HIGH IMPACT MEDIUM DIFFICULTY

KEY IMPACTS

American Competitiveness
In global markets

Technical Solutions

- 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 CO_2 (R-744), propane (R-290), etc.
- Substitute blowing agents with hydrofluoroolefins, hydrocarbons, water

Concentration Areas[22]

Type	Sector	Mt CO_2e/yr
Refrigerants	Residential air conditioning	46
	Commercial refrigeration	41
	Commercial air conditioning	8
	Residential refrigeration	1
Foams	All	12
Fire protection	All	3

Key Deployment Barriers	Key Federal Actions
Lack of in-service leak detection and motivation for reclamation	Improve sensors and management systems Guidance on proper installation and reclamation/recycling approaches Recycling and leak detection
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 Higher-performance ultra-low GWP refrigerants
Flammability and safety concerns	Risk assessments for ultra-low GWP refrigerants

= R&D = market $ = finance = policy

Embodied Construction Material Life Cycle Emissions

HIGH IMPACT MEDIUM DIFFICULTY

KEY IMPACTS

American Competitiveness
In global markets

Technical Solutions

- **Building design:**
  - Repurpose existing buildings 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

Concentration Areas

- **Residential:** 70% of a typical new home's embodied emissions come from just three materials: concrete, insulation, and cladding[23]
- **Commercial:** U.S. office building material embodied emissions 2013–2018 were 37% steel, 29% concrete, 1% wood[24]

Key Deployment Barriers	Key Federal Actions
Inconsistent methodologies for life cycle assessments (LCAs); high costs/low quality of environmental product declarations (EPDs)	(finance) Provide market incentives/direct funding for EPD creation (policy) Establish U.S. whole-building LCA standards/guidelines (policy) Support state and local procurement policies
Builders don't measure/consider emissions	(market) Support industry efforts and tools (market) Educate builders on no-cost and cost-savings strategies
Validation of low embodied carbon (LEC) materials	(R&D) Field-validate new low-carbon materials to de-risk market adoption
LEC space is dense and difficult to understand	(market) 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	(market) Improve incentives for LEC materials via grants and awards

= R&D = market = finance = policy

CROSS-CUTTING OPPORTUNITIES

In this section, we highlight six additional opportunities to consider in federal program planning for building decarbonization, all of which apply to more than one of the segments presented above:

1. Building Electrical Infrastructure
2. Grid Edge Resource Management
3. Dual Fuel and Cogeneration
4. On-Site Solar Generation
5. Thermal Energy Networks
6. Energy Modeling and Analysis

Cross-Cutting Opportunity: Building Electrical Infrastructure

KEY IMPACTS

Affordability
Avoiding infrastructure oversizing makes electrification faster and less costly while making electricity more affordable for all

Context

- 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

Technical Solutions

- 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.)

Key Deployment Barriers	Key Federal 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 native load balancing and novel storage integration solutions to reduce peak load

⚙ = R&D 🛒 = market $ = finance ✍ = policy

Cross-Cutting Opportunity: Grid Edge Resource Management

KEY IMPACTS

Affordability
Generates revenue for customers and increases affordability for all

Safety
Supports resilience for buildings and communities

Context

- The cost of delivering electricity may soon surpass the cost of producing it[6]
- 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 can make more efficient use of distribution *and* bulk grid infrastructure

Technical Solutions

- 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)

Key Deployment Barriers	Key Federal Actions
Lack of valuation and incentives to drive adoption and utilization of behind-the-meter grid resources	(policy) Support utility and regulator decision-making on consumer compensation, rate design, and incentive programs (policy) Support state requirements for demand-side resource valuation in integrated utility planning and performance-based utility regulation (market) Support new business models for stacking value across grid-edge assets
Higher cost for connected products and storage	(finance) Support utility program rebates for connected equipment and storage, particularly in low-to-moderate income homes and under-resourced communities
Lack of control capabilities and standards	(policy) Support industry-led standardization of communications protocols for distribution management (R&D) Controls to manage multiple loads against grid and occupant objectives

(gear icon) = R&D (cart icon) = market (dollar icon) = finance (pencil icon) = policy

Cross-Cutting Opportunity: Dual Fuel and Cogeneration

KEY IMPACTS

Peak Demand
Can moderate peak impacts of electrification

Affordability
Can avoid peak charges

Context

See also: Residential Furnaces and Boilers, Commercial Rooftop Units, Boilers, and Centralized Water Heating

- 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

Technical Solutions

- 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

Key Deployment Barriers	Key Federal 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 low switchover defaults into installer training; develop operational guidance 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

