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Demand-side solutions in the US building sector could achieve deep emissions reductions and avoid over $100 billion in power sector costs

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Article

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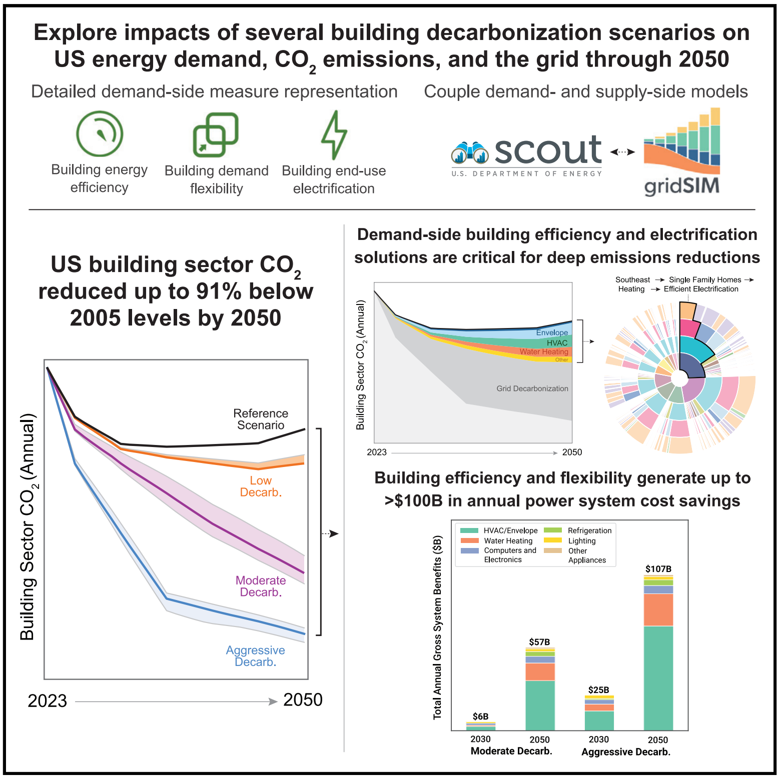
Graphical abstract



Highlights

- US building CO$_2$ emissions can be reduced up to 91% vs. 2005 levels by 2050
- Nearly half of annual CO$_2$ reductions are from efficiency and electrification
- Demand-side solutions can save over $100 bn in power system costs per year
- Early retrofits, and building codes and standards are key demand-side levers

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In brief

Buildings are a top source of US greenhouse gas emissions and electricity demand and are therefore a critical focus for achieving net-zero emissions by 2050. However, demand-side building decarbonization pathways and their interactions with power sector decarbonization remain underexplored. Here, we quantify the impacts of multiple building decarbonization scenarios on energy demand, emissions, and the grid. We find that, by 2050, demand-side solutions could substantially reduce building emissions and avoid over one-third of power sector decarbonization costs.

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Demand-side solutions in the US building sector could achieve deep emissions reductions and avoid over $100 billion in power sector costs

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SCIENCE FOR SOCIETY Meeting the US 2050 net-zero emissions target requires a rapid and cost-effective low-carbon transition across the entire energy system. Commercial and residential buildings are a primary source of emissions and are key to this transition. In addition to switching to low-carbon electricity generation sources (i.e., renewables), decarbonizing buildings requires the pursuit of demand-side solutions that improve the efficiency and flexibility of building operations (e.g., high-performance windows, smart thermostats) and switch to efficient and low-carbon electric equipment (e.g., heat pumps). Although such demand-side solutions can reduce emissions now, they are underrepresented in the energy system modeling that informs key decision-makers. We address this need by including several demand-side measures in a detailed model of building sector energy use and accounting for interactions between these measures and the electrical grid. Demand-side measures in buildings, particularly efficient envelopes, electric heat pumps and smart control systems, can work together with power grid decarbonization to reach net-zero targets while saving over US$100 billion in annual power system costs.

SUMMARY

Buildings are energy-intensive and a primary source of US end-use sector carbon emissions. Although building emissions today are 25% below their 2005 peak, far deeper reductions are needed to reach the US 2050 net-zero emissions goal. However, plausible decarbonization pathways that consider both buildings and their interactions with the power grid remain poorly understood. Here, we couple detailed modeling of building energy use and the grid to quantify building decarbonization potential and associated grid impacts. We find up to a 91% reduction in building CO_2 emissions from 2005 levels by 2050 using a portfolio of building efficiency, demand flexibility, and electrification measures alongside rapid grid decarbonization. Building efficiency and flexibility could generate up to $107 billion in annual power system cost savings by 2050, offsetting over a third of the incremental cost of full grid decarbonization. Our results underscore multiple benefits of demand-side solutions for deep decarbonization of US buildings.

INTRODUCTION

In line with the Paris Agreement's target of limiting global warming to 1.5°C, the US established an ambitious goal to reduce net greenhouse gas (GHG) emissions by 50%–52% from 2005 levels by 2030 and to reach net-zero emissions economy-wide by no later than 2050; this includes a goal to reach 100% carbon-free electricity by 2035.[1] Achieving these goals will require unprecedented acceleration in the adoption of mitigation solutions across every sector of the economy.

Previous research on energy system decarbonization pathways has tended to focus on supply-side solutions for low-carbon energy generation and CO_2 removal technologies rather than demand-side approaches, including those in buildings and other end-use contexts.[2,3] Increasingly, however, studies suggest that demand-side approaches are essential for climate change mitigation.[4–6] In the US, building energy consumption is a substantial driver of the CO_2 emissions from energy end-use sectors, accounting for 1.7 Gt CO_2 in 2022, or 35% of the US total.[7] Buildings also account for 74% and 42% of annual US electricity sales and end-use natural gas consumption, respectively.[7] Total building energy-related CO_2 emissions peaked in 2005 at 2,327 Mt CO_2, the benchmark year for US climate goals, and have declined by 25% in the 17 years since then.[7]

Building decarbonization solutions improve the efficiency of energy end uses, flexibly manage building loads and other distributed energy resources to improve reliability of the power grid, and/or convert building services to low-carbon sources of electricity. Of the three approaches, building energy efficiency (EE) is the most extensively studied and widely considered as a beneficial, low-cost option for mitigating climate change,[8] although its role is shifting alongside aggressive decarbonization of the energy supply.[9] Demand flexibility (DF) is a complementary solution that leverages demand-side assets such as smart thermostats, connected appliances, and behind-the-meter storage and generation to reduce peak building demand and shift demand to times of high renewable energy generation, flattening the overall shape of building demand on the grid. Flexibility will play an increasingly important role as variable renewable energy accounts for a larger share of power generation and distribution networks are challenged by growing demand for clean electricity.[10–15] Finally, building end-use electrification (EL) has emerged as a key pillar of economy-wide decarbonization, particularly as the cost and performance of EL technologies have improved while ambitious targets for power sector decarbonization have been announced.[16,17]

Recent research on pathways to economy-wide decarbonization in the US represents building sector solutions as part of an accelerated transition and reveals a number of common themes.[1,18–23] First, final building energy demand is reduced significantly, up to 41% compared with business-as-usual in 2050. Second, rates of building space and water heating EL accelerate dramatically across studies: electric shares of new equipment sales in 2050 reach up to 90% for certain end-use segments, such as residential space heating. Third, regarding the power sector, studies assume a 70%–100% reduction in fossil fuel use for electricity generation by 2050.[20,21] Some studies assume an aggressive target of achieving carbon-free electricity by 2035.[1,22] Finally, most studies project remaining building emissions in 2050: 48–214 Mt CO_2 (2%–9% of 2005 levels) in Larson et al.,[20] 55–131 Mt CO_2 (2%–6% of 2005 levels) in Williams et al.,[21] and roughly 100–300 Mt CO_2 (4%–13% of 2005 levels) in Kerry and McCarthy,[1] depending on the scenario. In cases with aggressive grid decarbonization, remaining building emissions are owed primarily to the assumption that full EL is not achieved across building end uses; these remaining emissions in the studies are offset by deployment of negative emissions sources to achieve net-zero emissions for the building sector as a whole.

Existing cross-sectoral decarbonization studies tend to represent building decarbonization solutions and adoption drivers with a coarse degree of detail and, while they calculate the total and net costs of deep decarbonization across sectors, the cross-sectoral studies do not undertake detailed cost modeling for the building sector or assess the implications of ambitious building technology deployment scenarios on the power sector. Recent studies focused on building sector GHG emissions demonstrate the potential for deep emissions reductions but have similar limitations to the cross-sectoral studies in their representation of technologies and assessment of power system cost impacts.[24–26] Overall, therefore, pathways for building energy and emissions reductions are currently underexplored at sufficient levels of detail to understand cross-sectoral linkages and inform holistic energy system decarbonization strategies that leverage both supply- and demand-side assets toward achieving climate goals.

Here, we address this knowledge gap by modeling US building energy demand, energy-related building CO_2 emissions, and power system costs through 2050 under multiple scenarios of building EE, DF, and end-use EL, as well as multiple levels of grid decarbonization. We find potential for up to a 91% reduction in building CO_2 emissions from 2005 levels by 2050, without corresponding increases in building sector electricity use, given aggressive deployment of demand-side measures and full decarbonization of the electricity supply by 2035. Demand-side measures in buildings account for up to nearly half (45%) of total 2050 CO_2 reductions beyond a reference case, with the remainder attributable to the decarbonization of the electricity supply. Furthermore, aggressive deployment of building efficiency and flexibility generates up to $107 billion in annual power system cost savings by 2050, offsetting more than a third of the incremental cost of full grid decarbonization. By assessing cross-sectoral linkages between building and power sector decarbonization and attributing our findings to specific measures, end uses, building types, and regions, this study can inform concrete policy approaches that accelerate energy system decarbonization across both demand- and supply-side technologies to fulfill ambitious targets for climate change mitigation in the US.

RESULTS

Methods summary

We define a comprehensive set of building EE, DF, and end-use EL technologies and operational approaches (collectively referred to as demand-side measures) that are deployed under 12 scenarios of US building and power sector decarbonization from 2023 to 2050 as outlined in Table 1. Scenarios are organized into three groups, with one scenario in each group serving as a benchmark against which other group scenarios are compared with explore sensitivities to key input assumptions. The three benchmarks represent low, moderate, and aggressive potentials for building decarbonization, respectively. We quantify remaining CO_2 emissions from the building sector in 2050 in order to highlight the potential need for negative emissions to offset these remaining emissions and fully decarbonize the building sector. Throughout our paper, we compare building CO_2 emission reductions against 2005 building energy-related CO_2 levels (2,327 Mt CO_2) given the use of a 2005 reference point for the US economy-wide net zero emissions target. Emissions are reported as energy-related CO_2 throughout with the exception of our accounting of fugitive emissions sources, which are reported in CO_2-eq units using a 100-year Global Warming Potential—see discussion.

Table 1. Scenario groups, benchmarks, and sensitivity cases

Reference case: 2021 EIA Annual Energy Outlook (AEO 2021) Reference Case (Building Demand); Brattle GridSIM Reference Case (Electricity Supply CO_2 Intensity); AEO 2021 Reference Case (Onsite Fossil Fuel Combustion CO_2 Intensity)

Alternate scenario group	BM scenario	Sensitivity scenarios
1: Low	demand-side measure deployment: - high rate of building electrification to heat pumps (HPs) only - no additional efficiency or demand flexibility deployment beyond reference case grid decarbonization: GridSIM Reference Case	(1.1) low BM without efficient electrification (electrification to a mix of resistance and HPs)
2: Moderate	demand-side measure deployment: - moderate rate of building electrification to HPs - building technologies with breakthrough[a] performance/cost enter the market by 2035 - elevated building codes/standards take effect in 2030 - additional deployment of building controls that enable demand flexibility packaged with equipment and envelope efficiency, efficiency-only retrofits for existing building envelope, and moderate rate of resistance heating/water heating conversion to HPs grid decarbonization: 80% CO_2 reduction vs. 2005 by 2050	(2.1) moderate BM with early retrofits that accelerate the rate of baseline technology stock turnover (2.2) moderate BM without breakthrough[a] technologies reaching the market (2.3) moderate BM without breakthrough technologies reaching the market or elevated building codes and appliance efficiency standards being enacted (2.4) moderate BM without any additional efficiency/flexibility deployment beyond the reference case (electrification to HPs only)
3: Aggressive	demand-side measure deployment: - high rate of building electrification to HPs - building technologies with breakthrough performance/cost enter the market by 2030 - elevated building codes and standards take effect in 2025 - additional deployment of efficiency and flexibility as described for moderate scenario group but with high rate of resistance heating/water heating conversion to HPs grid decarbonization: 100% CO_2 reduction vs. 2005 by 2035	(3.1–3.4[b]) same as 2.1–2.4 sensitivity settings but relative to aggressive BM

Twelve scenarios are simulated in addition to a reference case: three benchmark scenarios represent low, moderate, and aggressive potentials for building decarbonization; the remaining nine scenarios are used to explore key sensitivities relative to the benchmarks. BM, benchmark.

[a] Breakthrough and other technology assumptions further detailed in the "scenario measure features" sub-section of the experimental procedures and Tables 5 and 6.

[b] Scenario 3.4 is identical to scenario 1 on the demand side; the two scenarios differ only in level of grid decarbonization (reference case in scenario 1 vs. 100% reduction by 2035 in scenario 3.4) and slight differences in assumed retail electricity rates (see supplemental information for details).

Demand-side measure deployment is assessed with the Scout model[27] relative to the EIA Annual Energy Outlook (AEO) 2021 Reference Case forecast, which includes projections for both new and existing building stock and largely carries forward historical trends in building technology adoption and energy consumption. Annual electricity emissions factors and hourly power system costs are projected by the GridSIM model[28] under different grid decarbonization scenarios. These projections are multiplied by Scout projections of annual building electricity demand and hourly system load impacts through 2050 to assess electricity CO_2 emissions and power system cost reductions across the full measure portfolio. Measure installed cost data from Scout are used to estimate the total incremental costs of deploying the measure portfolio. Full-portfolio reductions in CO_2 emissions from on-site combustion of fossil fuels are assessed by coupling Scout projections of annual building fossil fuel demand through 2050 with EIA fossil fuel emissions intensities. Additional details on the modeling framework, measures, and scenarios are reported in the experimental procedures and in the supplemental information, which also includes additional modeling outputs (Notes S1–S5).

Up to a 91% reduction in US building CO_2 by 2050

First, we estimate the potential magnitude of changes in US building electricity use, energy use, and CO_2 emissions to 2050 under various scenarios of demand-side measure deployment and grid decarbonization. Figure 1D shows that US building CO_2 emissions could be reduced up to 67% and 91% below 2005 levels by 2030 and 2050, respectively, under a scenario with aggressive deployment of efficiency and EL, replacement of existing technology stock before the end of its useful lifetime (subsequently referred to as ‘‘early retrofitting’’), and a grid that fully decarbonizes by 2035 (scenario 3.1). Under this scenario, 216 Mt CO_2 emissions remain in 2050, which is consistent with remaining building emissions in previous deep decarbonization studies and would require mitigation via negative emissions sources (see discussion).

The most aggressive scenario also avoids more than one-third of total building energy use (Figure 1B) and decreases total building electricity use 13% below the reference case by 2050 despite the high level of building end-use EL (Figure 1A). Several other scenarios produce less favorable results, however. Moderate scenarios (2–2.4) fail to reduce building emissions more than 77% below 2005 levels, leaving a minimum of 532 Mt CO_2 unabated in 2050, which is inconsistent with estimates of available negative emissions offsets for the sector. Low potential scenarios (1–1.1), which push high EL alone under slow grid decarbonization, are even further from a net-zero-compatible pathway for the US energy system, leaving a minimum of 1,181 Mt CO_2 unabated in 2050, including under high EL to heat pumps with a mix of performance levels (scenario 1). Moreover, high EL without a parallel focus on efficiency (scenarios 1–1.1, 2.3–2.4, and 3.3–3.4) drives increases in building electricity use of up to 23% in 2050.

Figure 1C isolates the contributions of various levels of demand-side measure deployment (per Table 1) to total building CO_2 emissions reductions. Full deployment of demand-side measures accounts for up to nearly half of total CO_2 reductions from the reference case in 2050 in scenarios where additional grid decarbonization beyond the reference case is assumed (39%–45% in scenarios 2, 2.1, 3, and 3.1). The influence of demand-side measures on CO_2 emissions reductions is strongly dependent on the deployment of efficiency, as the next section explores further: when only building EL is assumed, the share of total CO_2 emissions reductions attributable to the demand side drops to 18% and 26% under power grids that are 80% decarbonized by 2050 and 100% zero-carbon by 2035, respectively (scenarios 2.4 and 3.4). Figure 1D further accounts for the decarbonization of building electricity demand that remains after assessing demand-side measure deployment; this notably reduces the range of results for each scenario group and indicates the strong influence of grid emissions assumptions on total building sector CO_2 levels.

Efficiency deployment level strongly affects reductions

Decision-makers may use various regulations and market-based instruments to influence the adoption rates and performance of demand-side measures. Figure 2 compares reductions in annual site energy and CO_2 emissions from demand-side measures between the three benchmark scenarios and nine sensitivity cases in 2050 (resulting in low, moderate, and aggressive scenario groupings in Figures 2A–2C, respectively); the figure also shows cumulative changes in CO_2 from 2023 to 2050, and results for 2030 are reported in Figure S1. The comparisons isolate the influence of key dynamics that could be affected by policy levers: a decrease in the efficiency of EL (scenario 1.1 vs. 1); the addition of early retrofits (2.1/3.1 vs. 2/3); failure to introduce breakthrough efficiency (2.2/3.2 vs. 2/3); failure to introduce more aggressive building energy codes and appliance efficiency standards (2.3/3.3 vs. 2.2/3.2); and removal of all additional market-viable efficiency and flexibility deployment beyond the reference case (2.4/3.4 vs. 2.3/3.3). Additional market-viable efficiency and flexibility deployment consists of (1) operational controls that enable load shedding and shifting paired with high efficiency equipment and envelope components, (2) efficiency-only upgrades to windows and roofs in existing buildings, and (3) switching from resistance-based heating and water heating to heat pumps.

Assuming early retrofit behavior (scenarios 2.1/3.1) produces moderate increases in 2050 annual site energy savings and avoided annual CO_2 in the range of 10%–23% relative to the moderate and aggressive benchmark scenarios (scenarios 2 and 3). The aggressive group benchmark (scenario 3), which does not assume early retrofitting behavior, nevertheless reduces annual building emissions to 89% below 2005 levels by 2050, or 262 Mt CO_2, which is still consistent with other economy-wide net-zero pathway studies.[1,20] Indeed, the impacts of early retrofits on annual energy and CO_2 are more prominent in the near term, as demonstrated by the cumulative results in Figure 2 and the annual results for 2030 (Figure S1). Increasing early retrofits adds 22%–39% to cumulative CO_2 reductions from 2023 to 2050 and 38%–65% to 2030 energy and CO_2 reductions; in both cases, these changes are among the highest of any sensitivity dynamic examined. Since by definition early retrofits occur mostly in the first half of the modeling time horizon, this result is intuitive and underscores the need to increase retrofit rates in order to help avoid "lock-in" of high emissions technologies,[29] deliver immediate CO_2 reductions, and manage the overall carbon budget. By 2050, however, these findings suggest that most of the decarbonization potential for US buildings can be captured by ensuring that building technology installation choices from 2023 onward—driven by new building additions and regular end-of-life technology replacements—are pushed toward more efficient and flexible options served by low-carbon or carbon-free fuel sources.

In contrast to the incrementally positive impacts of early retrofits, decreasing the efficiency of EL by assuming a large share of electric resistance equipment alongside heat pumps (scenario 1.1) has substantial negative impacts relative to the low potential benchmark (scenario 1), precluding 26%–27% of reductions across metrics. Similarly, in the moderate and aggressive benchmark scenarios, collective removal of three efficiency dynamics—breakthrough efficiency, aggressive codes and standards, and additional market-viable efficiency with flexibility (scenarios 2.2–2.4 and 3.2–3.4)—significantly counteracts energy and CO_2 reductions, together precluding up to 65% and 58% of 2050 site energy and CO_2 reductions, respectively, and up to 67% of cumulative CO_2 reductions from 2023 to 2050. The stronger sensitivity of cumulative CO_2 reductions to efficiency deployment is an initial reflection of the greater near-term influence of efficiency measures that will be further demonstrated in the next section. Of the three efficiency dynamics, the largest incremental energy and CO_2 impacts come from removal of market-viable efficiency with flexibility that is not assumed in the reference case (15%–29% annual, 21%–37% cumulative) and from removal of aggressive codes and standards (16%–25% annual, 20%–24% cumulative). Failure to market breakthrough efficiency has the lowest incremental impacts (10%–12% annual, 6%–7% cumulative), suggesting that highly efficient and flexible technologies already on the market today could recapture most of the energy and CO_2 reductions that would be lost without the

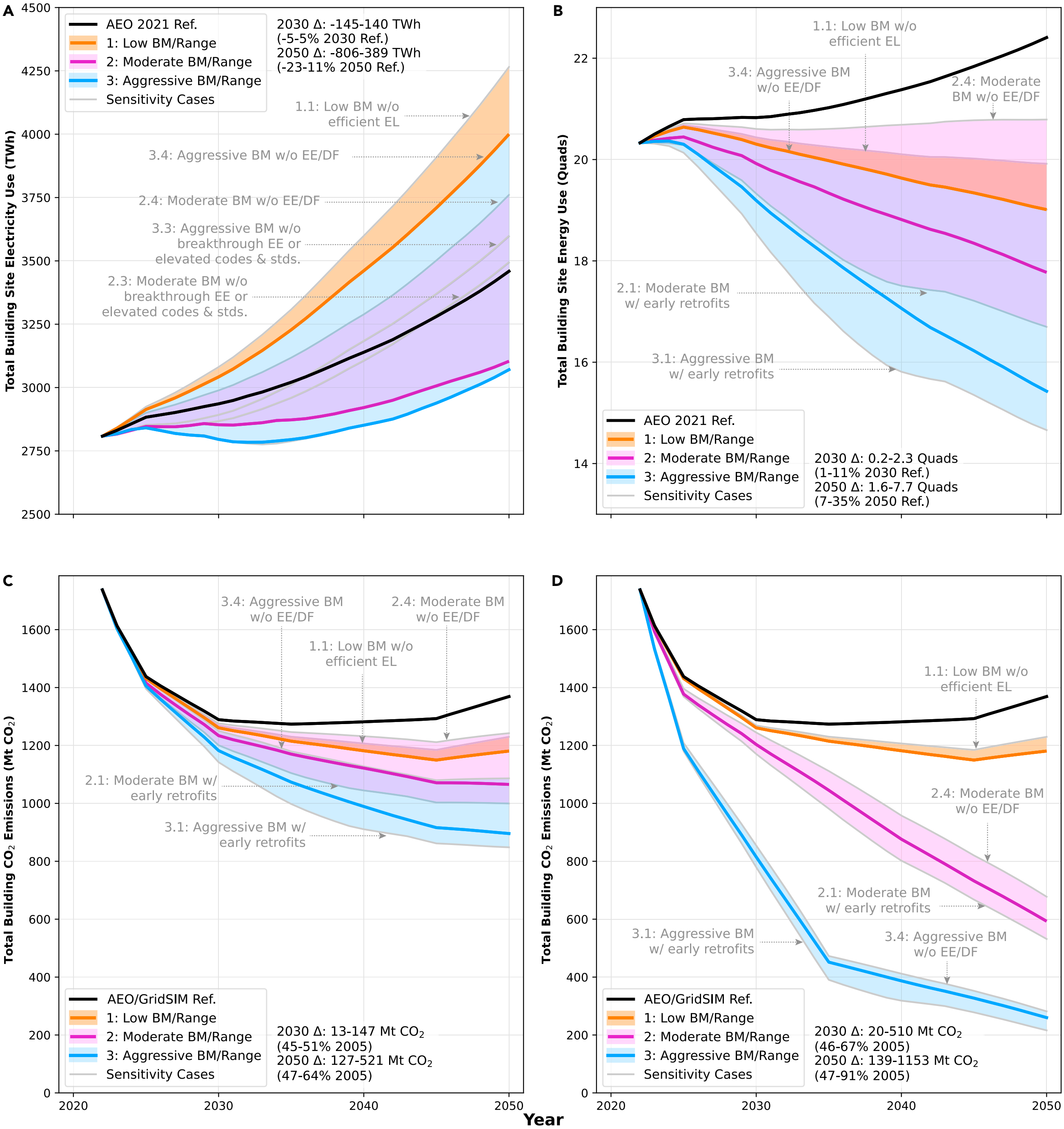


Figure 1. By 2050, US building CO_2 emissions can be reduced up to 91% vs. 2005 levels without increasing electricity use given deployment of a broad suite of demand-side measures alongside full electricity decarbonization

(A–D) Three benchmark (BM) scenarios representing low, moderate, and aggressive building decarbonization futures are highlighted from 2022 to 2050 relative to the EIA Annual Energy Outlook (AEO) 2021 Reference Case forecast of building site electricity (A), building site energy (B), and a reference forecast of building CO_2 emissions that pairs AEO projections of building demand and fossil-based emissions intensities with GridSIM Reference Case CO_2 emission intensities for electricity (C and D). (C and D) represent the emissions that result solely from the application of additional building efficiency, flexibility, and electrification (C) vs. those resulting from the joint consideration of additional demand-side measure deployment and decarbonization of remaining reference case building electricity demand (D). Aside from the reference case and benchmark scenarios, nine additional scenarios are simulated to explore key sensitivities in the results; the sensitivity range around each benchmark scenario is denoted by colored shading. Bounding sensitivity scenarios for each benchmark are annotated, as are any other scenarios in which site electricity use increases by 2050 relative to the reference case in (A). The range of possible changes from the reference case across the full scenario set is summarized for 2030 and 2050.

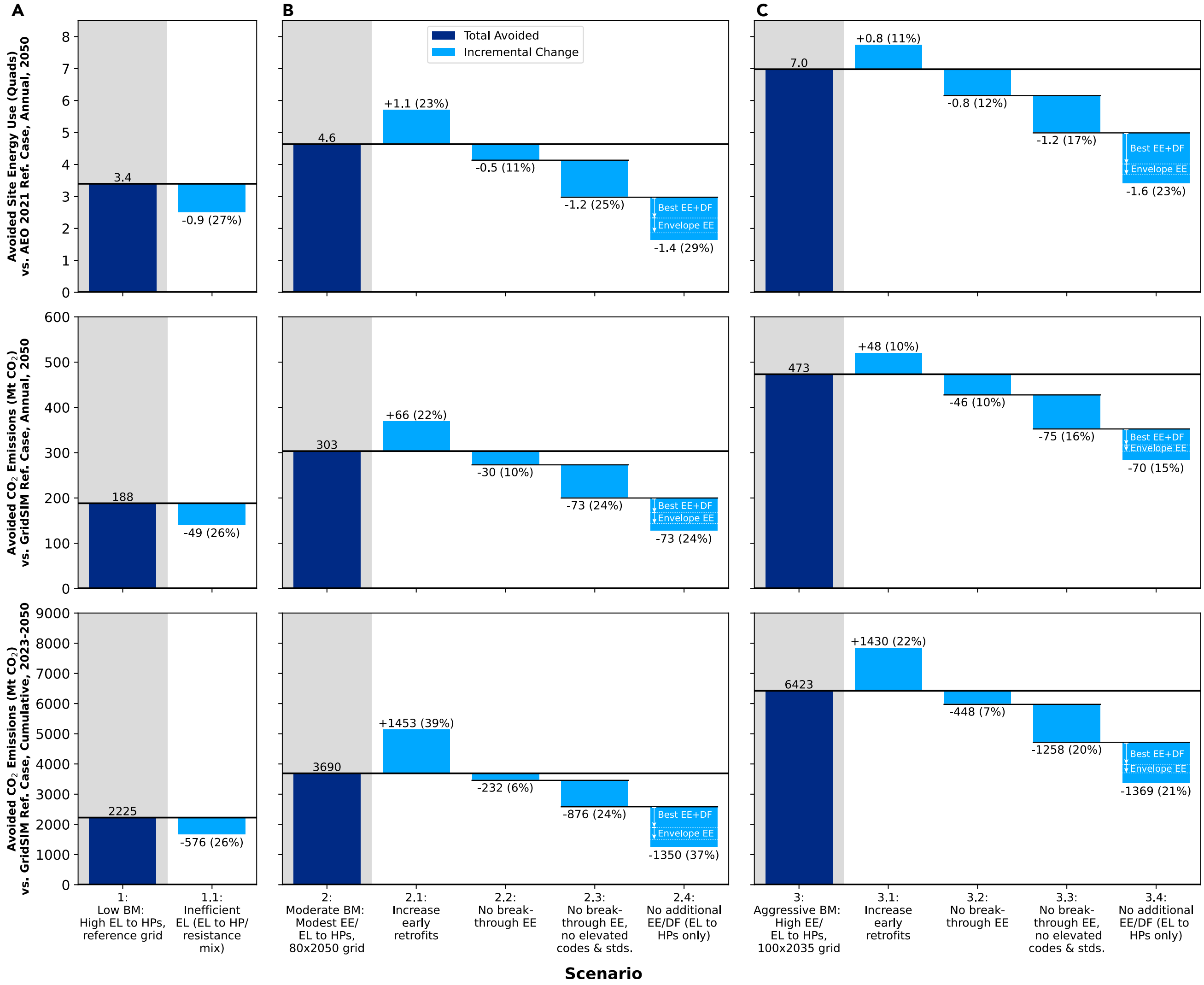


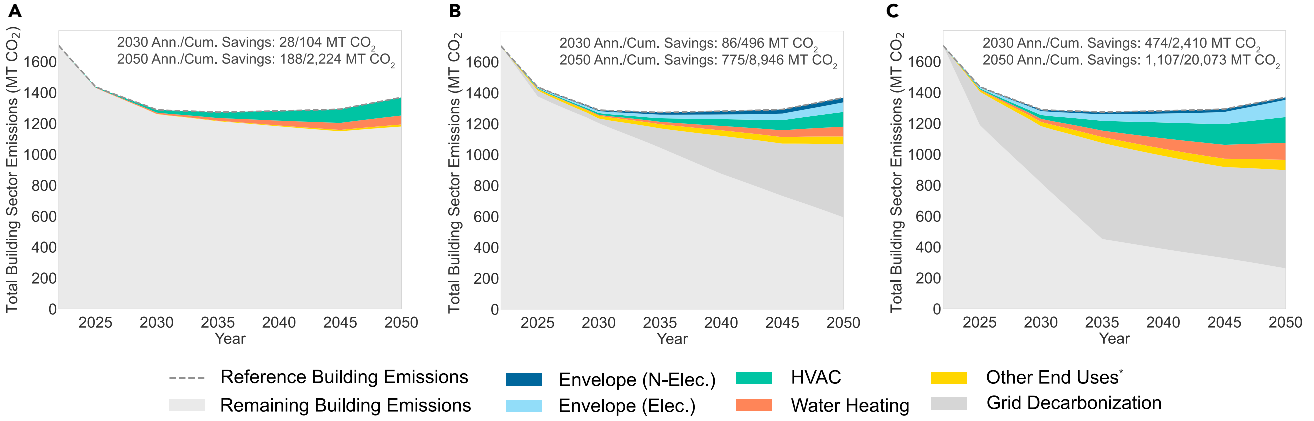
Figure 2. Building energy and CO_2 reductions through 2050 depend strongly on the level of demand-side efficiency deployment

(A–C) Results for nine sensitivity side cases are organized into three groups—low (A), moderate (B), and aggressive (C)—and assessed relative to the 2050 avoided annual energy use (top row) and CO_2 emissions (middle row) of the three benchmark (BM) scenarios (1, 2, and 3); cumulative avoided CO_2 emissions between 2023 and 2050 are also shown (bottom row). The sensitivity cases assess the influence of five dynamics on annual energy and emissions: reductions in efficiency of electrification via substantial conversion from fossil-based heating and water heating to electric resistance technologies (1.1); failure to increase the market-available technology performance ceiling via eventual introduction of breakthrough efficiency technologies with very low cost and performance (2.2, 3.2); failure to increase the market-available technology performance floor via implementation of more aggressive building performance codes and appliance efficiency standards (2.3., 3.3); and failure to deploy additional market-viable efficiency and flexibility options not represented in the reference case—deployment of advanced operational controls with efficient equipment and envelope components that reduce energy waste and enable flexibility (“Best EE+DF”), efficiency-only upgrades for certain envelope components in existing buildings (“Envelope EE”), and switching increasing shares of resistance heating and water heating to heat pumps (2.4, 3.4). Energy efficiency, electrification, and heat pumps are abbreviated in the figure as EE and EL, and HP, respectively.

introduction of breakthrough technologies, albeit at a higher upfront cost.