⚙ = R&D 🛒 = market $ = finance ✍ = policy

Cross-Cutting Opportunity: On-Site Solar Generation

KEY IMPACTS

Affordability
Can impact rates positively or negatively

Safety
Supports resilience for buildings and communities

Context

- Currently costs 3x more than utility-scale photovoltaic (PV) but uses less land[25]
- States with high solar adoption are transitioning from net metering to other compensation structures
- With storage, can provide value at grid edge and bulk power scales, especially where there are transmission and distribution constraints
- With storage, can provide electrical resilience to individual buildings and community microgrids

Technical Solutions

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

Key Deployment Barriers	Key Federal Actions
Economic and greenhouse gas value of mid-day solar generation diminish as deployment increases	(policy) 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	(R&D) Technology and controls demonstrations (policy) Technical assistance for distribution planners
Batteries and islanding controls have high up-front costs	(R&D) Affordable islanding technology and controls (e.g., vehicle-to-everything) (market) Programs to reduce permitting costs (policy) Policies and incentives to increase affordability (policy) Support of state regulation exploring new ownership models

= R&D = market = finance = policy

Cross-Cutting Opportunity: Thermal Energy Networks

KEY IMPACTS

Affordability
Paid for through rates

Peak Demand
Can moderate peak impacts of electrification

Context

- Thermal energy networks (TENs) use pipes to provide heating and/or cooling to multiple buildings
- Existing TENs include district energy systems that serve about 8% of commercial building floor area[15]
- TENs offer increased efficiency (by capturing waste heat from HVAC, refrigeration, and data centers) and flexibility (e.g., seasonal storage via geothermal boreholes)

Technical Solutions

- *New TENs* are commonly designed as ambient-temperature water loops; *existing TENs* can retain steam/hot water distribution using low-carbon heat sources, transition to ambient-temperature loops, or fully decentralize heating
- 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.

Key Deployment Barriers	Key Federal Actions
Uncertainty in technical and financial performance	(policy) Support of utility pilots, community input, and knowledge sharing (R&D) Modeling, subsurface characterization, and system design validation tools (finance) Capital and loan guarantees from federal and state agencies
Lack of value proposition and regulatory certainty for TEN business models	(R&D) Comprehensive valuation of benefits, including system-wide/peak-load savings (policy) Integrated distribution system planning requirements for utilities (policy) Data collection to support utility and third-party ownership model decisions (policy) Best practices for state and local regulation, including allowing deeper drilling
High cost of drilling geothermal boreholes	(market) Training and apprenticeships in drilling, HVAC installation (market) Incentives for new drilling businesses and water-well drillers

= R&D = market = finance = policy

Cross-Cutting Opportunity: Energy Modeling and Analysis

KEY IMPACTS

Energy, Emissions, and Cost Assessments
Used to estimate and measure savings, determine code compliance, and explore policy effects

Context

Modeling supports building decarbonization via:

- 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

Technical Solutions

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

Key Deployment Barriers	Key Federal Actions
Models of key low-carbon technologies may not be up to date or are limited	[R&D] Update models for heat pumps and thermal energy storage (TES) [R&D] Heat pump and TES sizing methods [market] Standard templates for common low-carbon systems
Calibration, validation, and uncertainty analysis not highly valued	[R&D] Improved data integration and calibration/validation methods; best practices for uncertainty quantification [policy] Support BPS/other use cases that require accurate predictive modeling
Performance-based modeling is costly	[market] Further integrate design, codes, and BPS software
Lack of under-resourced community metrics in stock models	[R&D] Update model inputs/outputs to delineate under-resourced communities
Lack of standard decarbonization scenario assumptions	[R&D] Publish standardized building scenario definitions, supporting datasets, and measure definitions

[R&D] = R&D [market] = market [finance] = finance [policy] = policy

THANK YOU

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DATA GENERATION AND COLLECTION APPROACH

1. Develop and visualize database with detailed segmentation of buildings sector emissions, energy, and peak demand through 2050.
2. Down-select to ~30 segments from #1 based on site energy, emissions, peak demand (electric segments), and similarity of technology solutions that address the segment.
3. For each segment, solicit detailed subject matter expert (SME) input to initially assess and add the following:
   a) Potential impact vs. level of difficulty to address/manage (high/medium/low)
   b) Primary and supporting technical solutions to address/manage
   c) Major barriers to solution deployment (technology, market, installation, O&M)
   d) Key federal actions to address barriers (R&D, market transformation, regulatory).
4. Compile all responses collected in #3 into a summary table and conduct follow-up conversations with SMEs to verify results.
5. Translate summary table from #4 into individual slide highlights for each segment that cover impact/difficulty, technology solutions and concentration areas, barriers, and federal actions; iterate with SMEs to finalize content.
6. Identify and develop slides for cross-cutting opportunities that apply across multiple segments; iterate with SMEs to finalize content.
7. Publish slides for use in program planning and prioritization work.