Envelope, HVAC, and water heating solutions lead impacts

Next, we attribute total building CO_2 emissions reductions to end-use sources, demonstrate the sequencing of CO_2 emissions reductions by demand-side measure type, and highlight the segments of building energy use with the greatest potential to drive CO_2 reductions. Figure 3 presents CO_2 emissions reductions wedges across the three benchmark scenarios—low (scenario 1, Figure 3A), moderate (scenario 2, Figure 3B), and aggressive (scenario 3, Figure 3C). Reductions are largely attributable to thermal end uses: lower energy demand from heat transfer through the building envelope and more efficient and less carbon-intensive HVAC and water heating equipment. In the moderate and high potential benchmarks (scenarios 2 and 3), where fossil-based equipment EL is deployed in parallel with envelope



*Includes computers and electronics, cooking, refrigeration, lighting, washing, drying, and ventilation

Figure 3. Demand-side measures contribute nearly half of total building CO_2 reductions by 2050 under moderate to aggressive decarbonization benchmarks; reductions are largely attributable to thermal end uses

(A–C) CO_2 emissions reduction wedges are shown relative to a reference line that reflects AEO 2021 Reference Case building demand and fossil fuel emissions intensities with GridSIM emissions intensities for electricity for each of the low, moderate, and aggressive benchmark scenarios (1, 2, and 3) and (A–C), respectively. Reductions from electrifying and improving the efficiency and flexibility of building end uses (demand-side measures) are indicated with colored wedges for each affected end use. Within the demand-side wedges, CO_2 reductions from improved envelope efficiency (which reduce demand for both electric and non-electric heating and cooling energy) are assessed before and reported separately from the overlapping reductions of measures that improve HVAC equipment efficiency. More broadly, reductions from electric efficiency and flexibility improvements are assessed before considering additional decarbonization of the power supply beyond the reference case, while reductions from electrification are staged in parallel with power supply decarbonization. Power supply decarbonization further reduces the emissions from any reference case building electricity that remains after accounting for deployment of efficiency and flexibility measures; these reductions are indicated with a dark gray wedge in each scenario.

improvements and more efficient and flexible electric equipment, envelope improvements account for the single-largest share of CO_2 emissions reductions (33%–37%) among end uses. Reductions in HVAC and water heating equipment energy use account for an additional 32%–35% and 21%–23% of end-use emissions reductions, respectively. While other end uses register sizable reductions in these scenarios—notably, computers and electronics, lighting, and cooking—collectively these end uses account for just 14%–17% of end-use reductions in 2050.

The strong influence of envelope improvements on CO_2 emissions reductions that are attributable to building measures in Figure 3 is consistent across the moderate and aggressive benchmarks. Further attribution of envelope measure impacts to those reducing electric vs. non-electric loads, however, reveals differences between the two benchmarks. A greater share of non-electric envelope impacts is observed in the moderate benchmark (33% vs. 13% in the aggressive benchmark), as lower equipment EL rates leave more non-electric demand for envelope measures to affect through 2050. This result underscores the potential importance of envelope efficiency deployment as a hedge against slow rates of load EL that would otherwise impede deeper levels of building sector emissions reductions.

The end-use reduction wedges in Figure 3 grow through 2050 with increasing deployments of building efficiency, EL, and flexibility measures. In the moderate and aggressive benchmarks, these deployments occur alongside an electric grid that progressively decarbonizes beyond a reference case, which already assumes significant near-term reductions in electricity emissions due to state-mandated renewable portfolio standards (see supplemental experimental procedures for more details). Figure 3 reiterates the finding from Figure 1 that demand-side measures contribute up to nearly half of total annual building sector CO_2 reductions in 2050—39% (302 Mt of 775 Mt CO_2) and 43% (471 Mt of 1107 Mt CO_2) in the moderate and aggressive benchmarks, respectively. Considered cumulatively from 2023 to 2050, demand-side contributions to CO_2 reductions are 41% (3.7 Gt of 8.9 Gt CO_2) and 32% (6.4 Gt of 20.1 Gt CO_2) in the moderate and aggressive benchmarks, respectively. Figure 4A shows that in the aggressive benchmark, most demand-side CO_2 reductions through 2050 come from building EL measures (280 Mt of 1,107 Mt CO_2, or 25% of total reductions); however, building efficiency measures demonstrate a stronger degree of near-term influence, delivering roughly double the reductions of building EL measures between 2023 and 2030 (vs. about half between 2030 and 2050). This finding is largely owed to the gradual ramp-up of load EL rates under full grid decarbonization (see Figures S15–S18). Under more moderate assumptions with slower rates of EL and grid decarbonization, efficiency measures carry even greater relative near-term influence, delivering about three times the CO_2 reductions of EL measures between 2023 and 2030 (Figure S3A).

Figure 4B highlights that, under the aggressive decarbonization benchmark, 262 Mt of annual building CO_2 emissions remain in 2050, or 11% of the sector's 2005 CO_2 emissions level. Given the fully decarbonized electricity supply in this scenario, remaining emissions come from fossil-fired equipment that has not been switched to electric service by 2050. A large portion of these remaining non-electric emissions are attributable to heating, water heating, and cooking end uses (8% of 2005 levels in

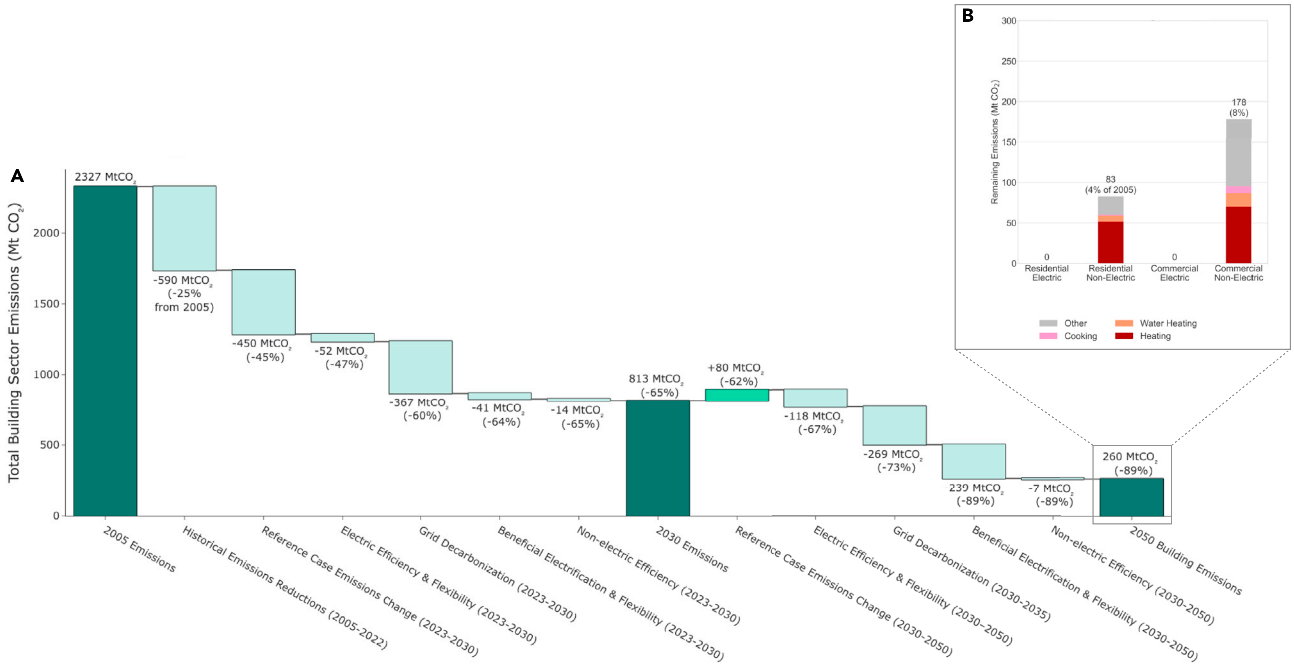


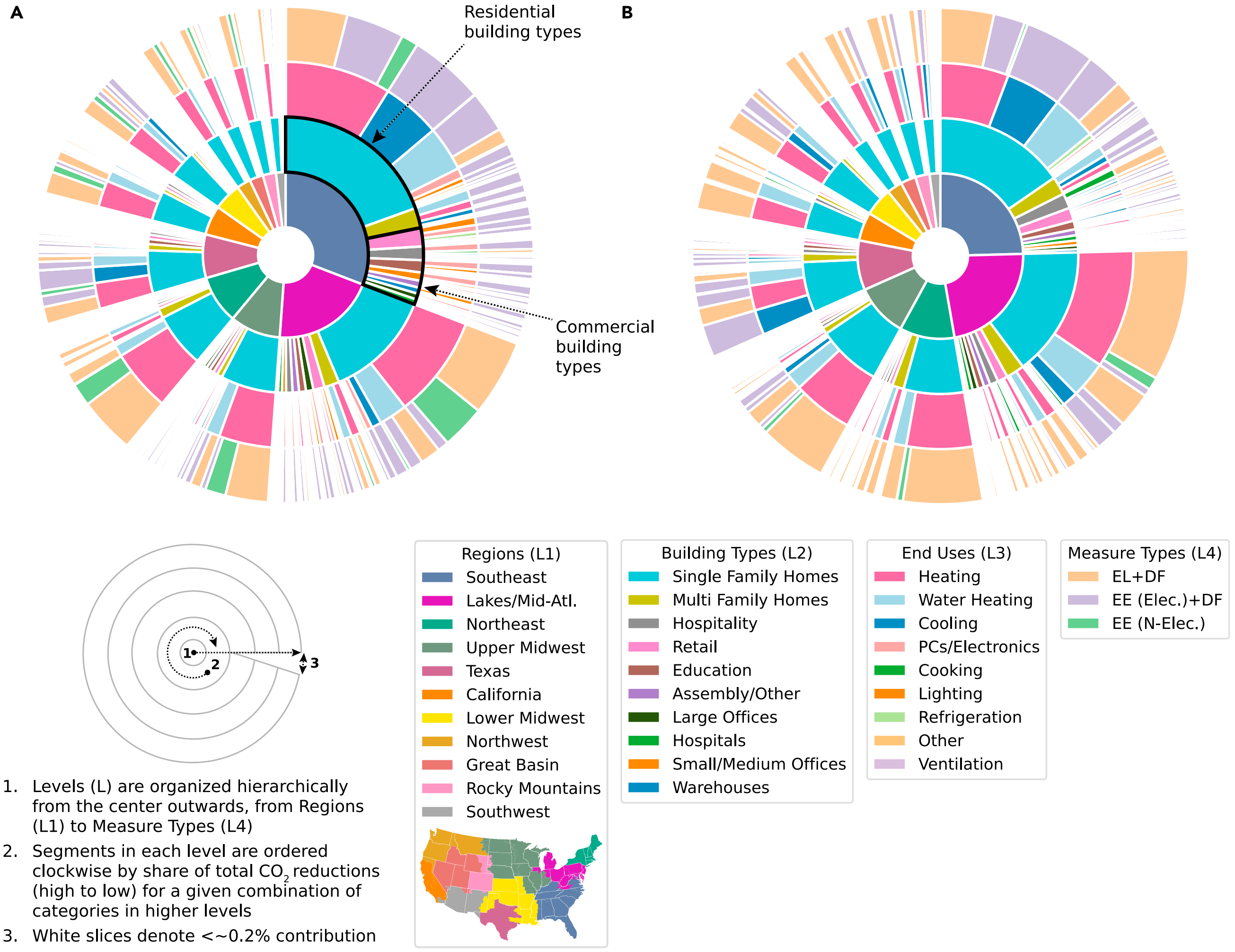
Figure 4. Under an aggressive decarbonization benchmark, demand-side efficiency measures drive near-term reductions in building CO_2 (through 2030), while electrification measures deliver the majority of their impacts in out years (2030–2050)

(A) Reductions from the 2005 building sector emissions level are broken out between 2005 and 2030 and between 2030 and 2050 by source: historical reductions (from 2005 to 2022); reductions projected in the reference case forecast; further demand-side reductions via building efficiency, flexibility, and electrification beyond the reference case; and further decarbonization of the building electricity supply beyond the reference case. A subset of both electrification and efficiency measures is represented with demand flexibility features. Reductions from electric efficiency and flexibility improvements are assessed before considering additional decarbonization of the power supply beyond the reference case, while reductions from electrification and flexibility are staged in parallel with power supply decarbonization. Non-electric efficiency impacts are applied to any non-electric demand that remains after considering the deployment of building load electrification measures. (B) Emissions that remain in 2050 are segmented by building type and end use; the "Other" end use consists of miscellaneous loads such as water pumps, generators, grills, and manufacturing in commercial spaces.[30]

total)—particularly in commercial buildings, which face strong barriers to EL[16] leading to lower EL rates over the long term (see Figures S15–S18). While significant policy attention is focused on addressing such barriers, less is given to the larger segment of remaining non-electric "Other" building CO_2 emissions in Figure 4, which mostly come from loads like manufacturing in commercial spaces and residual fuel oil that EIA classifies as "non-building."[30] These loads, which may be harder to electrify, would comprise nearly 5% of 2005 building sector emissions if left unaddressed.

Figure 5 presents further segmentation of demand-side CO_2 emissions reductions under the aggressive decarbonization benchmark, including geographical breakouts by 11 grid regions, which are aggregations of the 25 EIA Electricity Market Module (EMM) regions used in the modeling for this study (see experimental procedures). The figure reveals a more diverse set of reduction opportunities than that suggested by the higher-level end-use attribution of Figure 3. Considered across the building sector as a whole in 2030 (Figure 5A) and 2050 (Figure 5B), emissions reduction opportunities are strongly weighted toward single family homes in highly populated regions with large heating and cooling service demands and higher reference case electricity emissions—in particular, the Southeast and Great Lakes/Mid-Atlantic. Within these region/building type segments, the most substantial shares of 2030 CO_2 reductions come from heating EL, followed closely by efficiency improvements that reduce heating energy—improvements to the building envelope and conversions of resistance-based heating to heat pumps. The heating fuel source most impacted by efficiency in 2030 differs across regions: more CO_2 reductions come from electric heating efficiency in the Southeast, given the near-term prevalence of resistance-based heating equipment in homes in this region, while CO_2 reductions from non-electric heating efficiency are more prominent in the Great Lakes and other regions like the Northeast and Upper Midwest, where there is higher near-term use of fossil-based heating equipment. This result underscores the importance of considering the intersection of region, building type, and dominant fuel source to determine the types of improvements with the largest potential to deliver near-term emissions reductions. By 2050, end-use and measure type contributions are more heavily weighted toward heating and water heating EL in the regions with high fossil-based demand, which displaces the associated potential for non-electric efficiency (EE) impacts over the long term.

While residential building CO_2 reduction potential in Figure 5 is strongly driven by single family homes, emissions reductions in commercial buildings are far more heterogeneous,



1. Levels (L) are organized hierarchically from the center outwards, from Regions (L1) to Measure Types (L4)
2. Segments in each level are ordered clockwise by share of total CO_2 reductions (high to low) for a given combination of categories in higher levels
3. White slices denote <~0.2% contribution

Figure 5. Under an aggressive decarbonization benchmark, building CO_2 emissions reduction opportunities are strongly weighted toward single family homes in highly populated regions with large heating and cooling service demands and higher reference case electricity emissions

The plot further segments the aggressive decarbonization benchmark scenario's total building emissions reductions in 2030 (A) and 2050 (B), across all building types. Emissions reductions are segmented across the following dimensions, beginning with the inner ring of each plot and moving outwards: region (aggregations of 25 EIA Electricity Market Module regions[31] to 11 higher-level regions); building type (aggregations of the 3 residential and 11 commercial EIA Annual Energy Outlook building types to 2 and 8 residential and commercial building types, respectively, which lumps mobile homes into the "Single Family Homes" category); energy end use; and measure type (electrification paired in some cases with flexibility (EL+DF), electric efficiency paired in some cases with flexibility (EE (Elec.)+DF), and non-electric efficiency (EE (N-Elec.)). Segments within each level are ordered clockwise by share of total CO_2 reductions (high to low), and white slices denote segments with less than approximately 0.2% contribution to total CO_2 reductions.

given the wide variety of commercial building types and uses (also see Figure S4). Nevertheless, when aggregated across building types, commercial building emissions reductions constitute an important driver of building sector decarbonization, contributing 28% and 25% of total reductions across regions in 2030 and 2050, respectively, and up to 32% in Texas in 2030 (also see Figure S7). Five commercial building types—retail, education, hospitality, offices, and assembly buildings—are consistently among the top contributors to emissions reductions in the most influential regions, therefore solutions that apply across these building types will be particularly impactful. Commercial heating reductions are notable, especially in colder regions such as the Great Lakes/Mid-Atlantic, Northeast, and Upper Midwest. Other commercial end uses—notably lighting and computers (PCs)/electronics in 2030, water heating in 2050, and cooking in hospitality environments in 2050—are attributed reduction shares that are comparable with or greater than those of heating in warmer regions like the Southeast.

Up to \$107 billion in annual power system cost savings by 2050

Finally, we examine the implications of widespread demand-side measure deployment in buildings for power sector decarbonization. Specifically, we analyze the same measures and grid scenarios discussed previously under the moderate and

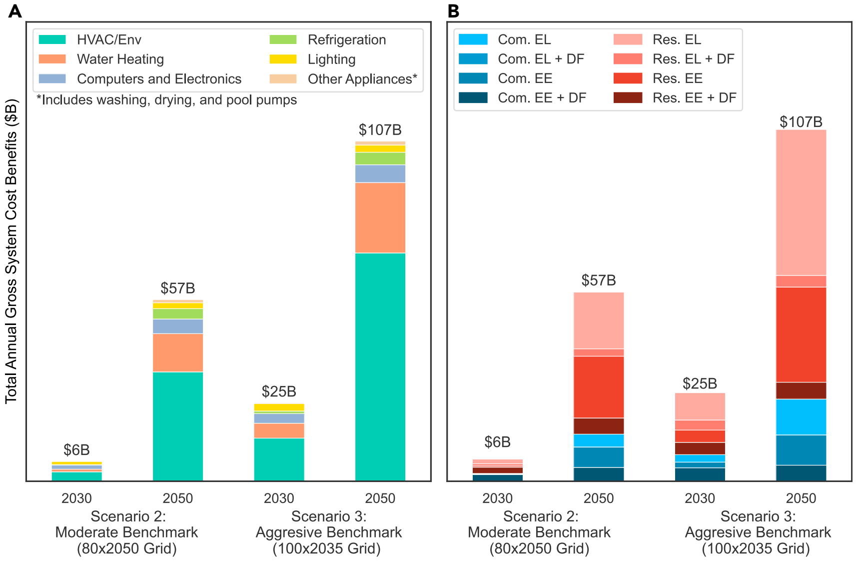


Figure 6. Moderate to aggressive deployment of building efficiency and flexibility measures generates $57–$107 billion in annual power system cost savings by 2050, or 34%–35% of the incremental cost of additional power supply decarbonization before accounting for the cost of the portfolio of demand-side measures

System cost savings are broken out by end use (A) and by measure and customer type (B). Benefits of the measure portfolio represent avoided generation and transmission investments given full portfolio deployment, in 2022$. EL measure benefits involve switching from an inefficient to an efficient EL measure, yielding positive power system benefits in our analysis. Energy efficiency measures are abbreviated in the figure as EE. A subset of both EL and EE measures is represented with DF features. Non-electric measures are excluded from these results, thus excluding natural gas system cost savings. Avoided distribution system investments are also not accounted for in our analysis.

aggressive decarbonization benchmark scenarios (2 and 3) to determine the extent to which the demand-side measures impact bulk power system generation and transmission costs and to gain insight into the cost-effectiveness of the measure portfolio.

Given that the focus of this analysis is on power sector cost savings, we specifically analyze measures that reduce building electricity use. When considering EL measures, we assess the potential benefits of efficient building end-use EL relative to a baseline that deploys a substantial portion of less efficient resistance heating and water heating equipment in lieu of heat pumps (consistent with EL efficiency assumptions from scenario 1.1, see methods). This allows us to isolate the impacts of efficiency and flexibility, including deployment of more efficient and flexible building end-use EL measures.

Decarbonizing the US power supply will require a large buildout of renewable generation, energy storage, and flexible clean generation technologies with significant implications for costs. Under moderate to aggressive grid decarbonization in the absence of additional building efficiency, flexibility, and efficient building end-use EL measures, the total amount of generation capacity needed in 2050 is 2.6–3.1 times the current amount of power system capacity (Figure S9). The increase is due to the incremental load growth from inefficient building end-use EL and EL of transportation, as well as satisfying the goal of a deeply decarbonized power sector. This compares to approximately 50% higher generation capacity in 2050 under reference case assumptions that are limited to the impacts of existing state-level climate legislation. By 2050, in the absence of new demand-side measures, we estimate $385–$520 billion per year in capital expenditures and production costs (Figure S10). This range is 1.8–2.4 times the $216 billion of forecasted 2050 annual expenditures in the GridSIM Reference Case.

Building end-use efficiency and flexibility can reduce the cost of decarbonizing the power sector by reducing overall electricity consumption and peak demand, and shifting usage to hours when it is less costly to serve. The result is a reduction both in fixed generation and transmission costs (i.e., capital investment and fixed operations and maintenance) and in variable generation costs (i.e., fuel and variable operations and maintenance) that were otherwise incurred to serve demand under the power sector decarbonization targets, before taking into account building efficiency and flexibility (see experimental procedures). Figure 6 shows that, by 2050, we estimate that these benefits could amount to gross cost savings of $57–$107 billion per year, or 34%–35% of the incremental fixed and variable costs of additional power supply decarbonization before accounting for the cost of the portfolio of demand-side measures. Consistent with the estimates of emissions savings, Figure 6A shows that HVAC and envelope measures account for a large share of total system cost savings due to the overall magnitude of heating and cooling loads and the high efficiency of technologies that are available to reduce them. Figure 6B further shows that efficient EL measures generate the largest share of cost savings in the aggressive benchmark (scenario 3), while EE and electric efficiency with flexibility (EE + DF) measures generate a larger share of cost savings under the moderate benchmark with slower EL. Finally, a majority of the 2050 cost reduction potential (74%–76%) is attributable to residential measures, which generally have larger electricity savings potential than commercial measures.

The gross benefits discussed above do not account for the costs of the demand-side measures. Under the aggressive benchmark, where technologies with breakthrough cost and performance characteristics are assumed to enter the market earlier, and the total cost of demand-side measure deployment is generally lowest, the total incremental cost of the measure portfolio in 2050 is $127 billion, of which 84% is covered by the $107 billion in system cost savings benefits that the measure portfolio generates. This estimate is strongly influenced, however, by a small portion of measures with high incremental deployment costs that are more than double their benefits

(Figure S12). Generally, these high-cost measures are packages of best currently market-available HVAC equipment with flexible control capabilities and envelope efficiency improvements. Excluding this high-cost portion of the measure portfolio retains most of its system cost benefits ($99 billion) but at a substantially lower total incremental deployment cost ($73 billion). These findings suggest that initiatives aimed at reducing the incremental costs of installing the highest-performing HVAC and envelope technologies on the market today would be one of the most effective strategies for driving down the overall costs of reducing building electricity demand to support accelerated grid decarbonization.

DISCUSSION

We show that strategic reduction and management of US building energy demand alongside full grid decarbonization could sharply decrease building sector CO_2 emissions by mid-century, up to a 91% reduction from 2005 levels. A reduction of this magnitude would avoid nearly one-quarter of the total energy system CO_2 emissions projected for 2050 under reference case conditions, more than 1 Gt CO_2 in absolute terms. Moreover, our results demonstrate that demand-side solutions in buildings greatly reduce the costs of power sector decarbonization, avoiding up to well over $100 billion per year in power system costs by 2050. Our study represents building decarbonization measures and their interactions with the grid in detail, although key methodological limitations remain that are discussed further in the experimental procedures.

There are no "silver bullet" solutions for building decarbonization. Decarbonizing the electricity supply contributes more than half of total building CO_2 reduction potential in 2050 and enables CO_2 reductions from building EL, for example, yet parallel demand-side changes are needed to reach deeper levels of emissions reductions while mitigating increases in power system costs. On the demand side, we find that solely pursuing EL significantly limits demand-side contributions to CO_2 emissions reductions and that if parallel gains in efficiency and flexibility are not made, building electricity demands could grow substantially, putting strain on the electric grid. Because building end-use EL only occurs gradually under a reasonable range of stock turnover and adoption assumptions, building efficiency and flexibility are important near-term strategies with substantial contributions to overall reductions in building sector CO_2 emissions and power system costs through 2050. Efficiency and flexibility can also support increased EL at all scales: at the building scale (e.g., by decreasing the required capacity of electrified equipment and avoiding behind-the-meter electrical infrastructure upgrades); at the distribution scale (e.g., by mitigating new loads that could necessitate upgrades to transformers and other distribution grid infrastructure); and at the bulk power scale (e.g., by reducing the system peak generation capacity needed to serve electrified end uses).

Our analysis directly represents a heterogeneous portfolio of building solutions and quantifies their individual and collective contributions to energy system CO_2 emissions reductions through mid-century. This portfolio includes measures that reduce and/or manage demand for building energy services, such as improvements to the building envelope and operational controls, and we show that such measures are as critical to energy and CO_2 reductions as building equipment efficiency and EL measures. Our modeling approach contrasts markedly with that of previous cross-sectoral decarbonization studies, which tend to reduce building sector decarbonization to aggressive equipment EL and lack the detailed, bottom-up treatment of building technology development and deployment dynamics that is needed to guide real-world policy approaches.

While our results encourage more substantive consideration of buildings as a critical demand-side resource for energy system decarbonization, our data also underscore the unprecedented scale and speed with which building technology development and deployment must occur to enable the deepest levels of building sector emissions reductions and power system benefits by 2050. Table 2 shows that, in our aggressive benchmark, 98 million fossil-based and resistance furnaces and 141 million fossil-based and resistance water heaters are converted to heat pumps in residences between 2023 and 2050, resulting in a 4- and 12-fold increase in the deployment of residential air source heat pumps and heat pump water heaters over the reference case, respectively (Table S1). Commercial heat pumps serve 644 more TBtus of heating and water heating service demand annually by 2050 than in the reference case, a 10-fold increase (Table S2). These heat pump deployments occur alongside widespread building envelope retrofits to more efficient components—by 2050, 109 million of the homes and 43 billion of the commercial square feet built by 2023 have undergone at least one component retrofit at or above the latest ENERGY STAR/IECC/ASHRAE 90.1 performance levels, implying efficiency retrofit rates of 3% and 1.6% per year, respectively. Another 34 million homes and 58 billion commercial square feet added in 2023 or later are at or above this envelope performance tier, or 97% and 90% of new residential and commercial construction over this period, respectively. Finally, advanced controls unlock more efficient and flexible energy management capabilities in many buildings—such controls are deployed with 79% and 57% of all residential and commercial HVAC stock, respectively, and serve 75% of all commercial lighting stock by 2050.

Realizing this unprecedented level of change in the building sector will require a rapid and sustained increase in investment alongside policy and regulatory support. The recently passed Inflation Reduction Act and Bipartisan Infrastructure Law include several funding programs that support building decarbonization, but initial estimates suggest that these laws will only spur a fraction of the low-carbon building technology deployment that our study finds is necessary to achieve aggressive emissions reductions by mid-century (e.g., Smedick et al.[32]). Key deployment barriers include lack of familiarity with low-carbon technologies among installers and consumers, high initial technology installation costs, uncertainty about technology performance and impacts on energy bills, and the slow pace with which incumbent technologies are retired. As such, legislative advancements must be accompanied by complementary levers for accelerating progress, such

Table 2. Achieving the deepest building CO_2 reductions by mid-century requires deployment of high-performance building technologies and operational approaches at an unprecedented scale and speed

	Residential			Commercial		
Advancement	2030	2050	Annualized △ (2023–2050)	2030	2050	Annualized △ (2023–2050)
Convert fossil-fired and resistance heating/WH equipment to HPs	43 M units	239 M units	8.5 M units/yr (52% sales)	84 TBtus service demand	644 TBtus service demand	23 TBtus service demand/yr (20% sales)
HPWHs	27 M units	141 M units	5 M units/yr	33 TBtus demand	317 TBtus demand	11 TBtus demand/yr
ASHPs	16 M units	98 M units	3.5 M units/yr	51 TBtus demand	327 TBtus demand	12 TBtus demand/yr
Envelope retrofits at or above ESTAR/IECC/90.1 levels in the column year	26 M homes	109 M homes	4 M homes/yr (3% existing[a] homes)	7 Bsf	43 Bsf	1.5 Bsf/yr (1.6% existing[a] sf)
Roofs	26 M homes	109 M homes	4 M homes/yr	6 Bsf	43 Bsf	1.5 Bsf/yr
Windows	21.5 M homes	104 M homes	4 M homes/yr	7 Bsf	43 Bsf	1.5 Bsf/yr
Walls[b] and/or floors	6 M homes	32 M homes	1 M homes/yr	2 Bsf	15 Bsf	0.5 Bsf/yr
New building shells constructed at or above ESTAR/IECC/90.1 levels in the column year	9 M homes	34 M homes	1 M homes/yr (97% new homes)	12 Bsf	58 Bsf	2 Bsf/yr (90% new sf)
Pair new/replacement HVAC equipment with advanced controls[c] that enable demand management	21% of all installed units	79% of all installed units	3% of all installed units	9% of all service demand	57% of all service demand	2% of all service demand
Pair new/replacement lighting with advanced controls[c] that enable demand management	4% of all installed units	49% of all installed units	2% of all installed units	59% of all service demand	75% of all service demand	3% of all service demand

The actions shown reflect an aggressive benchmark in which building efficiency, flexibility, and electrification are aggressively deployed alongside a power grid that decarbonizes 100% by 2035. M, million. WH, water heating. HPWH, heat pump water heater. ASHP, air source heat pump. TBtus, trillion British thermal units. Bsf, billion square feet. sf, square feet.

[a] Benchmarked to existing homes/sf in 2023.

[b] Includes air sealing.

[c] Controls measures at or above the "Best" performance tier.

as aggressive building codes and standards, supportive electricity rate designs, market transformation activities that encourage early retrofits, and emerging technology research and development.

Moreover, even if the ambitious deployment milestones in Table 2 are achieved, additional advancements will be needed to address building CO_2 emissions that could remain by 2050—at least 216 Mt CO_2 annually from building operations, in our assessment (scenario 3.1). (This does not account for unmitigated embodied emissions from building material life cycles outside the operational phase, which may also be substantial.[24]) Remaining building emissions could be offset by two sources of negative emissions: (1) land use, land-use change, and forestry (LULUCF) and (2) negative emissions technologies (NETs) such as direct air capture, bioenergy with carbon capture and storage, or other forms of natural or engineered carbon removals. The role of these offsets in energy system decarbonization is the subject of vigorous debate; nevertheless, the potential magnitude of offsets provides a benchmark for the compatibility of remaining building sector emissions with a net-zero by 2050 target. Historical data and modeling suggest that LULUCF and NETs could offset roughly 750 Mt CO_2-eq and up to 500 Mt CO_2 in the US, respectively.[33,34] Allocated proportionally to end-use sector contributions to US GHG emissions,[33] these offsets amount to about 375 Mt CO_2 for buildings, enough to address the remaining CO_2 emissions from building operations in our most aggressive decarbonization scenarios (3–3.1). However, available offsets will likely need to be weighted toward harder-to-abate energy services such as aviation, long-distance transport, and shipping,[35] and large uncertainties concerning the scalability of NETs make them a high-risk bet for building emissions offsets.[36] Blending renewable hydrogen fuel with the US natural gas supply or replacing natural gas with hydrogen entirely could further abate up to 61 Mt CO_2 from US building heating by 2050[37]; however, existing evidence casts doubt on the widespread use of hydrogen heating, given disadvantages on economics, efficiency, and resource intensity,[38] and hydrogen heating may present particular affordability issues for the customers that are least able to electrify equipment.[39]

Furthermore, our building CO_2 emissions estimates could be affected by consideration of the fugitive emissions associated with building operations: GHG emissions from leakage of building equipment refrigerants and from methane leaks in the natural gas supplied to buildings. An initial assessment of these two fugitive sources demonstrates that accounting for avoided methane leakage from EL and efficiency delivers up to 5× the CO_2-eq impacts of accounting for added refrigerant leakage from EL, resulting in small but notable overall increases in total estimated CO_2-eq emissions reductions (see Note S5 and Figure S14). This finding is supported by the limited existing literature on this topic[40,41]; however, such studies concern the individual building scale rather than the stock scale reflected here. Moreover, fugitive emissions estimates are likely sensitive to assumptions about reference case developments in equipment refrigerants and considerable uncertainties in estimated methane leakage rates. We consider the estimation of fugitive emissions in buildings, as well as the assessment of embodied emissions generated outside the building operation phase, to be important areas for further research.

The US transition to a low-carbon energy system is well underway, with energy-related CO_2 emissions having fallen steadily over the past decade. But achieving the deeper levels of emissions reductions targeted by economy-wide decarbonization plans will require a comprehensive mix of solutions addressing both the generation and end uses of energy. Buildings occupy a critical intersection between energy supply and demand and, as such, offer a wide range of opportunities to reduce or enable reductions in US CO_2 emissions. As the power grid decarbonizes, building EL is a clear strategy for reducing emissions, but building efficiency and flexibility are equally essential, both to limit the scale of the required supply-side transformation and to facilitate high rates of EL—a true "all-of-the-above" menu of solutions to decarbonize the built environment.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to the lead contact, Jared Langevin (jared.langevin@lbl.gov).

Materials availability

No materials were used in this study.

Data and code availability

The code base used to generate the paper's results, results data, and supporting datasets is available on GitHub.[42] Instructions for executing the Scout model to generate the demand-side data for the study, along with other key data and results, are also available. Original data have been deposited to Mendeley Data: https://doi.org/10.17632/sc4jxrn9nh.1.

Building and grid modeling frameworks

Figure 7 summarizes key data produced by the building and grid models used in this analysis and highlights model linkages. Here, we describe each of these models and their interaction in greater detail.

Scout modeling of the building sector

Building decarbonization solutions are represented using Scout (scout.energy.gov), a hybrid[43] building stock modeling framework for estimating the short- and long-term annual impacts of EE, flexibility, and EL measures on building energy use, CO_2 emissions, and operating costs at the scale of US regions or across the US as a whole. (In the model classification quadrants of Langevin et al.,[43] the Scout framework 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.) Simulations are consistent with Scout v.0.7.3[44] with a few study-specific modifications to the code and measure base.[42] Here, we focus on key elements of Scout's modeling approach for the current assessment; further details are found in this paper's supplemental experimental procedures as well as in the experimental procedures and supplemental information of Langevin and co-workers.[12,45]

Scout analyses are founded on bottom-up representation and aggregation of specific segments of the US building technology stock and its annual energy use, $S_y^{\text{euse}-\text{ref}}$, and CO_2 emissions, $S_y^{\text{carb}-\text{ref}}$, under reference case building and power sector evolution in each year y between 2023 and 2050:

$$S_y^{\text{euse}-\text{ref}} = \sum_r^R \sum_b^B \sum_f^{F_b} \sum_u^{U_{b,f}} \sum_t^{T_{b,f,u}} \sum_v^V S_{r,b,f,u,t,v,y}^{\text{stk}-\text{ref}} I_{r,b,f,u,t,v,y}^{\text{euse}-\text{ref}} \qquad \text{(Equation 1)}$$

$$S_y^{\text{carb}-\text{ref}} = \sum_r^R \sum_b^B \sum_f^{F_b} \sum_u^{U_{b,f}} \sum_t^{T_{b,f,u}} \sum_v^V S_{r,b,f,u,t,v,y}^{\text{stk}-\text{ref}} I_{r,b,f,u,t,v,y}^{\text{carb}-\text{ref}} \qquad \text{(Equation 2)}$$

where $S_{r,b,f,u,t,v,y}^{\text{stk}-\text{ref}}$ is the stock total for the typical reference case building technology in class t in year y that serves end use u with fuel type f in building type b,

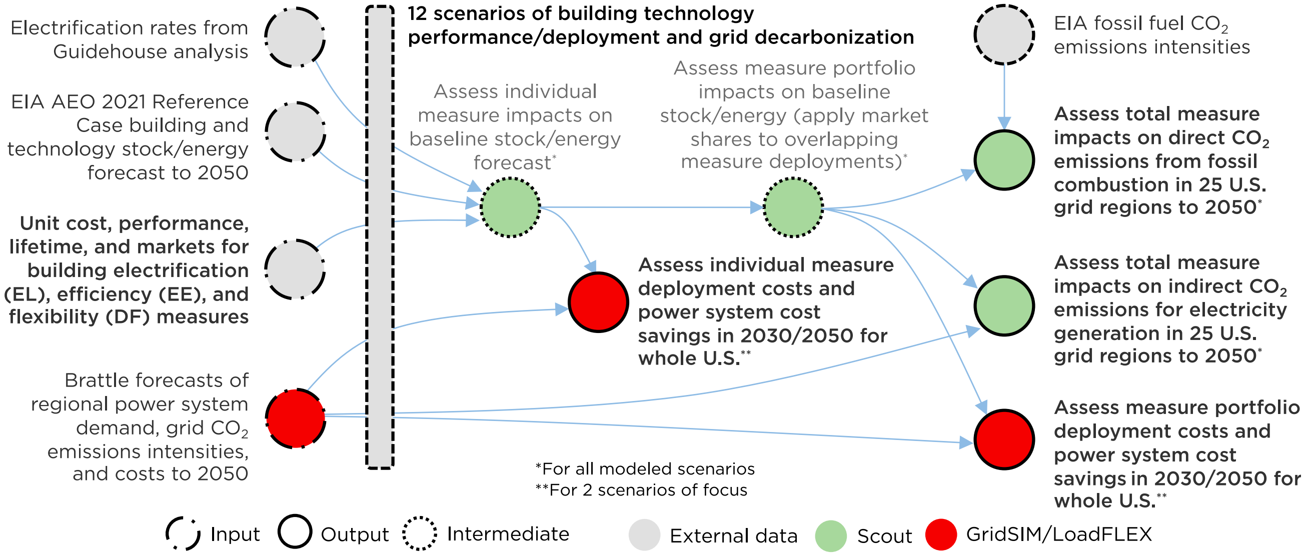


Figure 7. Results are generated through an integrated demand- and supply-side modeling workflow and outputs

Demand-side measures (building efficiency, flexibility, and electrification) are assessed with the Scout model relative to the EIA Annual Energy Outlook 2021 Reference Case forecast from 2023 to 2050, with rates of building electrification exogenously determined via target scenarios developed in consultation with Guidehouse. Resultant Scout scenario measure costs, hourly system load impacts, and estimates of annual building electricity demand through 2050 are coupled with power sector projections from the GridSIM model to assess measure-level deployment costs, electricity CO_2 emissions reductions, and power system cost reductions. Direct reductions in CO_2 emissions from on-site combustion of fossil fuels are assessed by coupling Scout estimates of annual building fossil fuel demand through 2050 with EIA fossil fuel emissions intensities.

vintage v, and region r (e.g., the stock in a "microsegment" of the building sector, subsequently denoted by X); $I^{euse-ref}_{r,b,f,u,t,v,y}$ is the reference case site energy use per unit stock of the given technology microsegment in year y; and $I^{carb-ref}_{r,b,f,u,t,v,y}$ is the reference case average CO_2 emissions per unit stock deployed in year y (unit energy consumption multiplied by average CO_2 emissions per unit consumption). We draw reference case estimates of building technology stock evolution, unit energy consumption, and CO_2 emissions per unit fossil-based fuel consumption from the 2021 EIA AEO Reference Case.[30] AEO 2021 total and unit-level consumption data are calibrated to base year data from the 2012 Commercial Building Energy Consumption Survey (CBECS) and 2015 RECS,[46,47] which account for variations in the installed base of building and technology stock and consumption across building vintages, types, and regions. Reference case estimates of CO_2 emissions per unit electricity consumption are drawn from the Brattle GridSIM Reference Case (see below for additional details). The region set R is consistent with the 25 EIA EMM regions,[48,49] with aggregation to 11 higher-level regions for reporting purposes and sets of building types (B), fuel types (F_b), end uses ($U_{b,f}$), and technology types ($T_{b,f,u}$) correspond to those used in the National Energy Modeling System building modules to develop the AEO forecast.[48,49] The set of building vintages (V) reflects two bins—buildings constructed by 2023 and in 2023 or subsequent years, with associated implications for technology stock turnover calculations. See supplemental experimental procedures for further details on region mapping and stock calculations.

Changes in reference case building energy and emissions projections under various scenarios of building decarbonization are assessed at the level of individual building decarbonization measures, each of which is applied to particular segments of the reference case building stock during the year range that the measure is made available to energy consumers. Alternate scenario estimates of energy, $S^{euse-alt}_{y,m}$, and CO_2 emissions, $S^{carb-alt}_{y,m}$, are constructed that reflect the effects of measure m deployment through year y on reference case outcomes:

$$S^{euse-alt}_{y,m} = \sum_{r}^{R_m}\sum_{b}^{B_m}\sum_{f}^{F_{b,m}}\sum_{u}^{U_{b,f,m}}\sum_{t}^{T_{b,f,u,m}}\sum_{v}^{V_m}\Big(S^{stk-ref}_{X,y}\, I^{euse-alt}_{X,y,m,mt}\, \sigma_{X,y,m} + S^{stk-ref}_{X,y}\, I^{euse-ref}_{X,y}\left(1-\sigma_{X,y,m}\right)\Big)a_{X,y,m} \qquad \text{(Equation 3)}$$

$$S^{carb-alt}_{y,m} = \sum_{r}^{R_m}\sum_{b}^{B_m}\sum_{f}^{F_{b,m}}\sum_{u}^{U_{b,f,m}}\sum_{t}^{T_{b,f,u,m}}\sum_{v}^{V_m}\Big(S^{stk-ref}_{X,y}\, I^{carb-alt}_{X,y,mt}\, \sigma_{X,y,m} + S^{stk-ref}_{X,y}\, I^{carb-ref}_{X,y}\left(1-\sigma_{X,y,m}\right)\Big)a_{X,y} \qquad \text{(Equation 4)}$$

where region set R_m, building type and vintage sets (B_m and V_m), fuel types ($F_{b,m}$), end uses ($U_{b,f,m}$), and technology types ($T_{b,f,u,m}$) are the subsets of the sets in Equations 1 and 2 that measure m applies to (an applicable "market"); $S^{stk-ref}_{X,y}$ is a single reference case building stock microsegment from the measure's applicable market in year y; $I^{euse-ref}_{X,y}$ and $I^{carb-ref}_{X,y}$ are the reference case energy and fuel CO_2 per unit stock deployed as described for Equations 1 and 2; $I^{euse-alt}_{X,y,m,mt}$ and $I^{carb-alt}_{X,y,m,mt}$ are the same for the alternate case deployment of measure m of type mt; $\sigma_{X,y,m}$ is the portion of the reference case stock that has been captured by measure m through year y; and $a_{X,y,m}$ is a market share adjustment. The market share adjustment accounts for economic competition between measure m, a reference case counterfactual technology, and any other alternate scenario measures that provide the same energy service through year y. For example, a low-cost reference case cooling technology might compete with two higher-cost measure alternatives, resulting in market share adjustments of 0.5 for the reference case technology (captures 50% of the competed market) and 0.25 for each of the competing alternatives (each capture 25% of the competed market). See supplemental experimental procedures for additional details on handling of stock turnover and overlaps across measures. Note that setting the $\sigma_{X,y,m}$ term in Equations 3 and 4 to zero produces reference case counterfactual results at the measure level, $S^{euse-ref}_{y,m}$ and $S^{carb-ref}_{y,m}$, which are compared against the results of Equations 3 and 4 to assess measure-specific energy and CO_2 impacts.

To facilitate representation of a wide range of building decarbonization solutions, the per-unit energy consumption and CO_2 emissions terms in Equations 3 and 4, $I^{euse-alt}_{X,y,m,mt}$ and $I^{carb-alt}_{X,y,m,mt}$, are dependent on the measure type mt, and are calculated as follows:

$$I^{euse-alt}_{X,y,m,mt} = \begin{cases} I^{euse-ref}_{X,y}\, RP^{euse-ann}_{X,y,m}, & mt \in [EE, EL] \\ I^{euse-ref}_{X,y}\, RP^{euse-tvar}_{X,y,m} & mt \in [EE+DF, EL+DF] \end{cases} \qquad \text{(Equation 5)}$$

$$I^{\mathrm{carb-alt}}_{X,y,m,mt} = \begin{cases} I^{\mathrm{carb-ref}}_{X,y}\, RP^{\mathrm{euse-ann}}_{X,y,m}, & mt = EE \text{ or } mt = EL \text{ and } f \in X = electric \\ I^{\mathrm{carb-ref}}_{X,y}\, RP^{\mathrm{euse-ann}}_{X,y,m} \left(\tau^{\mathrm{alt}}_{r,f=elec,y} \middle/ \tau^{\mathrm{ref}}_{r,f\in X,y}\right), & mt = EL \text{ and } f \in X \neq electric \\ I^{\mathrm{carb-ref}}_{X,y}\, RP^{\mathrm{carb-tvar}}_{X,y,m} & mt \in [EE+DF, EL+DF] \end{cases} \qquad \text{(Equation 6)}$$

where $RP^{\mathrm{euse-ann}}_{X,y,m}$ and $RP^{\mathrm{euse-tvar}}_{X,y,m}$ both denote the unit-level site energy consumption of measure m in year y relative to the counterfactual reference case technology that provides the same energy service, but the former is calculated using annual energy performance metrics (e.g., COP, EF, annual consumption ratios, etc.) while the latter accounts for time-varying relative energy performance across all hours in a year; $RP^{\mathrm{carb-tvar}}_{X,y}$ is interpreted in the same manner as $RP^{\mathrm{euse-tvar}}_{X,y}$ but for relative CO_2 emissions per unit instead of energy use; $\tau^{\mathrm{ref}}_{r,f\in X,y}$ and $\tau^{\mathrm{alt}}_{r,f=elec,y}$ are average annual CO_2 intensities for the reference case technology fuel type ($f \in X$) and electricity ($f = elec$), respectively, for a measure m that electrifies building loads ($mt = EL$) in region r and year y. The time-varying energy and CO_2 performance terms in Equations 5 and 6 ($RP^{\mathrm{euse-tvar}}_{X,y}$ and $RP^{\mathrm{carb-tvar}}_{X,y}$) address measures with DF features that non-uniformly shed and/or shift building loads across time. Further details on the hourly load calculations for such measures are available[12] and hourly emissions and consumer cost calculations are further detailed in the supplemental experimental procedures.

Equation 6 assesses each measure's CO_2 per unit stock $I^{\mathrm{carb-alt}}_{X,y,m,mt}$ relative to a counterfactual term $I^{\mathrm{carb-ref}}_{X,y}$ that reflects reference case fuel CO_2 intensities. In the case of a microsegment X with an electric fuel type f, this effectively stages the CO_2 impacts of reductions in electricity consumption from demand-side measures *before* the impacts of additional grid decarbonization beyond the reference case. This approach differs from most previous cross-sectoral decarbonization studies, which tend to attribute reductions in existing electric CO_2 emissions to the power sector, thus precluding any CO_2 impacts from building EE. (A notable exception is Schreyer et al.,[50] which also effectively assesses the emissions impacts of demand-side efficiency before the impacts of additional decarbonization of the electricity supply.) For EL measures, the CO_2 impacts of changing from a fossil-based fuel and equipment type to electric equipment are assessed in parallel with grid decarbonization and attributed to the measure via the CO_2 intensity ratio $\left(\tau^{\mathrm{alt}}_{r,f=elec,y} / \tau^{\mathrm{ref}}_{r,f\in X,y}\right)$. For non-EL measures, the same ratio is applied to any reference case electricity that remains after measure deployment to account for the impacts of additional grid decarbonization on building CO_2 emissions.

Finally, alternate scenario energy and CO_2 results at the measure-level are aggregated across the full measure portfolio M to develop national-scale energy and CO_2 emissions time series from 2023 to 2050, $S^{\mathrm{euse-alt}}_{y}$ and $S^{\mathrm{carb-alt}}_{y}$, that can be directly compared against the reference case estimates of Equations 1 and 2:

$$S^{\mathrm{euse-alt}}_{y} = \sum_{m}^{M} S^{\mathrm{euse-alt}}_{y,m} \qquad \text{(Equation 7)}$$

$$S^{\mathrm{carb-alt}}_{y} = \sum_{m}^{M} S^{\mathrm{carb-alt}}_{y,m} \qquad \text{(Equation 8)}$$

While Equations 1, 2, 7, and 8 focus on the whole US building sector, other aggregations of the results to the regional level or across subsets of building types, fuel types, and measures are enabled by the bottom-up approach that is used to construct these high-level energy and emissions estimates.

GridSIM and LoadFlex modeling of the power sector

Power system outcomes are modeled with GridSIM,[28] a proprietary long-term power system simulation and capacity expansion model developed by The Brattle Group. GridSIM analyzes how clean energy policies and technological change will affect future power system outcomes, particularly in high-renewable futures, over a multi-decade planning horizon. Like other expansion models, GridSIM identifies the cost-minimizing generation capacity expansion plan and accompanying power system operations, given information about existing power generation and transmission, and expectations about electricity demand, technology costs, fuel prices, and environmental policies, among other considerations.

GridSIM models electricity demand on a chronological hourly basis, so that storage can be scheduled and traditional generation can be committed to balance variable wind and solar output. This is necessary for representing the value of each technology and developing a credible investment trajectory in a high-renewable future.

In addition, GridSIM incorporates how the effective load-carrying capability (ELCC) of each type of variable wind and solar resource is likely to decline in the future with increasing penetration. It incorporates declining ELCC curves, accounting for correlated generation profiles and their coincidence with peak net loads. This, along with the chronological operations representation described above, enables GridSIM to project a realistic generation build mix and associated marginal costs. Table 3 summarizes key methodological elements of the GridSIM modeling framework as it was applied in this study, and further details are provided in the supplemental experimental procedures.

Brattle's LoadFlex model[54] is used in conjunction with GridSIM to calculate the economic benefits of measures with DF features at the grid level. LoadFlex simulates the hours of dispatch for each flexibility measure that maximize economic benefits across energy and generation capacity. If, on any day, shifting a measure's load from its baseline would result in a net increase in system costs rather than a reduction, the measure is not dispatched (i.e., no load is shifted from baseline). The dispatch of each measure is constrained by the physical behavior of each measure at the building level as represented in Scout; these constraints are further described in the supplemental experimental procedures.

Building-grid model coupling

Building and grid models are loosely coupled via a one-way exchange of data between GridSIM and Scout that occurs in both directions without any real-time feedback. Regarding the former, GridSIM projections establish reference and alternative scenario values for the CO_2 intensity of the building electricity supply, which are used to calculate the CO_2 per unit stock terms in Equations 2 and 4. Regarding the latter, GridSIM estimates of power system costs are adjusted to reflect Scout estimates of hourly electricity demand impacts from building efficiency, flexibility, and efficient EL deployment at the grid region level in a given year, taking into account seasonal changes in load shapes, $\Delta D_{r,y,h,m,mt}$:

$$\Delta D_{r,y,h,m,mt} = \left(D^{ref}_{r,y,h,m,mt} - D^{alt}_{r,y,h,m}\right) a_{r,y,m} \qquad \text{(Equation 9)}$$

where $D^{ref}_{r,y,h,m,mt}$ is the reference case electricity demand profile of all stock segments affected by measure m of type mt in grid region r, projection year y and hour h, $D^{alt}_{r,y,h,m}$ is the same profile after measure m is deployed in isolation (e.g., considering only the measure's unit-level impacts on load and baseline stock turnover across the grid region), and $a_{r,y,m}$ is a market share adjustment that accounts for competition between measure m and other technologies that provide the same end use service in region r through year y. The market share adjustment term in Equation 9 enables aggregation of measure-level impacts across a full portfolio with overlaps in the applicable baseline markets of individual measures in the portfolio; excluding this term yields results for the individual measures, before considering aggregation and competition across a portfolio.

Table 3. Summary of key GridSIM modeling elements as applied in the current analysis

Input	Summary
Geographic scope and resolution	Contiguous US, 25 EIA Electricity Market Module (EMM) regions.[31]
Temporal scope and resolution	Annual results are forecasted between 2020 and 2050 in 5-year increments. Within a given projection year, GridSIM utilizes a "typical days" representation of hourly load conditions, which is a common approach for capacity expansion models. The 365 days of the year are clustered based on similarities in daily load level and hourly shape. Reducing the number of days modeled to a subset based on these representative clusters allows the model to capture the full range of load and renewable generation conditions that are necessary to consider from a planning standpoint, while keeping the model runtime manageable. Using typical days also allows the model to retain intra-day hourly chronology, which is important to accurately account for the impact of the hourly profiles of demand-side efficiency, flexibility, and electrification programs.
Load forecast	*Reference case:* Annual electricity projections are based on regional peak demand and energy forecasts from the 2021 AEO Reference Case.[30] Current load shapes are based on aggregated 2020 hourly utility load data from the FERC 714 dataset,[51] with modifications to account for changes in the annual load factor implied in the AEO growth rates. *Decarbonization scenarios (2 and 3):* additional incremental load is assumed to represent electrification of the transportation and buildings sectors. Elevated growth in transportation demand assumes that 95%, 50%, and 35% of light-duty, medium-duty, and heavy-duty vehicles are electric by 2050, respectively. Elevated growth in building demand is consistent with deployment of the measure set assumed in this study's inefficient electrification scenario (1.1) at the electrification rate assumed for the given decarbonization scenario, which results in up to a 23% increase over reference building annual electricity demand by 2050 in the high decarbonization benchmark scenario (3).
Existing unit characteristics	The assumed capacity, heat rate, location, fixed operations and maintenance (O&M), and variable O&M of existing generation is based on assumptions in the 2021 AEO. Planned retirements of existing units are based on documentation of NREL's ReEDS model (version 2019).[52]
New generator costs	Capital, variable O&M, and fixed O&M costs are based on the moderate case in NREL's 2021 Annual Technology Baseline.[53]
Fuel prices	Near-term fuel prices are based on forward market data (where available), and blended to the long-run fuel price trajectory from the 2021 AEO.
Transmission	Transmission capability in GridSIM is represented as a "pipe and bubble" framework, which aggregates transmission capacity into larger "pipes" between load and generation "bubbles" as defined by 25 EIA EMM regions. Transmission capacity is based on the 2021 AEO Reference Case.[30] Like most bulk system capacity expansion models, GridSIM does not model the distribution system.

The calculation of the reference case term $D^{ref}_{r,y,h,m,mt}$ in Equation 9 differs by measure type mt. For efficiency and flexibility measures, the calculation bases reference case electricity demand on that of the appropriate counterfactual technology or technologies from the AEO forecast. For EL measures, an "inefficient" EL counterfactual is developed that assumes the deployment of a substantial mix of electric resistance heating and water heating alongside heat pumps to fulfill the added electric service. Settings for the inefficient counterfactual measures are consistent with those from scenario 1.1 in Table 4 and are described further in the next section.

Measure-level results from Equation 9 are multiplied by GridSIM's marginal cost forecasts for each grid region and summed across all hours of the year, regions, and measures to develop portfolio-level estimates of avoided system cost benefits in year y, ΔB_y:

$$\Delta B_y = \sum_{m}^{M} \sum_{r}^{R_m} \sum_{h=1}^{8760} \Delta D_{r,y,h,m,mt} \, M_{r,y,h} \qquad \text{(Equation 10)}$$

where $M_{r,y,h}$ is the GridSIM marginal system cost forecast (2020\$/MWh) for region r, projection year y, and hour of the year h, and system costs are inclusive of energy, capacity (generation/transmission), and, if applicable, renewable energy credits but do not include distribution costs. To ensure internal consistency between the avoided system cost estimates and the treatment of EL load impacts in Equation 9 as incremental to an inefficient EL reference, the added regional electricity demand from inefficient EL is reflected in the GridSIM capacity expansion forecast that determines the marginal system costs $M_{r,y,h}$ of Equation 10. Additional details on GridSIM's marginal cost outputs are available in the supplemental experimental procedures.

Finally, incremental measure deployment costs are calculated to enable direct comparisons between measure costs and benefits. As with system cost savings, incremental costs are calculated first at the measure-level, and then aggregated to a portfolio-level estimate in year y, ΔC_y:

$$\Delta C_y = \sum_{m}^{M} \Delta I_{y,m} \, CRF_m \, S^{stk-ref}_{y,m} \sigma_{y,m} \, a_{y,m}, \qquad \text{(Equation 11)}$$

$$CRF_m = \frac{i\,(1+i)^l}{(1+i)^l - 1} \qquad \text{(Equation 12)}$$

where $\Delta I_{y,m}$ is the incremental, unit-level installed cost of measure m in 2020\$ compared with a counterfactual reference case technology in year y, CRF_m is a capital recovery factor that annualizes incremental measure costs using the assumed real discount rate $i = 5.88\%$ and measure lifetime l, $S^{stk-ref}_{y,m} \sigma_{y,m}$ is the total portion of applicable reference case stock that the measure captures through year y before competition, and $a_{r,y,m}$ adjusts for competition of measure m with other measures in the portfolio. Our 5.88% real discount rate assumption reflects the weighted average cost of capital of a utility making resource investment decisions after removing the effects of inflation, which is assumed to be 2%.

Building decarbonization scenarios

Table 4 details the 12 scenarios considered in this study along with key modeling assumptions. Individual scenarios are distinguished by the three demand-side measure features introduced previously—EE, load EL, and DF—and by four input dimensions that span both the demand- and supply-side of building energy use.

- Market-available technology performance range: the energy performance levels of building technologies available for purchase by end-use consumers, bounded by a minimum performance "floor" and a maximum performance "ceiling." DF measure features are integrated with a subset of EE measures, and thus the level of DF deployment depends on scenario settings for the EE dimension.
- Electrification of building loads: the rate at which fossil-based equipment is converted to electric service via EL measures, and the efficiency level of the converted equipment. As with the market-available technology performance range dimension, DF features are integrated with a subset of EL measures.
- Early retrofits: a small but increasing fraction of consumers that choose to replace existing building equipment and/or shell components before the end of their useful lifetimes.
- Power sector: the annual average CO_2 emissions intensity of the electricity supplied to the building sector across the modeled time horizon (2023–2050).

Here, we elaborate on the measure features and input dimensions that distinguish our modeling scenarios.

Scenario measure features

The EE, EL, and DF measure features considered in this study represent, respectively: persistent reductions in equipment energy use (e.g., via installation of a higher-performance device) or in the demand for energy services (e.g., via improved building envelopes or operational controls); conversions of fossil-based heating, water heating, and cooking to electric service; and load shedding and shifting in response to grid needs. Measure features are sometimes mixed; for example, heat pump EL measures or more efficient EE measures can be scheduled to operate in off-peak hours on the grid in a given region to increase DF. In each modeled year, measures compete for market share across four tiers of energy performance.

- Tier 0: AEO 2021 Reference Case counterfactual technologies, which reflect the sales-weighted average technology in the AEO forecast
- Tier 1: Market-available technologies that meet the latest ENERGY STAR, IECC, or ASHRAE 90.1 performance guidelines in the projection year[55–57]
- Tier 2: The best performing technologies currently available on the market, including equipment that packages both EE and DF features
- Tier 3: Breakthrough technologies with aggressive cost and performance targets that are assumed to be achieved at scale by the time of market entry in a future year

Cost and performance characteristics for Tier 1 and 2 technologies are modified over time as needed to maintain a consistent incremental cost and performance difference from their Tier 0 counterfactuals across the model time horizon. Where possible, measure unit-level installed cost, performance, lifetime, and market/market entry settings are drawn from previous building sector analyses[12,45] and updated to reflect the latest expectations and ambitions for building technology development.[58,59] Table 5 outlines key data sources for these inputs at each measure tier and Tables 6 and 7 include detailed input values for key envelope, HVAC, and water heating measures across each of the tiers. Detailed inputs are also separately available via a list of definitions for the approximately 170 individual building measures that are represented in scenario runs.[64]

We note that while EE and EL measure features are represented across all four performance tiers, DF features are restricted to the best available performance tier (Tier 2). This restriction simplifies the handling of DF features in the analysis and reflects the assumption that such features are most likely to be packaged with higher-end technology offerings. We acknowledge that Tier 3 breakthrough technologies would also fall into this higher-end category; however, the technology roadmapping process that determines performance and cost targets for these technologies (Table 5) focuses on annual performance metrics and does not encompass DF assessment, therefore DF features are not represented for Tier 3 measures.

Scenario input dimensions

The settings for four key input dimensions distinguish the 12 scenarios outlined in Table 4: market-available technology performance range, rate and efficiency of load EL, early retrofit assumptions, and degree of power grid decarbonization.

A scenario's market-available technology performance range denotes the lowest- and highest-performing technologies made available to consumers in a given year (the bounding technology performance "floor" and "ceiling"). In our scenarios, the technology performance floor is represented by either Tier 0 or 1 technologies, depending on assumptions about building performance codes and appliance efficiency standards. When more aggressive codes and standards are not assumed (scenarios 1–1.1, 2.3–2.4, 3.3–3.4), the technology floor is set to the Tier 0 level, consistent with the reference case counterfactual technology. Scenarios that assume enactment of more aggressive codes and standards by a certain year (2–2.2, 3–3.2) remove the Tier 0 technologies from market competition in that year and set the performance floor to be consistent with Tier 1 technologies for the remainder of the modeling time horizon. Similarly, the technology performance ceiling is represented by Tier 2 or 3 technologies, depending on assumptions about the introduction of technologies with breakthrough cost and performance characteristics. When breakthrough technology introduction is not assumed (scenarios 1–1.1, 2.2–2.4, 3.2–3.4), the technology performance ceiling is set to Tier 2; otherwise, the ceiling is set to Tier 3 beginning in the year that breakthrough technology introduction is assumed (as in scenarios 2–2.1 and 3–3.1). Step changes in both the technology performance floor and ceiling are implemented on a technology class-by-class basis but are reflected globally across all building energy segments that associate with the technology class.

Rates of building heating, water heating, and cooking load EL are exogenously specified based on a separate analysis conducted in consultation with Guidehouse. The analysis pairs Guidehouse's expert judgment of HVAC and water heating market characteristics and key adoption drivers and barriers with an assessment of equipment stock turnover and shipments to develop four plausible scenarios of conversions from fossil-based to electric equipment in the residential and commercial heating and water heating sub-sectors. The Guidehouse conversion scenarios demonstrate differing degrees of movement in annual sales toward heat pumps by a given year under varying assumptions about federal and utility incentives, state and local restrictions, and product innovations (see Table S3). Conversion rates are distinguished by region, building type, fuel, equipment type, and scenario, as shown in Figures S15–S18 for the two EL scenarios adapted for our analysis, "optimistic" (used in scenarios 2–2.4) and "most aggressive" (used in scenarios 1–1.1 and 3–3.4). The weighted average national heat pump sales shares as a portion of total unitary AC plus heat pump and total storage water heater sales are shown in Table 8, which provides values assumed in other recent studies for context. We also assume natural gas cooking conversions, which were not assessed in the Guidehouse analysis; here, we set conversion rates to the values developed for the heating end use on the recommendation of the Guidehouse analysts. Further details about the conversion rates and adaptation of the Guidehouse analysis are available in the supplemental experimental procedures.

Electrification conversions generally occur with high efficiency in our scenarios, as fossil-based heating and water heating equipment moves to air source heat pumps and heat pump water heaters, respectively. Ground-source heat pump (GSHP) adoption is represented at AEO 2021 Reference Case levels across all scenarios. In scenario 1.1., we explore the implications of "inefficient" EL of heating and water heating, where fossil-based equipment is converted to a mix of heat pumps and electric resistance heating and water heating. The share of heat pumps vs. resistance in the technology mix is consistent with AEO 2021-forecasted electric equipment sales shares in 2021—53% heat pumps (including GSHPs)/47% resistance (residential heating), 9%/91% (residential water heating), 56%/44% (commercial heating), 4%/96% (commercial water heating).[65,66] Cooking EL carries an efficiency increase that is based on the average change in energy intensity between gas

Table 4. Summary of modeling scenarios and key assumptions

	Market-available technology performance and cost range			Electrification of load			
Scenario	Raise floor	Raise ceiling	Additional efficiency/flexibility not in reference case[a]	Switching rate	Efficiency level	Early retrofits	Power grid
1: Low benchmark (BM), high EL to HPs under reference grid	N/A	N/A	N/A	Guidehouse most aggressive (see Table 8 for details)	switch to HPs (mix of HP performance levels depends on market-available range)	N/A	GridSIM Reference Case
1.1: Low BM without efficient EL	N/A	N/A	N/A	Guidehouse most aggressive	switch to BAU sales mix of HPs/resistance[b]	N/A	GridSIM Reference Case
2: Moderate BM, modest EE and EL to HPs under 80 × 2050 grid	moderate (elevated codes and standards take effect in 2030)	moderate (breakthrough technology enters market in 2035)	- HVAC, appliance, and commercial lighting and plug load controls - efficient window and roof replacements - conversion of resistance-based heating and water heating to HPs per Guidehouse optimistic rate (see Table 8 for details)	Guidehouse optimistic	switch to HPs	N/A	moderate (80% reduction in grid emissions from 2005 levels by 2050)
2.1: Moderate BM with early retrofits	moderate	moderate	- HVAC, appliance, and commercial lighting and plug load controls - efficient window and roof replacements - conversion of resistance-based heating and water heating to HPs per Guidehouse optimistic rate	Guidehouse optimistic	switch to HPs	represented (see Table 9 for details)	moderate
2.2: Moderate BM without breakthrough EE	moderate	N/A	- HVAC, appliance, and commercial lighting and plug load controls - efficient window and roof replacements - conversion of resistance-based heating and water heating to HPs per Guidehouse optimistic rate	Guidehouse optimistic	switch to HPs	N/A	moderate
2.3: Moderate BM without breakthrough EE or elevated codes and standards	N/A	N/A	- HVAC, appliance, and commercial lighting and plug load controls - efficient window and roof replacements - conversion of resistance-based heating and water heating to HPs per Guidehouse optimistic rate	Guidehouse optimistic	switch to HPs	N/A	moderate

(*Continued on next page*)

Table 4. *Continued*

	Market-available technology performance and cost range			Electrification of load			
Scenario	Raise floor	Raise ceiling	Additional efficiency/flexibility not in reference case[a]	Switching rate	Efficiency level	Early retrofits	Power grid
2.4 Moderate BM without EE	N/A	N/A	N/A	Guidehouse optimistic	switch to HPs	N/A	moderate
3: Aggressive BM, high EE and EL to HPs under 100 × 2035 grid	aggressive (elevated codes and standards take effect in 2025)	aggressive (breakthrough technology enters the market in 2030)	2–2.3 with Guidehouse most aggressive rate of resistance-based heating and water heating conversion to HPs	Guidehouse most aggressive	switch to HPs	N/A	aggressive (100% zero-carbon grid by 2035)
3.1: Aggressive BM with early retrofits	aggressive	aggressive	2–2.3 with Guidehouse most aggressive rate of resistance-based heating and water heating conversion to HPs	Guidehouse most aggressive	switch to HPs	represented	aggressive
3.2: Aggressive BM without breakthrough EE	aggressive	N/A	2–2.3 with Guidehouse most aggressive rate of resistance-based heating and water heating conversion to HPs	Guidehouse most aggressive	switch to HPs	N/A	aggressive
3.3: Aggressive BM without breakthrough EE or elevated codes and standards	N/A	N/A	2–2.3 with Guidehouse most aggressive rate of resistance-based heating and water heating conversion to HPs	Guidehouse most aggressive	switch to HPs	N/A	aggressive
3.4: Aggressive BM without EE	N/A	N/A	N/A	Guidehouse most aggressive	switch to HPs	N/A	aggressive

Scenarios are differentiated by the degree of demand-side building efficiency, flexibility, and electrification deployment as well as by the degree of decarbonization of the electricity supplied to buildings. Three benchmark scenarios are highlighted in gray; remaining scenarios in each group are used to explore key sensitivities relative to the benchmarks.

[a] Reference case: AEO 2021 Reference Case projections.

[b] 53% HPs/47% resistance res. heating, 9%/91% res. water heating, 56%/44% com. heating, 4%/96% com. water heating.

Table 5. Summary of building decarbonization measure energy performance tiers and key input data sources

Measure performance tier	Features assessed	Market entry year	Key data sources	
			Performance	Cost
0: AEO Reference Case counterfactual technologies	EL[a]	2023	AEO 2021 Reference Case forecast[30]	AEO 2021 Reference Case forecast[30]
1: Currently available ESTAR/IECC/90.1	EE, EL	2023	latest ENERGY STAR specifications[55]; IECC 2021[56]; 90.1–2019[57]	EIA equipment cost forecasts (major end use equipment)[60]; NREL Residential Measures Database (residential envelope)[61]; RSMeans (residential/commercial envelope)[62]; Guidehouse Grid-Interactive Efficient Building (GEB) Technologies Data Report (plug loads)[63]
2: Currently best available on the market	EE, DF, EL	2023	GEB Roadmap and underlying measure potential analysis, updated to latest performance specifications (all EE + DF measures)[12,13,59]; EIA equipment performance forecasts (major end use equipment EE)[60]	EIA equipment cost forecasts (major end use equipment EE cost component)[60]; Guidehouse GEB Technologies Data Report (DF cost component of all EE + DF measures, EE cost component for plug loads measures)[63]; NREL Residential Measures Database (envelope)[61]
3: Prospective cost and performance targets	EE, EL	2030 (aggressive); 2035 (moderate)	DOE BTO Roadmaps[58] or targets based on highest potential performance level when recent Roadmap is unavailable[b]	

See Scout GitHub repository[64] for full measure list and details.

[a] When on the market, reference case heat pumps and/or a mix of reference case heat pumps and reference case electric resistance (for inefficient EL scenario 1.1) are subject to the same Guidehouse electrification rates as electrification measures in higher performance tiers; such reference case electrification technologies represent an efficiency gain over comparable fossil-based equipment.

[b] Relevant in particular to HVAC, water heating, and refrigeration technologies. For these technologies, an aggressive performance target is established for the market entry year using the high-end of currently market-available technologies as a benchmark; an installed cost is then calculated using Scout given this performance level to meet a 5 year consumer payback period. This process is consistent with that used to develop cost and performance targets in existing BTO Roadmaps, such as those for Windows & Envelope and Sensors & Controls. For ASHPs, separate cost targets are calculated in cold climates vs. non-cold climates; all HP targets are all based on a fuel switching context in which the HP is replacing fossil-based heating/water heating equipment.

and electric cooking units in the AEO 2021 Reference Case forecast—73% for residential cooking and 55% for commercial cooking.[65,66]

Two scenarios in our analysis (2.1 and 3.1) assume that, in each year, a small fraction of consumers decides to replace existing equipment and/or envelope components before the end of their useful lifetimes, thus accelerating the pace with which building decarbonization measures can penetrate baseline markets. Annual early retrofit fractions are specified separately by building and equipment or envelope component type as summarized in Table 9. Residential and commercial fractions are initialized for the start year 2023 on the basis of building renovation data from the American Housing Survey and EIA CBECS, respectively.[46,67] To produce these initial rate estimates, we focus on the proportion of buildings in the year from the data that report retrofitting a given technology before the end of its expected useful lifetime. For example, for commercial HVAC equipment, we find the total number of buildings constructed between 1990 and 2008 that report having previously undergone an HVAC renovation in the CBECS survey (conducted in 2008), under the assumption that HVAC equipment typically functions for 20 years and thus would not be regularly replaced until 2010 at the earliest. We divide this number by the total number of buildings constructed in that time period, and annualize by dividing the result by 18 years (2008–1990). Note that this approach folds all early replacements into an annual "snapshot" rate—e.g., in the HVAC example, we count early replacements that occur before 2008 for 1990 vintage HVAC equipment, which is nearing end-of-life, and for post-1990 vintage HVAC equipment that still has several more years on its useful lifetime. To represent the effects of building policies that encourage early retrofitting behavior,[68,69] we represent a 4-fold escalation in each initial annual rate by 2035, with rates remaining at the 2035 value in all subsequent years. For EL measures, we represent 100% conversion of any baseline stock that turns over and converts to electric service via early retrofits, assuming that consumers who are persuaded to undergo early retrofits will also be encouraged to electrify their equipment.

Finally, power grid decarbonization is represented at three levels in our analysis, all of which are based on GridSIM forecasts. The lowest level, reference case grid reflects only the impacts of already-enacted state-level renewable portfolio standard mandates; this trajectory is paired in scenarios 1 and 1.1 with the most aggressive rates of building EL to explore the emissions implications of accelerating EL under a slowly decarbonizing grid. Moderate scenarios (2–2.4) reflect a grid that is decarbonized 53% vs. 2005 levels by 2030 and 80% by 2050, which is consistent with the 2050 reduction goal of the 2016 US Mid-century strategy[70] and results in similar grid development to existing modeling scenarios that assume low renewable energy costs.[71] Finally, our most aggressive scenarios (3–3.4) reflect a grid that is 79% decarbonized by 2030 and 100% decarbonized by 2035, consistent with the Biden-Harris Administration clean electricity goal.[1] As described in Table 3 and further in the supplemental experimental procedures, overall growth in electricity demand is consistent with the AEO 2021 Reference Case in the GridSIM reference forecast, but reflects higher levels of transportation and building electricity demand growth in the 80x2050 and 100x2035 scenarios. Distributed generation adoption—primarily rooftop solar photovoltaic (PV)—is represented across all cases as a decrement to building electricity demand and grows at AEO 2021 Reference Case levels, from 0.22 quads site electricity in 2023 to 0.7 quads site electricity in 2050.[30]

Table 6. Detailed measure settings for residential and commercial envelope and HVAC solutions across performance tiers

Measure	Perf. tier	Affected markets	Market entry year	Building type	Energy performance	Installed cost (in 2017\$ unless otherwise noted)
Ref. case ASHP (EL)	0	all unitary fossil-based HVAC equipment[a], associated envelope (EL, EL + DF); all electric resistance or air source heat pump HVAC equipment, associated envelope (EE, EE + DF)	2023	residential	4.63 COP (cooling), 2.58 COP (heating)	\$5,150/unit (new homes); \$9,150–\$10,150/unit (existing homes)
				commercial	3.3 COP (cooling and heating)	\$141/kBtu/h cooling
ESTAR ASHP, 90.1/IECC envelope (EL, EE)	1	all unitary fossil-based HVAC equipment[a], associated envelope (EL, EL + DF); all electric resistance or air source heat pump HVAC equipment, associated envelope (EE, EE + DF)	2023	residential	*equipment:* 4.69 (cooling), 2.70 (heating), *envelope components:* R-2.5-3.7, 0.25-0.4 SHGC (windows); R-15-25 (walls); R-47-60 (roofs); R-15-31 (floors); 5 ACH (air seal)	*equipment:* \$6,100/unit (EE, EL new homes); \$11,100/unit (EL existing homes), *envelope components (2016\$):* \$48/ft^2 glazing (windows); \$8.9/ft^2 wall (walls); \$2.1/ft^2 roof (roofs); \$5/ft^2 footprint (floors); \$0–\$1.2/ft^2 wall (new-existing air seal)
				commercial	*equipment:* 3.4 COP (cooling and heating), *envelope components:* R-2.25-2.98 (windows); R-16.8-25.3 (walls); R-0-19.6 (floors); R-25-31 (roofs); 0.4 CFM/ft^2 @ 0.3 in. w.c. (air seal)	*equipment:* \$141/kBtu/h cooling, *envelope components (2016\$):* \$56.2/ft^2 glazing (windows); \$27.4/ft^2 wall (walls); \$5/ft^2 footprint (floors); \$6.3/ft^2 roof (roofs); \$0–\$0.9/ft^2 wall (new-existing air sealing)
Best available ASHP, envelope (EL + DF, EE + DF)	2	all unitary fossil-based HVAC equipment,[a] associated envelope (EL, EL + DF); all electric resistance or air source heat pump HVAC equipment, associated envelope (EE, EE + DF)	2023	residential	*EL + DF, EE + DF:* consistent with residential ASHP + envelope/pre-cooling load savings shape developed in Langevin et al.[12] and updated in Langevin et al.[59,b]	*equipment:* \$6,357/unit (EE + DF, EL + DF new homes); \$11357/unit (EL + DF existing homes, *envelope components:* \$57/ft^2 glazing (windows); \$10.8/ft^2 wall (walls); \$4.5/ft^2 roof (roofs) (2016\$); \$5–\$6.8/ft^2 footprint (new-existing floors); \$0.31–\$2/ft^2 wall (new-existing air seal)
				commercial	*EL + DF, EE + DF:* consistent with commercial HVAC + envelope/pre-cooling load savings shape developed in Langevin et al.[12] and updated in Langevin et al.[59,c]	*equipment:* \$178/kBtu/h cooling, *envelope components (2016\$):* \$56.2/ft^2 glazing (windows); \$37–\$41.8/ft^2 wall (walls); \$7/ft^2 roof (roofs); \$10–\$11.9/ft^2 footprint (floors); \$0.46–\$2.2/ft^2 wall (new-existing air seal)

(*Continued on next page*)

Table 6. ***Continued***

Measure	Perf. tier	Affected markets	Market entry year	Building type	Energy performance	Installed cost (in 2017$ unless otherwise noted)
Prospective ASHP, envelope, controls (EL, EE)	3	all unitary fossil-based HVAC equipment,[a] associated envelope (EL, EL + DF); all electric resistance or air source heat pump HVAC equipment, associated envelope (EE, EE + DF)	2030/2040 (equipment and windows/all other envelope, aggressive); 2035/2040 (moderate)	residential	*equipment:* 12 COP (cooling), 6 COP (heating), *envelope components:* R-13, 0.09 SHGC cooling (windows); +R-40 (walls add-on); R-15-31 (floors); 1 ACH (air seal),[d] *controls:* 30% heating and cooling savings	*equipment:* $5,520/unit (non-cold climates); $6,223/unit (cold climates), *envelope components (2016$):* $55/ft^2 glazing (windows), $0.75/ft^2 wall (walls add-on); $0.79/ft^2 footprint (floors); $0.9–$1.2/ft^2 wall (new-existing air seal),[d] *controls (2023$):* $0.5/ft^2 floor
				commercial	*equipment:* 12 COP (cooling), 6 COP (heating), *envelope components:* R-10, 0.09 SHGC cooling (windows); +R-40 (walls add-on); +R-50-64 (roofs add-on); 0.2 CFM/ft^2 @ 0.3 in. w.c. (air seal), *controls:* 30% HVAC savings	*equipment:* $51/kBtu/h cooling (non-cold climates); $41 kBtu/h cooling (cold climates), *envelope components (2016$):* $66/ft^2 glazing (windows); $1.9/ft^2 wall (walls); $0.55/ft^2 roof (roofs); $0.16–$0.53/ft^2 wall (new-existing air seal), *controls (2023$):* $1/ft^2 floor

See Scout GitHub repository[64] for full measure list and details.

[a] Excludes large commercial boiler/chiller configurations; prospective residential HVAC controls measures are limited to single/multi-family homes, and prospective commercial HVAC controls measures are limited to offices, schools, food service, and retail.

[b] For residential EL + DF measures, hourly load savings impacts from Langevin et al.[59] are added on top of an increase in annual efficiency from that of the fossil-fired baseline equipment to electric equipment with a market-weighted average performance level (4.55 COP [cooling] and 1.88 COP [heating]), per market share-weighted electric equipment performance from AEO 2021 Reference Case forecast.

[c] For commercial EL + DF measures, hourly load savings impacts from Langevin et al.[59] are added on top of an increase in annual efficiency from that of the fossil-fired baseline equipment to electric equipment with a market-weighted average performance level (4.13 COP [cooling] and 2.32 COP [heating]), per market share-weighted electric equipment performance from AEO 2021 Reference Case forecast.

[d] No prospective residential roof target has been established.

Table 7. Detailed measure settings for residential and commercial water heating solutions across performance tiers

Measure	Performance tier	Affected markets	Market entry year	Building type	Energy performance	Installed cost (in 2017$ unless otherwise noted)
Reference case HPWH (EL)[a]	0	all fossil-based storage water heating equipment (EL, EL + DF); all electric storage water heating equipment	2023	residential	3.3 UEF	$2,075/unit
				commercial	3.9 COP	$299/kBtu/h water heating
ESTAR HPWH (EL, EE)	1	all fossil-based storage water heating equipment (EL, EL + DF); all electric storage water heating equipment	2023	residential	*EL:* 3.30 UEF (new homes); 2.2 UEF (existing fuel switching homes, which assumes integrated 120V to avoid panel upgrade) *EE:* 3.30 UEF	$2,075/unit
				commercial	N/A	N/A
Best available HPWH (EL + DF, EE + DF)	2	all fossil-based storage water heating equipment (EL, EL + DF); all electric storage water heating equipment	2023	residential	*EL + DF, EE + DF:* consistent with HPWH load savings shape Langevin et al.[12] and updated in Langevin et al.[59,b]	$2,756/unit
				commercial	3.9 COP	$299/kBtu/h water heating
Prospective HPWH (EL, EE)	3	all fossil-based storage water heating equipment (EL, EL + DF); all electric storage water heating equipment	2030 (aggressive); 2035 (moderate)	residential	3.55 UEF	$2,266/unit
				commercial	3.9 COP	$33/kBtu/h water heating

See Scout GitHub repository[64] for full measure list and details.

[a] Reference case residential and commercial HPWHs are consistent with ESTAR residential HPWH and Best commercial HPWH performance and cost settings, and are therefore not separately assessed from these measures in the model runs.

[b] For residential EL + DF measures, hourly load savings impacts from Langevin et al.[59] are added on top of an increase in annual efficiency from that of the fossil-fired baseline equipment to electric equipment with a market-weighted average performance level (1.13 UEF), per market share-weighted electric equipment performance from AEO 2021 Reference Case forecast.

Table 8. Comparison of the Guidehouse 2030 and 2050 heat pump sales shares consistent with the electrification rates assumed in this study against 2019 heat pump sales shares and heat pump sales shares assumed in other recent decarbonization studies that addressed the building sector

		Guidehouse (%)				USF, evolved energy, LBNL (%)[21]		Energy innovation (%)[22]		Princeton (%)[20]		ACEEE (%)[18]	
		Optimistic		Most aggressive		BASE 350		NDC pathway		E+		NREL EFS high	
Sub-sector	2019 US HP sales market share (%)[a]	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Residential heating	37	50	76	75	90	60	85	100	100	60	90	61	86
Residential water heating	1	20	60	50	85	45	55	100	100	45	60	44	59
Commercial heating	9[b]	20	42	30	66[c]	50	75	100	100	50	80	39	71
Commercial water heating	0.10	5	30	10	50	45	60	100	100	40	60	18	40

Guidehouse heat pump heating sales shares represent portion of total sales of central AC equipment plus heat pumps (residential) and portion of total commercial space heating consumption (commercial); rates for comparable studies are typically relative to total heating equipment sales. Sales shares are exclusive to heat pumps and do not include electric resistance technologies.

[a] Based on AHRI and DOE rulemakings market share and shipments data.

[b] Reflects RTU market data.

[c] Assumes 85% of RTU sales are HPs by 2050; caps non-RTU HP sales at 50% by 2050 to reflect significant retrofit challenges for this segment (e.g., converting fossil-fired boilers).

Analysis limitations

Key methodological limitations are grouped into those concerning the buildings and power system modeling for this study.

Regarding the buildings modeling, rates of end-use EL are determined based on exogenously developed scenarios; the scenarios reflect expert judgments of plausible levels of fossil-based equipment conversions to heat pumps under different market and regulatory conditions paired with analysis of HVAC and water heating stock totals and rates of stock turnover. This approach reflects the lack of reliable bottom-up models of consumer EL decisions in the buildings context. The EL rates in our analysis can serve as useful benchmarks for policy programs that seek to drive the levels of building emissions reductions estimated in our study; however, additional research is needed to compare the conversion rates used in our analysis against real-world data on consumer fuel switching costs and decision-making across US regions, both historically and given additional policy support for EL in the coming years. This research must also improve the understanding of the full range of factors that influence consumer EL decisions, including consideration for resilience and the possibility of continued reliance on fossil-fuel backup service (e.g., dual fuel heat pump configurations).

Second, our building decarbonization scenarios reflect the effects of an increased technology performance floor—e.g., through more aggressive building energy codes and performance standards and appliance efficiency standards—as an increase in minimum market-available technology performance levels across all regions that begins in a certain year. While appliance efficiency standards can be increased across regions via federal regulations, building energy codes and performance standards are adopted at the local and state

Table 9. Rates of early retrofit assumed in scenarios 2.1 and 3.1 and supporting data sources

Data source	Component retrofitted (year range)	Starting annual early retrofit rate (%)	by 2035 (4×)
Building type: Commercial			
CBECS 2012[46]	lighting (2000–2008)	1.5	6
CBECS 2012[46]	HVAC (1990–2008)	0.9	3.6
CBECS 2012[46]	roof (1990–2008)	0.6	2.4
CBECS 2012[46]	windows (1990–2008)	0.3	1.2
CBECS 2012[46]	insulation (1990–2008)	0.3	1.2
Use commercial HVAC	water heating	0.9	3.6
N/A	all other	0	0
Building type: Residential			
AHS 2019[67]	HVAC (1990–2008)	0.5	2
AHS 2019[67]	roof (1990–2008)	0.27	1.08
AHS 2019[67]	windows (1990–2008)	0.23	0.92
AHS 2019[67]	insulation (1990–2008)	0.06	0.24
Use residential HVAC	water heating	0.5	2
Use commercial lighting	lighting	1.5	6
N/A	all other	0	0

Early retrofit rates represent equipment or envelope component replacements before end-of-life; initial rates increase through 2035 and remain flat thereafter.

levels and, in practice, adoption timelines will vary from jurisdiction to jurisdiction. Moreover, our analysis represents the effects of more aggressive building codes and standards on market-available envelope component performance levels in both new construction and retrofit contexts. Although we base envelope performance levels on model IECC and ASHRAE building energy codes with provisions for both new construction and major renovations,[56,57] performance requirements for renovations are sometimes less stringent, reflecting the difficulty of upgrading envelopes in existing buildings. Moreover, some jurisdictions may consider envelope retrofits like basic insulation and air sealing to be minor upgrades, or may apply codes more narrowly to new construction only. Increased adoption of building performance standards that apply to existing buildings may fill these gaps, but enactment of such performance standards is still at an early stage. Accounting for these nuances would reduce the influence of codes and envelope retrofits on results, but further measure development is needed to explore the magnitude of this effect.

Third, we generate grid profiles of hourly building demand and demand reductions based on data from a previous study[12,59] and inherit the data limitations noted in that study: possible under-representation of the diversity in end-use load profiles, a coarse resolution of representative weather conditions that drive loads, and the use of typical meteorological year weather conditions that do not reflect the most extreme within-year variations in hourly weather patterns or the effects of climate change. An additional limitation is the use of typical electric heating load profiles to assess the hourly load impacts of heat pump measures not specifically assessed in Langevin et al.[12]: in practice, temperature responses can vary across different heat pumps.[72] Taken together, these limitations could collectively result in either under- or over-estimation of the peak load impacts of building efficiency and flexibility measures, with associated implications for grid modeling estimates. We also note the need to extend modeling of DF features to the breakthrough measure tier: as mentioned, breakthrough measure characteristics are based on roadmapping analysis that focuses on annual performance metrics that do not encompass measure flexibility characteristics.

Fourth, we note uncertainties in our reference case forecast of building demand and technology evolution, which is based on the 2021 AEO Reference Case.[30] Key drivers of uncertainty in the AEO projections include energy prices and economic activity, as well as changes in building market conditions, technological breakthroughs, and laws or regulations that go into effect after each AEO is developed.[73] These factors have resulted in a 7% difference, on average, between AEO-projected and actual building energy consumption between 1994 and 2021. AEO projections also tend to overestimate building consumption and errors tend to be larger for years farther out in the forecast.[73] Use of the AEO Reference Case may therefore slightly inflate the energy reduction potential of our decarbonization scenarios, particularly in the long run.

Finally, we recognize limitations in the scope of our demand-side analysis. First, the building decarbonization measures we explore do not include emerging community/district-level decarbonization strategies, such as renewable geothermal heating and cooling on campuses or in urban centers, which may become increasingly important in the US for decarbonizing dense clusters of large commercial buildings. Second, we assess only operation-phase building emissions and do not account for other life-cycle GHG emissions associated with building material manufacturing, transport, construction, and disposal. These emissions are an important source of building sector GHG contributions, and will only grow in significance as operational emissions from buildings are reduced to support economy-wide decarbonization goals.

Regarding power system modeling, our estimates of avoided power system costs only include avoided generation costs (capital expenditures and production costs) and avoided transmission costs. The analysis does not currently account for distribution costs, which would need to increase to accommodate new EL-related load. Taking these additional costs into account would increase the overall power system costs across all grid scenarios, and would likewise increase the gross benefits of the demand-side measures by avoiding generation, transmission, and distribution costs. We identify the assessment of avoided distribution costs as an important opportunity for expanding our research.

Second, geographic variation in the power system modeling is limited to 25 regions. We do not account for nodal variation in prices, which would require significant computational power in a national modeling study. We also do not account for transmission congestion within regions. Representation of these additional within-region constraints likely would result in larger estimates of power system investment, and higher demand-side measure benefits in our study.

Third, we estimate the system cost benefits of demand-side efficiency and flexibility based on marginal costs. While marginal costs do endogenously account for the supply-side impacts of inefficient building EL and EL of the transport sector, for this study GridSIM's generation capacity expansion decisions do not endogenously account for interactions between further demand-side efficiency and flexibility measures and supply-side resource options. GridSIM does have the capability to allow such demand-side resources to compete with supply-side measures, and this could provide valuable insight regarding the quantity and type of power generation resources that would be avoided through demand-side investment, as well as a more robust view of how power system operations would change due to the addition of cost-effective demand-side measures.

Finally, we do not account for interactions and linkages with decarbonization in other sectors that may impact hourly building demand (e.g., increased deployment of residential electric vehicle charging, behind-the-meter batteries, distributed generation, and other distributed energy resources). Considering these sectoral linkages would require specific deployment assumptions, as well as additional hourly building load modeling that explores the coordination of building efficiency and flexibility with other distributed energy resources and its implications for building sector energy and emissions and power system costs.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.07.008.

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AUTHOR CONTRIBUTIONS

Conceptualization, J.L., A.S.-M., A.J.S., and R.H.; methodology, J.L., A.S.-M., R.H., J.O., and K.P.; software, J.L., A.S.-M., J.O., K.P., and H.C.-P.; investigation, J.L., A.S.-M., J.O., K.P., and H.C.-P.; resources, J.L. and R.H.; data curation, J.L., A.S.-M., J.O., and K.P.; writing – original draft, J.L., A.S.-M., R.H., J.O., and K.P.; writing – review & editing, J.L., A.S.-M., A.J.S., R.H., J.O., and K.P.; visualization, J.L., A.S.-M., R.H., J.O., and K.P.; supervision, J.L., A.J.S., and R.H.; project administration, J.L. and A.J.S.; funding acquisition, J.L. and A.J.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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